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Contents

Abstract

The 10th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS'17) was be held in Rome (Italy) on 6-8 September, 2017. The EEMODS conferences have been very successful in attracting distinguished and international presenters and attendees. The wide variety of stakeholders has included professionals involved in manufacturing, marketing, and promotion of energy efficient motors and motor driven systems and representatives from research labs, academia, and public policy.

EEMODS'15 provided a forum to discuss and debate the latest developments in the impacts of electrical motor systems (advanced motors and drives, compressors, pumps, and fans) on energy and the environment, the policies and programmes adopted and planned, and the technical and commercial advances made in the dissemination and penetration of energy-efficient motor systems. In addition EEMODS covered also energy management in organizations, international harmonization of test method and financing of energy efficiency in motor systems. The Book of Proceedings contains the peer reviewed paper that have been presented at the conference.

1 Introduction

This book contains the papers presented at the tenth international conference on Energy Efficiency in Motor Systems (EEMODS). EEMODS' 2017 organised in Rome, Italy, by University of L'Aquila on 6-8 September 2017. This major international conference has been very successful in attracting an international community of stakeholders consumption (including manufacturers, consumers, governments, international organisations, academia and experts) dealing with motor systems (motors, drives, pumps, compressors, fans, etc.) to discuss the progress achieved in technologies, industrial applications and policies, the strategies that need to be implemented to further progress this important work. Potential readers who may benefit from this book include researchers, engineers, policymakers, and all those who can influence the design, selection, application, and operation of motor system. Following the success of the previous EEMODS Conferences (Lisbon (1996), London (1999), Treviso (2002), Heidelberg (2005), Beijing (2007), Nantes (2009), Washington D.C. (2011), Rio de Janeiro (2013), Helsinki (2015)) the University of L'Aquila, with the scientific and technical support of the European Commission Joint Research Centre, has organizing the 10th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS'17).

EEMODS'17 has been very successful in attracting distinguished and international presenters and attendees. The wide variety of stakeholders included professionals involved in manufacturing, marketing, and promotion of energy efficient motors and motor driven systems (pumps, compressors, fans, etc.), policy makers and research. Segments represented come from manufacturing, academia, research, utilities, and public policy.

EEMODS’17 has provided a forum to discuss and debate the latest developments in the impacts of electrical motor systems on energy and the environment, the energy efficiency policies and programmes, standards (including ISO 50.001) and programmes adopted and planned, and the technical and commercial advances made in the dissemination and penetration of energy-efficient motor systems.

The three-day conference will include plenary sessions where key representatives of governments and international organizations, manufacturers, program managers and experts will present their views and programmes to advance energy efficiency in motor systems, for example, through international co-operation on efficiency requirements. Parallel sessions on specific themes and topics will allow in-depth discussions among participants.

The conference was very international by nature, and aims to attract high quality and innovative papers and participants from every corner of the world.

The papers presented in the scientific/technical sessions during the 3 days covered the following topics:

1. Electric Motors
2. Emerging Motor Technologies
3. Power Electronics and Drives.
4. Pumping Systems
5. Compressed Air Systems
6. Fan / Exhauster Systems
7. Refrigeration Systems
8. Mechanical Power Transmission
9. Motors in Household Appliances and HVAC

10. Motors and Drives for Transportation and other Applications
11. Industrial Management Policies
12. Motor System Audit and Programmes
13. Policies, Programmes and Financing
14. Global Test Standards
15. System Efficiency
16. Utility Programmes
17. Market surveillance and enforcement mechanisms.

2 POLICIES

EU Member States Energy Efficiency Policies for the industrial sector based on the NEEAPs analysis.

Paolo Bertoldi

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Abstract

The EU has been promoting energy efficiency through a number of policies such as the Eco-design, the Energy Efficiency Directive (EED), etc. Only a few polices have been targeting the industrial sector. In addition, climate policies (e.g. The EU Emission Trading scheme, ETS) have also contributed to improving energy efficiency in industry. EU Member States (MSs) have introduced additional polices at national level to promote energy efficiency in industry. The Energy Efficiency Directive initially and then the EED have required MSs to submit to the European Commission National Energy Efficiency Plans (NEEAPs) every three years. MSs in their NEEAPs present the present and planned policies in the different sectors in order to reach the 2020 energy efficiency targets.

There are several national policies in the industrial sector. The present paper analyses the major national energy efficiency policies (e.g. voluntary agreements, training, financial incentives, etc.) and their impact on energy savings based on the most recent NEEAPs of 2014. The paper in particular focuses on policies that stimulate energy efficiency in motor systems. The paper highlights some particularly successful policies and it makes recommendation on a possible successful package of policies to stimulate energy efficiency in the industrial sector and in motor systems.

Introduction

The need to increase energy efficiency progress in the EU was reinforced in the Conclusions of the European Council meeting of 8-9 March 2007. The EU's Climate and Energy package sets three key objectives to be achieved by 2020, namely: to reduce EU greenhouse gas emissions to 20% below 1990 levels; to increase the share of EU energy consumption produced from renewable resources to 20%; and to improve EU energy efficiency by 20% fixing a maximum level of energy consumption.

To provide a legal basis to the energy efficiency target, the Energy Efficiency Directive[1], (EED), was adopted in October 2012. The Directive quantifies the 20% energy efficiency target defined in the Climate and Energy package, establishes a common framework of legally binding measures for the promotion of energy efficiency in the EU in order to the target by 2020, and paves the way for greater energy efficiency beyond that date.

The Directive, which is a key part of the EU's overall climate and energy legislative package, requires EU Member States to set indicative national energy efficiency targets and legally binding measures to help the EU reach its 20% energy efficiency target by 2020. In particular, all EU Member States are required to implement policy measures that improve energy efficiency at all stages of the energy chain from production to final consumption.

In compliance with the Directive’s requirements, Member States have to present the progress and efforts made in the so-called National Energy Efficiency Action Plans (NEEAPs), which are due every three years starting from 2014. The NEEAPs are regarded

[1] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2012/30/EU and repealing Directives 2004/8/EC and 2006/32/EC, OJ L 315, 14.11.2012, p.1.

as strategic national policy documents placing energy efficiency at the heart of energy policy [1][2]. They outline national energy efficiency targets and detail actions put in place to ensure that energy savings are generated in all sectors of the economy. The previous experience gained through the submission of NEEAPs under the Energy Services Directive 2006/32/EC (ESD)[2][3] has provided a strong foundation upon which Member States have continued to develop and strengthen their energy efficiency policy strategies. While only a few Member States have had experience with preparing energy efficiency policy strategies prior to the ESD adoption, the ESD experience has helped Member States move from a simple list of measures to comprehensive strategies that plan, monitor and report the efforts made in energy efficiency in the various sectors of the economy. Improvements especially for New Member States (EU13) are now noted due to this experience built up over the years with the ESD implementation.

The EED is more ambitious than its predecessor ESD and its scope has been expanded. In addition to energy efficiency measures at the end-use level, Member States are obliged to report measures taken to improve the efficiency of the supply sector (e.g. cogeneration), which also count towards the EED energy efficiency targets.

Energy Saving Obligations (officially Energy Efficiency Obligation Schemes, EEOSs) on energy companies to achieve 1.5% annual energy savings among their customers every year have been introduced in Article 7, giving the option to MSs to use also alternative measures resulting in equal savings [3]. Other measures introduced are: requirement for the public sector to renovate annually 3% of central government building stock; measure on metering and billing; and long-term strategies for the renovation of the national building stock.

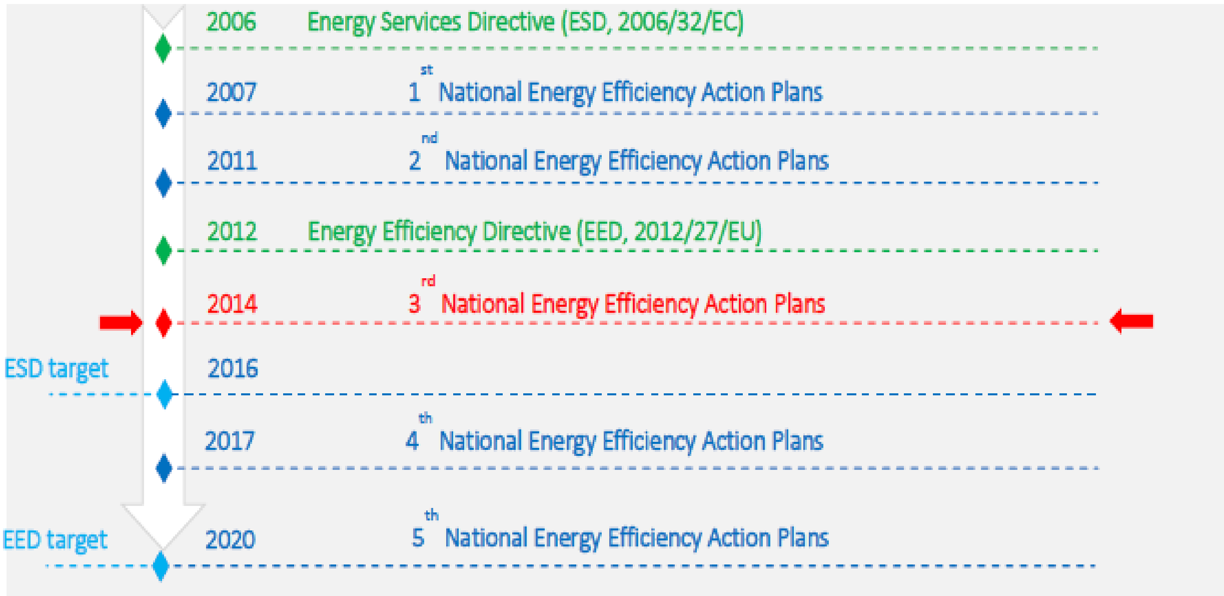

Figure 1: Timeline of National Energy Efficiency Actions Plans under the ESD and EED

As per the Directive's requirements, the European Commission's responsibilities include evaluating the plans and assessing the extent to which Member States have made progress towards the achievement of the national indicative energy efficiency targets and towards the implementation of the Energy Efficiency Directive in general. As with the analysis of previous NEEAPs under the ESD, the Joint Research Centre has undertaken

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[2] European Union, 2006, Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC

[3] In compliance with the ESD, the first and second ESD NEEAP were due in 2007 (a year after the entry into force of the ESD) and 2011

the task of evaluating the first National Energy Efficiency Action Plans of the EED and the results of this work are presented in this paper. As the final round of the NEEAPs under the ESD coincided with the submission of the first NEEAPs[4] under the EED, these were replaced by the first EED NEEAP.

For the industrial sector it is of particular interest Article 8 of the EED, which addresses energy audits and places the following obligations on MSs with respect to the promotion of energy audits [4] [5] [6]. MSs are required to promote the availability of high quality energy audits to all final energy customers. MSs must establish mandatory energy audits for larger enterprises[5] that must be carried at regular intervals and must ensure that that the minimum criteria for energy audits detailed in Annex VI of the EED are met. Organisations that are implementing energy or environmental management systems [7] [8] are exempt from this requirement provided that the systems incorporate regular energy audits that meet the minimum criteria given in Annex VI. Furthermore, Article 8 requires the Member States to develop programmes to encourage small to medium-sized enterprises (SMEs) [9] to undergo energy audits and implement the recommendations from these audits.

More recently the EU has also adopted energy and climate targets for 2030, as follows:

- 40% cut in greenhouse gas emissions compared to 1990 levels;
- at least a 27% share of renewable energy consumption;
- at least 27% energy savings[6].

Following this new target the Commission has proposed an amendment to the EED to extend Article 7 till 2030 and to give a legal based for the 2030 energy efficiency target.

The EU legislative framework is complemented by policies, programmes and measures implemented by the MSs, as described in the NEEAPs. This is an important driver for the observed trends in energy consumption in the EU.

However several barriers still prevent the full uptake of all the cost-effective energy efficiency solutions, hence additional and effective policies are needed [10] [11] [12] [13] [14].

[4] also requests information on the progress of the ESD targets.

[5] As requirement to undergo mandatory and regular energy audits applies only to enterprises that are not SMEs a key task for MSs will be to identify relevant enterprises. Therefore a formal and standardised definition of SMEs is needed. The EED uses the definition given in Commission Recommendation 2003/361/EC. The category of micro, small and medium-sized enterprises are defined as "*enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding EUR 50 million and/or an annual balance sheet total not exceeding EUR 43 million*".

[6] In December 2016 the European Commission has proposed a target of 30%

Energy Consumption Trends in the Industrial Sector

In the period from 2000 to 2015, the European Union has reduced its energy consumption. This decrease has allowed reducing energy indicators such as energy intensity and energy consumption per capita, turning into a sign of higher competitiveness as global actor. In 2014, the EU had already met the target values set in the EED for 2020 (Figure 2) in terms of final energy consumption (1,061 Mtoe in 2014 vs 1,086 Mtoe of the target) and it was on track to reach the target value for primary energy consumption (1,505 Mtoe in 2014 vs 1,483 Mtoe of the target; corresponding to a gap of 1.5%). In 2015 final energy consumption increases (1,084 Mtoe) compared to the previous year, but still remains under the 2020 target. Primary energy consumption increases as well (1,530 Mtoe in 2015; corresponding to a gap of 3.2%), by interrupting the decreasing trend started in 2010. Over this period, the financial and economic crisis has caused remarkable change in the dynamics and growth rates of the different economic sectors and in the EU Member States, and it has contributed to get the energy consumption back on track towards the EU energy and environmental targets for 2020.

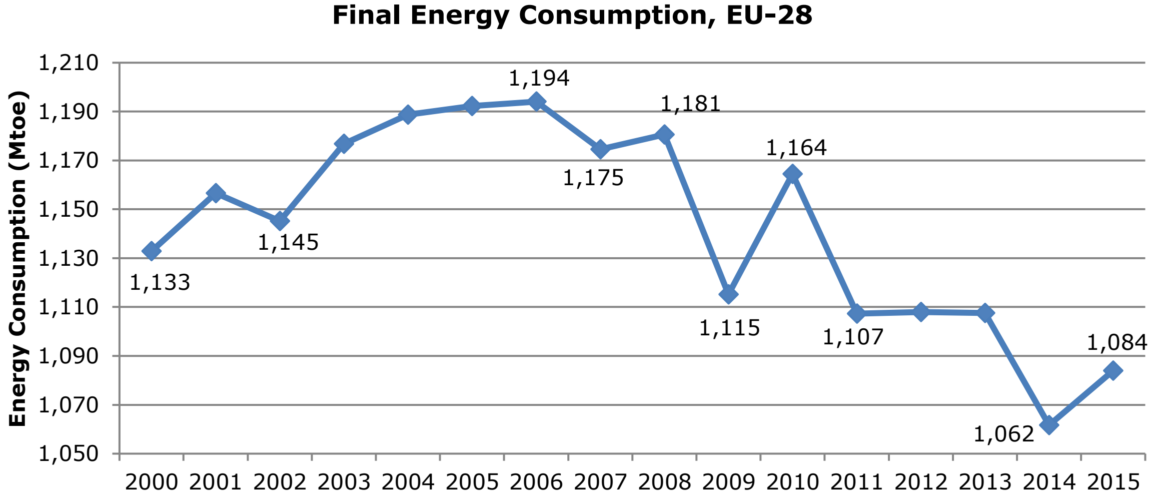

Figure 2: Final Energy Consumption in the EU-28, 2000-2015. Source: Eurostat

This energy was mainly consumed by four sectors as illustrated in Figure 3. In 2015, the sector with the largest share of final energy consumption was the transport sector, which consumed 33.09% of the total amount of final energy consumption. The second was the residential sector, consuming 25.38%. Industry is third with a consumption of 25.35%, and lastly there is the service sector, with a share of 13.55%.

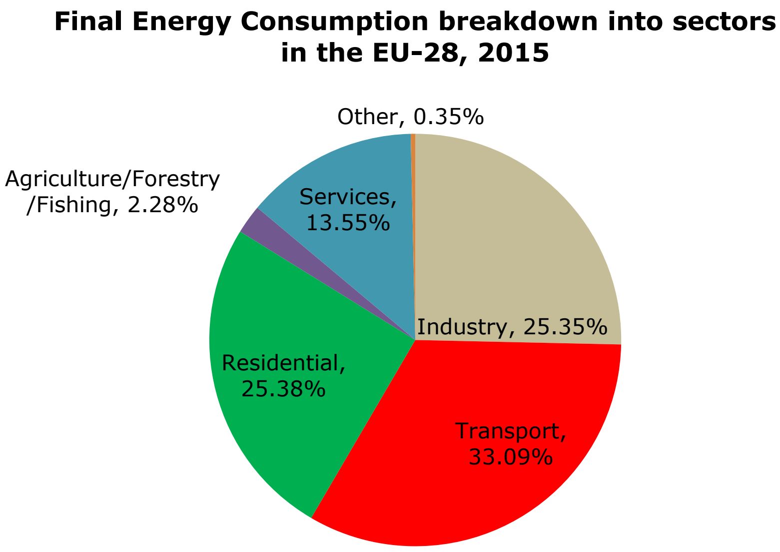

Figure 3: Share of energy source to final energy consumption in the EU-28 in 2015. Source: Eurostat

Distinguishing by economic sectors as shown in figure 4, the transport and the tertiary sector have increased their final energy consumption over the analysed period; whilst in the others (i.e. residential and industry sectors) the final energy consumption has declined. The increasing trend in the tertiary sector is expected to continue as per the on-going tertiarisation process in the EU. On the other hand, the decreasing trend in industry sector has been highly influenced, among others, by the financial and economic crisis and structural changes.

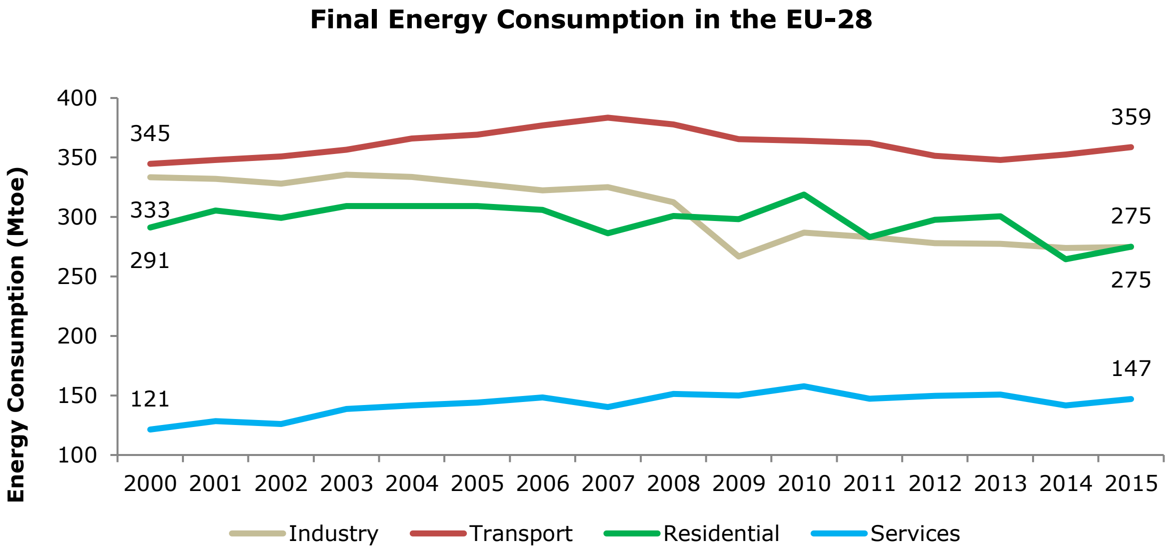

Figure 4: Final energy consumption in main sectors in the EU-28, 2000-2015. Source: Eurostat

Industry final energy consumption in the EU-28 has fallen by 17.6% in the period 2000-2015. A similar decrease has been observed both in EU-15 and NMS-13 areas which have reduced their consumptions by 17.5% and 18% respectively. The maximum annual consumption of this period took place in the year 2003 when it reached 335.6 Mtoe, while the minimum occurred in 2009 when the final energy consumption decreased to 267 Mtoe, as illustrated in Figure 5. 2009 is the year with the lowest consumption not only during the analysed period but also considering the 26-years period comprised between 1990 and 2015. This has probably been due to the impact of the financial and economic crisis. A decreasing trend in the final energy consumption has been registered during the last 16-years period with exception for the years 2003 and 2010 when the consumption rebounded from the dramatic drop by 14.6% in year 2009. Since 2010, the decreasing trend has been continued reaching in 2014 the second lowest value over the 1990-2015 period. In 2015 a slight increase (0.28%) has been registered but energy consumption in industry is expected to keep a decreasing trend in the future due to the ongoing industry reallocation that could lead to a permanently smaller manufacturing sector in the EU.

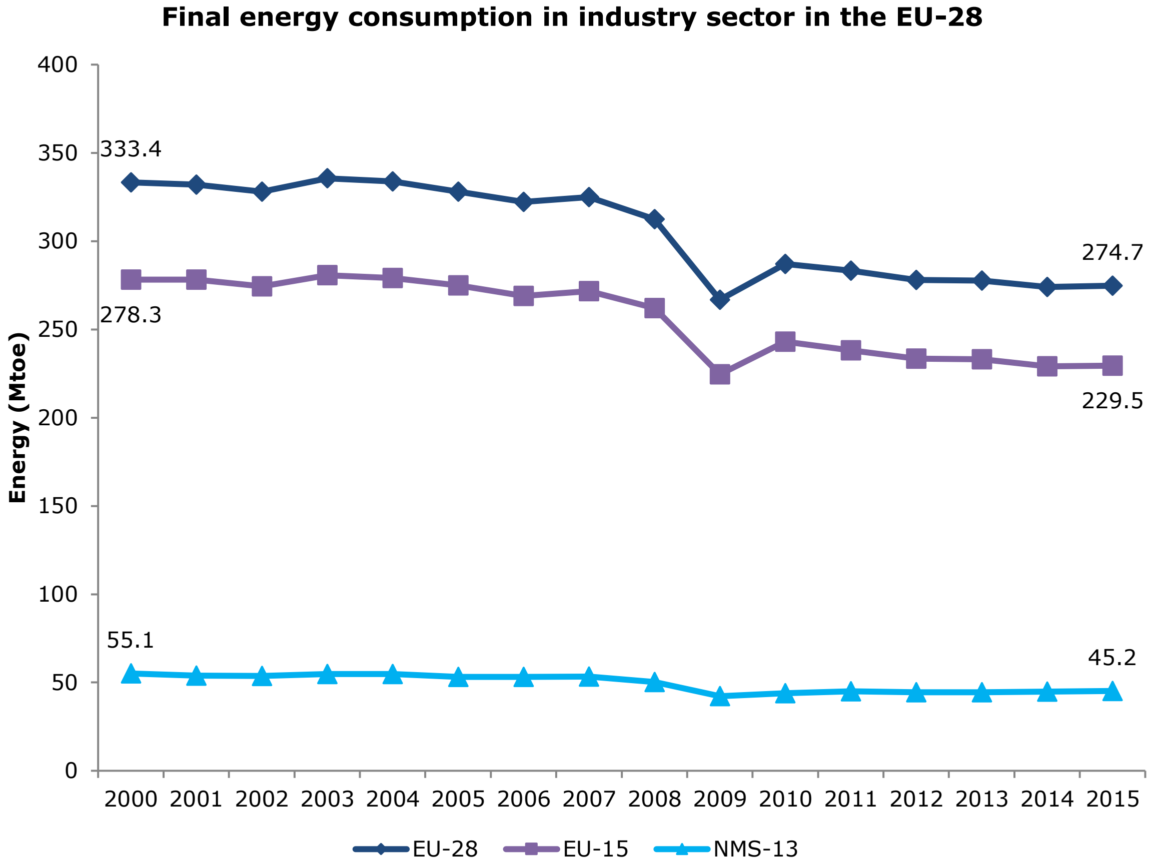

Figure 5: Industry sector: final energy consumption in the EU-28, 2000-2015. Source: Eurostat

In 2015, gas and electricity were the main contributors to the energy mix in the industry sector with 86.6 Mtoe and 85.7 Mtoe respectively. These fuels represented over 60% of the energy mix; gas accounted for 31.53% and electricity for 31.18% of the total consumption. The rest of the energy mix was constituted by solid fuels (12.70%), petroleum products (10.14%), renewable energies (7.78%), derived heat (5.51%) and non-renewable waste (1.16%) (figure 6).

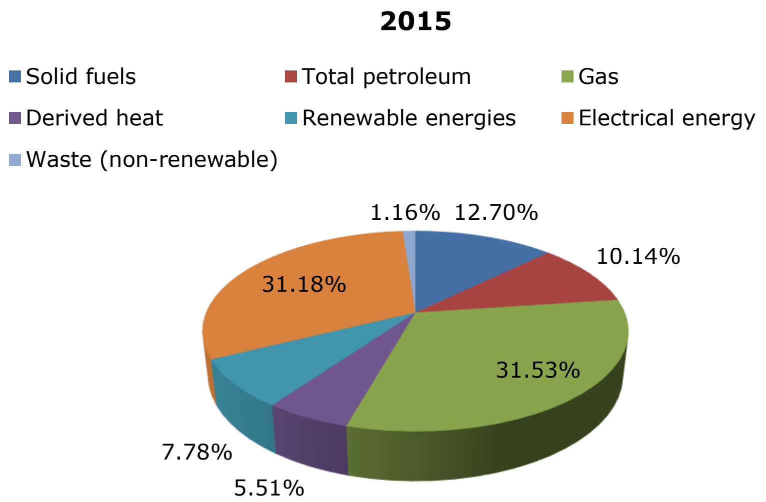

Figure 6 Industry sector: final energy mix by percentage in 2015. Source: Eurostat

The final energy consumption in the industry sector is broken-down into different industry subsectors: Construction, Mining and Quarrying, Iron and Steel; Non-Ferrous Metals; Chemical and petrochemical; Non-Metallic Minerals; Food and Tobacco; Textile and Leather; Paper, Pulp and Print; Transport Equipment; Machinery; Wood and Wood Products; and Other Industries. The industry final energy consumption per subsector is reported in figure 7

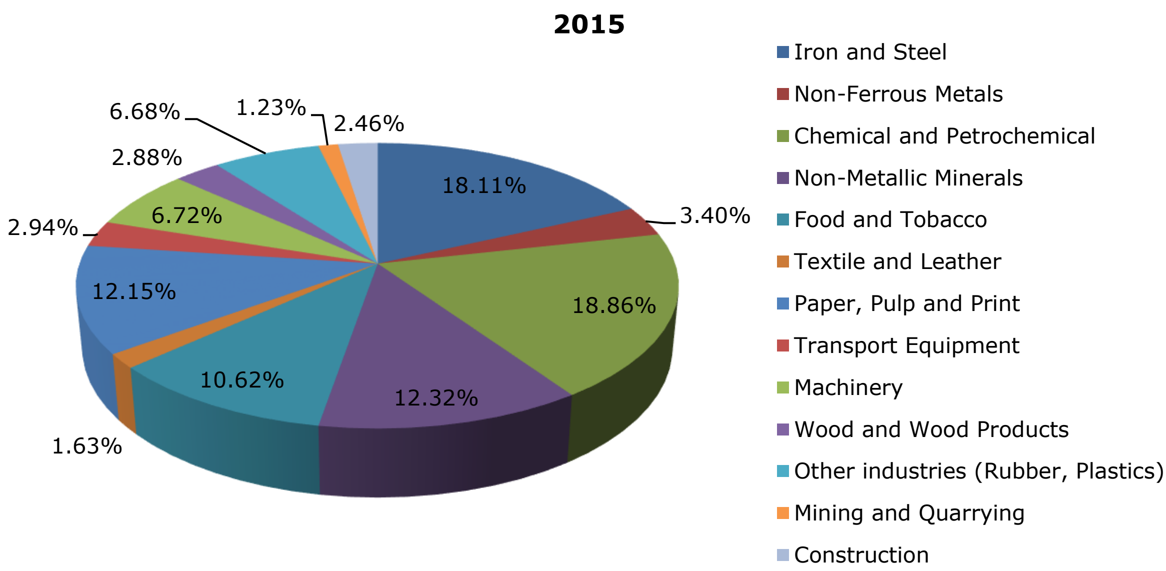

Figure 7: Industry sector: final energy consumption percentage by subsectors in 2015. Source: Eurostat

An interesting indicator used as benchmark for the analysis of the energy efficiency levels in the manufacturing industry is the average energy consumption per unit of production. This ratio is shown for three main industrial products in EU-28: steel, cement and paper. Overall, this parameter shows stable values over the period 2000-2014. In 2014, the energy consumption per ton of produced paper was 0.3446 toe/t, representing a drop by 11.66% in comparison to year 2000. Among the three analysed products paper showed the highest ratio over the whole period, as illustrated in Figure 8. In 2014, the production of one tonne of crude steel consumed 0.2830 toe/t on average in EU-28. Crude steel is the product which has reduced its energy consumption per unit of production the most (by -18.28%). Cement has instead increased its ratio of energy consumed per unit of production by 3.23% during the analysed period, reaching 0.081 toe/t in 2014.

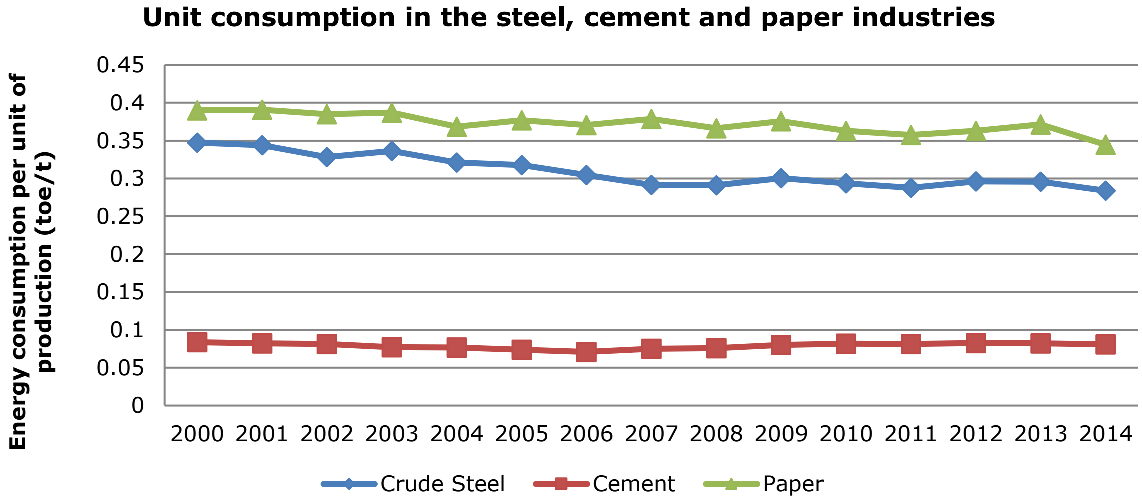

Figure 8: Average energy consumption per tonne of produced crude steel, cement and paper in EU-28, 2000-2014. Source: Odyssee

Policy measures under the National Energy Efficiency Action Plans

Various policy measures are reported in the NEEAPs targeting each sector of the economy, individually or in a horizontal manner. A number of countries have had a long tradition in promoting energy efficiency before action at the EU level was taken, with some measures starting well before the ESD adoption in 2006. Specifically, Austria, Denmark, France, Finland, Germany, Italy, the Netherlands, Sweden, and the UK have implemented energy efficiency policy measures since the 1990s, including in the industrial sector. Following the ESD adoption, a sharp increase of measures starting in the period 2007-2009 was observed and then a subsequent second peak in 2014 largely attributed to the introduction of the NEEAPs under the EED.

The 2014 EED NEEAPs include a mixture of "old" measures already reported in the previous NEEAPs (2008 and 2011) under the ESD as well as new measures, introduced in 2014 or planned to be introduced in the following years. Around 60% of the measures mentioned in the EED NEEAPs are measures previously notified in the last two NEEAPs under the ESD [15] [16]. Half of these measures were mentioned in both ESD NEEAPs, while the other half in the second ESD NEEAP only. In addition, both the ESD and the EED allow counting the impact of previously existing and continuing measures for meeting energy savings targets, which explains the large number of measures starting before the years of preparing the NEEAPs. All of this is indicating a general continuation of energy efficiency policy at national level. Member States with long tradition in energy efficiency policy (such as Denmark, Finland, Germany, France etc.) typically have no space for many new measures and instead largely rely on existing measures, which are periodically reinforced and aligned with the new requirements of the EU directives. The description of policy measures was provided with varying degree of detail. Typical policy information included the policy type, implementation timeframe, sectors targeted and short descriptions. There are some good examples with information categorised according to general information (e.g. Category; Duration; Target groups; Measure description; relevant webpage), implementation details (e.g. Geographical scope; Budget and financial resources, Implementing authority), achieved/expected impact, calculation methodology, assumptions as well as monitoring & verification.

As requested by Article 24(2) of the EED, the European Commission published a NEEAP Template[7] to support Member States with the NEEAP reporting requirements. While the NEEAPs were legally required to report on the information specified in the EED Annex XIV Part 2, the template encouraged Member States to adopt a common structure by listing compulsory elements[8] together with explanatory notes. The existence of the template was overall positively perceived and resulted in more homogeneous reporting among Member States compared to past NEEAPs submitted under the ESD. In compliance with the template and Article 24(2), implementation details of horizontal measures such as EEOSs had to be outlined followed by measures targeting each end-use sector (buildings, public sector, industry, transport) and energy supply sector. To complement the template published by the European Commission, additional guidelines were published in the Commission Staff Working Document "Guidance for National Energy Efficiency Action Plans"[17].

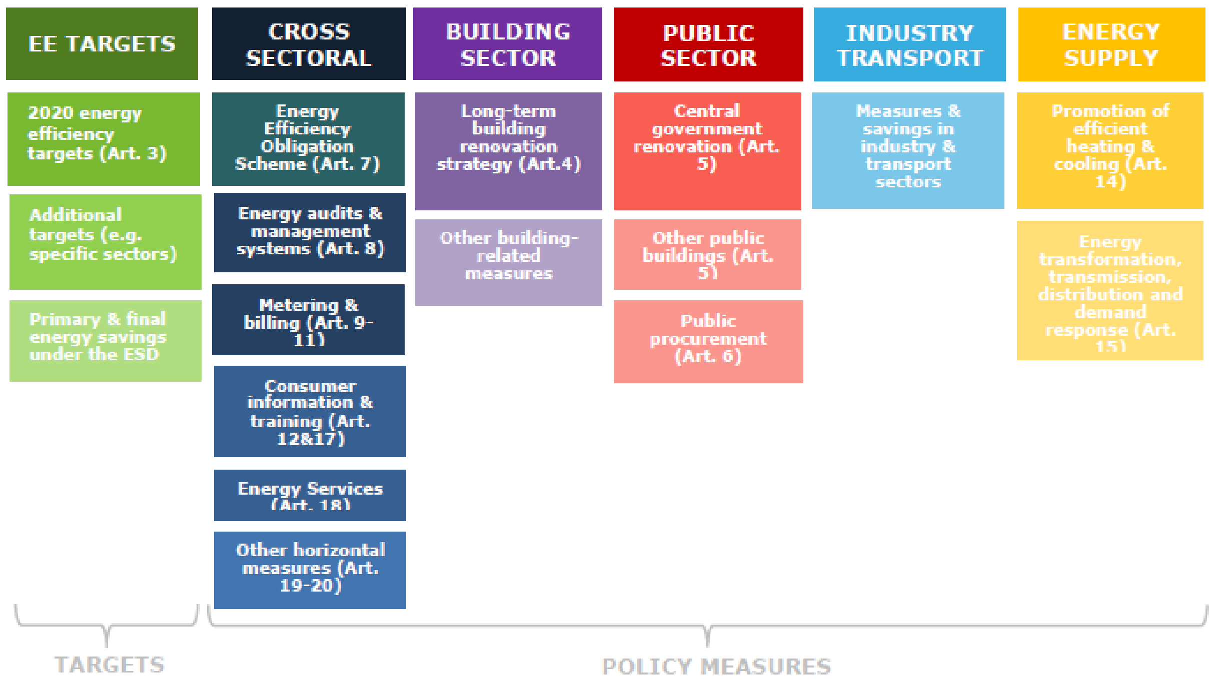

Figure 9: Structure of the NEEAP reporting template

In order to consolidate the information provided in the NEEAPs, policy matrices classifying measures according to sectors targeted and policy types have been developed for each Member State. The sectors considered are residential, services, industry, transport, public and energy supply. The policy measures were divided in the following categories: regulatory, financial and fiscal, information & awareness, qualification, training and quality assurance, market-based, voluntary agreements, infrastructure investments and other measures.

Table 1 provides a detailed breakdown of the types of policy measures considered.

[7] Implementing decision 2013/242/EU7 of 22 May 2013
[8] The elements of the template are listed in Annex D of the EED

Table 1. Categorisation of policy measures

Regulatory	Building codes; Minimum energy performance standards (MEPS) for new and existing buildings; Energy efficiency standards for appliances & equipment; refurbishment obligations; Procurement regulations; Phase-out of inefficient equipment
Financial and fiscal	Grants/subsidies; Preferential loans; Tax incentives; Energy taxation
Information and awareness	General Information; Information campaigns; Information Centres; Energy Audits; Energy labelling schemes; Governing by Example; Information exchange; Awareness campaigns; Demonstration programmes;
Qualification, training and quality assurance	Professional training; Training courses; Vocational education, quality standards
Market-based	Incentives facilitating Third Party Financing / ESCOs; Energy Efficiency Obligation Schemes (EEOSs); White certificates[9]; Incentives for the producers of innovative technologies; Technology deployment schemes
Voluntary action	Voluntary certification and labelling programs; Voluntary and negotiated agreements;
Infrastructure investments	Investments in transportation infrastructure (e.g. railways, road networks), energy infrastructure (e.g. generation plants, electrical grid, substations, and local distribution); Smart meter roll-out;
Other	Other measures that do not fall under one of the above categories

Measures in the industrial sector

Various financial incentives are offered to industry actors. Fiscal measures are also available. As example through the Energy Investment Allowance programme, Dutch companies are allowed to deduct 41.5% of energy efficiency investment costs from their taxable profits. Taxation on energy is a measure used by some Member States. In Austria taxation also covers industry. Higher taxes on electricity and natural gas for non-ETS industry apply in the Netherlands. In Germany, while energy taxes apply to all sectors, the manufacturing industry can benefit from "peak equalisation" if they can show that they have a certified energy management system or environmental management. This scheme allows enterprises in manufacturing industry to claim relief on up to 90 % of their energy and electricity tax, to safeguard their international competitiveness.

Voluntary agreements are a common policy instrument for the industry sector. The assessment of the NEEAPs shows that 9 Member States have established such agreements with industry actors, with the aim to engage various enterprises in energy efficiency measures. Specifically, Belgium (Flanders), Denmark, Finland, Ireland, Luxembourg, the Netherlands, Portugal, Sweden and the UK have mentioned voluntary agreements as a measure targeting the industrial sector. In Denmark, the main policy instrument for industry has been a 3-year voluntary agreement scheme which obliges companies to implement energy management and improve energy efficiency in their production in exchange of energy saving tax and as a rebate. This successful scheme ended at the end of December 2013 and a new voluntary agreement is under way. In

[9] Energy efficiency obligations coupled with a trading system for energy efficiency measures resulting in certified energy savings (tradable white certificates). Obligations can be coupled with various trading options: trading of certified energy savings, trading of eligible measures without formal certification, or trading of obligations.

Finland, medium-sized industrial companies and energy intensive industries can enter into an agreement, which allows them to receive subsidies of up to 25% of the investment costs of energy-efficient measures. As an example of this policy instrument, the second generation agreement has recently been concluded for the period 2014-2020 in Wallonia, which originally started in the 1990s involving industry federations, single enterprises and the government. This agreement consisted in a contract established between the Wallonia government and the most energy intensive industries via their federation. It has been reinforced and now includes the possibility of industries exploiting renewable energies and implementing an accounting system related to the CO_2 emissions associated with their products and services. Industries participating in this agreement are also invited to present a roadmap to 2050 whereby they outline their strategy to achieve specific energy efficiency and emissions reduction targets. In the Flanders Region of Belgium, a new agreement with companies operating under and outside the ETS system and consuming more than 0.1 PJ/year of primary energy has been established for the period 2014-2020. Participating companies undertake an energy audit every four years and implement periodic energy plans based on the audit outcomes. In exchange for this commitment the Flemish Region does not impose further energy efficiency or CO_2 reduction obligations (unless they are imposed by the EU).

In addition to the obligation of energy audits for large enterprises stipulated in Article 8 of the Directive, support for energy audits in industry is provided in various countries. In Finland, the Energy Audits programme, launched in 1992, is one of the most consolidated energy policies for the industry sector of the country. Subsidies are available for the realization of energy audits and cover 40% of the eligible costs for all organizations and 50% of the costs of SMEs that have signed an energy efficiency agreement. Subsidies for energy audits have also been mentioned for France (on-going), Wallonia (on-going), Greece (to start in 2015) and Lithuania (completed). In Portugal, the on-going SGCIE - Management System of Intensive Energy Consumption – programme has the objective to promote energy efficiency and monitor energy consumption for intensive consuming installations (>500toe).

Energy savings in the industry sector are also achieved through market-based instruments. In Italy, the white certificate scheme plays an important role for improving the energy efficiency of industry. In particular, all the energy savings claimed in the NEEAP for energy efficiency improvement measures in the industry sector are generated by actions implemented under Italy's existing white certificate scheme. The UK has the CRC Energy Efficiency Scheme (CRC), which is a mandatory scheme aimed at improving energy efficiency and cutting emissions in large, but non-energy intensive, public and private sector energy users. The Danish EEOS includes energy savings in enterprises covered by the emissions trading system (ETS). The newly-established EEOSs of Austria, Bulgaria, Denmark, Ireland, Luxemburg and Malta also plan to cover the industry sector.

The European Union Emission Trading Scheme, EU ETS (Directive 2003/87/EC) is another market instrument mentioned in some NEEAPs. For example, the most important measure for the industry sector in France is the national implementation of the EU ETS. France plans to use the revenues of the allowances auctioning for building renovation. In Germany, the EU ETS is expected to generate 2.5 Mtoe of primary energy savings in the period.

Conclusions

The NEEAPs have provided a strategic platform for Member States to set energy efficiency targets, outline planned or implemented end-use and supply level measures and evaluate the energy savings resulting from the implementation of these measures. With the introduction of the EED, the scope of the NEEAPs has been enhanced as MSs are now obliged to also cover measures taken to improve the efficiency of the supply sector and take into account the ETS sector. These measures may also count towards the EED energy efficiency targets, thereby moving from end-use ESD targets to more holistic targets considering all sectors of the economy. The previous experience with the ESD NEEAPs and the guidance provided by the European Commission's template has also allowed MSs to create more comprehensive and coherent strategies.

The legal requirements outlined in EED Annex XIV to be addressed in the NEEAPs were met with a varying level of detail. Several NEEAP measures reported by the MSs stem from the implementation and enforcement of other EU directives or regulations. While the majority of the measures presented in the NEEAPs are existing measures (expected for MSs with successful long lasting measures), the EED has also been a driver for new measures in MSs. In addition to the establishment of EEOSs, new or updated policy measures in the area of financing, information exchange, regulations as well as transport-related measures have been identified. Major measures in terms of energy savings generated have also been identified.

Measures in the industrial sector tend to be based on existing and working policies and programmes, in particular financial, incentives, energy taxation, voluntary agreements, energy audits, information and training and energy companies' obligations.

In conclusion, the EEDs offer a good frame that complements other EU directives (e.g. Eco-design and Energy Labelling, EPBD) and helps MSs to adopt targets and a structured and strategic plan based on national policies meeting the target. The NEEAP is a key tool for the presentation of the plan and for the monitoring of the energy savings already achieved and expected in the future. The quality of NEEAPs has progressed over time, also thanks to the template provided. A key role in the EED is played by Art. 7, which imposes mandatory targets. The positive experience gained in the EU through the NEEAPs and the associated energy saving reporting could be used also by other jurisdictions outside Europe to help prepare national energy efficiency strategies.

References

[1] Jean-Sébastien Broc, Paolo Bertoldi and Veronika Czakó, 2013, On the way to change of scale: review of NEEAPs' energy efficiency strategies for buildings, in ECEEE 2013 Summer Study Proceedings

[2] Paolo Bertoldi, Caiman Cahill, 2013, The role of NEEAPs, measurement methods and national targets to achieve the EU 2020 energy saving goal, in ECEEE 2013 Summer Study Proceedings

[3] Paolo Bertoldi, et al., 2015, How is Article 7 of the Energy Efficiency Directive being implemented? An analysis of national Energy Efficiency Obligation Schemes, in ECEEE 2015 Summer Study Proceedings

[4] Paolo Bertoldi and Tiago Serrenho, 2015, Energy Audits and Energy Management Systems under the Energy Efficiency Directive: what is the current situation? , in Proceedings of the EEMODS'15 Conference, Helsinki, September 2015

[5] Backlund Sandra, Thollander Patrik. Impact after three years of the Swedish energy audit program. Energy, Volume 82, 15 March 2015, Pages 54–60

[6] Fleiter Tobias, Gruber Edelgard, Eichhammer Wolfgang, Worrell Ernst. The German energy audit program for firms—a cost-effective way to improve energy efficiency? Energy Efficiency (2012)

[7] Thollander Patrik, Mikael Ottosson. Energy management practices in Swedish energy-intensive industries. Journal of Cleaner Production, Volume 18, Issue 12, August 2010, Pages 1125-1133

[8] Böttcher Christian, Müller Martin. Insights on the impact of energy management systems on carbon and corporate performance. An empirical analysis with data from German automotive suppliers. Journal of Cleaner Production, In Press, Corrected Proof, Available online 11 June 2014

9] Thollander Patrik, Dotzauer Erik. An energy efficiency program for Swedish industrial small- and medium-sized enterprises. Journal of Cleaner Production, Volume 18, Issue 13, September 2010, Pages 1339-1346

[10] Trianni Andrea, Cagno Enrico, Worrell Ernst, Pugliese Giacomo. Empirical investigation of energy efficiency barriers in Italian manufacturing SMEs. Energy, Volume 49, 1 January 2013, Pages 444-458

[11] Cagno Enrico, Trianni Andrea. Evaluating the barriers to specific industrial energy efficiency measures: an exploratory study in small and medium-sized enterprises. Journal of Cleaner Production, Volume 82, 1 November 2014, Pages 70–83

[12] Brunke Jean-Christian, Johansson Maria, Thollander Patrik. Empirical investigation of barriers and drivers to the adoption of energy conservation measures, energy management practices and energy services in the Swedish iron and steel industry. Journal of Cleaner Production, Volume 84, 1 December 2014, Pages 509–525

[13] Thollander Patrik, Backlund Sandra, Trianni Andrea, Cagno Enrico. Beyond barriers – A case study on driving forces for improved energy efficiency in the foundry industries in Finland, France, Germany, Italy, Poland, Spain, and Sweden. Applied Energy, Volume 111, November 2013, Pages 636–643

[14] Trianni Andrea, Cagno Enrico, Farné Stefano. Barriers, drivers and decision-making process for industrial energy efficiency: A broad study among manufacturing small and medium-sized enterprises. Applied Energy, In Press, Corrected Proof, Available online 7 April 2015

[15] European Commission, 2009, Commission Staff Working Document SEC(2009)889 final "Synthesis of the complete assessment of all 27 National Energy Efficiency

Action Plans as required by Directive 2006/32/EC on energy end-use efficiency and energy services: Moving Forward Together on Saving Energy

[16] European Commission, 2014, Commission Staff Working Document, SWD(2013) 541 final, "Progress Report on energy efficiency in the European Union Accompanying the document Report from the Commission to the European Parliament and the Council Progress Report on the application of Directive 2006/32/EC on energy end-use efficiency and energy services and on the application of Directive 2004/8/EC on the promotion of cogeneration based on a useful heat demand in the internal energy market {COM(2013) 938 final}"

[17] Commission Staff Working Document "Guidance for National Energy Efficiency Action Plans" Accompanying the document the Commission Implementing Decision establishing a template for National Energy Efficiency Action Plans under Directive 2012/27/EU of the European Parliament and the Council SWD(2013) 180 final

ISO 50001: How can it accelerate more energy efficient motor-driven systems?

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Abstract

ISO 50001 [1], an international standard setting the requirements for energy management systems (EnMS), is raising energy management and energy efficiency to a higher level of priority within companies and organizations, and improving the efficiency of motor-driven systems. The ISO 50001 EnMS continual improvement approach facilitates systematic thinking and creates a culture change within an organization around energy that involves people throughout the organization with various roles and responsibilities. ISO 50001 requires top management support and continual review of the EnMS to increase the investment of energy efficient technologies and practices. The standard requires identification of significant energy uses (SEUs), providing more context of the importance of energy consuming motor-driven systems within the overall facility energy footprint. It requires identifying, prioritizing, and implementing projects to improve the performance of these systems. ISO 50001 also requires staff to be trained on SEUs and to create operational control procedures around SEUs which helps to maximize critical motor-driven system energy efficiencies. Finally, ISO 50001 requires organizations to establish energy efficient design and procurement policies and procedures that empower the investment of system-optimized and best-available motor-driven system products. All of the above elements of ISO 50001 provide a management structure to accelerate implementation and investment of motor-driven systems within both manufacturing facilities and commercial buildings.

This paper will review the ISO 50001 standard, and also a US Department of Energy (U.S. DOE) program called Superior Energy Performance (SEP) that uses ISO 50001, and the results of SEP certified facilities. Analysis of energy performance data provided to U.S. DOE shows an increase in operational energy savings for motor-driven systems after implementation of ISO 50001. Case studies will be presented of several SEP certified facilities showing the types of energy saving projects implemented under the ISO 50001 EnMS and how motor-driven systems contributed to the overall continual improvement of the respective energy management systems.

Introduction

The energy efficiency opportunities of motor-driven systems have been well-known for many years. Within the United States manufacturing sector energy savings of the industrial sector have been estimated between 62 to 104 billion kWh per year, or 11 to 18 percent of motor-drive system electricity [2]. Yet despite this opportunity, the full savings potential has not been realized. Likewise, technology advancement in motor-driven systems, motor designs, and motor-driven equipment packages continues to further increase the energy saving potential. *The overarching problem of why the energy saving potential of motor-driven systems has not be reached is not a technological problem, but that organizations have not integrated energy within their business operations and managed energy as other business functions have been, such as, quality, safety, etc.*

Published in 2011, ISO 50001 provides organizations with an internationally recognized framework for implementing an energy management system (EnMS). An EnMS helps an organization internalize the policies, procedures, and tools to systematically track, analyze, and improve energy efficiency. It considers maintenance practices, operational controls, and the design and procurement of renovated, modified, and new equipment, systems, processes, and facilities. With ISO 50001, energy management is integrated into normal business processes involving multiple types of employees across the organization.

ISO 50001 is based on the Plan-Do-Check-Act (P-D-C-A) structure to continual improvement held in common with the ISO 9001 (quality management), ISO 14001 (environmental management), and other management systems. ISO 50001 is designed to be compatible with these management systems. Figure 1 shows the P-D-C-A ISO 50001 diagram with its key elements.

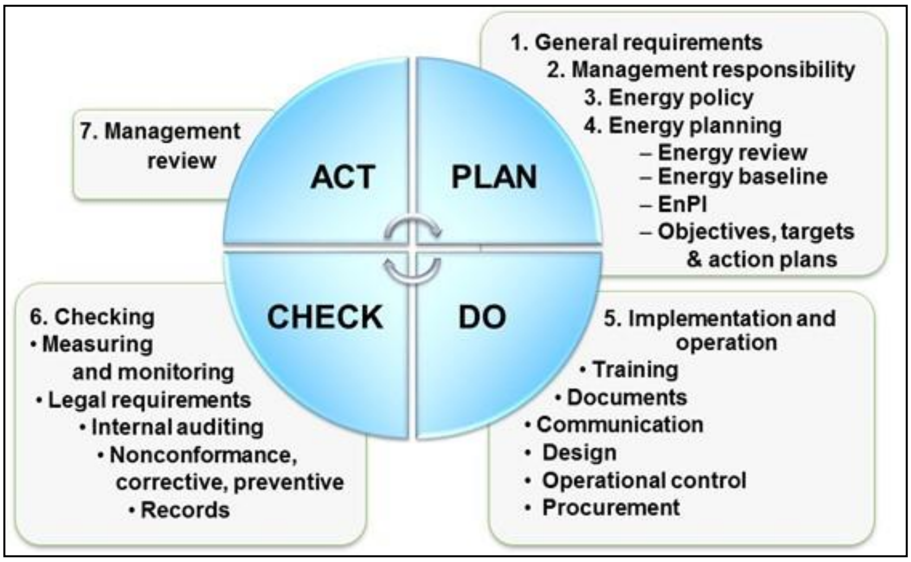


Figure 1 – Key ISO 50001 Energy Management System standard P-D-C-A elements

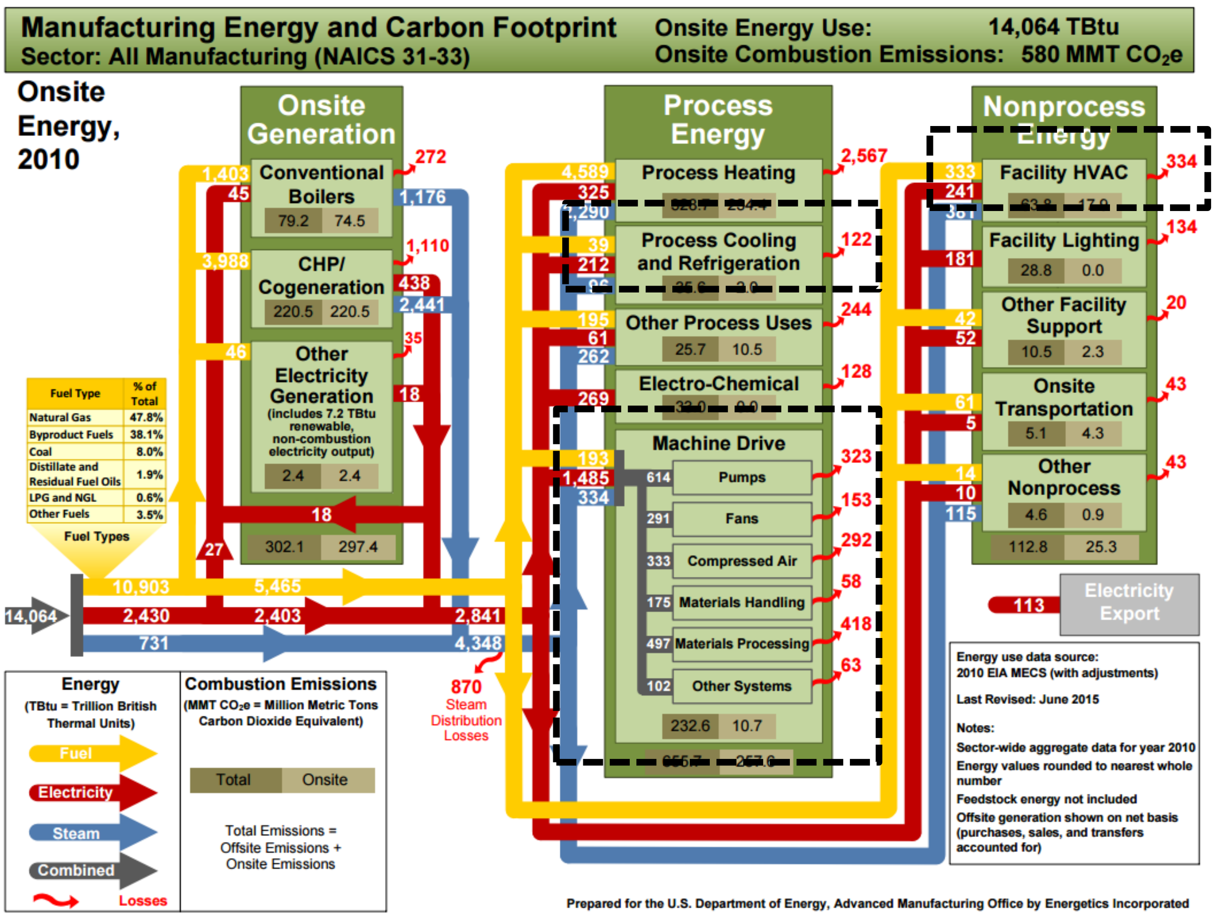
The U.S. Department of Energy (U.S. DOE) created the Superior Energy Performance (SEP) program to add energy performance improvement verification on top of the ISO 50001 facility certification. Therefore, facilities that are "SEP certified", are ISO 50001 certified and have a facility-wide verified energy performance improvement over a given number of years [3]. As of August 2017, sixty two facilities have been certified to SEP throughout North America. Of these, a subset of forty-three facilities has provided energy savings data to the U.S. DOE for analysis. These analyses show that facilities reduce their baseline energy consumption by 12.9%, on average, over a typical three year period. The energy savings of these forty-three facilities were third party verified and amounted to a total of 3.71 trillion Btu (390 TJ) source energy[10]. This is equivalent to the amount of energy consumed by over 100,000 typical US vehicles in one year.

Motor-Driven System Energy Consumption in U.S. Manufacturing:

Motor-driven systems are one general class of energy system type within the overall scope of an ISO 50001 EnMS. Within a typical manufacturing facility in the U.S., motor-driven systems can be a significant consumer of energy.

[10] "Source" energy refers to the energy consumed at the facility ('site') plus the energy required to convert, transmit, and distribute the energy. For more details on the conversion from site to source, see section on SEP Program Energy Savings Verification.

In 2010, U.S. manufacturers consumed 14,064 trillion BTUs (TBtu) (14.8 EJ) of energy (‘site’). 2,430 TBtu (2.6 EJ) was in the form of electricity (purchased from offsite sources). When including the electricity generated onsite, the US Manufacturing sector consumed 2,841 TBtu (3.0 EJ) of electricity for Process and Non-process end uses. Figure 2 below illustrates the flow of energy (fuel, electricity and steam), including where it is used and lost due to inefficiencies across the US manufacturing sector [4].



Note: Process Cooling and Refrigeration, Machine Drive, and Facility HVAC are highlighted in the

Figure 2 – US Manufacturing Energy and Carbon Footprint, Site Energy in 2010, in Imperial Units

Figure 2 shows that machine driven systems are made up of pumps, fans, compressed air, materials handling, materials processing and other systems and consume 1,485 TBtu (1.6 EJ) or 52% of total site electricity. When considering Process Cooling and Refrigeration and Facility HVAC, two additional end uses primarily driven by motor-driven systems, the total electricity consumed throughout the US manufacturing sector increases to 1,938 TBtu (2.0 EJ) or 68% of total site electricity. Using these estimates, 68% of site electricity consumption and 14% of total site energy consumption was attributable to motor driven systems in 2010.

However, from this total electricity consumption, only a fraction is applied in direct end-use to produce a product. The majority is lost due do motor-driven system inefficiencies. For example, **Figure 3** shows that in 2010, only 704 TBtu (0.74 EJ) or 35% of the total energy consumed by machine driven systems was applied to produce products. The remaining 65% was lost [5]. An ISO 50001 EnMS can help to identify where opportunities for improvement exist and can optimize motor driven system operations.

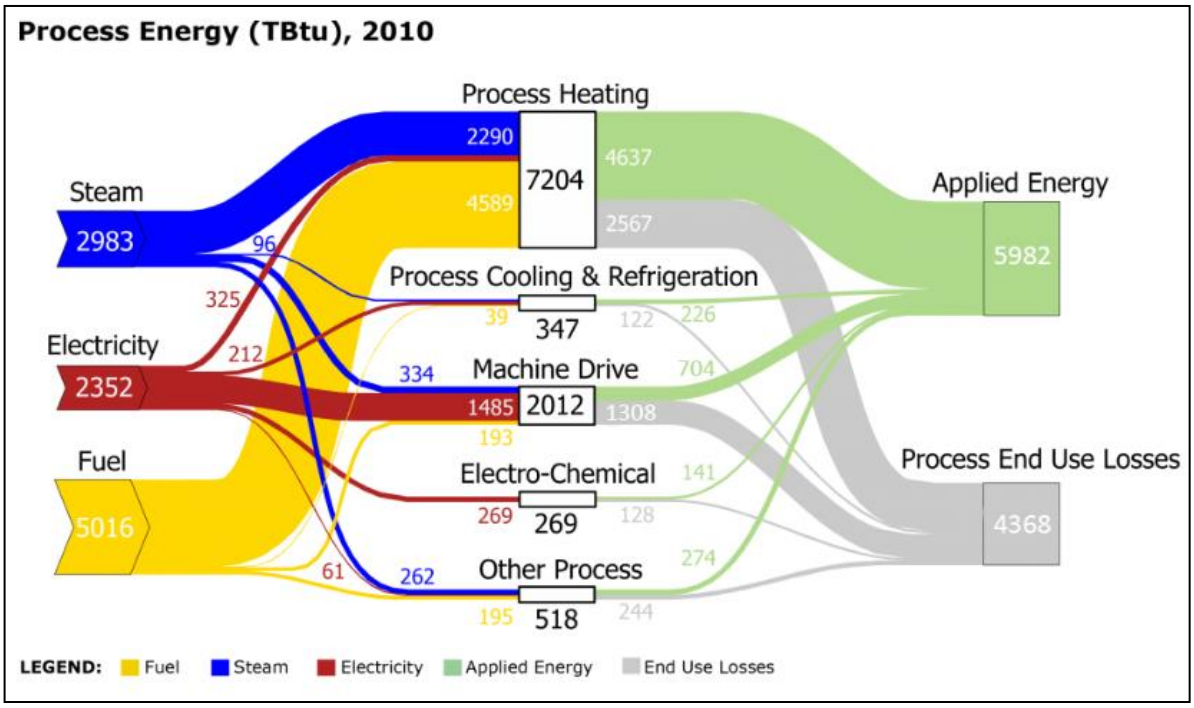


Figure 3 – US Manufacturing Sector Sankey Diagram, Process End-use Energy

The five largest U.S. manufacturing subsectors in terms of estimated motor-driven-system-related electricity consumption in 2010 are listed in Table 1 below:

Table 1 – U.S manufacturing sectors with the largest overall motor-driven system energy consumption

— **Manufacturing subsector**	— **Site motor-driven system electricity in TBtu (and EJ)**	— **Primary motor-driven system electricity in TBtu (and EJ)**
— Chemicals	— 434 (0.46)	— 1302 (1.37)
— Paper and allied products	— 282 (0.30)	— 846 (0.89)
— Food products	— 219 (0.23)	— 657 (0.69)
— Petroleum and coal products	— 199 (0.21)	— 597 (0.63)
— Primary metals	— 145 (0.15)	— 435 (0.46)

Table 1 illustrates the importance of motor-driven systems at the national level within the U.S. manufacturing sector. However, evaluating the dependence of motor-driven systems within any given sector reveals that some sectors traditionally viewed as "non-energy intensive" rely heavily on motor-driven systems. The sectors with the largest share of energy consumption for motor-driven systems are summarized in Table 2. Table 2 shows the percent of total site energy consumption for motor-driven systems.

Table 2 – Subsectors with the greatest percent of energy consumption for motor-driven systems

— **Manufacturing subsector**	— **% of total site energy consumption for motor-driven systems**
— Computer and electronic products	— 43%
— Printing and related support	— 42%
— Plastic and rubber products	— 38%
— Textile product mills	— 37%
— Apparel	— 33%
— Furniture and related products	— 31%
— Electrical equipment and appliances	— 30%
— Machinery	— 30%

Comparing the two tables, none of the sectors listed in Table 1 appear in Table 2. This means that while motor-driven systems may not be a dominant energy use for large (in terms of energy consumption relative to other industries in the U.S.) industries, the implementation of ISO 50001 at these industries could realize significant motor-driven system energy savings. Table 2 also shows that the implementation of ISO 50001 at smaller industries will likely have a large focus on motor-driven systems. Many of the facilities within the sectors listed in Table 2 are small to medium sized facilities (in terms of overall energy consumption). This indicates that the implementation of ISO 50001 at small to medium sized facilities will likely focus on motor-driven systems.

SEP Program Energy Savings Verification

ISO 50001 lays a foundation for achieving continual improvement in energy performance through systematically integrating energy-related decision making into other business decisions. Continual improvement is achieved in part through selecting energy performance indicators (EnPI) and tracking them on an ongoing basis. ISO 50001 accommodates the selection of EnPIs that fit the facility's needs, but does require that at least one is developed and tracked for each Significant Energy Use. Strong EnPIs will relate energy consumption to variables/conditions that impact energy consumption. These variables, known as "relevant variables", may include units of physical output (e.g., number of widgets, volume of product), operating parameters (e.g., pressure, flowrate), or external conditions (e.g., ambient temperature).

SEP builds on ISO 50001's energy performance tracking requirements by introducing a facility-level metric. This metric, the Superior Energy Performance Indicator or SEnPI, is used to determine facility-level wide energy performance. It is calculated by comparing actual energy consumption in a 12-month period to predicted energy consumption over the same period. The prediction is based on a model of energy consumption that adjusts energy consumption for facility-level relevant variables. An SEnPI less than 1 indicates that the facility-level energy performance is improving [6].

An onsite audit to verify a facility's claimed energy performance improvement is conducted by a SEP Performance Verifier (SEP PV). The SEP PV is a 3rd party specialist trained in SEP's measurement and verification requirements. A facility cannot receive SEP certification until the SEP PV approves of the claimed energy performance improvement. This provides credibility to the energy performance improvement achieved through SEP certification.

Improvements to motor-driven systems are especially valued when calculating the SEnPI. The SEnPI is calculated using primary energy. When converting to primary energy, site energy is multiplied by a factor accounting for generation, transmission, and distribution energy losses. As a default, this factor is 3 for electricity aligning with the 33% efficiency of the U.S. electrical grid. The default is 1 for fossil fuels as minimal losses are assumed with the generation, transmission, and distribution of fossil fuels. With this energy accounting practice, improvements to electrically-driven motor systems will be valued three times more than improvements to fossil fuel-driven systems.

Increasing the Efficiency of Motor-Driven System with ISO 50001

ISO 50001 establishes a systematic approach to managing and achieving energy performance improvements using a P-D-C-A business process including a continual improvement framework. Organizations with an ISO 50001 EnMS will closely track energy use, identify savings opportunities, and continually improve energy performance. The EnMS will be aligned with existing corporate management systems and their policies and practices. Key features of the P-D-C-A EnMS structure are as follows:

1. **PLAN:** Engage management and **plan** for energy management, including performing an energy review. Major sub-steps include:

- **Engaging management.** Securing top management's support for the EnMS with their commitment to the EnMS by instituting and supporting an energy policy
- **Energy team.** Creation of a diverse energy team that has a management representative and has been provided resources from management
- **Energy review.** A key task within the Energy Review is to identify the significant energy uses (SEUs). Significant is defined as "energy use accounting for substantial energy consumption and/or offering considerable potential for energy". Major motor-driven systems, such as compressed air, refrigeration, & large pumps and fans would likely be considered SEUs. The SEUs are important, because the rest of the EnMS centers on them, including: establishing energy objectives, targets and action plans; ensuring the training and competence of relevant personnel; planning for effective operation and maintenance; and monitoring, measuring and analyzing their performance.
- **Identifying Opportunities for Improvement.** Opportunities for energy performance improvement are a critical key component of the energy review. Energy opportunities can be identified through energy assessments or other means. Opportunities can include capital projects, maintenance actions, & operational and behavioral practices. Opportunities are then prioritized. As an example, if a compressed air system has been identified as one of the SEUs, a compressed air energy assessment could be completed during this sub-step.

- **Energy baseline.** Defining a period as a basis for comparison of energy performance.
- **Energy performance indicators (EnPIs).** Developing metrics for energy performance.
- **Objectives and targets.** This step involves determining the energy goals to be pursued, and then setting energy objectives, targets, and action plans to achieve the goals. If motor-driven systems are SEUs, they would be included in this step, and even some motor-driven systems that are not SEUs could also be included. An organization could have an objective to reduce overall facility energy consumption by 20% from the 2016 baseline. As an example, a compressed air system could have a target of improving its energy performance by 10% over the next year, and be one step in meeting the overall objective. The action plan for this system would likely come from a compressed air energy assessment done during the energy review, subsequently implementing the compressed air projects with the highest priority.
- **Energy management action plans.** Planning the actions (e.g., energy efficiency projects) required achieving and verifying the improvements stated in the goals.

2. **DO:** Implement energy management, including **doing** actions to improve efficiency by implementing action plans. An energy team would develop the support systems for energy improvement, such as:

- **Competence training and awareness.** According to ISO 50001, personnel working on SEUs must be competent to perform tasks related to energy performance. Any motor-driven systems that are SEUs would fall under this requirement. As an example, for a compressed air system, this would include the staff responsible for the compressor room, and also the users of compressed air.
- **Broad communications** to all employees within the organization about the EnMS
- **Operational controls.** Energy teams would implement operational controls (e.g., maintenance and operational practices) related to energy use and performance. Operational control involves effective operating and maintenance criteria to be put in place for the motor-driven systems that are SEUs, and possibly other motor-driven systems. Operational control criteria for motor-driven systems can be part of an action plan(s), or can be a separate activity. Using compressed air example, maintenance and operational practices having to do with the entire compressed air system should be considered, from the compressor room all the way to the compressed air end uses.

3. **CHECK:** Measure and **check** results. The Energy team will check on the progress of the energy management action plans, overall energy performance, and effectiveness of the EnMS. The Checking step ensures appropriate monitoring/measurement activities are in place to evaluate if the EnMS is meeting the energy policy and planned objectives. For motor-driven systems, the efficiency of each major system could be checked against a baseline or target. As an example, for a compressed air system, its peak cfm/kW and part load energy performance could be monitored over time.

4. **Act:** Organizations will evaluate the effectiveness of the overall EnMS. They will also review results of the EnMS to ensure its continuing appropriateness, suitability, and effectiveness. Additionally, they will continue to promote and support continual improvement of the EnMS and energy performance. Organizations will therefore conduct regular (usually annual) management reviews between management and the energy team to determine actions for improving the EnMS.

Key Tools for ISO 50001 Implementation

The U.S. DOE has developed a number of tools to help organizations implementing an EnMS.

Energy Management System Implementation Tools from U.S. DOE

50001 Ready Navigator [https://energy.gov/eere/amo/50001-ready-program]

Implementing an EnMS requires a systematic approach to energy management and energy performance improvement. The "50001 Ready Navigator" is a web-based toolkit that helps organizations implement an energy management system through 25 key steps. It includes forms, checklists, templates, examples, and other guidance to help an organization throughout the EnMS implementation process. It also prepares and organization to become "50001 Ready" which a U.S. DOE recognition program.

Facility Level Energy Performance Improvement Tool from U.S. DOE

Energy Footprint Tool [https://energy.gov/eere/amo/downloads/energy-footprint-tool]

The Energy Footprint Tool helps manufacturing, commercial and institutional facilities track their energy consumption, factors related to energy use (such as weather), and significant energy uses. It was specifically developed for organizations that are implementing an EnMS. The Energy Footprint tool tracks energy sources (e.g., electricity, natural gas, etc.) and relevant variables (e.g., heating and cooling degree days, operating hours, occupancy rates). The tool produces charts and graphs based on the entered data, allowing for comparison of energy types, trends, energy consumption, and energy end-use. The tool can also output the energy data into a table that is compatible with EnPI Lite (see below).

Energy Performance Indicator Tool Lite (EnPI Lite) [https://energy.gov/eere/amo/50001-ready-program]

The Energy Performance Indicator Tool Lite (EnPI Lite) is an on-line regression analysis tool that calculates facility level energy performance improvement. EnPI Lite is a companion tool to 50001 Ready Navigator, and enables regression-based energy performance modeling for facilities. EnPI Lite is web-based and accepts inputs from EPA's Portfolio Manager and the Energy Footprint Tool.

Tools for Energy Review from U.S. DOE

The U.S. DOE has developed a number of tools to improve the energy performance of crosscutting systems. The following tools aid organizations to improve the energy performance of specific systems and pieces of equipment within a facility. These tools are currently being updated to be web-based and open-source.

Compressed Air Systems [See https://energy.gov/eere/amo/articles/airmaster]

AIRMaster+ analyzes energy use and savings opportunities in compressed air systems. AIRMaster+ can baseline existing and model future system operations improvements, and evaluate energy and cost savings from energy efficiency measures. The AIRMaster+ LogTool companion tool determines the operating dynamics of a compressed air system.

Pumping Systems [See https://energy.gov/eere/amo/articles/pumping-system-assessment-tool]

The Pump System Assessment Tool (PSAT) assesses the efficiency of pumping system operations. PSAT uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings.

Fan Systems [See https://energy.gov/eere/amo/articles/fan-system-assessment-tool]

The Fan System Assessment Tool (FSAT) quantifies energy consumption and savings opportunities in fan systems. FSAT can be used to understand fan system operational characteristics, determine the economic benefit of system modifications, and establish which options are most economically viable when multiple opportunities exist for fan system modification.

Steam System Modeler [See https://energy.gov/eere/amo/articles/steam-system-modeler]

The Steam System Modeler tool allows the user to input the metrics of their steam system, generate a list of detailed steam specific steam properties, and test a variety of adjustments on individual equipment. The modeler allows up to 3-pressure-header basic models of the current steam system.

Process Heating Systems [See https://energy.gov/eere/amo/downloads/process-heating-assessment-and-survey-tool-excel-version-phastex-v101]

The Process Heating Assessment and Survey Tool (PHAST) introduces methods to improve the energy performance of heating equipment, both fossil fuel- and electric-based (some of which can have large motor-driven systems, like industrial process heat pumps). The tool is used to perform a heat balance that identifies major areas of energy consumption under various operating conditions, and test scenarios to reduce energy consumption.

Motor-driven System Case study Results from U.S. DOE SEP Program

The SEP program has over 50 certified facilities. Many of these facilities implemented motor-driven energy saving actions to help achieve their overall energy performance improvement. The following will summarize the motor-drive system results within selected SEP certified facilities.

Energy Savings Data Collection and Methodology

Part of the Superior Energy Performance (SEP) Measurement and Verification process is to undergo a "Bottom-Up" check to compare against the "top-down" SEnPI facility energy saving result mentioned previously. The Bottom-Up check is the sum of energy saving improvement actions that are reconciled with the energy savings resulting from the Top-Down regression analysis model or from the SEnPI calculation. Eighteen SEP certified facilities voluntarily provided Bottom-Up energy saving project data to the US DOE. The bottom-up project data includes a project description, implementation date, energy savings data, and whether the project required capital expenditure (capital or operational project).

In order to better understand the composition of energy efficiency improvement projects, the energy savings from the bottom-up project lists of 18 companies were analyzed in three different ways:

1. Motor vs. Non-Motor: Energy improvement projects were classified as motor-driven system or non-motor-driven system improvements. For the purpose of this paper, motor-driven system improvements are defined as any improvements to compressed air, heating, ventilation and air conditioning (HVAC), variable frequency drives installed on motors, and fan, pump, and "other" motor-driven systems upgrades.
2. Capital vs. Operational: ISO 50001 provides a management structure for identifying previously unseen energy improvement opportunities, which can be operational improvements that require no significant capital costs. Therefore, the projects and associated energy savings were further disaggregated into two more categories: (1) projects requiring capital expenditures and (2) no/low-cost operational improvements.
3. Business-as-Usual vs. Impacted by EnMS: Lastly, projects and associated energy savings were also grouped into "pre" and "post" EnMS implementation to better understand the impact the EnMS had on these facilities. The first SEP implementation training date was used for two facilities that had a preexisting EnMS in place. Full attribution of energy efficiency project savings to the EnMS or SEP program is not possible, but this method provides insight into how the EnMS affected the distribution and type of energy efficiency projects at these select facilities.

Analysis Results: Operational vs. Capital Projects

Of the total population of 263 projects, 81 projects (31%) were categorized as improvements to motor driven systems, accounting for almost 300,000 million British thermal units (MMBtu) (317 TJ) of source energy savings annually. A breakdown of project types can be seen in **Table 3**.

Table 3 – Breakdown of Motor Driven System Projects

Project Type	**Number of Projects**	**Reported Source Energy Savings in MMBtu (and TJ)**
Compressed Air	24	83,000 (87.6)
HVAC	33	103,000 (108.7)
VFD Related	9	16,000 (16.9)
Fans	1	2,000 (2.1)
Pumps	9	44,000 (46.2)
Other Motors	5	48,000 (50.6)

Over half (55%) of these source annual energy savings (attributable to motor-driven systems) resulted from operational improvements such as shutting down oversized pumps/fans/compressors, optimizing air/fluid flow, fixing compressed air system leaks, or optimizing motor controls—all requiring no/low costs to implement. The remaining 45% of source energy savings required larger capital expenses. This result shows the importance of the ISO 50001 management structure in helping plant staff to identify previously unseen energy improvement opportunities, many of which require no capital costs. Though the EnMS will help identify capital investments that can further improve energy performance, these larger capital opportunities, such as replacing major energy consuming equipment, are often more apparent to the facility staff.

The analysis of the non-motor-driven system projects showed that only 37% of the annual energy savings were the result of low/no-cost operational improvements. These results suggest there was proportionally more high-impact "low-hanging-fruit" for motor-driven systems than for other types of systems, e.g., a boiler system or lighting.

Analysis Results: Business as Usual vs. Energy Management System Operational Project Results

Figure 4 shows the progression of operational energy efficiency improvements from business as usual project implementation practices (pre-implementation of ISO 50001) to those partially or fully operating under an ISO 50001 EnMS. This progression is shown for three different project categories: all projects, motor-driven system projects only, and remaining projects (other than motor-driven systems). The split between operational and capital projects across all projects remained relatively constant before and after the EnMS implementation. However, the proportion of operational motor-driven system projects increased by 20% following the EnMS initiation date, while the proportion of the remaining projects decreased by 7%. For these facilities, the EnMS shifted focus from implementing capital projects to operational improvements for their motor-driven systems.

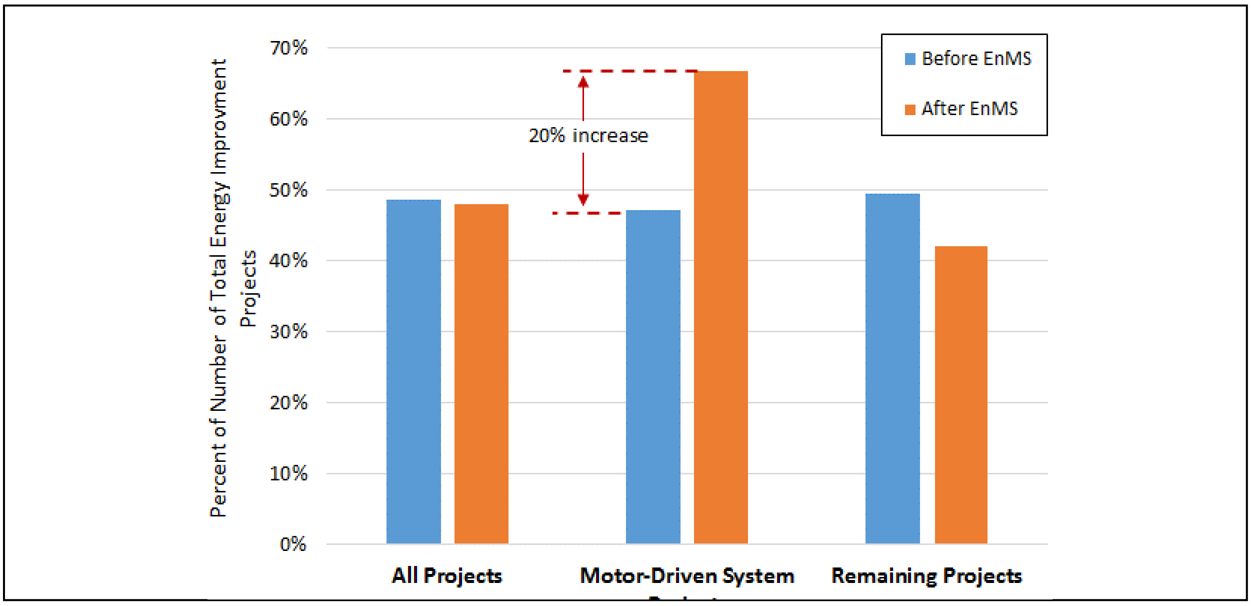


Figure 4 – Operational Improvement Projects before and after EnMS Implementation Date

Figure 5 shows the progression of annual energy savings from operational projects across the same three categories: all projects, motor-driven system projects, and remaining projects. The proportion of annual energy savings from operational motor-driven system projects almost doubled from 46% before the EnMS was implemented to 83% following EnMS implementation—a 37% jump. A similar jump occurred for non-motor driven systems, though the jump was less significant: from 28% of non-motor-driven system savings to 45% following EnMS implementation. Results show the increase in *operational* project energy savings following the implementation of ISO 50001 is greatest for motor-driven systems. More importantly, the results show that ISO 50001 leads to the implementation of operational (and low/no cost) energy saving projects for motor driven systems. These savings may not have been realized without the implementation of ISO 50001.

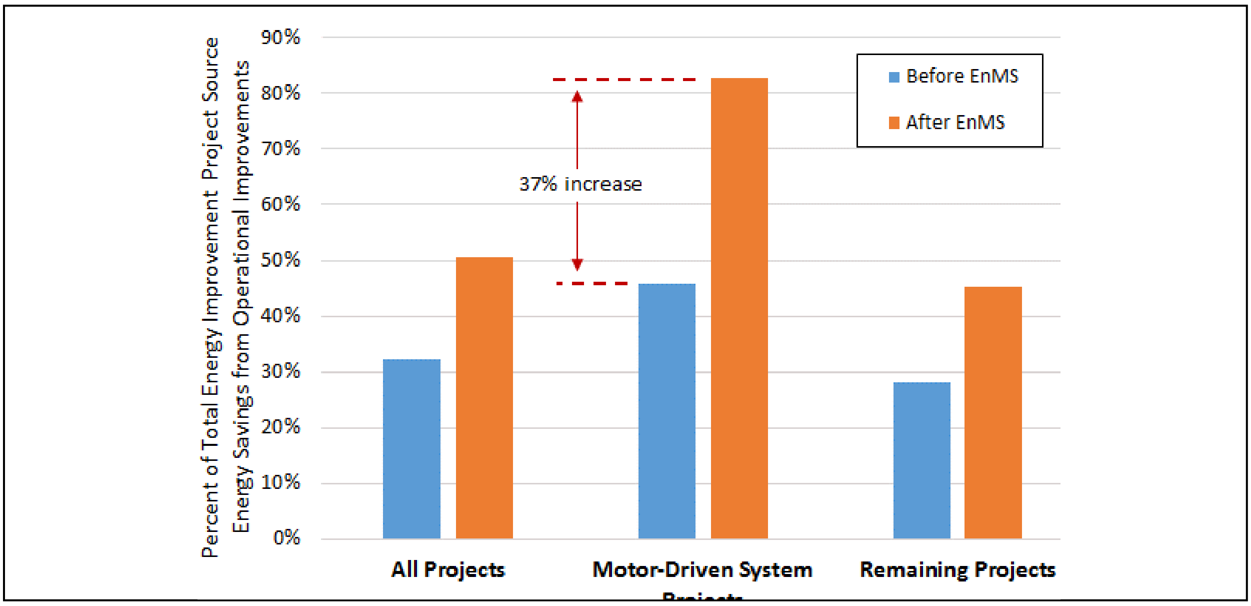


Figure 5 – Percent of Source Energy Savings from Operational Improvements, Before and After EnMS Implementation Date

ISO 50001 and SEP Case Studies

Cummins Rocky Mount Engine Plant

Rocky Mount Engine Plant (RMEP) is the largest energy consuming facility of all 300 Cummins facilities worldwide. It accounts for about 10% of the company's annual energy consumption and was thus chosen to be the pilot plant for ISO 50001 and SEP implementation. RMEP implemented an ISO 50001 EnMS in 2011, improving its energy performance by 12.6% over a two-year period, which was verified by a third party, SEP Verification Body in 2012. RMEP recertified to ISO 50001 and SEP in 2017 after improving its energy performance by 15.5% over seven years. This performance improvement exemplifies the ISO 50001 principle of continual improvement.

During RMEP's initial certification, plant staff replaced open blow offs with engineered nozzles in their machine line, drastically reducing the amount of compressed air required to blow off byproduct chips after milling, drilling, or cutting. This project alone has saved 5.3 million kilowatt-hours (kWh) annually, accounting for much of the plant's 12.6% improvement. The metering system managed under the ISO 50001 EnMS made visible two compressed air line leak projects. RMEP has saved 1.2 million kWh and $79,000 annually after repairing the leaks. Plant personnel acknowledged that these savings are a direct impact of the EnMS.

Based on the successes realized at RMEP, Cummins began implementing ISO 50001 and SEP Enterprise-wide, which enables multiple sites to share a common ISO 50001 EnMS managed by a "Central Office." This approach promotes consistency, leverages resources, accelerates system adoption, and streamlines EnMS implementation, making the process more cost effective (per site) and further increasing savings. Cummins has set a goal to certify 40 sites to ISO 50001 by 2020, 11 of which will also be SEP certified. These 40 sites represent approximately 90% of the company's manufacturing energy footprint.

Nissan Smyrna, Tennessee, Plant

As seen in **Figure 6**, Nissan's Smyrna, Tennessee, plant improved its energy performance by 24% over six years, leveraging the ISO 50001 EnMS and SEP performance improvement targets and achieving third-party verification [7].

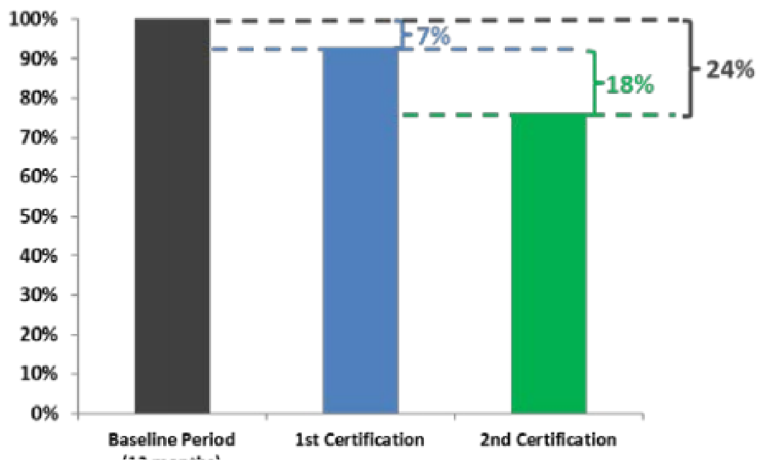


Figure 6 – Normalized Facility Energy Consumption Over Two Nissan Smyrna, Tennessee facility SEP Certification Cycles [7]

Nissan first implemented an ISO 50001-compliant EnMS in 2010, which became fully operational in early 2011. The Smyrna plant identified its painting process as the most significant energy user, consuming approximately 70% of the plant's total energy. The plant's process heating and compressed air and pump (both motor-driven) systems were identified as the most cost-effective opportunities to save energy.

Starting in 2010, plant personnel undertook a 155 million USD paint plant project, which reduced paint plant energy consumption by 40%. Initially, only a 30% reduction was projected. The verified savings justify future investment for energy projects and exemplify the importance of the rigorous measurement and verification protocol under SEP.

As part of the paint plant project, Nissan installed compact booths and recycled 75% of booth air. Fan and pump motors are also now controlled by VFDs, which reduce electricity consumption by matching motor speed to load requirements [8]. The plant also underwent a motor speed reduction project, which alone has saved over 13,000 MMBtu (13.7 TJ) of source energy annually. The entire paint plant is sub-metered and managed under the ISO 50001 EnMS, which provides valuable feedback to optimize operations.

Energy savings were also achieved outside of the paint shop. Staff underwent an operational improvement effort to better manage the compressed air system in the plant's stamping shop, resulting in savings of almost 15,000 MMBtu (15.8 TJ) of source energy annually. Energy consumption and savings from all of these projects are monitored under the ISO 50001 EnMS and verified by SEP.

Nissan recognizes that the ISO 50001 EnMS and SEP provide the discipline and credibility needed for funding future energy efficiency projects, which was initially a challenge. Nissan credits the EnMS with initiating a cultural shift toward continual improvement. Based on these successes, Nissan not only recertified its Smyrna plant, but also joined SEP Enterprise-wide. To date, Nissan has certified three plants to ISO 50001 and SEP, and could potentially expand the EnMS to its sites in Mexico.

Washington Hilton Hotel, Washington, DC

Hilton Worldwide was the first company in the commercial buildings and hospitality sector to become certified to SEP. Hilton Worldwide operated under a mature energy monitoring system known as "LightStay." LightStay was used to measure and analyze environmental measures such as energy, water, waste, and carbon dioxide. ISO 50001 expanded the LightStay program as a mechanism for continual improvement, and it drove energy performance despite having a preexisting mature energy program.

The Washington, DC, Hilton Hotel achieved a 15.9% energy performance improvement by implementing 13 energy improvement projects. Seven of the projects involved motor-driven systems, accounting for approximately 6% of the total energy performance improvement. A chilled water pump upgrade accounted for half of the motor-driven system savings. Other motor-driven system energy projects involved upgrading the chiller, installing a VFD to a condenser pump, installing an electronically commutated motor, and replacing a condenser water pump [9].

Table 4 – Washington Hilton Energy Saving Project including Motor-Drive Systems

Washington, DC Projects	Savings
Chiller 1, 2, and 3 Flow *	0.37%
Boiler #1 Control Upgrade	1.08%
VFD Install - Condenser Pump #2 & #1 *	0.88%
Chilled Water Pump Upgrade *	3.00%
LED Lighting Upgrade	3.72%
2013 Energy Efficiency Upgrades	1.35%
Service Hot water upgrade	1.76%
Chiller overhaul (2013)	0.72%
Condenser Water Pump Replacement (30 hp) *	0.33%
Boiler pressure reduction	0.87%
ECM Motor *	0.77%
Remove old DX split systems	0.11%
Replace AHU 7 & 10 (10 hp) *	0.11%
Washington Hilton Total	**15.07%**

*projects that are motor driven systems

Conclusions

The energy saving potential of motor-driven systems has not been achieved because of <u>lack of technological solutions, but because organizations have not fully integrated energy into their business operations and managed energy in a systematic manner as other business functions such as quality and safety.</u> ISO 50001 provides a framework to develop the policies, procedures, and tools to systematically track, analyze, and improve energy efficiency. It also considers improving maintenance practices, better operational controls, and incorporating energy efficiency into procurement and design of facility equipment, systems and processes. Organizations that use ISO 50001's framework for establishing an EnMS will improve the energy efficiency of their motor-driven systems, and these improvements will have persistence, as long as the EnMS is maintained.

A number of key tools for implementation of ISO 50001 have been developed, including 50001 Ready Navigator, which is a web-based toolkit that helps organizations implement an energy management system through 25 key steps. Also, a number of tools to improve the energy performance of crosscutting systems such as pumps, fans, and compressors (which are identified in the Energy Review step of the EnMS) are also available.

The results from case studies of motor-driven system efficiency improvements resulting from the implementation of an EnMS based on ISO 50001 show significant improvements in motor-driven system efficiency, both in the industrial and commercial sector. For most organizations, motor-driven systems are significant energy users, and therefore, a focus of the ISO 50001 EnMS, throughout the plan-do-check-act cycle. Further, analysis of ISO 50001 implementations revealed that the EnMS yields an increase in operational energy savings. In summary, implementing an EnMS based on ISO 50001 provides a superior framework for improving motor –driven system efficiency versus the traditional project-based approach.

References

[1] "ISO 50001:2011 Energy management systems -- Requirements with guidance for use," International Organization for Standardization, 2011. https://www.iso.org/standard/51297.html.

[2] "United States Industrial Electric Motor Systems Market Opportunities Assessment," Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Oak Ridge National Lab, Xenergy, Inc., December, 1998.

[3] "Superior Energy Performance program," U.S. Department of Energy , www.energy.gov/isosep.

[4] "Manufacturing Energy and Carbon Footprints (MECS 2010)," https://energy.gov/eere/amo/downloads/all-manufacturing-2010-mecs.

[5] "Static Sankey Diagram of Process Energy in U.S. Manufacturing Sector," U.S. Department of Energy, https://energy.gov/eere/amo/static-sankey-diagram-process-energy-us-manufacturing-sector.

[6] "SEP Measurement and Verification Protocol," U.S. Department of Energy, https://www.energy.gov/eere/amo/downloads/superior-energy-performance-measurement-and-verification-protocol-industry.

[7] "Nissan Case Study for Superior Energy Performance," U.S. Department of Energy, https://www.energy.gov/eere/amo/downloads/nissan-case-study-superior-energy-performance.

[8] "Showcase Project: New Paint Plant," Better Buildings, U.S. Department of Energy, https://betterbuildingssolutioncenter.energy.gov/showcase-projects/new-paint-plant.

[9] "The Business Value of Superior Energy Performance," U.S. Department of Energy, May 2016. https://betterbuildingssolutioncenter.energy.gov/sites/default/files/The-Business-Value-of-Superior-Energy-Performance-Part-1-Industrial-TUES.pdf.

Energy audits in the industrial sector according to ISO 50002 standard and its application in management systems based on ISO 50001: a case of study.

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Abstract

The industrial sector is one of the largest energy consumers in Colombia. The need for changes in how energy is used and supplied in different industrial processes represents the greatest challenge in moving towards sustainability. The energy audit based on ISO 50002 provide a minimum set of measures and / or guidelines to conduct a systematic analysis of energy use and energy consumption in any organization, building, equipment, system (s) and / or process (s). It is focused at: (i) to identifying, quantifying and to implementing(?) energy performance improvement opportunities; (ii) decreasing energy losses; and (iii) obtaining environmental benefits, therefore the purpose of this study is to present the application of the ISO 50002 standard in support of part of the energy review requirement of ISO 50001 through the analysis performed and the application on-site in a Food Ingredients Company; The stated hypothesis was validated by adopting in the company the guidelines provided by ISO 50002 for the development of the energy review in; collecting data, measurement; analysis of the current energy performance; And identification and evaluation of improvement opportunities. The results of the energy review in the company presents: the identification of electrical energy as the major energy consuming source; the area of highest contribution that is of the order of 67%, the energy audits in the air distribution system in the fermentation process, energy cost and the Improvement recommendations and savings opportunities for a total amount of 2.025.389.657 Columbian currency.

keywords

Energy Audits, ISO 50002, ISO 50001, sector industrial, Energy management, Energy performance, Energy savings

Introduction

Energy is a key element in economic and social development [1]; And is a critical resource for the industry [2] [3] due its use and consumption for the conversion of raw materials in usable products [4]; The costs considering the panorama of variability and uncertainty in the price of the different energy sources, and the commitments made between member countries in the route to achieve an energy system more efficient with less CO2 emissions. [5]. On a country level, the industrial sector can account for between 30-70% of the total national energy consumption and is certainly responsible for a great part of the global greenhouse emissions [6]. In Colombia, the industrial sector ranks as the second largest total energy consumption with a participation that oscillates between 35,98% and 41,83%.[11] [5] and the Cauca Valley region, is the highest per capita electricity consumption of country, followed by the Northwest, Central and Caribbean Coast, caused primarily by the level of economic activity in key sectors of electricity consumption such as Industry and Service [7]. In addition, the variation of price in dollars of KWh in Colombia.

[11] Percentages of average participation for the year 2015

The need to make changes in the way energy is used and supplied throughout the industrial processes represents the greatest challenge to engineers in moving toward sustainability. [4] One of the most promising strategies of saving energy and related costs in industry is to implement an energy management system (EnMS) [8]. Its introduction also helps to minimize impacts on the environment, improve indoor climate and Working conditions. [3] The ISO 50001 standard introduced in June 2011, was developed to provide a unified framework for energy management [9], specifies mandatory requirements for an energy management system. [8] [2], more than 35% of companies already certified in ISO 50001 have received benefits in terms of energy savings and increased competitiveness [8]. ISO 50001, such as other standards, is based on the Continuous Improvement Plan-Do-Check-Act Cycle [10], with an additional energy review within the planning processes; establishing the baseline, energy performance indicators (EnPIs), objectives, targets and action plans; Necessary to improve the energy performance of any organization. [11]

A structured and well-defined energy audit is the most effective method to evaluate the potential of energy savings and prepare a plan of corrective actions to achieve a clean industrial process and sustainable [4]. An energy audit is based on an appropriate measurement and observation of the use of energy, efficiency energy and consumption [12]; and through this process it is possible to analyze the energy balance of a system to define possible energy efficiency improvements, mitigate environmental impact and reduce energy costs. [13]

An energy audit can be performed with different analytical approaches depending on the needs of the company and can be classified in the following types: walk-through or initial diagnostic, mini-audit and maxi-audit [14]. Kumbhar and Joshi (2012) described three types of energy audits: a direct audit, an intermediate audit and an extended energy audit. Although the Kumbhar and Joshi classification is useful for examining individual facilities, it focuses on the scope and implications of environmental audits for actual and potential problems related with the material and energy flow management; and to regulate environmental performance [15]. In addition to the above, three types of energy audits have been defined according to level of detail: **Type 1**. It represents the minimum level of detail that could be appropriately referred to as an energy audit, it is advised for small organizations or facilities. **Type 2.** It is a detailed energy audit where opportunities are identified and evaluated with costs and quantified benefits. **Type 3.** It is an exhaustive energy audit that implies a variety of energy saving opportunities, significant contributions to the organization, generally it is profitable for organizations with high expenditure of energy. [12]

In order to define the requirements of the process to carry out an energy audit oriented at identifying opportunities to improve energy performance in any establishment and / or organization, the Energy Audit standard, ISO 50002-Requirements with guidance for use was approved in 2014. This standard seeks to harmonize the common aspects of energy audits to improve clarity and transparency. [12]

The purpose of this study is to present the application that has ISO 50002 in the energy review requirement of ISO 50001 in respect of analysis and the application on-site in a Food Ingredients Company.

1. Methodology

The present study was developed through the descriptive and exploratory analysis of the standards: 1) NTC ISO 50001 [11], requires an energy review; and 2) NTC ISO 50002 [12]; and as a way of connecting the findings with the theory or raised premise, was performed the application in situ in a company producing food ingredients.

Energy review activities were carried out by researchers from the Energy group - GIEN of the Autonoma de Occidente University within the framework of the National Strategic Program on Integrated Energy Management Systems, PEN-SGIE, where the company was linked as beneficiary entity. The PEN-SGIE is an initiative University-Enterprise-State and is made up of the UPME, Colciencias as a funding entity and 11 executing Colombian Universities.

Selection of the company producing Food Ingredients.

The company producing food ingredients selected for the realization of this study represents the most important multinational in Colombia and is the number one yeast producer in Latin America.

Realization of the Energy Review in the selected company.

The methodology used in the development of the energy review follows:

1. The criteria and guidelines established in the Colombian Technical Standard ISO 50002 of Energy Audits. [12]

2. Techniques and / or procedures acquired within the framework of the National Strategic Program of Integrated Energy Management Systems SGIE; that are listed in the book *Metodología para la implementación del Sistema de Gestión Integral de la Energía. Fundamentos y casos prácticos* [16].

2. Results and Discussion

Below, is presented a descriptive analysis that examines the ISO 50002 standard of energy audits, and the role it plays within the requirement energy review of ISO 50001. Finally, is presented is exposed an application case, that focuses on the Study of the consumption of electric energy because is the energy of greater consumption.

2.1 Descriptive analysis of ISO 50002 and its contribution to the requirement energy planning of ISO 50001

The ISO 50002 standard is based on good practices in energy management and energy audits and addresses requirements to identify opportunities to improve energy performance, reduce energy losses and obtain environmental and financial benefits. The process of an energy audit involves a series of steps that encompass from planning the energy audit, start up meeting, data collection, measurement plan, site visit, information analysis, audit report, and the final debriefing meeting.

The energy review carried out in accordance with ISO 50001 should include; the analysis of past and present energy uses and consumption based on measurement and other data, identification of areas of significant energy use, establishment and prioritization of energy performance improvement opportunities and estimation of future energy uses and consumption.

An energy audit based on ISO 50002 can support an energy review as it provides guidelines for data collection, monitoring, measurement and analysis of: energy use and consumption; and energy efficiency, as well as in the identification of opportunities to improve energy performance; As shown in figure 1 and it is detailed below.

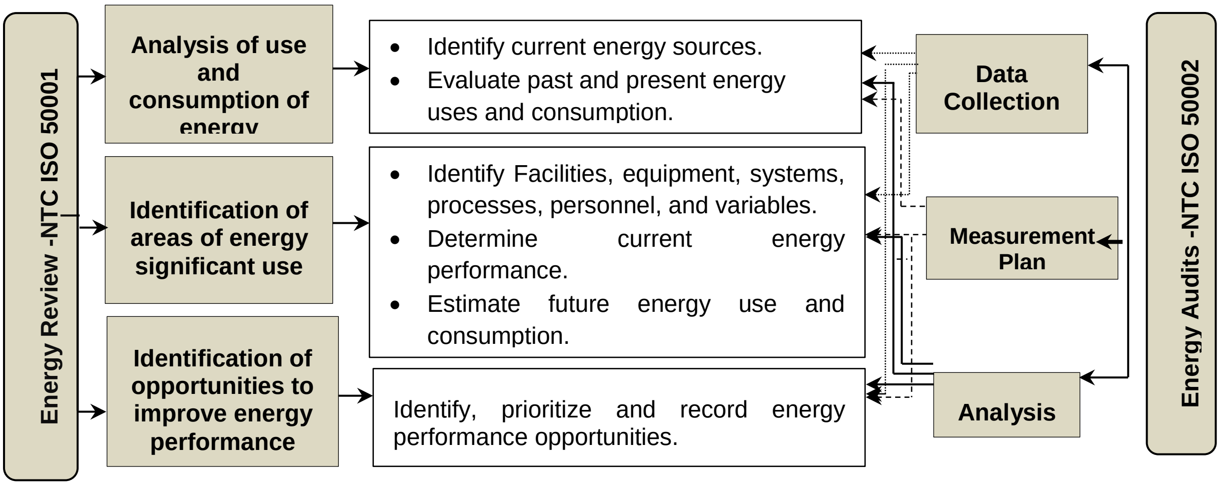

Figure 1. Scheme of the participation process of NTC-ISO 50002 in the energy review of ISO 50001

Source: Authors.

2.1.1 Data Collection

Data collection is the starting point for developing a comprehensive study of the use and consumption of energy in any system, area or equipment and process which will enable:

1. Knowing the sources and amounts of energy consumed as well as the behavior of consumption in any organization throughout its production chain, regardless of its nature and form. For this purpose, it will be essential to have historical and current energy consumption data (including data from the measured range, additional sub-measures to monitor something specific), and other relevant variables in the process such as products, by-products, residues, occupancy hours, area of site to be diagnosed, number of people, among others, detailed characteristics of energy uses, energy distribution systems and how the organization manages its use and energy consumption.
2. Determine of equipment, areas or processes of significant energy use. It is important to review the equipment for monitoring, configuration and analysis of the information and perform a load census considering the registration of existing systems, processes and equipment on the site, estimation of load factors, operating scheme and power of equipment that can be obtained through the plate data or with a measuring instrument such as a network analyzer or amperometric clamp, in this last requirement is important to consider the measurement plan which will be discussed later. The data should be collected for a sufficient time period.
3. Establish variables that most influence energy use, through the knowledge of the operational history, the valuation of future plans that may affect the performance and analysis of past elements or events that have an impact on the energy consumption in the period covered in the collected data thus obtaining understand and identify how they influence in the performance or control parameters.
4. Identify opportunities to improve energy performance, considering the results of the energy diagnosis or previous studies performed on the systems, processes and / or equipment consuming energy, including significant variables. It is appropriate to make supplier quotations for the improvements and to consider current energy tariff schedules, or reference rates to be used, among other economic data relevant to the financial analysis and / or return on investment.

2.1.2 Measurement Plan

Measurements are a useful tool to know the energy consumption existing in the organization, areas, systems, processes and equipment. It also serves to monitor the relevant variables of its operations, which will allow the performance determination, analyze the significant deviations presented and establish and implement improvements. The energy performance measurement data can be considered representative when they have the typical range of variation for the relevant variables and the period will be required time vary according to the uses of the energy and the nature of the processes involved. Shown below the elements to be considered in the definition of the measurement plan.

The main elements to consider in the measurement plan are:

- List of relevant measuring points and their processes, and equipment of associated measurement according to the nature of the variable to be measured, its magnitude, operating range, accuracy and conditions of use.
- Identification of any additional measuring points, measuring equipment, its processes and installation feasibility.
- Accuracy and repeatability required for measurements and its uncertainty
- Duration and frequency of each measurement, e.g. individual data points or continuous monitoring.
- An appropriate period of time when activities are representative.
- Relevant variables, e.g. operating parameters and production data.
- Responsibilities for carrying out the measurements, including personnel working for or on behalf of the organization.
- The calibration and traceability of the measuring equipment.
- Processing of data, including: graphs and elaborated tables of measurement results, methods used and any assumptions made, including the range of applicability of the calculations, the appropriate quality and validity checks of the results. e.g. Balance of mass, energy; among others. When it is not practical or economically feasible to analyze all the information, sampling techniques can be used, especially statistics where a 95% confidence level is acceptable (sampling described in ISO 19011: 2011, Clause B.3).

2.1.3 Analysis

Data analysis provides valuable information for decision-making related to energy use and consumption, energy performance, and the establishment of improvement actions, this last which at the moment of implementation it is necessary to start new processes of monitoring and analysis of data to know its effectiveness, as presented below.

When performing the analysis of the data collected, we can obtain relevant information from:

1. **Analysis of Current Energy Performance:** which provides the basis for evaluating improvements, this includes the following:

- Energy consumption by use and source.
- Accounting for energy uses.
- Where available and comparable with reference values of similar processes.
- A historical pattern of energy performance
- Expected improvements of energy performance.

- Where appropriate, the relationships between energy performance and relevant variables.
- Assessment of the existing performance indicators and If indispensable proposal for new indicators of energy performance.
- Current and historical energy data.
- Detailed cross-energy balance with data of sufficient sub-measurement.
- Balance of mass and others used to know the current performance in equipment, systems and processes.
- Assessment of design to meet the needs of the system.
- Assessment of energy performance improvements associated with changes in equipment, systems or processes.

2. **Identification of improvement opportunities, based on the following**:

Assessment design and configuration options to address system needs. (The minimum energy consumed by a system to deliver a product or service)

- Operating life, condition, operation and maintenance level of the audited objects.
- Technology uses existing energy compared to the more efficient market with the quote.
- Best practices, including actions, operational controls and behaviors.
- Energy use in the future and changes in operation.
- Quantification of a range of performance improvement opportunities specific and implementable detailing energy savings, among other benefits environmental, safety and others obtained.
- Draft list of opportunities for improvement, to review feasibility or suitability.
- Other analysis, technical or experimental approaches (e.g. engineering, pilot studies, simulations, thermal picture) to fully understand energy consumption.

3. **Evaluation of opportunities for improvement, based on the following:**

- Energy and economic savings over an agreed period of time and expected operational lifetime.
- Investment needed.
- Other non-energy gains such as productivity or maintenance, among others.
- The ranking of opportunities to improve energy performance.
- Potential interactions between several opportunities.
- Indicative or typical savings calculated using common rules for base energy.
- Return on investment, establishing typical periods.
- Presentation of analysis of economic agreements such as: Internal rate of return (IRR) or net updated value.
- All opportunities to improve energy performance with costs and benefits, including non-energy gains.

2.2 Application Case

This section presents the energy review according to ISO 50001, developed in a company producing food ingredients, applying the techniques and guidelines established in ISO 50002 Standard.

The company is dedicated to the production, sale and distribution of food ingredients used in the production of bread, pastry and confectionery such as: yeasts, fats or shortenings, oils and margarines, nutritional supplements and consumer products.

In order to carry out the energy review, was used the process of energy audit proposed in ISO 50002 (see Figure 2), which included the following stages:

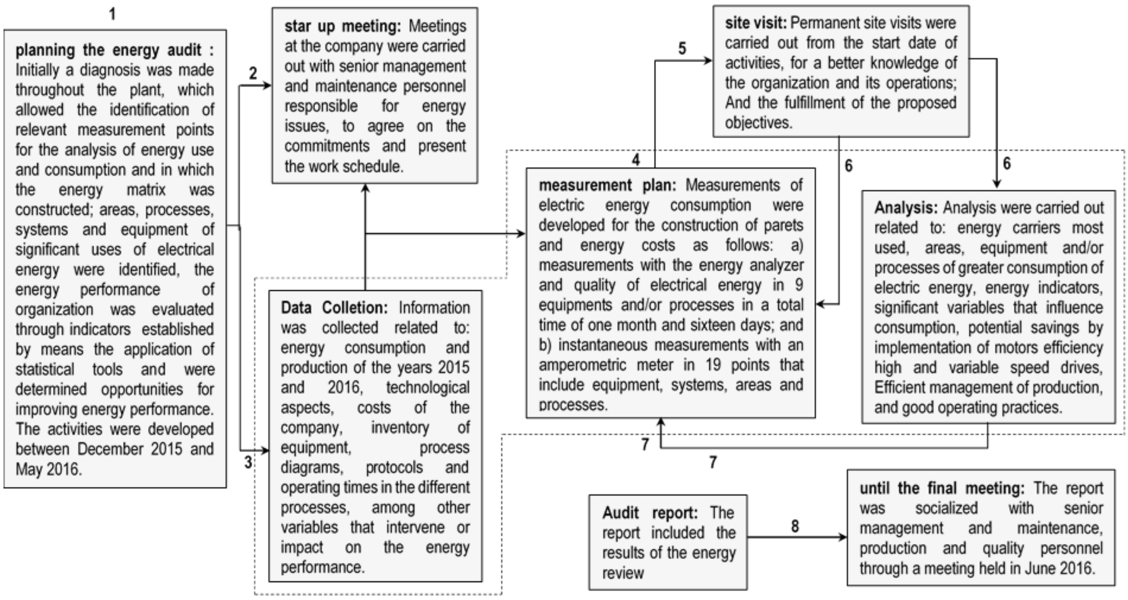

Figure 2. Scheme of the energy audit process according to NTC-ISO 50002

Source: Authors.

2.2.1 Analysis of the Use and Consumption of Electric Energy in the selected company

The electric energy is used in all areas of the company such as: yeast, margarine, powders and essences; Warehouse of raw materials and finished products, administration and others (where the consumption of PTAR and Casino are associated), distributed in the systems of lighting, refrigeration, air conditioners, compressors, agitators, motors, pumps, Blowers, battery charging, and Machinery of: pressing, molding, cutting, and packaging. Everything detailed above can be represented in a productive energy diagram, since it allows to describe the sequence of the different steps or stages and their interaction with energy and other factors involved in obtaining of a product and / or provision of a service. Next, is presented in figure 3, the energetic-productive diagram of the yeast area.

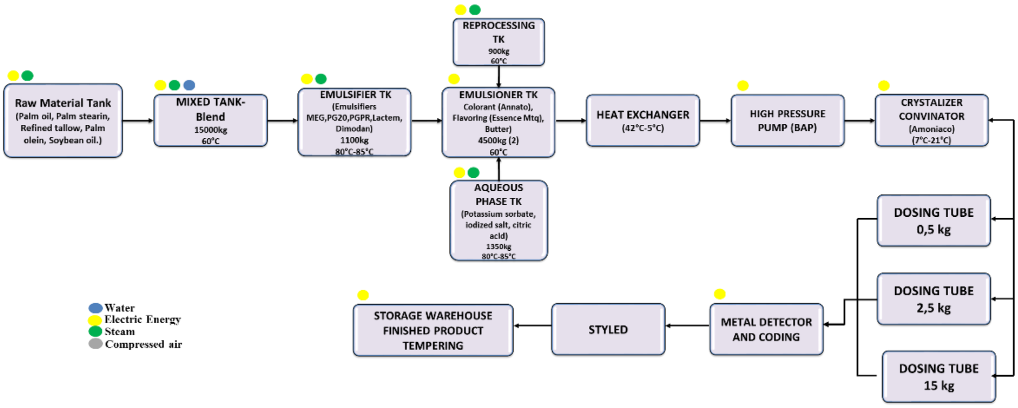

Figure 3. Energy-productive diagram of margarine processing

Source: Authors.

The trend of electricity consumption up to November 2015 was different from the previous year, energy consumption changed from 6,951,641 KWh / month to 6,669,139 KWh / month, as detailed in Table 1, which shows a reduction of 4.1% of consumption. The month of greatest energy consumption for the year 2014 was August, while March was the month of lower energy demand. For the period of study of the year 2015 the month of January was the one of greater consumption and October was the one of smaller consumption (figure 4). As for the cost of electricity, from 2015 to November 2016, there has been an increase of 10.78%, due to increases in the rate of 23% due to the phenomenon of the child that was presented in Colombia.

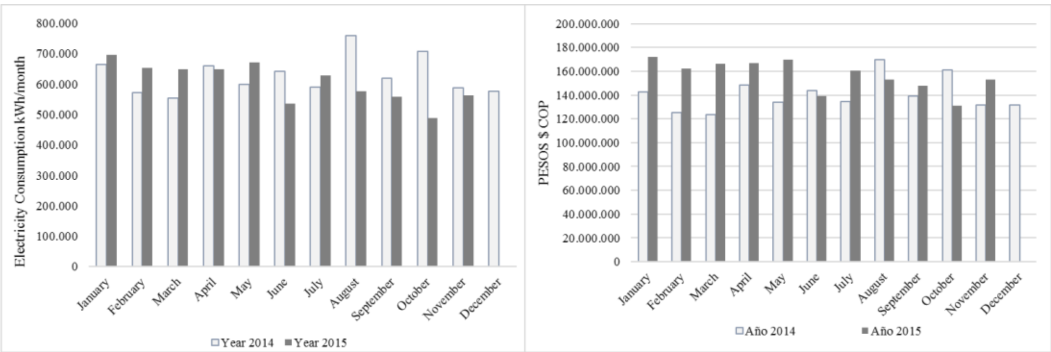

Figure 4. Electricity consumption and costs trend by month-year 2014 and 2015

Source: Authors

Table 1. Electricity consumption and costs data for 2014 and 2015

Variable \ Month	Year 2014		Year 2015	
	Energy Consumption Month-KWh/Month	Energy Invoice Cost month/$ COP	Energy Consumption Month-KWh/Month	Energy Invoice Cost month/$ COP
January	664.796	142.784.964	**696.014**	172.214.744
February	571.499	125.046.786	652.818	162.062.069
March	**553.057**	123.319.116	648.376	166.314.928
April	660.510	148.586.492	649.163	166.880.332
May	597.737	133.706.879	671.637	169.749.535
June	642.424	143.951.664	536.427	138.864.857
July	590.079	134.280.207	628.608	160.659.633
August	**758.799**	169.871.547	575.259	152.852.069
September	618.150	139.297.513	559.075	147.685.252
October	706.788	160.898.154	**489.187**	130.960.252
November	587.800	131.832.398	562.575	152.829.125
Total	**6.951.641**	**1.553.575.720**	**6.669.139**	**1.721.072.795**

Source: Authors

Distribution of energy sources most used in the plant through the elaboration of an Energy Matrix

Energy Matrix

In relation to the energy weight of each energy carrier in the total consumption matrix (see figure 5.), the electric energy by minimum difference has a greater participation than natural gas with percentages of 54% and 46% and Values of 6,669,139 and 5,686,118.10 KWh respectively up to November 2015. The above considering that natural gas expressed in cubic meters' unit was converted to kilowatt hours with the equivalence factor of 1m^3 constitutes 11 KWh.

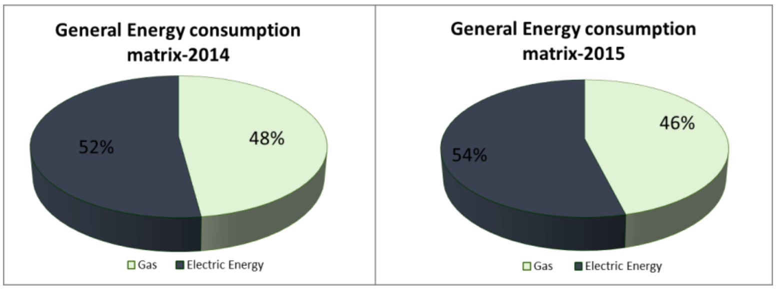

Figure 5*.* Energy matrix of global consumption year 2014-2015.

Source: Authors

2.2.2 Identification of areas of energy significant use

In order to establish the distribution of electric energy consumption in the company, the data of 18 sub-meters used in each cost center or area previously defined in the analysis of energy consumption. Additional measurements were taken in the different equipment, processes and / or systems to determine the consumption by area with more precision, were used the equipment analyzers of network and quality of electric energy 435 Series II Fluke. Whose Accuracy for KWh is ± 1% ± 10 beads, accuracy volts ± 0.1% accuracy amperes ± 1%. The results obtained from this analysis were represented in paretos diagrams, since this tool allows to identify 20% of the areas, equipment, processes and / or systems of the company that originate 80% of the consumption of the energy carrier;

And thus, prioritize and focus on actions or opportunities for improvements that significantly impact in saving of kind energy, economic and among others.

When were made measurements of electricity consumption was possible to obtain more precise information of consumption for each area, in order that these could be related with the production. Next, is shown in Table 2 the schedule of measurements made in the company by the energy characterization team. In the case of the measurements of consumed instantaneous power were made three shots at full, medium and low load at each point and was determined the average.

Table 2. Schedule of measurements made in the company.

MEASUREMENT WITH CONSUMER ANALYZER AND ENERGY QUALITY		POINTS MEASURED INSTANT POWER CONSUMED (BY AREAS)				
Equipment and Areas Measured	Measured days	Area of Yeast	Area of Margarine	Area of powders and mixtures	Area of essences and laboratory	Offices, Warehouse, Cold room Caravan, Casino and PTAR
A/A Logistics and bakery	1,6	Blower	Circuit 440V	Circuit BI. 220V	Ammonia Compressor	Warehouse of raw materials and finished products
Busbar 1	7	Cooling tower	Circuit 220V	Circuit BI. 440V	Laboratory	Administration
Busbar 2	7,8	Ammonia Compressor		Ammonia Compressor	Essences	PTAR
Cut 220V	3	Cold room of yeast				Casino
PTAR 440V	6,9	Packing				Cold room Caravan
Receiver 220V	4,9	Separation				
Receiver 440V	5,7					
Temperi 220V	4,3					
Temperi 440V	4,4					
Total	**45,6**					

Source: Authors

Distribution of global consumption of electrical energy of the plant.

According to the measurement carried out and based on consumption information for the year 2015, was determined that the yeast area is the highest consumption with a contribution of 68%, and a value of 4.982 MWh / year, followed by the powder area with an energy weight of 13% and a total consumption of 1.002 MWh / year, the margarine area has 10% of consumption, while the Warehouse of raw materials and finished products as well as the administration area have a contribution of 3%; with consumption of 752,2 MWh / year; 219.7 MWh / year, and 184,37 MWh / year respectively. It is important to clarify that the energy expenditure of only the caravan room that is in the same management circuit is 40.8 MWh / year, indicating that the administration area has an energy demand of 143.5 MWh / year. The minimum contributions correspond to Others and essences with percentages of 2% and 1% correspondingly. (See figure 6)

Distribution of electricity consumption by areas and by equipment and / or system in general.

The distribution of electric energy consumption is presented below, identifying the most critical equipment that represents 20% and demand 80% of the total electric global energy consumption and in the different areas of the organization, additional energy costs are related, for this purpose was used an average tariff value of 2015 of $ 258.7 KWh (see figure 7. and table 3.)

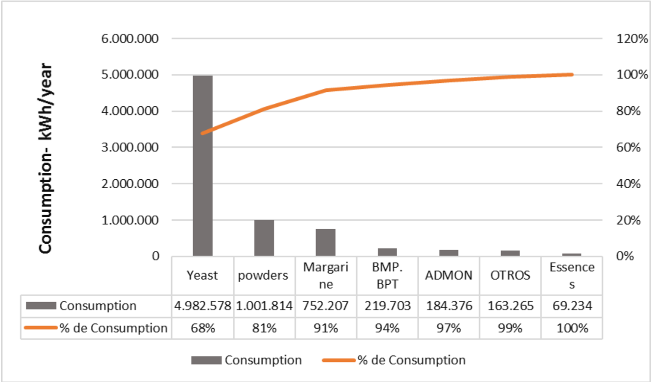

Figure 6. Distribution of electricity consumption by area- year 2015

Source: Authors

Table 3. Distribution of electricity consumption by area year 2015

Area	Equipment and/or circuits	Energy Consumption Kwh/Month	Percentage of Electric Power Consumption%	Accumulated	Cost per Process $ COP
Yeast	Blower	185.321	48%	48%	$50.344.221,36
	Cooling tower	57.047	15%	63%	$15.497.415,19
	Ammonia Air Compressor	54.622	14%	77%	$14.838.477,78
	Cold room of yeast	39.363	10%	87%	$10.693.325,41
Margarine	Circuit 440V	27851,7	47%	47%	$7.566.192,82
	Circuit 220V	16276,7	28%	75%	$4.421.728,32
	Temperi 220V	9668,7	16%	91%	$2.626.599,04
Powders and Mixtures	Circuit BI. 220V	68097,8	88%	88%	$18.499.448,35
	Circuit BI. 440V	5479,3	7%	95%	$1.488.506,64
Essences and Laboratory	Air Compressor	3724,19	45%	45%	$1.011.714,54
	Laboratory	3351,5	40%	85%	$910.468,49
Offices, Warehouse, Cold room Caravan, Casino and PTAR	Warehouse of raw materials and finished products	13983,9	37%	37%	$3.798.866,27
	Administration	9596,6	25%	62%	$2.607.012,36
	PTAR	5933,55	16%	78%	$1.611.908,19
	Casino	5130	14%	91%	$1.393.615,80

Source: Authors

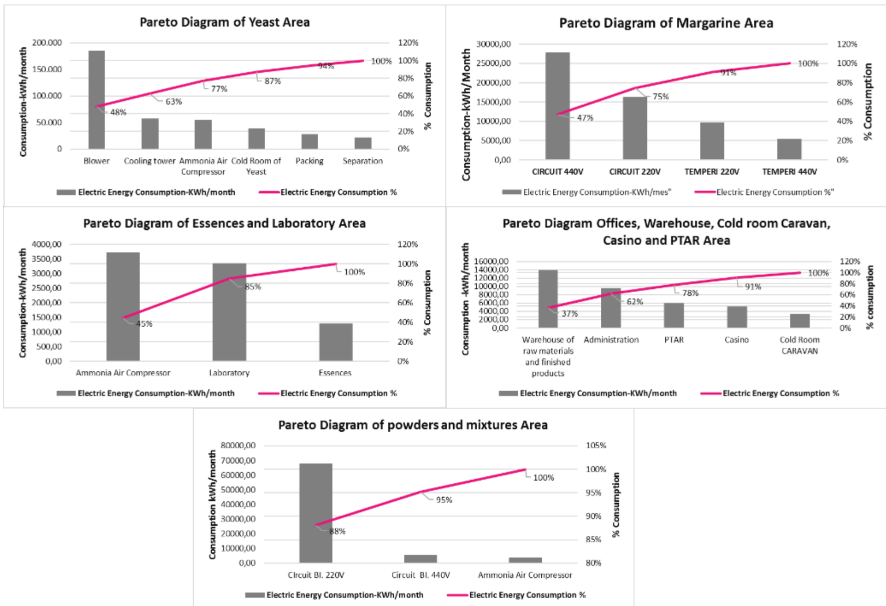

Figure 7. Distribution of electricity consumption by area

Source: Authors

Analysis of control variables that impact on energy consumption.

The analysis of control variables is introduced to determine if the initial relationship between two variables: dependent and the independent (s) is true. This allows to increase the internal validity of a study, event and / or manifestation of a certain phenomenon (cause-effect relationship). In this study, was carried out this analysis in all areas and for this purpose were used tools such as: a) control charts that helped to: demonstrate if the process is stable and consistent over time, evaluate the effectiveness of a change, communicate the energy performance of the process and identify the presence of a variation by special causes; And b) dispersion graphs energy vs. Production that allows to analyze if there is some kind of relationship between two variables and its degree by calculating the Pearson correlation coefficient, on the other hand through this graph and the methodology set forth in [22], were established indicators to quantify and compare the energy performance Throughout the period; and analyze the result obtained on the base of expected action. Showing up next analysis of the control variable in powders and mixtures area (Figure 8) and the energy performance indicators: energy consumption indicator-IC and the cumulative sums indicator-CUSUM defined in the yeast area (Figure 9).

Analysis of control variables in powders and mixtures area

It was determined that there is no relation between consumption and production, since there are evidences days mainly on Sundays in which the production is zero and has associated a consumption value reaches the average; and on Monday is has highest energy expenditure and the lowest on Saturday. According the control limits, it was detected that, although the process has operated within the control limits (UCL = 4510.4; LCL = 968.8); regularly they are presented on Mondays, Saturdays and Sundays; Consumptions that are close to lower limit.

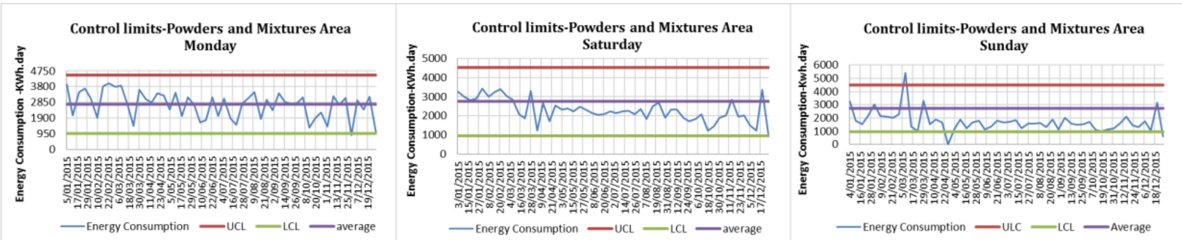

Figure 8. Control limits graph powder and mixture area

Source: Authors.

Analysis of Energy Performance Indicators

It was determined according to the Electric Energy Consumption Indexes, that the critical production value in the yeast area where the variation of the consumption index is minimal for a production range between 30 and 160 Tons; Is at a production level greater than 112 Tons and the minimum energy consumption indicator in which the best energy performance according to this level of production presented is 970.84 KWh / Ton. As for the indicator of cumulative sums it is evident that in the period of analysis they have stopped consuming 2.628.274,04 KWh and over-consumption 2.231.747,14 KWh.

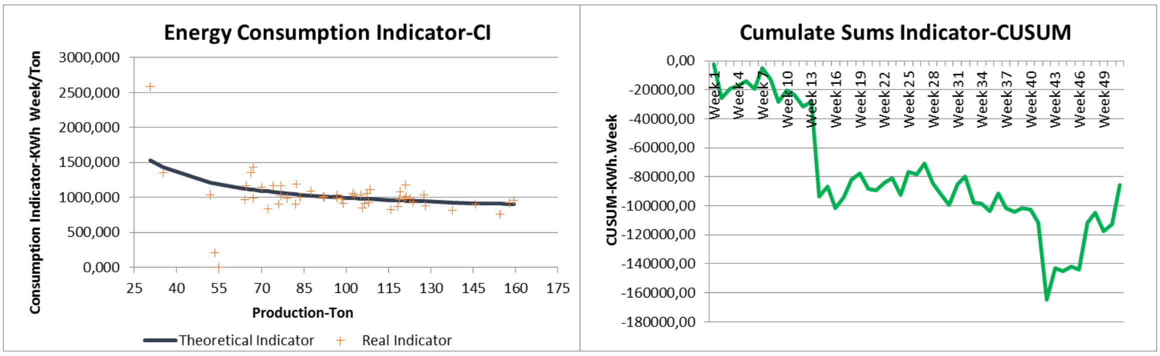

Figure 9. Indicators of energy consumption and cumulative sums-CUSUM

Source: Authors

Results of the review of energy significant uses and consumption, which identified the types of equipment, areas and / or processes that most impact on these consumptions and how they are used, subsequently developed two audits in the system Air distribution in the fermentation process and for change from direct start to speed variator; based on ISO 50002, to provide recommendations for the improvement of energy performance.

Energy audits in the air distribution system in the fermentation process.

The air system is used in the fermentation process, which is indispensable in the metabolic process of yeasts. Within the air system, the Blowers are the most energy-consuming equipment and have a power of 350Hp at 440V and a real capacity of 5700 CFM (9684,362 m3 / h), the company has four of them. Next, air distribution scheme in the front view plant (Figure 10) and the fermentation aeration system (Figure 11).

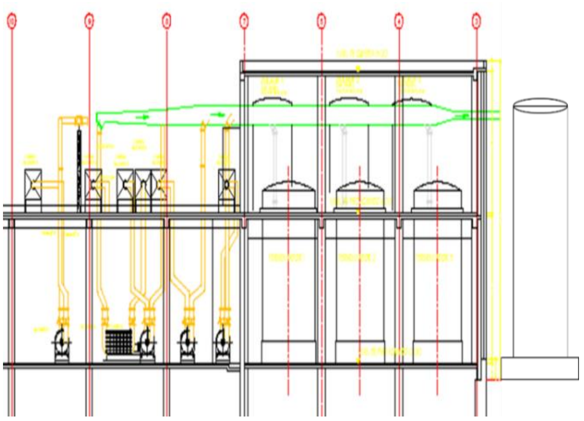

Figure 10. Air distribution scheme in plant

Source:Information provided by the company and adjusted by the managers of program

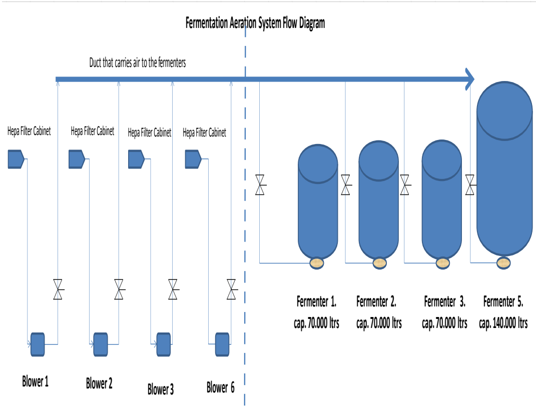

Figure 11. Diagram of the fermentation aeration system

Source:Information provided by the company and

To determine the actual consumption of the Blowers; was measured electrical energy consumption in the different stages of operation using a Fluke 337 amperimetric clamp, it is important to consider that the equipment is subject to a series of restrictions on the output of the air flow through a manual valve, which is manipulated according to the needs of the production. Table 15 shows the consumption of electric energy when the equipment operates without flow restriction and / or different percentages, were taken records at the maximum capacity or 100%, 75%, 50%, 25%, 0%, Which equals consumption of 260KWh, 250KWh, 236KWh, 190KWh, 97KWh, respectively. With the above data was constructed Figure 12, corresponding to the operation of the ignition initially of a Blower until arriving at the fourth Blower, with these graphs was determined the equations that characterize the operation and consumption when each Blower comes into operation. With these equations, it is possible to identify the consumption of electric energy in relation to the consumption of CFM.

Table 5. Blower consumption data at different percentages of output flow restriction

Measurements Blower 1			Measurements Blower 1,2			Measurements Blower 1,2,3			Measurements Blower 1,2,3,6		
% Operation	CFM	KWh	% Operation	CFM	KWh	% Operation	CFM	KWh	% Operation	CFM	KWh
100%	5225	260	100%	10450	520	100%	15675	780	100%	20900	1040
75%	3918,75	250	75%	7837,5	500	75%	11756,25	750	75%	15675	1000
50%	2612,5	236	50%	5225	472	50%	7837,5	708	50%	10450	944
25%	1306,25	190	25%	2612,5	380	25%	3918,75	570	25%	5225	760
0%	0	97	0%	0	194	0%	0	291	0%	0	388

Source: Authors

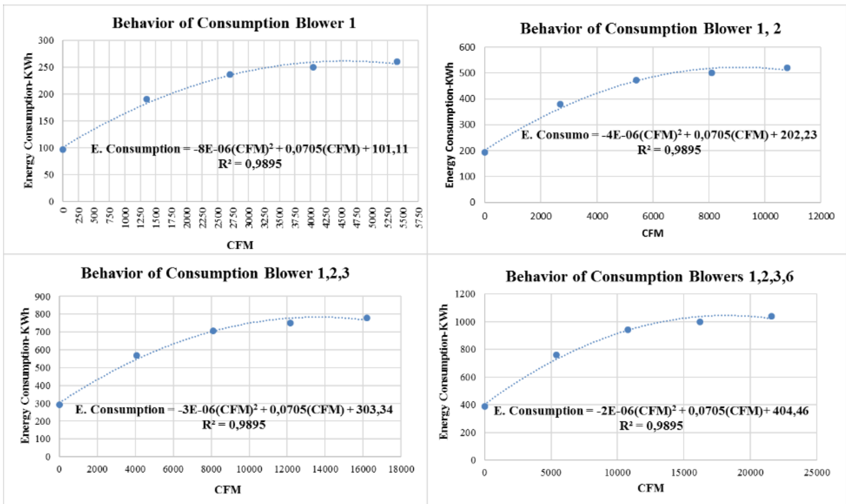

Figure 12. Behavior of consumption according to performance of the Blowers

Source: Authors

Subsequently, with the formats consumption of flow rates for each fermenter hour by hour supplied by the company and the equations, we proceeded to calculate the consumption of electric energy of the washes of the fermentation tanks and to the production. The results showed an average electric energy consumption of Blowers in fermentation of 215,473.43 kWh/month with an average monthly cost of $ 56,023,092 pesos; and for the washes of the tanks revealed a consumption of 11,340.71 kWh / month, equivalent to a cost of $ 2,948,583 average month. Since the programs are not updated to establish optimal wash times and conditions according to the production scheme, it is advisable to review and evaluate the protocols to reduce energy consumption.

Energy auditing for changeover from direct start to speed variator

In the process of yeast there are four Blowers that have a direct start system, where for issues energy efficiency it is advisable to implement in each Blower a more efficient system for starting the motors and their control of power consumed according to the Load required.

To perform the analysis, was used SIEMENS SINASAVE simulation software to verify the behavior of a motor 260 KW with the direct start versus the speed variator (see figure 14)

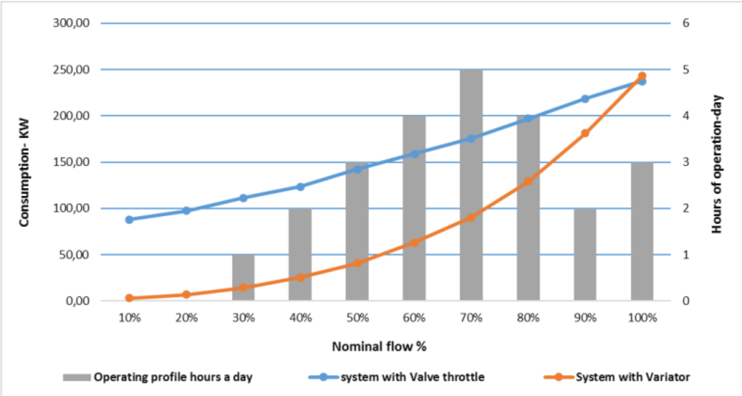

Figure 14. Consumption behavior of a Blower with direct start system and variable speed drive

Source: Authors

The following table shows the simulation data that evidence with an investment of 34.540.000 million COP, are obtained savings up to 49'715,666 pesos, and a time of return of investment of approximately one year. It is important to mention that this projection is viable for the four Blowers that are currently installed.

Table 6. Results of the variable speed drive simulation

System with throttle of Valve (KW)	System with variator (KW)	Flow Rate (%)	Operating Profile hours a day	Daily power consumed System with throttle of Valve (KWh)	Daily power consumed System with variator (KWh)	Monthly power consumed System with throttle of Valve (KWh)	Monthly power consumed System with variator (KWh)	Year power consumed System with throttle of Valve (KWh)	Year power consumed System with variator (KWh)
87,82	2,91	10%	0	-	0	-	-	-	-
97,31	6,95	20%	0	-	0	-	-	-	-
111,56	14,52	30%	1	112	15	1023	133	12272	1597
123,42	25,5	40%	2	247	51	2263	468	27152	5610
142,41	40,89	50%	3	427	123	3916	1.124	46995	13494
159,03	62,95	60%	4	636	252	5831	2.308	69973	27698
175,64	90,11	70%	5	878	451	8050	4.130	96602	49561
197,00	129,11	80%	4	788	516	7223	4.734	86680	56808
218,36	181,23	90%	2	437	362	4003	3.323	48039	39871
237,35	242,99	100%	3	712	729	6527	6.682	78326	80187
				Difference in consumption	1.738	Difference in consumption	15.935	Difference in consumption	191214
				Daily Savings	$451.961	Monthly Savings	$4.142.972	Year Savings	$49.715.666

Source: Authors

2.2.3 Opportunities energy saving and actions to improve energy performance

Based on the analysis of use and consumption of electrical energy, the identification of areas, equipment, systems, processes and variables that affect the efficient use of operations; which were detailed previously, the opportunities for improvement are showed in Table 7.

Table 7. Opportunities energy saving and actions to improve energy performance

Operational Practices			
Find	**Opportunity identified**	**Estimated Energy Saving (consumption kWh/año)**	**Estimated annual saving (COP)**
Through the measurements made by the energy characterization team was verified that the first margarine refrigeration room - Temperi 1 consumes 44% more than second the margarine refrigeration room-temperi 2.	The possible causes or factors associated with the previous event correspond: - Efficiency of equipment - Efficiency of gases - Failure in temperature control - Leaks or holes in doors, ceilings etc.	555.360	$222.704.347
The programs to establish optimal washing times and conditions according to the production scheme are not updated	Establish up-to-date procedures with washing time, tank rinses and equipment used in yeast	56.160 (Equivalent to 5% of the electricity consumption)	$11.229.435
Modification of Productive Energy Systems			

Source: Authors

Table 7. Opportunities energy saving and actions to improve energy performance (Continued)

Modification of Productive Energy Systems			
Find	**Opportunity identified**	**Benefits obtained**	
Loss of energy in cold rooms by leaving doors open for an extended period of time	Staff awareness to avoid leaving the doors of refrigeration rooms open for a long time.	Decrease in energy consumption and other associated costs.	
Boards that have associated loads of different processes without order.	Grouping of circuits and organization in the boards.	It allows to establish lines of monitoring of energy performance and at the same time to evaluate this latter by cost centers and/or process.	
Lack of measurement to track energy consumption	Installation of 20 meters of electrical energy, corresponding to equipment determinant in the different processes.	Perform better monitoring and control of energy consumption in the plant, achieving to respond to significant deviations of energy performance in the minimum time.	
Data of Energy consumption and production that disagree for were not registered at the same time.	Register with the same periodicity the information energy and productive so that there are parity when are carried out the corresponding analyzes	Correctly evaluate energy performance through the establishment and implementation of energy indicators that provide information on the amount of energy contributed in the process.	
Technology Reconversion			
Find	**Opportunity identified**	**Estimated annual energy saving (consumo kWh)**	**Estimated annual saving (COP)**
Motors with direct start were found	Automatic system of speed variator for Blowers.	191.124	$49.715.666
Find	**Opportunity identified**	**Expected savings and return on investment**	
In the yeast area, specifically in the fermentation process there are 4 motors of 350HP and a standard efficiency of 85%.	Engine change to a high efficiency of 95.8%	Return on investment is 2 years. Savings at 10 years that it represents the useful life of the equipment is $518.187.791,88 and net income is $ 435.089.182,90, Applied to the four engines with the same characteristics and operating time of 4.560 h/año, the total profit would be $ **1.740.356.732 COP**	

Source: Authors

3. Conclusion

An Energy Audit based on ISO 50002, provides a minimum set of measures and / or guidelines to perform a systematic analysis of energy use and energy consumption in an organization, building, equipment, system (s) and / or process (s), this constitutes a substantial piece in the development of an energy review, as it could be validated through the analysis carried out and the application in situ in a company dedicated to the production, sale and distribution of food ingredients, where through the various guidelines and / or requirements of ISO 50002 for data collection, measurement plan, analysis of current energy performance and identification and evaluation of improvement opportunities; It was possible to determine the participation of each area in the consumption of global electric energy and to establish the area of yeast as the highest consumption with a percentage of 68% and a value of 4,982,578 KWh/year; Additional to the above in this area were identified: I) Blowers as the most consuming equipment with a 48% share, and II) a critical production value greater than 112 Tons where the variation of the consumption index is minimal for one production range between 30 and 160 Tons; It was also possible through more detailed audits to identify opportunities for improvement by: production management, implementation of good operational practices in the refrigeration rooms, washing of equipment and tanks of the fermentation process; Modifications made in the energy-production system and technological conversion in high efficiency motors and variable speed drives that directly impact the energy efficiency of the company, generating considerable savings in cost.

4. Acknowledgement

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References

[1] Rey J., Velasco E. (2006) Libro de Eficiencia Energética en Edificaciones y Auditorías Energéticas. ISBN 84-9732-419-6, Thomson editores Espain. Can be ordered from: https://books.google.com.co

[2] Jovanovi B., Filipovi, J. (2016) ISO 50001 standard-based energy management maturity model e proposal and validation in industry. Journal of Cleaner Production 112 p.2744-2755.

[3] Dzene, I., Polikarpova, I., Zogla, L., Rosa, M. (2015) Application of ISO 50001 for implementation of sustainable energy action plans. Energy Procedia 72, p.111 – 118.

[4] Kluczek A. and Olszewski P. (2016). Energy audits in industrial processes. Journal of Cleaner Production 30, p. 1-17

[5] UPME, Proyección de Demanda de Energía Eléctrica y Potencia Máxima en Colombia Revisión marzo de 2015, p.25-26, 62. Can be ordered from: http://www.siel.gov.co

[6] Boharb, A., Allouhi, A., Saidur R., Kousksou T., Jamil A., Mourad Y., Benbassou A. (2016). Auditing and analysis of energy consumption of an industrial site in Morocco. Energy 101, p.332-342.

[7] UPME, Proyección de Demanda de Energía Eléctrica y Potencia Máxima en Colombia Revisión junio de 2016, p.50. Can be ordered from http://www.siel.gov.co

[8] Bonacina F., Corsinia A., De Proprisa L., Marchegiania, A., Moric F. (2015). Industrial Energy Management Systems in Italy: state of the art and perspective. Energy Procedia 82 p. 562 – 569.

[9] QUYEN, H., Thanh Tung LE. (2012). The Energy Management According to ISO 50001:2011 Standard and AEMAS Scheme Feasibly Implement in Viet Nam. IEEE, p.289.

[10] ISO 50001 standard-based energy management maturity model e proposal and validation in industry. Journal of Cleaner Production 112 (2016) p.2744-27.

[11] ISO 50001:2011(E). International standard, energy management systems-requirements with guidance for use. International Organization for Standardization 2011.

[12] ISO 50002:2014 (E). International standard, Energy Audits-requirements with guidance for use. International Organization for Standardization 2014.

[13] Dongellini M., Marinosci, C., Morini, G., (2014). Energy audit of an industrial site: a case study. Energy Procedia 45 p.424 – 433.

[14] Cagno, E., Trucco, P., Trianni, A., Sala, G., (2010). Quick-E-Scan: a methodology for the energy scan of SMEs. Energy 35 (5), p.1916-1926.

[15] Heras-Saizarbitoria, I., Dogui, K., Boiral, O., 2013. Shedding light on ISO 14001 certification audits. J. Clean. Prod. 51, p.88-98.

[16] Castrillon, R., Quispe, E.C., Gonzalez, A., Urhan, M. & Fandiño, D. (2015) Metodología para la implementación del Sistema de Gestión Integral de la Energía. Fundamentos y casos prácticos. ISBN 9789588713540. Cali, Colombia.

Improvement of Electric Motor Systems in Industry (IEMSI)

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Abstract

In March 2011, the Swiss government decided to withdraw from the use of nuclear energy in the long term. In its "Energy Strategy 2050", the federal government defined a variety of measures, in particular aimed at increasing the production of electricity from renewable sources, significantly reducing energy consumption and stabilising electricity consumption. For the past five years, statistics have pointed to a decrease in annual overall energy consumption in Switzerland, while electricity consumption has remained more or less stable. In Switzerland, industry accounts for a large proportion of electricity consumption, particularly for motor systems. A survey conducted between 2010 and 2014 encompassing more than 4,100 industrial motor systems revealed that more than 50 percent of the motors in use had by far exceeded their technical service life. Although such systems can still perform and fulfil their function, they are nevertheless outdated, and in many cases are also oversized and inappropriately controlled. The same survey revealed that only 20 percent of the motor systems are equipped with variable speed drives, and that two-thirds of them have a load factor below 60 percent. For all these reasons, the Swiss Federal Office of Energy (SFOE) decided to launch a new programme called "Improvement of Electric Motor Systems in Industry" (IEMSI). This programme is to broaden the existing "topmotors.ch" (TM.ch) programme that was launched in 2007 with the main aim of reducing the energy consumption of motors and drive systems through information, education, networking and promotion of premium motors. It costs around 2.0 million euros and its impacts were evaluated in 2014. The results of the evaluation showed that it achieved its objective, but that the range of its impacts was limited. In view of this, the IEMSI programme was developed as a strategy focusing on the extensive implementation of recommendations and voluntary measures aimed at reducing the electricity consumption of motor systems in industry, based on:

- Active communication
- Tools for spot checks, as well as for detailed analysis
- Events
- Market survey

The programme is planned for a 5-year period with a budget of over 3.0 million euros, and its impact is to be monitored through market data, as well as the annual Swiss energy statistics, which include a separate category for industrial motor systems. The paper presents the four instruments of the IEMSI programme in detail, together with its monitoring tools.

Introduction

The Swiss electricity production mix mainly comprises hydropower and nuclear energy (60 and 34 percent respectively).[12] The remaining 6 percent is produced in conventional thermal power plants (gas, oil and non-renewable waste incineration) and other renewable energies.

In 2011, the Federal Council and Parliament decided that Switzerland has to withdraw from the use of nuclear energy on a step-by-step basis. The existing five nuclear power plants are to be decommissioned when they reach the end of their safe service life, and will not be replaced by new ones. As a result of this decision and various other profound changes (e.g. low electricity prices) that have been observed for a number of years, in particular in the international energy arena, the Swiss energy system will require successive restructuring in the period up to 2050. In view of this, the Federal Council developed a long-term energy policy ("Energy Strategy 2050") based on the revised energy perspectives.[13] At the same time, it produced an initial package of measures aimed at securing the country's energy supply over the long term.

The initial package of measures concerns three sectors: households, services and industry. The statistics show that the industry sector accounts for almost one-third of the country's electricity consumption and that electric motor systems account for more than half of electricity consumption in the industry sector. Furthermore, an extensive survey in the industry sector revealed that a large percentage of electric motor systems are oversized, too old and inefficiently operated. Based on the savings potential of electric motor systems, Switzerland's annual electricity consumption could be reduced by up to 5%.

The initial package of measures contains three instruments for the promotion of energy efficiency in order to facilitate the implementation of the efficiency potentials: a) regulation, b) voluntary measures without subsidies, and c) voluntary measures with subsidies. In this paper, and in order to limit the broad scope of energy efficiency, the focus is on electric motor systems and the "Improvement of Electric Motor Systems in Industry" (IEMSI) programme relating to the voluntary measures without subsidies, the main objective of which is to reduce electricity consumption in the industry sector.

This paper contains a brief description of the survey conducted in the industry sector, and of the "Topmotors" programme. It presents the IEMSI programme in greater detail, as well as tools for monitoring its impact, and concludes with a brief summary.

Starting point

The findings are based on the EASY financial incentives programme[14] regarding the age of the motor systems, as well as their effective load factor and their mode of control with manual adjustment versus the use of variable frequency drives (VFDs). Between 2010 and 2014, "Topmotors" was responsible for the EASY programme. Its main goal was to improve the energy efficiency of electric motor systems and obtain an overview of the electric motors currently in use in the Swiss industry sector, and in large buildings and infrastructure systems. More than 4,100 motors were analysed using a standard software tool:

- Application (pump, fan, compressor, etc.)
- Size

[12] Schweizerische Elektrizitätsstatitisk 2015 (Swiss Electricity Statistics for 2015), Swiss Federal Office of Energy, July 2016, p. 3.

[13] Botschaft zum ersten Massnahmenpaket der Energiestrategie 2050 (Dispatch to Parliament concerning the initial package of measures relating to Energy Strategy 2050), Swiss Federal Office of Energy, September 2013.

[14] EASY, Efficient energy use in motor systems, pilot programme for financial incentives in 2010 to 2014. Link: http://www.topmotors.ch/Easy/

- Age
- Annual operating hours
- Use of variable frequency drive (VFD [yes/no]).

The focus on age, operating hours, size and type of drive (manual or VFD) is based on the following rationale in the industry sector: "old" motors can be easily improved because they are amortised and are usually in a low-efficiency category. Also, motors with long operating are applicable for being improved profitably because they have higher cost effectiveness and the additional cost for premium motors can be amortised more quickly. Medium-sized and large motors are responsible for a larger share of energy use and are thus targeted primarily in a company-wide improvement concept. Motors without VFD driving pumps and fans tend to possess significant efficiency potential. With these four categories, a large share of efficiency improvements can be identified and realised.

The results illustrate the importance of improving the efficient use of motors by choosing efficient components with the right size and smart controls, as well as the need for further action.

Motor system age

The age of all motors was analysed in order to obtain an overview and determine whether any correlations exist between age and output size. The actual age of the motors (from their purchase and installation date) was compared to a standard operating life expectancy, i.e. the expected service life until a replacement is necessary. This is based on "Ecodesign" motor studies and defined as:

- < 1 kW 10 years
- 1-10 kW 12 years
- 10-100 kW 15 years
- > 100 kW 20 years

The results show that, overall, 56% of all analysed motors were older than their "operating lifetime expectancy". On average, these "too old motors" were 99% too old. This means they were almost twice as old as expected.

Variable frequency drive (VFD)

All motor systems in the sample were checked for the use of a VFD. Very few are equipped with VFD today. In fact, only 19.8% of all the motor systems in the survey were already equipped with a variable frequency drive. The findings of several "Topmotors" projects in the industry sector showed that approximately 60% of all motors can be operated with a VFD and the speed can thus be automatically adapted to the variable load of the process. This is an indication that, in many cases, energy can be saved through the proper use of a VFD to modify the speed of the motor to the actual requirement. If properly used, a VFD can reduce energy consumption by between 30 and 60% in a closed loop pump or fan application.

Load factor

In the course of the EASY programme, from the more than 4,100 motor systems that were included in the survey, a sample of 104 with high savings potential were selected to be metered in greater detail. Here, various factors such as electrical input, load fluctuation, starting conditions, operating hours, interruptions, etc., were recorded. The measured data were evaluated in order to draw conclusions concerning the necessary size and load of the motors. The average load factor of all measured motors was 52%. Motors with an average load factor of less than 60% are generally considered oversized if special starting torque requirements do not apply. In this case, 68% of the motors were found to be oversized. Today, motors indicate an even efficiency curve at loads of between 100 and 60%, with the peak at around 70 to 80%. With longer periods of use below 50%, the efficiency of the motor is lower. A low average load factor thus indicates an efficiency rate below the nominal level.

"Topmotors" programme (TM.ch)

The goal of the "Topmotors" programme (www.topmotors.ch) is to generate and disseminate knowledge about efficient motor systems, applications (pumps, fans, compressors, etc.) and their correct use and adaptation to the mechanical needs of a process. The target audience is factory personnel, energy efficiency consultants, manufacturers and their sales staff, universities, public officials engaged in MEPS, etc. This knowledge is presented in a variety of ways, including fact sheets, workshops, software tools, newsletters, websites, etc.

The impacts of TM.ch since its launch in 2007 were evaluated in 2014 based on its three main strategic goals: information and education, networking and promotion of premium motors.

With the products it has developed and introduced over the years, TM.ch has succeeded in reaching several different target groups. However, around half the energy-intensive companies were not aware of the existence of the programme, and the same applies to the OEM companies. This was identified as an area in need of improvement for the next programme through the adoption of a broader and more systematic approach to the target groups.

With respect to the second strategic goal, namely to network participants and market players in order to accelerate the development of more efficient motor systems, the evaluation revealed that TM.ch has been providing opportunities for them to meet, exchange ideas and network at workshops, as well as during international and national events such as motor summits.

The third strategic goal concerns the promotion of premium motors. Here it appears that TM.ch did not have a direct impact on the strategy of motor manufacturers and OEM suppliers. However, on the demand side (manufacturers' and suppliers' customers) it was able to play a certain role by making users aware of the benefits of purchasing premium motors and thus exerting pressure on the manufacturers and suppliers. By applying its "spot-check" method in order to assess the savings potentials, "TM.ch" was able to establish direct contact with companies. However, the "spot check" was mostly suitable for large companies, but not for extensive deployment among small and medium-sized firms. Although TM.ch had a certain impact and created some awareness, its reach was not extensive, particularly among OEM manufacturers and suppliers. Nevertheless, it was able to initiate and generate a strong impulse for promoting efficient electric motor systems, and during its first period of seven years its activities included:

- The development of two numeric tools, as well as a standard protocol for measurements
- The publication of 13 technical manuals and information sheets
- The publication of 17 technical papers
- Mailing of newsletters (up 3 per annum)
- Organisation of 9 workshops and 4 motor summits.

The evaluation report strongly recommended the continuation of the programme, but also cited some weaknesses that need to be addressed, e.g. the need to define a strategy for broader implementation. The findings therefore provided the main inputs for the development of the IEMSI (Improvement of Electric Motor Systems in Industry) programme that is the topic of the next section.

Alongside the IEMSI programme, a variety of research, education and technical projects are currently in progress within "Topmotors", including further education for industrial energy optimisation and the development of a "motor test" box for quick integrated audits. These go beyond the scope of this paper, but still deserve a mention.

IEMSI programme

The main goal of the IEMSI programme is to extend the TM.ch programme and thus to achieve a broader implementation and increase the number of targeted groups. As mentioned in the evaluation report, the IEMSI programme can operate with similar activities and approaches to those of TM.ch, but with a broader impact.

In Switzerland there are more than 90,000 small and medium-sized companies with an annual electricity consumption ranging from 100 MWh to more than 20 GWh. The IEMSI programme has to be set up for these companies and contribute towards the attainment of the following objectives:

- 15% of the companies to be made aware of the IEMSI programme via the Internet, technical papers or special events
- Downloading of at least one document by 10% of the companies
- Analysis carried out by 5% of the companies
- Implementation of efficiency measures by 2% of the companies
- Cost efficiency ratio of the programme to be lower than 5 cents per kWh (accumulated electricity savings over the duration of the measures).

The IEMSI programme comprises four blocks: a) communication, b) tools, c) events and d) market, and has a duration of five years and a budget of 3.0 million euros.

Communication

Communication should be designed to motivate the companies to implement efficiency measures by providing them with information via:

- Newsletters (4 times per annum)
- Technical booklets and information sheets (at least two per annum)
- Success stories (at least two per annum)
- Technical papers (at least two in German and one in French per annum)

As the "Topmotors.ch" brand has become well established over the years, it has been decided to keep it for the IEMSI programme, and all the documentation will be available and downloadable directly from the www.topmotors.ch website, which will be revamped to meet the state of the art in web design with enhanced functionalities and be available in at least in three languages: German, French and English. The structure of the website is depicted in Figure 1.

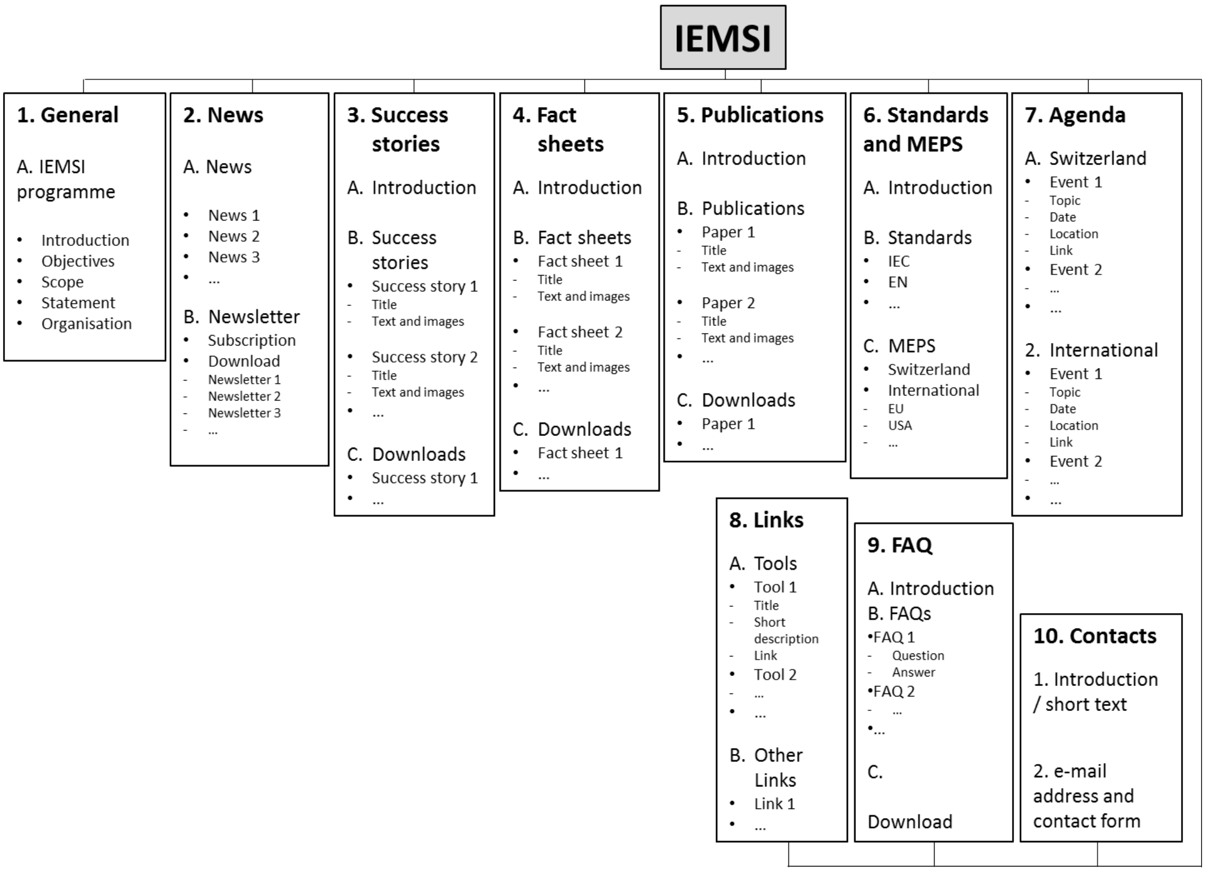

Figure 1: Structure of the IEMSI website.

Tools

The evaluation indicated that the "spot check" is suitable for large companies, but not yet for broad implementation by small and medium-sized firms. This aspect is to be addressed in the IEMSI programme. Furthermore, there are several software tools available for estimating the savings potential for electric motors, pumps, fans, etc. The range of existing software tools can be confusing, and in view of this a uniform analysis method and associated tools still need to be developed. The analysis method has to support a system-based approach while taking the complete system into account, from the power supply through to the corresponding process. It should also proceed on a step-by-step basis, where the first step is to perform a spot check which will enable the company to decide within a few minutes whether or not it is worth taking further steps to estimate the savings potential. The next step would be to make a more detailed assessment of the savings potential:

- Spot check with 4 to 5 questions to be answered within less than 5 minutes as a GO/NO-GO decision-making tool
- Preliminary analysis (2 hours up to a maximum of 3 days) to obtain an initial assessment of the savings potential, with a margin of error of between 20 and 50%
- Detailed analysis (up to a maximum of 10 days) to obtain a more detailed assessment of the savings potential, with a margin of error of less than 10%

The company can abort after each step if the savings potential is either negligible or too expensive to implement. A company can already benefit immediately upon completion of the preliminary analysis by implementing those efficiency measures that do not require a more detailed analysis.

Figure 2: Spot check for pumps.[15]

The analysis method will be implemented in an "all-in-one" downloadable software tool for electric motor systems such as pumps, fans, and compressors for compressed air and cooling. Figures 2 and 3 show an example of a spot check and preliminary analysis for pumps, based on a web tool and an excel sheet.[16] Companies of all sizes should be able to perform the spot check and preliminary analysis by themselves, but they may need the assistance of an external energy consultant for the detailed analysis, depending on the size of the company and the experience of their employees.

Preliminary analysis tool for efficient pump systems

Detailed results

Electricity price: 16 cents per kWh

							Savings potential		Recommendations
No.	**Identification**	**Other identification**	**Location**	**P**	**t**	**Year**	**Total**		**Detailed analysis**
				[kW]	[h/a]	Construction year	[kWh/a]	[EUR/a]	
2	Pump mixer Nr. 3	A2		10'000	3'000	1900	5'825'023	932'004	Detailed analysis highly recommended
5	Pump cooling section B	B2	Workshop	100	2'000	1990	49'225	7'876	Detailed analysis highly recommended
7	Circulation pump Nr. 1	C21		10	8'000	2010	12'339	1'974	Detailed analysis recommended
3	Circulation pump offices north and west	A3		250	100	1980	10'724	1'716	Detailed analysis recommended
8	Vacuum pump workshop	C22		9	8'000	2010	2'160	346	no action needed
1	Pump mixer Nr. 2	A1		10	2'000	2010	1'839	294	no action needed
9	Pump cooling section A	C23		10	2'000	2010	1'839	294	no action needed
4	Circulation pump office south	B1		3	5'000	2014	1'228	196	no action needed

Figure 3: Result of a preliminary analysis for pump systems based on an EXCEL tool.[17]

Special events

In order to increase access to the target groups, three types of events are planned: a) international and national motor summits, b) workshops and c) webinars.

The motor summits take the form of two-day international and one-day national conferences held on an alternating basis every two years and intended to attract between

[15] *Efficient pump systems: spot check*. Link: http://www.proepa.ch/

[16] *SwissEnergy campaign for efficient pump installations*. Link: www.effiziente-pumpen.ch

[17] *Efficient pump systems: preliminary analysis*. Link: http://www.proepa.ch/

100 and 200 participants (technicians, engineers, managers, policy makers, etc.). They focus on topics relating to electric motor systems, ranging from regulations and policy to technology.[18] By contrast, the workshops and webinars focus on a specific topic. The workshops are half-day events that are held three times a year (two in German and one in French) for a maximum of 40 participants (mainly technicians and engineers). The webinars are a new type of event that takes the form of a 45-minute presentation on a single topic. Here the main objective is to provide an opportunity for those who are unable to attend a motor summit or workshop to learn more about efficient electric motor systems. Four webinars are planned per annum (three in German and one in French).

Market

Sales data

Electric motors account for around half of Switzerland's annual electricity consumption with motors with an output ranging from less than 0.12 kW to over 1,000 kW. (what does this mean?) In Switzerland's industry sector there are more than 2 million electric motors. In 2014, Switzerland tightened its regulations governing electric motors between 0.75 kW and 375 kW based on EU Directive (EC) No. 640/2009:

With effect from 1 January 2015: IE3 (7.5 kW – 375 kW) or IE2 with VSD

New, with effect from 1 January 2017: IE3 (0.75 kW – 375 kW) or IE2 with VSD

However, at the moment no data are available for quantifying the impacts of the new regulations. With the initiation of the IEMSI programme, however, specific market data for Switzerland will become available (cf. data acquisition table shown in Figure 4). The sales data will make it possible to monitor the development of the various motor efficiency classes based on their nominal power, and thus to assess and quantify the transition from IE2 to IE3 and higher efficiency classes.

[18] *Motor summits 2016*. Link: www.motorsummit.ch

Number of electric motors sold in Switzerland								
Nominal power (kW)	IE1 (IEC 60034-30-1)		IE2 (IEC 60034-30-1)		IE3 (IEC 60034-30-1)		IE4 (IEC 60034-30-1)	
	4-pole only	All other poles	4-pole only	All other poles	4-pole only	All other poles	4-pole only	All other poles
0.12 to <0.18								
0.18 to <0.25								
0.25 to <0.37								
0.37 to <0.56								
0.56 to <0.75								
0.75 to <1.1								
1.1 to <1.5								
1.5 to <2.2								
2.2 to <3.7								
3.7 to <5.5								
5.5 to <7.5								
7.5 to <11.0								
11.0 to <15.0								
15.0 to <18.5								
18.5 to <22.0								
22.0 to <30.0								
30.0 to <37.0								
37.0 to <45.0								
45.0 to <56.0								
56.0 to <75.0								
75.0 to <90.0								
90.0 to <110.0								
110.0 to <150.0								
150.0 to <185.0								
185.0 to <220.0								
220.0 to <250.0								
250.0 to <1000.0								

Figure 4: Data acquisition table for the annual sales data of electric motors in Switzerland.

Producer and supplier data

In the same way as in the "TM.ch" programme, producer and supplier data will continue to be available in the form of a price estimation based on the nominal power in euros per kW for motors and VSD ranging from 0.12 kW to 1,000 kW where available in the supplier/producer product range. Figure 5 shows an example of an information sheet for motor prices, which can serve as a useful tool for calculating investment costs as well as the pay-back time following the replacement of an old motor with a premium or super premium model.

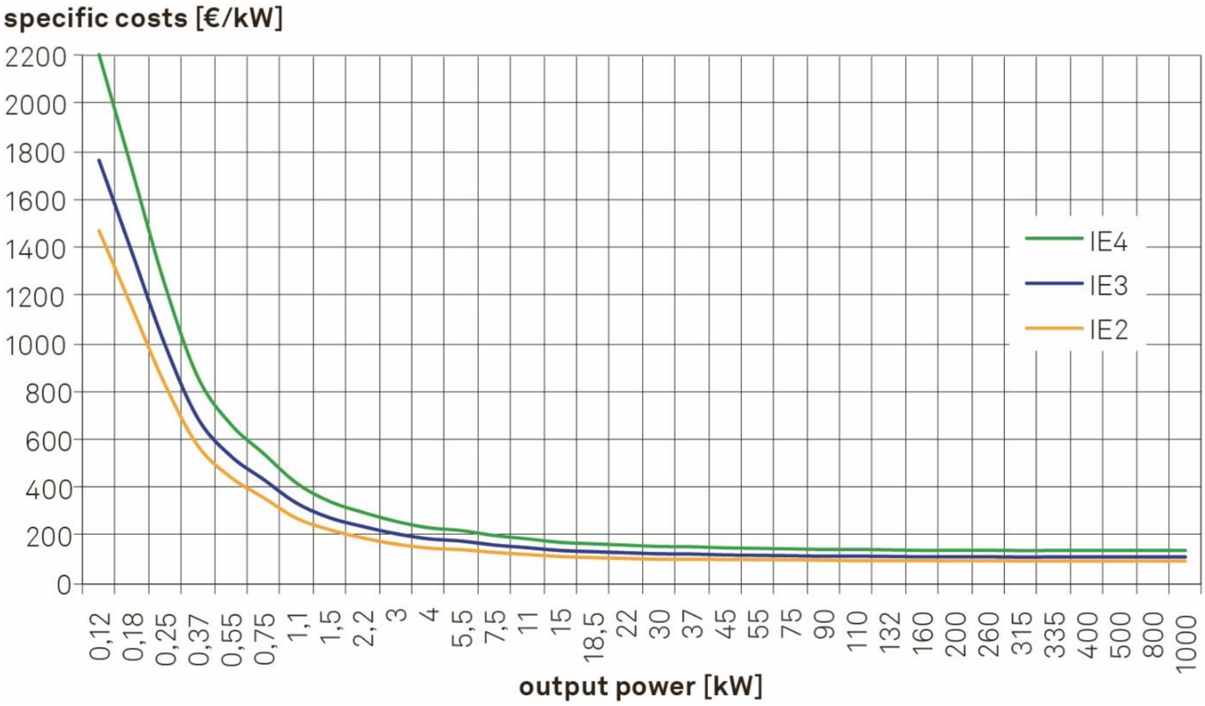

Figure 5: Specific electric motor prices by efficiency class and nominal power.[19]

IEMSI programme as a first step towards implementing efficiency measures

The implementation of efficiency measures is the last step in a four-step process, as depicted in Figure 6, starting with a) information and rising awareness, followed by b) advising, c) quantification and d) implementation.

Figure 6: The four-step process for implementing efficiency measures.

The Swiss energy policy system specifies mandatory requirements, e.g.

- MEPS (Minimum Efficiency Performance Standard) for circulation and water pumps, fans and electric motors[20]
- Audits, agreements on energy reduction targets and energy monitoring for companies with an annual electricity consumption ≥ 0.5 GWh[21]

[19] Information sheet 10: Motor prices, Topmotors, October 2014. Link: http://www.topmotors.ch/Download/

[20] Energy Ordinance, Appendices 2.10, 2.13, 2.17 and 2.19, last revision January 2017. Link: https://www.admin.ch/opc/de/classified-compilation/19983391/2017010101 000/730.01.pdf

[21] Leitfaden zur Unterstützung der Kantone bei der Umsetzung des Grossverbraucherartikels, Swiss Federal Office of Energy, May 25th 2009. Link: http://www.bfe.admin.ch/dossiers/03848/index.html?lang=de

The aim of the audit is to identify profitable efficiency measures with a payback time of less than 4 years, in order to reach agreement on energy reduction of either 2 percent per annum over 10 years or 15 percent in 3 years. The MEPS, audits and the agreements on energy savings are part of the quantification and implementation steps.

Although the legal framework conditions have helped to stabilise and even decrease Switzerland's energy consumption since 2008, especially of combustibles (fuels),[22] more needs to be done regarding the reduction of electricity consumption, especially by motor systems. The legal framework conditions only permit the implementation of a certain proportion of the full efficiency potential. For this reason, Switzerland's energy policy also supports voluntary measures based on a system-related approach from the initial process through to the electricity injection point within the system, instead of just improving the efficiency of single components (e.g. electric motors, pumps, etc.). However, producers, OEM suppliers and users need to be informed and their awareness has to be increased, which actually corresponds to the first step in the four-step process described above. In fact, this is what the IEMSI programme is designed to achieve.

Regarding the other three steps (advising, quantification and implementation), there are also other programmes, based on voluntary measures, in addition to the mandatory MEPS and audits. One of these is the platform for advising and quantifying the energy saving potential among small and medium-sized companies based on a subsidy programme,[23] and the other is a competitive tenders programme that provides subsidies through an auction process that rewards efficiency measures with the best cost-efficiency ratio.[24]

The IEMSI programme has been designed to support the objectives defined in Switzerland's Energy Strategy 2050 regarding the target levels for the reduction of electricity consumption: minus 3 percent and minus 13 percent in 2020 and 2035 respectively.[25] Furthermore, the following section describes how the impact of the IEMSI programme will be monitored in order to assess its impact.

The IEMSI programme has some similarities with the IEA 4E Electric Motor System Annex (EMSA), but has a stronger focus on the market and the implementation of efficiency measures.

Impacts of the IEMSI programme

All four blocks of the programme will be monitored and static data will be made available, e.g.:

- Number of downloads (tools, success stories, technical booklets and information sheets)
- Number of visitors to the website
- Number of mailed newsletters
- Number of participants at events (workshops, webinars)
- Market statistics
- Feedback forms

This will make it possible to quantify the size of the reached audience, as well as to estimate the number of preliminary and detailed analyses that have been carried out.

[22] Schweizerische Gesamtenergiestatistik 2016, SFOE, July 2017, p. 2. Link: http://www.bfe.admin.ch/themen/00526/00541/00542/00631/index.html?lang=de&dossier_id=00763

[23] PEIK: Platform for energy efficiency in SMC, Swiss Energy program, SFOE. Link: www.peik.ch

[24] Swiss Competitive Tenders Efficient Motor Systems, Dr. Richard Phillips, EEMODS'15, September 2015, Helsinki, Finland. Link: http://www.eemods15.info/programme/

[25] Energy Strategy 2050 after the popular vote, SFOE, 29 May 2017, p. 6. Link: http://www.bfe.admin.ch/energiestrategie2050/index.html?lang=en&dossier_id=06702

It may also be possible to make a pre-evaluation at mid-term or a full evaluation at the end of the programme to get more precise information about its impacts.

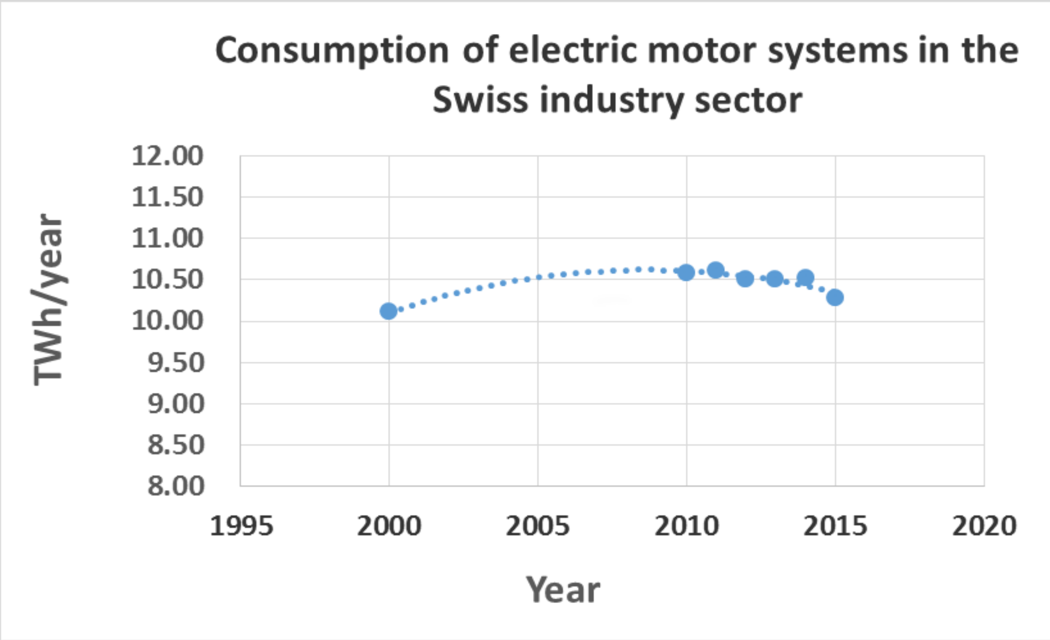

Figure 7: Development of electricity consumption of electric motor systems in the industry sector since 2000.[26]

The Swiss Federal Office of Energy also publishes annual electricity statistics by sector as well as application, together with statistics concerning competitive tenders.[27] These provide an overview of the development of electricity consumption during the year. They also include a category for electric motor systems. Figure 7 shows the development of their electricity consumption in the industry sector since 2000: as we can see, following a steady increase in the period from 2000 to 2010, consumption stabilised, and even decreased slightly, from 2011 onwards. This confirms the positive impacts of the efficiency measures that have been implemented in recent years through regulation and policy, as well as programmes such IEMSI which over the next five years will continue to help stabilise and reduce electricity consumption in the industry sector.

Summary

Based on a survey encompassing more than 4,100 electric motors, the findings regarding the age of the motor systems, as well as their effective load factor and their mode of control, show that a) 56% have exceeded their operating life time expectancy, b) only 20% are equipped with a variable frequency drive (although experience has shown tha approximately 60% of them could be operated using a VFD) and c) 68% are oversized.

Based on these findings, the "Topmotors" programme is to generate and disseminate knowledge about efficient motor systems and their correct use and adaptation to the mechanical needs of a process. The target audience is factory personnel, energy

[26] *Analyse des schweizerischen Energieverbrauchs 2000-2015 nach Verwendungszwecken (Analysis of Swiss energy consumption by application, 2000-2015)*, table 4-16, p. 64. Swiss Federal Office of Energy, October 2016. Link: http://www.bfe.admin.ch/themen/00526/00541/00542/02167/index.html?lang=de&dossier_id=02169

[27] Results of Swiss competitive tenders since 2010. Link: http://www.bfe.admin.ch/prokilowatt/06034/index.html?lang=de

efficiency advisers, manufacturers and their sales staff, universities, public officials engaged in MEPS, etc. The programme was launched in 2007 and cost around 2.0 million euros. Its impacts since its launch were evaluated in 2014 based on its three main strategic goals: information and education, networking and promotion of premium motors. The results of the evaluation were fairly positive in that they confirmed that "Topmotors" was in fact able to initiate a strong impulse for promoting efficient electric motor systems. The report strongly recommended the continuation of this programme, but also cited some weaknesses that need to be addressed, for example the need to define a strategy for broader implementation, and its findings were adopted as the main inputs for the development of the IEMSI programme.

The main goal of the IEMSI programme is to extend the activities of "Topmotors" and thus achieve broader implementation and increase the number of target groups. As noted in the evaluation report, the IEMSI programme can pursue similar activities and approaches to those adopted by "Topmotors", but with wider-ranging impacts. The IEMSI programme has therefore been divided into four blocks: a) communication, b) tools, c) special events and d) market, with a duration of five years and a budget of 3.0 million euros.

Communication should be designed to motivate companies to implement efficiency measures by providing them with appropriate information. As the "topmotors.ch" brand has become firmly established in the past few years, it was decided to retain it for the IEMSI programme, and all the documentation will be available and downloadable directly from the www.topmotors.ch website, which is to be revamped to meet state of the art web design with enhanced functionalities, and will be made available in at least three languages: German, French and English.

A uniform analysis method and associated tools are to be developed based on a solution that supports the entire system, from power supply through to the corresponding process. It should be implemented on a step-by-step basis, with the first step taking the form of a spot check that enables the company to decide within a few minutes whether or not it is worthwhile investigating the savings potential in greater detail. The next steps should permit an assessment of the savings potential, thus enabling companies to obtain immediate benefits by implementing the efficiency measures as soon as possible.

In order to increase access to the target groups, various events are to be held: a) international and national motor summits, b) workshops and c) webinars. The webinars are a new type of event that takes the form of a 45-minute presentation, the main objective of which is to provide those who are unable to attend a motor summit or workshop with an opportunity to learn more about efficient electric motor systems.

Electric motors account for around half of Switzerland's annual electricity consumption with motors with an output ranging from below 0.12 kW through to more than 1,000 kW. In 2014, Switzerland tightened its regulations based on EU Directive (EC) No. 640/2009. However, no data are available as yet for quantifying the impacts of the more stringent regulations. With the initiation of the IEMSI programme, specific market data for Switzerland will be made available, thus making it possible to monitor the development of the various motor efficiency classes. As far as the "Topmotors" programme is concerned, the producer and supplier data will still be available in the form of a price assessment based on the nominal power as a tool for calculating the investment costs, as well as the pay-back time for the replacement of an old motor with a premium or super premium model.

In order to assess the impacts of the IEMSI programme, all four blocks will be monitored and static data will be made available (e.g. number of downloads, number of visitors to the website, number of participants at the various events). The Swiss Federal Office of Energy also publishes annual statistics by sector and application which provide an overview of the development of electricity consumption during the year. The statistics include a category for electric motor systems showing the development of their electricity consumption in the industry sector since 2000 and confirming the positive impacts of the efficiency measures that have been implemented via regulations and policies, as well as by programmes like IEMSI which will continue to help stabilise and reduce electricity consumption in the industry sector over the next five years.

References

[1] *Schweizerische Elektrizitätsstatistik 2015 (Swiss Electricity Statistics for 2015).* Swiss Federal Office of Energy. July 2016. Orders: http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=de&dossier_id=00765

[2] *Message relative au premier paquet de mesures de la Strategie énergétique 2050 (Dispatch to Parliament concerning the initial package of measures for Energy Strategy 2050).* Swiss Federal Office of Energy, 4 September 2013. http://www.admin.ch/opc/fr/federal-gazette/2013/6771.pdf

[3] Die Energieperspektiven für die Schweiz bis 2050: Energienachfrage und Elektrizitätsangebot in der Schweiz 2000-2050 (Switzerland's energy perspectives for the period up to 2050: energy demand and electricity supply in Switzerland, 2000-2050). Swiss Federal Office of Energy, April 2013. http://www.bfe.admin.ch/themen/00526/00527/06431/index.html?lang=de&dossier_id=06421

[4] *Analyse des schweizerischen Energieverbrauchs 2000-2015 nach Verwendungszwecken (Analysis of Switzerland's energy consumption, 2000-2015, by purpose).* Swiss Federal Office of Energy, October 2016. http://www.bfe.admin.ch/themen/00526/00541/00542/02167/index.html?lang=de&dossier_id=02169

[5] Swiss audit programme, "EASY": Rita Werle, SAFE, Motor Summit 2014. Zurich, Switzerland. http://motorsummit.ch/data/files/MS_2014/ms14__tagungsband_komplett_web.pdf

[6] *Evaluation des Programms Topmotors*, Dr. M. Egger, A. Wütrich, Dreher and Partner (Evaluation of the Topmotors programme). Swiss Federal Office of Energy, February 2015. http://www.bfe.admin.ch/themen/00526/00541/index.html?lang=de&dossier_id=06281

[7] *Massnahmen zum Stromsparen bei elektrischen Antrieben: Marktanalyse in der Industrie*, W. Baumgartner et al. (Efficiency measures for electric motors: market analysis within the industry sector). Basic (on behalf of the Swiss Federal Office of Energy), December 2006. http://www.bfe.admin.ch/forschungelektrizitaet/01740/01748/01751/02198/index.html?lang=fr&dossier_id=02023

[8] *Wettbewerbliche Ausschreibungen für Stromeffizienz: Fakten und Zahlen 2010-2015 (Competitive calls for tenders for efficient electricity use: facts and figures, 2010-2015).* Swiss Federal Office of Energy, September 2016. http://www.bfe.admin.ch/prokilowatt/06034/index.html?lang=de

Analysis of Chinese Policies and Mechanisms for Energy Efficient Motor Systems

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Abstract

In the last two decades, China, as the "world factory", has consumed more than 70% of their electricity on industries, in which around 75% was used by Electric Motor Driven Systems. In 2014, China ranked No. 1 by consuming 28.3% of the global electricity use on motor systems. According to the Energy Conservation Law (approved in 1997, revised in 2007, 2016), China launched a series of national policies and programs improving energy efficiency of electric motors and motor systems. From 2010 to 2014, China has developed six batches of catalogues for energy-efficient motors and subsidized them through a national financial incentive program called "Jienenghuimin"[28] [1]. In 2013, China launched a three-year National Motor Energy Efficiency Improvement Plan (2013-2015), aiming to deploy high efficient motors, eliminate inefficient motors and improve motor system efficiency, in which Minimum Energy Performance Standards (MEPS) and labelling schemes were improved, catalogues of Eliminated High Energy Consumption and Backward Mechanical and Electrical Equipment (incl. motors, compressors, fans, pumps and transformers) were updating, national training and regional system audit programs such as Topmotors China Zhenjiang Pilot [2] [7] were conducted. But due to multiple barriers, the motor system energy saving potentials in China were still not well tapped.

With support of the Energy Foundation, Renergy Technology Consulting Beijing LLC has implemented a 1-year project "Mechanism Research & Policy Analysis on China Motor System Energy Efficiency Improvement", in which the existing policies and programs were reviewed and analyzed, barriers hindering motor system efficiency improvement in China were identified, and recommendations to improve the policies were made accordingly. In this paper, the key findings and results of this project are presented, including the development and harmonization of exiting MEPS, new development of China Energy Label (CEL) with QR code, related compliance and enforcement programs, analysis of the "Jienenghuimin" financial incentive program, as well as the barrier analysis for implementing Energy Efficiency Retrofit Projects both in Motor Users' and ESCOs' perspectives. In addition, lessons learned from the local level and financial sectors were summarized. This paper concludes with suggested options for improving motor system energy efficiency policies and mechanisms in China.

Key words: Analysis of Policies and Mechanisms, Electric Motor Driven Systems, China National Motor Energy Efficiency Improvement Plan, the "Jienenghuimin" Financial Incentive Program, Minimum Energy Performance Standards (MEPS), China Energy Label (CEL), Barrier Analysis, Policy Recommendations.

[28] Jienenghuimin means Promoting Energy-Efficient Products for the Benefit of the People, see the official website of this program: www.jienenghuimin.net.

Background

With the fast economic growth in the past decade, China's electricity consumption increased from 3643.2 Terawatt hours in 2009 to 5919.8 Terawatt hours in 2016. The Figure 1 shows that more than 73% of China's electricity were used on second industry from 2009 to 2016, and in which electric motor systems consumed more electricity than any other end use in China. According to the statistics, by 2013, the estimated installed capacity of the electric motor stock in China was about 2.1 TW, and their total electricity consumption was about 3,400 TWh/a, which accounted for 64% of China's total electricity consumption. In the industrial sector, electric motors consumed 2,900 TWh electricity which accounted for around 75% of industrial electricity consumption.

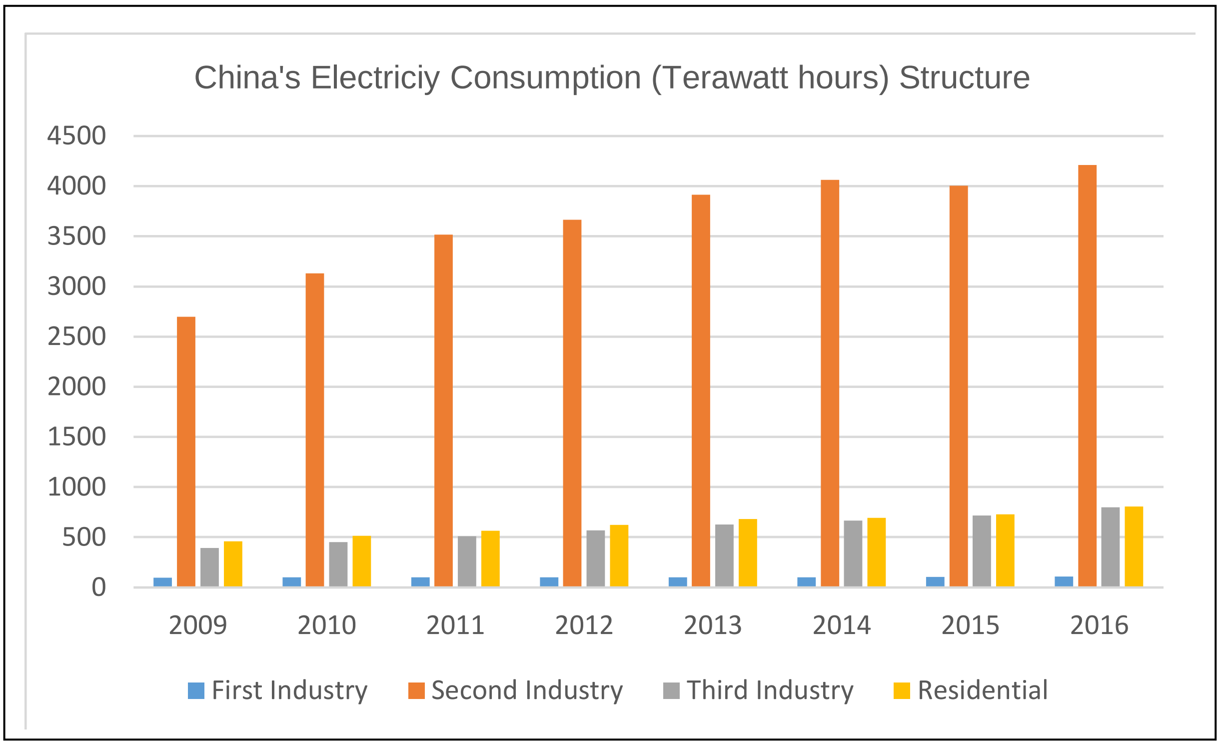

Figure 1. China's Electricity Consumption Structure from 2009 to 2016.

Data Source: National Energy Administration (NEA), China.

According to the statistics of the Ministry of Industry and Information Technology (MIIT), the average energy efficiency (EE) of Chinese motor systems is 10% to 20% lower than the level of developed economies. Problems exists with backward motor manufacturing technology with low innovation, lack of speed control, inefficient transmission systems, no automatic and intelligent system control, inadequate standardization services and enforcement, weak market-driven mechanisms etc.

In China, more than 60% of the electricity is generated by coal, so that the average emission factor of 1 kWh electricity in China is about 1 kilogram of CO_2. The significant electricity savings will help China contribute to tackling climate change by peak its carbon emissions by 2030.

Legal Framework

China's Energy Conservation Law [3] forms the legal basis of Motor EE & Motor System EE regulation. By 2016, it was revised twice since 1997 as shown below, and there is a specific article in each version to emphasize EE of the end-use equipment of motor driven systems.

- Version 1, Nov. 1997: article 39, II, *encouraging application and innovation on technologies such as efficient motors, fans, pumps as well as speed-adjusting technologies etc.*
- Version 2, Oct. 2007: article 31, *the state encourages industrial enterprises to adopt efficient energy-saving motors, boilers, kilns, fans, pumps and other equipment, the CHP cogeneration, waste heat and pressure utilization, clean coal and advanced energy monitoring and control technologies.*
- Version 3, Jul. 2016: article 31 did not change.

National Goals and Action Plan

In June 2013, the Ministry of Industry and Information Technology of China (MIIT) and the General Administration of Quality Supervision, Inspection and Quarantine of China (AQSIQ) co-launched a national program named "Electric motor energy efficiency improvement plan (2013-2015)" aiming to deploy 170 GW of high efficient motors (i.e. IE3 and IE4) and to eliminate 160 GW of older inefficient motors, to improve motor systems by motor replacement of 100 GW, and to refurbish 20 GW in replaced motors.

Since electric motors work with their respective application (pump, fan, compressor, etc.) as a system, it is obvious that only replacing motors cannot improve system efficiency effectively. Barriers hindering the implementation of this national plan were identified such as lacking analysis of cost-effectiveness of motors system efficiency, enforcement measures are not strong enough to supervise and monitor the market, the design, innovation of relevant technologies as well as energy service business models cannot adapt to the fast market change etc. Hence "system optimization" becomes more and more critical both in engineering, management as well as policy design.

To remove these barriers, with the funding of the Energy Foundation China, Renergy Technology Consulting Beijing LLC (Renergy), in cooperation with China Machinery Industry Energy and Resources Conservation Center (MERC), launched and implemented a project called "Mechanism Research & Policy Analysis on China Motor System Energy Efficiency Improvement" to support the goal of motor system efficiency improvement by 3% to 5% by 2020, which will result in 78 to 130 TWh per year of electricity savings.

This will be achieved by 2020 via providing recommendations for the policy effectiveness and implementation mechanism, developing guidelines and case studies on motor system efficiency, designing and conducting pilot training programs for the managers in factories by applying the guidelines and conducting technical know-how exchange between China and advanced regions.

Chinese Policies on Motor System Energy Efficiency

In early this century, China started developing policy framework and technical regulations such as Minimum Energy Performance Standards, Energy Labeling schemes, and financial incentive programs for electric motors and other equipment in the motor driven systems.

Minimum Energy Performance Standards (MEPS)

In the past two decades, China has developed a series of national MEPS for electric motors, including small power motors (6W – 3.7kW), small and medium three-phase asynchronous motors (0.75kW – 375kW), permanent magnet synchronous motors (0.55kW – 375kW) and high voltage induction motors (160kW – 25,000kW). The detailed information could be seen in Figure 2. In China, the MEPS are in place at IE2 level (see Figure 3.), but the planned increase towards the IE3 level in September 2016 was postponed.

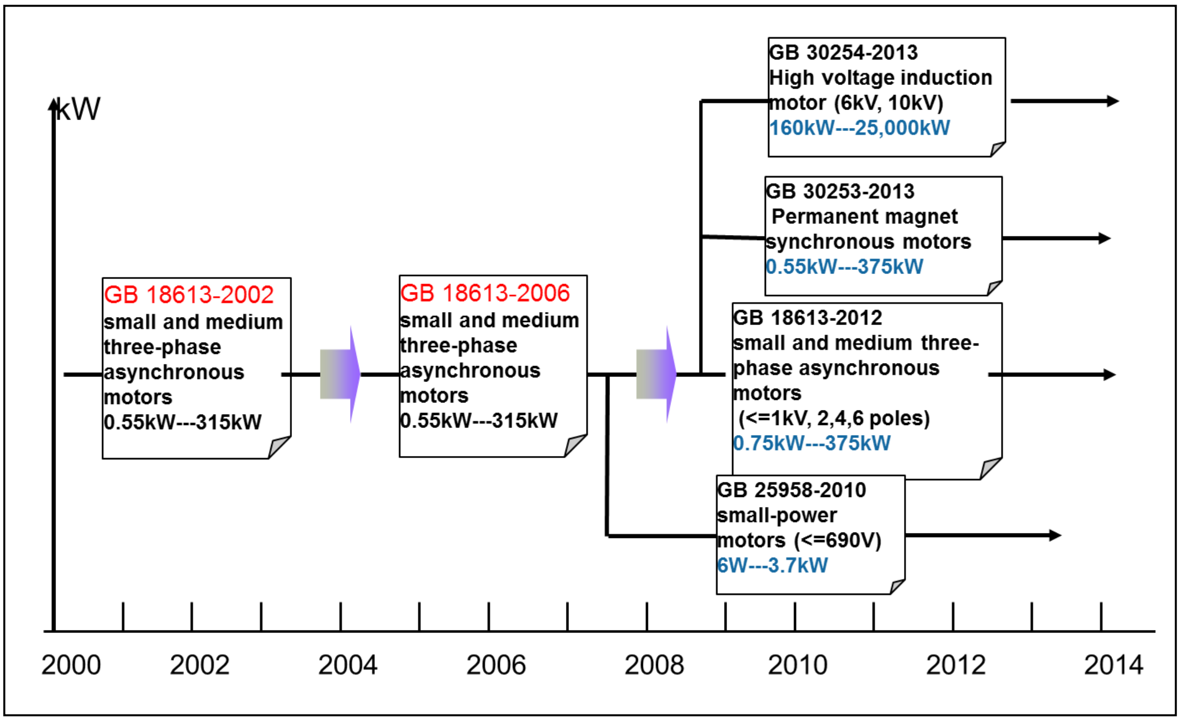

Figure 2 Development Roadmap of Chinese MEPS for Electric Motors.

Figure source: China National Institute of Standardization (CNIS), 2016.

GB18613-2006 old MPES	GB18613-2012 new MEPS	IEC60034-30-1	Average EE (%)	EE difference between tiers (%)	Chinese motor models
/	Tier 1	IE4	93.1	1.6	/
Tier 1	Tier 2	IE3	91.5	1.5	YE3 series
Tier 2	Tier 3	IE2	90.0	3.0	YE2,YX3 series
Tier 3	not allowed any more	IE1	87.0	/	Y,Y2,Y3 series

Figure 3 Energy Efficiency Tiers Mapping between Chinese and IEC MEPS for Electric Motors.

Figure source: Shanghai Electrical Apparatus Research Institute (SEARI), 2016.

On 20th April 2016, preparatory meeting for revising Motor MEPS GB18613-2012 was held in Beijing, The key points from standardization experts were as follows:

- Coordination of the existing MEPS;
- Alignment with IEC standards (extension to 0.12kW～1000kW, 50V～1000V, 8-pole motors added);
- Top-runner EE requirement, which is not same as Japan's Top Runner Programme, and only the models fulfil this requirement could get subsidies or be given priority by government procurement;
- Implementation of the target minimum allowable values of energy efficiency for motors (addressed in the article 4.4 of GB18613-2012: 7.5kW-375kW due Sept. 2016; <7.5kW due Sept. 2017)

MEPS for other equipment in the motor driven systems such as pumps for fresh water, AC contactors, air compressors and fans were also developed. These standards together with MEPS of electric motors, made current assessment of the whole motor driven system possible. The names of these standards are as below, and some of them are facing revision in 2017. For example, the first MEPS for air compressors GB 19153 entered into force in November 2003, and then was revised in 2009, now it is under the second revision. Since the United States of America (USA), the European Union (EU) are developing their own air compressor MEPS, the USA is also developing MEPS for fans, so it is the right moment to align their testing methods and energy efficiency indicators.

- GB 19762 - 2007 Minimum allowable values of energy efficiency and evaluating values of energy conservation of Centrifugal Pump for Fresh Water
- GB 21518 - 2008 Minimum allowable values of energy efficiency and energy efficiency grades for AC contactors
- GB 19153 - 2009 Minimum allowable values of energy efficiency and energy efficiency grades for displacement air compressors
- GB 19761 - 2009 Minimum allowable values of energy efficiency and energy efficiency grades for fan

China Energy Label (CEL)

Renergy is implementing an international energy efficiency program called "Topten" in China, aiming promoting best available technologies (BAT) on EE through third party testing, market research, EE product selection and benchmarking, consumer education, and policy advocacy. In past years, recommendations to improve the current China Energy Label scheme were well received by the key policy maker at CNIS. The key messages included: the label shall be easy to understand for consumers, add information on both efficiency and sufficiency to avoid the rebound effect called "Jevons Paradox"[29], add a QR code (Quick Response Code) to be used from smart devices etc. CNIS acknowledged Renergy's advice and integrated it into the revised Administration Regulation on Energy-Efficiency Labelling, which was officially enforced on 1st June 2016. A QR code was added to offer more information both for market monitoring and consumer guidance, and 150 product models were included in the 2016 Top-Runner product list. Besides benefit for consumers, the QR code also helps the local energy conservation supervision officers to monitor the market in a more convenient and efficient way. This achievement was significant for China and it was summarized by Topten International team so as to provide advice and references to relevant policy makers of the European Commission.

Figure 4 New China Energy Label since June 2016.

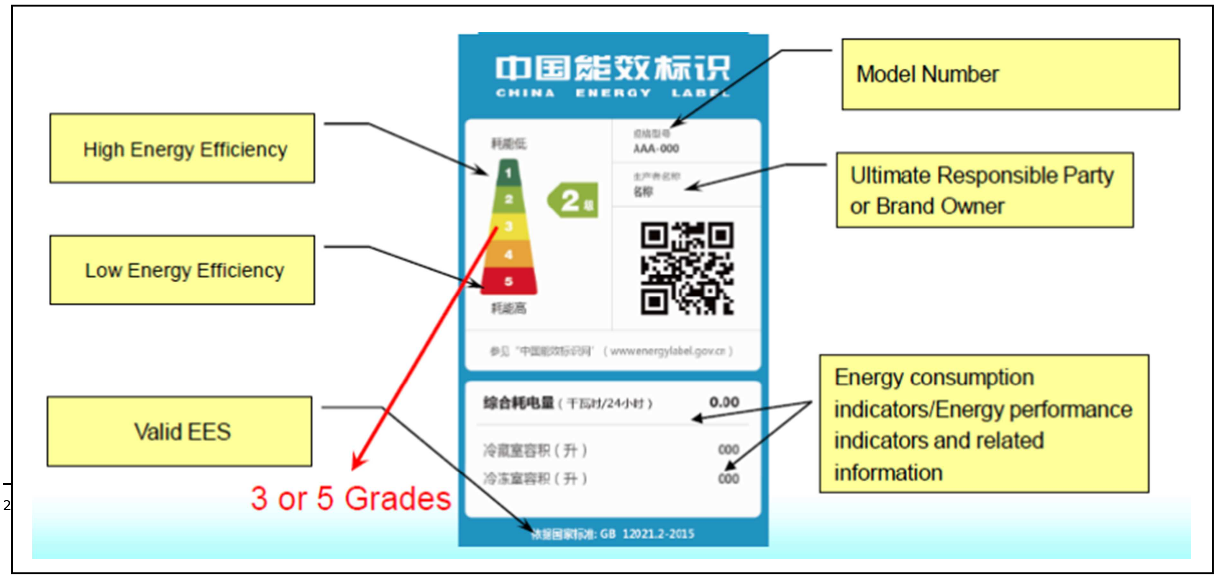

Figure source: China National Institute of Standardization, 2016

On 20th September 2016, Refurbished Motors were included into the new China Energy Label schemes to encourage motor refurbishment industry's innovation and development and this new regulation took into forces on 1st October 2016. Before that, the replaced old inefficient motors could only be recycled as wasted metal or illegally be sold to black market so that the inefficient repaired/refurbished motors again went to Chinese rural market or remote areas. The new CEL regulation regarding refurbished motors consists of the following key points:

- Quality of the refurbished motors shall be guaranteed;
- Energy efficiency of the refurbished motors needs complying to existing MEPS: GB18613;
- 380V, 50Hz, 0.75kW-375kW, 2,4,6 poles

Compliance and Enforcement (CEL)

Compliance and Enforcement are key to success of any policy implementations. But the situation of enforcement of MEPS and CEL are not optimistic as we expected. According to statistics from International Cooper Association (ICA) in 2014, 38.37% of small and medium three-phase asynchronous motors manufactured in China were IE2, and even 52.22% of them were below IE2, i.e. more than half of them were produced, sold and used illegally.

During implementation of the project, project team noticed this situation in factories, and most of motors we have seen were labeled as tier 3 (See Figure 5), but without checking if it was really complying with tier 3 EE requirements.

Figure 5 CEL of motors in factories, Jiangsu province, China

Figure source: photos taken by ZHENG Tan.

From December 2013 to April 2014, China conducted nationalwide Motor Manufacturers On-site Checking to monitor the market. Activities consisted of integrity and quality of their self-checking report, registration and implementation of China Energy Labeling, Conformity testing etc.

Consequences of non-compliance include public announcement of the non-complied companies and product models; ineligible products could not be sold and used; ineligible companies could not apply subsidy any longer; blacklist and notice to authorities, banks etc. to cease their loan or no longer provide any financial support, stop in charge person of ineligible companies to buy flight and train ticket etc.

Financial Incentives (Jienenghuimin Program + Tax Reduction)

From June 2010 to 2014, six batches of subsidized model lists (see Tabel below) for electric motors were developed and used, three types of motors were covered by the subsidy program, and the subsidy rate varies from 3.5 EUR to 13.3 EUR per kW. More than 33 million kW energy efficient motors got subsidized with 1.4 billion RMB (circa 186 million EUR) in total. 1.7 billion RMB (circa 226 million EUR) subsidies went to pumps, fans, compressors, transformers. It was estimated that by the end of 2016, around 100 million kW high energy efficient motors were promoted and 3 billion RMB (circa 400 million EUR) subsidies were given to energy efficient motors.

Due to lacking motivation to change, the motor users in China have been reluctant to alter their existing motor systems even they could get subsidized new energy efficient motors. Besides the subsidy from central government, Chinese local governments including provincial and municipal governments provide supplementary subsidies to attract more factories and ESCOs joining this program. For instance, Guangdong provinces gave 126 million EUR to motor users and ESCOs who implemented motor system EE retrofits projects from 2013 to 2016.

According to the statistics from ESCO Committee of China Energy Conservation Association (EMCA), by 2014, more than 3,200 ESCOs were active in China, their services generated in total 30 million tons of coal equivalent (TCE) of energy savings, which was equivalent to 75 million tons of CO_2 emission reduction, where 33% of total energy savings were caused by electric motor system retrofits. The central government also provided its support for ESCOs through tax reduction policies. In December 2010, the Ministry of Finance (MoF) and State Administration of Taxation jointly issued the Notice on Policy Issues of Value Added Tax, Business Tax and Corporate Income Tax in Promoting the Development of the Energy Service Industry, which gave energy service companies a temporary exemption from value added tax and business tax, an exemption from corporate income tax for the first three years of implementation, a 50% tax levy for the next three years.

Six batches of Chinese national subsidized model list for EE motors:

No. of batches	**Date of official announcement**	**Number of listed motor manufactures**	**Number of listed models: low-voltage three-phase asynchronous motor**	**Number of listed models: high-voltage motors**	**Number of listed models: permanent magnet motors**
1	August 1st 2010	13	996	0	65
2	March 8th 2011	48	1440	6653	343
3	July 26th 2011	34	677	8760	459
4	March 21st 2012	29	737	10669	388
5	December 2nd 2012	90	4752	14485	935
6	August 28th 2014	85	2041	10842	1150
Total			**10643**	**51409**	**3340**

China national subsidy program criteria for EE motors:

Type	Rated power (kW)	Subsidy (RMB/kW)	Subsidy (EUR/kW)
Low-voltage three-phase asynchronous motor	0.55 ≤ rated power ≤ 22	58	7.72
	22 ≤ rated power ≤ 315	31	4.13
High-voltage motors	355 ≤ rated power ≤ 25000	26	3.46
Permanent magnet motors	0.55 ≤ rated power ≤ 315	100	13.32

Historical exchange rates between the Chinese Yuan Renminbi (CNY) and the Euro (EUR) between 1/1/2014 and 2/24/2017 was used, i.e. 1 Euro = 7.5090 Yuan RMB.

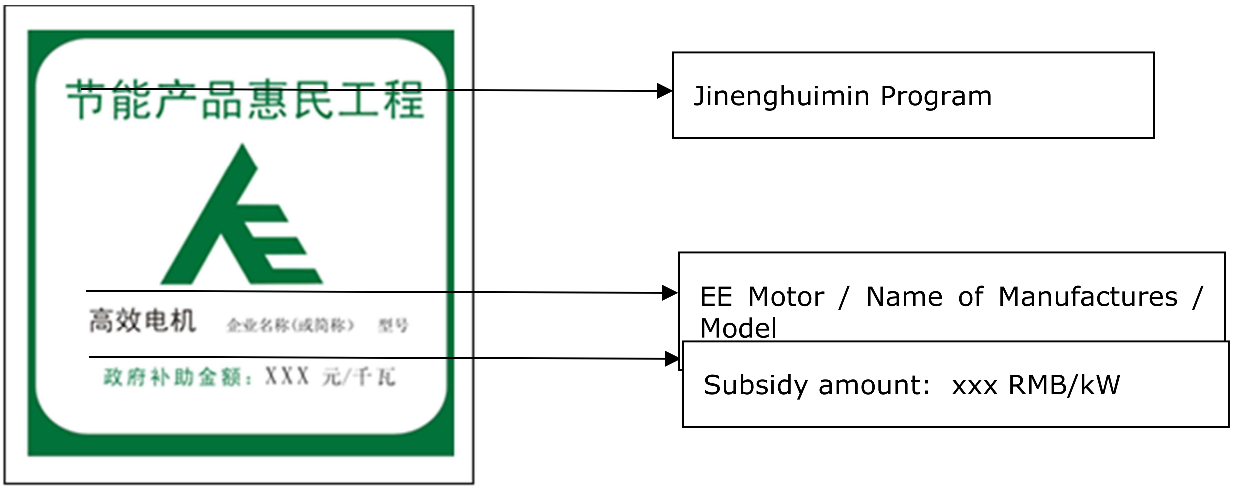

Figure 6 Label of China Subsidy Program for EE Products ("Jienenghuimin").

Figure source: www.jienenghuimin.net

The central government gradually realized that only subsidizing energy efficient electric motors could not significantly improve the energy efficiency of motor systems. On 23rd January 2017, the Ministry of Finance has officially announced that the national subsidy program "Jienenghuimin" for energy efficient motors stops since March 1st 2017.

Mechanisms for Improving Motor Systems Energy Efficiency in China

In order to improve the energy efficiency of electric motor systems in China, a bunch of implementing measures were taken. In this paper, we address the development trend of multiple mechanisms for improving EE of motor systems in China from the following **"Four Plus"** perspectives.

Single Equipment + Systems

According to global research [4] [5] [6], energy efficiency of a motor driven unit is dependent on multiplication of energy efficiency of individual component of the whole system (see Figure 7). Therefore, high energy efficiency of single equipment such as motors, pumps, fans and compressors is crucial and necessary making a high EE motor system possible. But a simple combination of super high efficient components might not reach optimal efficiency as a motor driven system. Adaptation to the real needs, to working conditions, as well as to cost-effectiveness of the investment are important for

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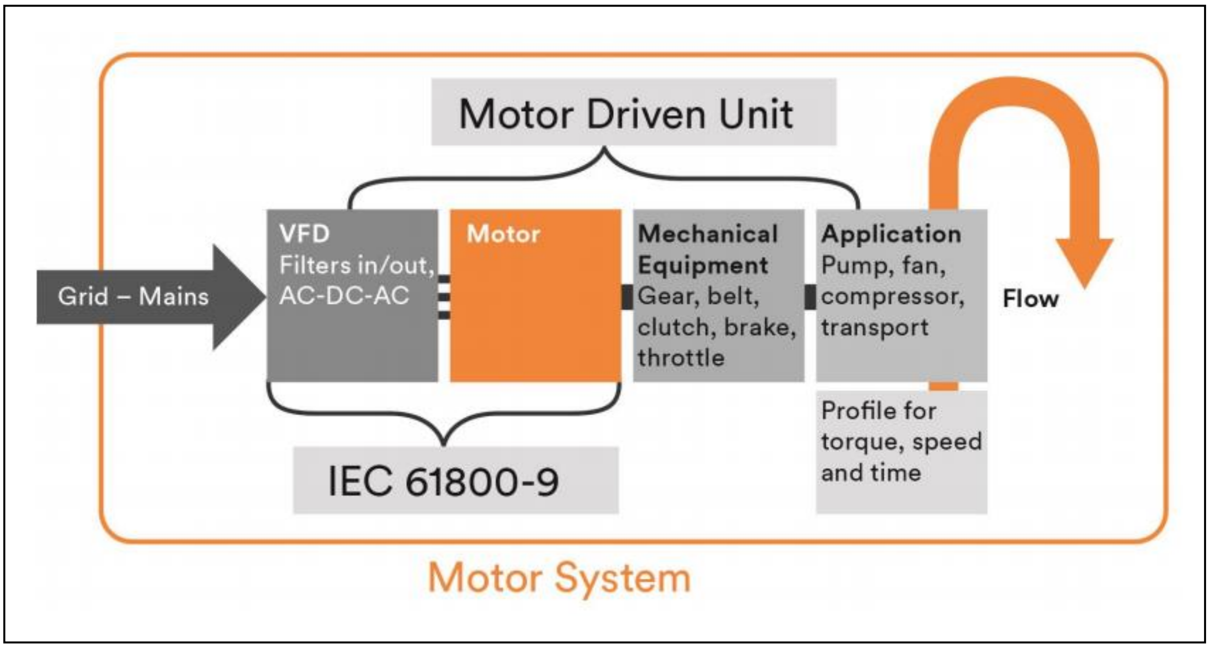

Figure 7 Think energy efficiency in a systematic way!

Source: Impact Energy Inc. 2016

Existing Stock + Incremental Market

China started making Catalogue of Eliminated High Energy Consumption and Backward Mechanical and Electrical Equipment since 2009. The Catalogues cover products such as electric motors, compressors, fans, pumps and transformers. By February 2016, four batches of catalogues were released, in which 386 motor models, 33 compressor models, 52 fan models, 125 pump models and 57 transformer models were listed, that all of them could not be manufactured, sold and used in China.

In addition, the Catalog of Energy-saving Mechanical and Electrical Equipment (Motor) (2016) and the Catalog of Energy Efficiency Star (Motor) (2016) were also developed to ensure high penetration rate of EE equipment for incremental market in China.

The Catalogue of Eliminated High Energy Consumption and Backward Mechanical and Electrical Equipment (Motor) (2016)

From December 2015 to March 2016, according to the China national energy performance standards such as:

· "Minimum allowable values of energy efficiency and energy efficiency grades for small and medium three-phase asynchronous motors"(GB 18613-2012),

· "Minimum allowable values of energy efficiency and the energy efficiency grades for cage three-phase high voltage induction motor"(GB 30254-2013),

in accordance with the principle of eliminating the products which are in backward technical level and have alternative products, MERC has developed a Catalogue of Elimination of High Energy Consumption and Backward Mechanical and Electrical Equipment (Motor) (2016) aiming to eliminate the following two Chinese motor series:

· JK and JS of small and medium three-phase asynchronous motors,

· JK and JS series of cage three-phase high voltage induction motors.

JK and JS, these two series models were widely used in the 90s last century in China, so they are old and inefficient according to the new MEPS. There will be a total of 58 product specifications to be eliminated by the end of 2017. This catalogue was officially announced by MIIT in April 2016, and it formed technical basis of phasing-out existing inefficient motors in China.

The Catalog of Energy-saving Mechanical and Electrical Equipment (Motor) (2016) and the Catalog of Energy Efficiency Star (Motor) (2016)

To encourage all industries to manufacture and use advanced, high-efficient energy-saving equipment, MERC has developed the Catalog of Energy-saving Mechanical and Electrical Equipment (Motor) (2016) and the Catalog of Energy Efficiency Star (Motor) (2016), the former one includes models with the energy efficiency level of tier 1 and tier 2 and the latter one only includes top energy efficient models with the energy efficiency level of tier 1.

a) Processing applications: by 18th August 2016, MERC has received 89 applications for "Energy-saving Mechanical and Electrical Equipment" from 41 motor manufacturers from 16 provinces and cities in China, 72 applications for "Energy Efficiency Star" from 33 motor manufacturers from 16 provinces and cities in China. Both catalogs included 3 kinds of motors, i.e. small and medium three-phase asynchronous motors, three-phase high voltage induction motor and permanent magnet synchronous motors.

b) Product selection and evaluation: an expert consortium was established to evaluate the products based on a comprehensive selection criteria, consisting of aspects of energy efficiency, environmental protection, quality, safety, technological innovation, producing capacity, sales data and the users' comments etc. On 7th September 2016, the product evaluation meeting for these two catalogs were successfully held in Beijing. The draft version of these two catalogs[30] were approved in this meeting and published by MIIT to call for comments during 28th September to 14th October 2016.

c) Results: after revision according to the feedback from industries and the public, the final catalogs[31] were published by MIIT on 15th November 2016, and will be effective during the next three years. The Catalog of Energy-saving Mechanical and Electrical Equipment (Motor) (2016) has in total 54 motor models in which 22 low-voltage models

[30] The official announcement (at least accessible by the end of 2016): http://www.miit.gov.cn/n1146295/n1652858/n1653100/n3767755/c5268960/content.html

[31] http://www.miit.gov.cn/n1146295/n1652858/n1652930/n4509607/c5361110/content.html

from 20 companies, 18 high-voltage models from 6 companies and 14 permanent magnet models from 11 companies. The Catalog of Energy Efficiency Star (Motor) (2016) has in total only 4 motor models in which 2 high–voltage models from 1 company and 2 permanent magnet models from 2 companies.

Energy Efficiency + Comprehensive Environmental Perspectives

Renergy has been promoting the Life Cycle Assessment (LCA) method to key policy makers, combining product energy efficiency evaluation in the use phase together with other parameters in the phases of design, manufacturing, recycling or refurbishment phases, etc. as well as economic parameters. On 21st September 2015, the Communist Party of China (CPC) Central Committee and the State Council, published a reform plan for promoting ecological progress in China, the plan is so- called the "Integrated Reform Plan for Promoting Ecological Progress". In article 46 of this plan, the establishment of a unified system for green products is required: *"Products that are licensed as environmentally friendly, energy-efficient, water-saving, circular, low-carbon, recyclable, or organic will be uniformly classified as green products, and standardized green product standards, certifications, and logos will be established for them. Improvements will be made to policies on fiscal and tax support and government procurement for the research and development, production, transport, delivery, purchase, and use of green products."* It soon was listed in the 2016 work points of "The Central Leading Group for Comprehensively Deepening Reforms". A working group was set up in which Renergy actively took part, together with its partner organizations, contributing with technical support and international policy perspectives. On 7th December 2016, the State Council officially announced guidelines and requirements for establishing the Green Products framework, in which main objectives and tasks, key measures and principles were clarified for the further implementation.

This reform is revolutionary for China's EE standards, labeling and certification systems, and will definitely influence Green Products' Evaluation of individual equipment of motor driven systems. Now a new question was raised that how a Green System will be determined based on this new concept of Green Products in China.

Training + Green Finance Instruments

Principles and Guidelines for Exploiting Electricity Saving Potentials of the Electric Motor Systems

To facilitate motor system users to exploit the electricity savings potentials of their motor systems and implement the energy-saving projects in a more cost-effective way, the project team developed the principles and guidelines for the target audience including technical experts in local governments, energy managers and technical engineers in the factories. The content consists of principles of screening motor system energy saving potential, energy saving potential assessment methods, motor system applications and transmission efficiency assessment guidelines. The drafty versions were discussed with factory staff and engineers and raised their interest to develop and to use this guideline. The final version was also recognized by external experts. Through discussions, the project team improved understanding about the factories' demand for the training courses and got recommendations (on easy readability, direct operability etc.) for further training programs.

Guidelines for Energy-saving Technological Upgrading of Motor Systems in the Cement Industry

From December 2015 to February 2016, the project partner MERC conducted field visits to Chinese cement manufactures and investigations for the cement industry regarding their energy-saving technological upgrading of electric motor systems, in cooperation with the China Building Material Federation. The cement industry consumes 57% of the energy in the building materials sector in China, which makes it the most energy-intensive industry where the electricity cost accounts for 30% to 35% of the total production cost. More than 60% of the Chinese cement production lines have so far implemented energy-saving technology upgrading programs of their motor systems. The electricity saving potential of reducing the energy demand of the rest cement production lines by around 20% still has not yet been tapped. The project team made the Guidelines for Energy-saving Technological Upgrading of Motor Systems in the Cement Industry and the content consists of motor system energy audits, implementation of technological upgrading, evaluation of energy savings, instructions on different kinds of motor systems in the cement industry and typical case studies.

Training Workshops

a) The project team developed training courses and materials for improving China motor system energy efficiency based on needs from the energy mangers and technical engineers from industrial enterprises, as well as from the local Energy Conservation Supervision Centers (ECSC)[32]. The training materials integrated the up-to-date domestic and international know-how and experiences, covering policies, technologies and applications, principles and guidelines for motor system check, applications of energy-saving technologies such as Variable Frequency Drives (VFDs) etc.

b) On 21st September 2016, in cooperation with Suzhou Institute of Energy Management, the project team conducted trainings for enterprises' senior managers and local energy conservation supervision centers in Jiangsu provinces. Around 200 participants from Jiangsu province, Suzhou city and Yancheng city etc. attended the training, and the training materials were well disseminated to them. In addition, an on-site training for 20 senior technicians was organized in a factory in Suzhou, electrical power testing, pump system energy efficiency evaluation as well as energy saving potentials and pay-back period calculation were introduced and demonstrated. The on-site training was interactive and intuitive for the trainees, so that it gained very positive feedback.

Green Finance

a) Stakeholders from financial sectors were invited as experts participating in the project. Green financing policies and tools like carbon trade, or energy savings trade were trained for target companies.

b) Local government such as Zhenjiang Economic and Information Technology Commission (ZEITC), who is mainly responsible for improving industrial EE, provided 10 million RMB into a money pool, as guarantee to leverage more fund from Banks. E.g. Bank of Jiangsu allocated 100 million RMB as green loan with very competitive loan rate either to factories who will implement EE retrofit projects of their motor systems, or to energy service companies who invest relevant EE retrofit projects and will be paid back with healthy future money flow.

Recommendations & Conclusion

During the project period, the project team communicated with key stakeholders in the policy making and implementing filed, via policy workshop, face-to-face presentations by visiting, and composed the policy recommendations based on our surveys and research. The **"Four Plus"** perspectives were specified and elaborated in a final policy report, in which our main recommendations are as follows,

- a) firstly, in the national level, making middle and long-term goals for improving motor system energy efficiency in China is needed; secondly, to improve the effectiveness of policy implementation, the coordination of existing policies in different phases and aspects are necessary, e.g. policies in production, integration, selling, using, refurbishment and recycling etc.

[32] According to statistics, by 2013, China had more than 2,100 Energy Conservation Supervision Centers and more than 16,000 staff in total.

- b) one key to success is to optimize the existing systems, including
  - to nationally raise the awareness of motor system efficiency, to strengthen capacity of large electricity users (whose annual electricity consumption is higher than 10GWh) by professional trainings, and to improve the management level of energy saving by adopting ICT technologies;
  - (governments at all levels) to introduce (financial or non-financial) incentive policies to guide users phasing-out inefficient equipment and to carry out greener production process and system optimization in parallel;
  - to foster independent third-party audit, assessment and verification institutions to support best available technology penetration and standardization processes.
- c) another key to success is to regulate the incremental market.
  - From the production aspect, to strengthen supervision and enforcement is important to avoid manufactures keeping producing inefficient equipment;
  - from the using perspective, green design of a production line is important and awareness raising for designers is needed to solve the over-capacity problem from the early stage;
  - high efficient models shall be strictly required during the whole process of approving a new project, equipment procurement, operational verification and so forth;
  - regular check and benchmarking of energy efficiency level within same industries are helpful to set new goals as a Top-runner of Motor System Energy Efficiency;
- d) market-driven forces, such as the use of taxation, green loan, electricity pricing, Energy Performance Contracting (EPC) and other economic means, are helpful, e.g., green finance instruments could help SMEs implement their retrofits projects on motor system efficiency optimization with lower acceptable financing cost.

It is worthwhile to conclude this paper with a significant improvement of China's EE policy on motor systems. The core concept of the project, "systematic efficiency", was highly recognized by policy makers in China. On 30th June 2016, MIIT published the 13th five-year plan (2016-2020) of industrial green development in China, in which it was firstly stated that **"the industrial energy saving shall focus from component to the whole system, from one part to the whole processes"**, and a national goal was set that **"the average energy efficiency of China's motor systems shall be improved by 5% by 2020"**. In addition, a road map establishing China's national standard for evaluating electric motor system energy efficiency was announced by CNIS on a meeting hosted by China Energy Conservation Association (CECA) on 4th December in Changsha, Hunan province. More research and analysis on the upcoming polices and mechanisms will be conducted by the project team in future.

Acknowledgement

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References

[1] Tan ZHENG et al., *An Investigation of China Subsidy Program for Energy Saving Products*, Proc. of the 7th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL 2013), in Coimbra, Portugal.

[2] Bo HU et al., *Topmotors China: Improving Motor System Efficiency with Motor-System-Check in Zhenjiang*, Proc. of the EEMODS 2015, in Helsinki, Finland.

[3] http://www.gov.cn/flfg/2007-10/28/content_788493.htm, Chinese Energy Conservation Law, 2007-10-28.

[4] Werle R and Brunner C. *Country experiences: motor systems programmes in Switzerland and China*, IEA Energy Efficiency in Emerging Economies, energy efficiency training week, 9 June 2016, Paris France.

[5] Werkhoven M., Werle R. and Brunner C. IEA 4E EMSA. *Policy Guidelines for Motor Driven Units: Part 1: Analysis of standards and regulations for pumps, fans and compressors*. Proc. of the 2016 Motor Summit, Zurich, Switzerland. Can be downloaded from www.motorsystems.org

[6] Shanghai Energy Efficiency Center. *Practical Technologies for Electric Motor Systems' Energy Conservation.* ISBN 978-7-5478-2091-9, pp. 1-5.

[7] Yixiao XU. *Motor System Efficiency needs to be improved.* China Economy & Informatization Magazine (10 September 2014). ISSN 1674-9138, pp. 44-46. This article is in Chinese and can be read from www.ccidgroup.com/sdgc/5904.htm

List of Abbreviations

CECA China Energy Conservation Association

CEL China Energy Label

CNIS China National Institute of Standardization

EE Energy Efficiency / Energy Efficient

ESCOs Energy Service Companies

EPC Energy Performance Contracting

IEC International Electrotechnical Commission

LCA Life Cycle Assessment

MEPS Minimum Energy Performance Standards

MERC Machinery Industry Energy and Resources Conservation Center of China

MIIT Ministry of Industry and Information Technology of China

MoF Ministry of Finance of China

VFDs Variable Frequency Drives

ZEITC Zhenjiang Economic and Information Technology Commission

The importance of additionality in evaluating the economic viability of motor-related energy efficiency measures

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Abstract

The additionality of an energy efficiency (EE) measure is defined as the supplementary impact of a measure beyond standard practices and autonomous changes. The consideration of additionality and the manner of accounting for it may strongly influence the cost-effectiveness of the EE measures and consequently the decision by policy makers. Many studies on energy efficiency improvement potentials fail to provide transparency regarding the methodology and underlying data (discount rate, lifetime etc.) used in their respective cost-benefit analyses for evaluating EE measures. Against this backdrop, this paper discusses various approaches based on US Environmental Protection Agency (EPA) guidelines, using the example of a 45 kW electric motor. We compare the case of disregarding additionality with several other approaches, i.e. only accounting for age (as applied by the Energy Agency for the Swiss Private Sector - EnAW) and other approaches that consider the salvage value as well as differences in investment cost and electricity savings (as applied by the ProKilowatt program, operated by Swiss Federal Office of Energy - SFOE). This study concludes that the chosen method very strongly impacts the results, i.e. by factors and potentially even resulting in opposite findings concerning cost-effectiveness. Choosing full investment costs may lead to the conclusion that the measure is not cost-effective while all other approaches result in the opposite conclusion (economically viable). For slowly expanding manufacturing sectors in an industrialized country like Switzerland (limited growth, mature capital stock) it is found that the additionality approach based exclusively on age overestimates the cost-effectiveness. This study therefore recommends alternative approaches which allow to establish the uncertainty range of cost-effectiveness, while maintaining transparency.

Introduction

The additionality of an energy efficiency (EE) measure is defined as the supplementary impact achieved by the measure beyond standard practices and autonomous changes [1]. Additionality is firmly linked to baseline scenarios, which provide reference points through which one can judge whether an activity is additional or not [2,3]. For example, in the case of replacing an old motor with a more energy efficient one, the baseline scenario would be the standard replacement at the end of the old motor's lifetime, while additionality may refer to the early replacement by a new efficient motor, where the existing (old) motor would otherwise have remained in service until the end of its lifetime. Furthermore, the additionality of an EE measure can be broadly categorized into two components, i.e. additional investment costs and energy savings due to measure implementation. It is notable, however, that both components lack methodological clarity and are not adequately covered in the cost-benefit studies on energy efficiency available in literature.

The consideration of additionality may strongly influence the cost-effectiveness of the EE measures and consequently the decision by policy makers. However, the majority of studies fail to provide transparency regarding the methodology and underlying data (discount rate, lifetime etc.) used in their respective cost-benefit analyses for evaluating EE measures. In particular, it is not typically explained whether additionality has been taken into account and, if so, how. One study that accounts for additionality is that of Jakob (2006) [4], who quantifies the marginal costs of EE investments (including additional insulation, improved window systems and heating and ventilation systems) for the Swiss residential sector. The US Environmental Protection Agency (EPA) outlined an advanced method to account for additionality of EE measures (see EPA metrics) [5], however the application of the method is found limited probably due to the challenges posed by the data unavailability (see discussion in results section).

Zuberi et al. (2017) [6] recently studied a wide range of EE measures for Swiss industrial motor systems and demonstrated that the economic potential for EE improvement increases substantially if additional costs are considered in the cost-benefit analyses. However, due to significant data challenges, the additionality approach applied by the authors only accounts for the age of the replaced equipment (as explained in Section - EnAW method). This raises the question of what is the suitable approach to account for additionality and how it can be adopted. Zuberi et al. [6] recommend the EPA approach as the method of choice. Against this backdrop, this paper discusses various approaches based on EPA guidelines, using the example of a 45 kW electric motor (see Case study: motor retrofit, for details of the choice). We compare the case of disregarding additionality with several other approaches, i.e. only accounting for age (as applied by the Energy Agency for the Swiss Private Sector - EnAW) and other approaches that consider the salvage value as well as differences in investment cost and electricity savings (as applied by the ProKilowatt program operated by Swiss Federal Office of Energy - SFOE).

Materials and methods

Cost-effectiveness of EE measures

Specific costs

Specific costs ($C_{spec,y}$, also referred to as levelized costs) of EE measures are determined in order to evaluate the economic viability of these measures. Specific costs are calculated by the following equation:

$$C_{spec,y} = \frac{ANF \times NPV_y}{ES_y} \qquad (1)$$

where:

NPV_y = net present value of measure for the base year, determined by Equation 2

ANF = annuity factor, determined by Equation 4

ES_y = annual potential energy savings by measure

y = EE measure

$$NPV_y = \sum_{t=2015}^{L} CF_t \times (1+r)^{-t+2015} \qquad (2)$$

where:

CF_t = annual cash flow, determined as Equation 3

r = real discount rate, taken as 10.5% (private perspective)

L = lifetime of measure

t = year

$$CF_t = I_y + O\&M_y - B_y \quad (3)$$

where:

I_y = Initial investment required to achieve the 'ES_y'. Its value is zero for all years after base year of implementation.

$O\&M_y$ = Operation and maintenance cost[33]

B_y = Annual benefits of the measure, i.e. the annual electricity cost savings over lifetime to be achieved from first year after implementation.

$$ANF = \frac{(1+r)^L \times r}{(1+r)^L - 1} \qquad (4)$$

Since the annual benefits (B_y) in Equation 3 are presented with a negative sign, EE measures with the negative specific costs are considered cost-effective. It is evident from the above equations that investment costs (I_y) and potential energy savings (ES_y) are the two main drivers for determining the cost-effectiveness of the EE measures. Hence, it is crucial to estimate the two parameters carefully for cranking EE measures in terms of their cost-effectiveness. In order to account for additionality while assessing the cost-effectiveness of the retrofit measures (refer to early replacement in this study) by Equations 1-3, 'I_y' should be replaced with additional costs or energy-relevant investments (EI). Similarly, annual benefits 'B_y' should also be adapted depending on the method of choice. Various approaches to account for additionality are discussed in the following section.

Accounting for additionality

The EnAW method

The Energy Agency of the Swiss Private Sector (Energie-Agentur der Wirtschaft – EnAW) was set up by the private sector in order to offer companies the opportunity to avoid the CO_2 tax introduced by the Swiss government in 2008, under the condition that they reduce their CO_2 emissions. EnAW conducts energy audits in collaboration with private companies, which are obliged to implement the measures with payback period of up to 4 years for industrial processes and 8 years for infrastructure (based on energy-relevant investment costs). Companies committing themselves to these objectives and entering a formal agreement with EnAW are reimbursed with the CO_2 tax paid. In addition, EnAW also partners with Swiss cantons which provide incentives to the individual companies to save electricity (see [7] for an example). EnAW companies can also apply for a refund of the network surcharge (KEV; cost-based compensation given to the renewable energy producers by collecting it from the electricity consumers in Switzerland) through target agreements [8]. More than 3600 companies (mostly large enterprises) have signed up with EnAW [9]. EnAW's criterion for estimating energy-relevant investments (EI) of EE measures is as follows:

$$EI = TI \times \left(1 - \frac{A}{L}\right) \qquad (5)$$

where:

TI = Total investment costs (CHF)

A = Age of the replaced equipment (years)

L = Lifetime of the equipment (years).

According to the equation, only the investment costs TI of the new equipment is considered. It is multiplied by a factor unique to each equipment based on its age of the old equipment at the time of replacement. The age of the equipment to be replaced is often unknown. In such cases, companies estimate value for the parameter, which increases the chances of errors and poses challenges for monitoring. Energy savings are determined by the following equation:

$$ES = ED_{old} - ED_{efficient} \qquad (6)$$

where:

[33] In this study, the O&M cost is assumed to be identical before and after implementing the measure and is hence neglected.

ES = Energy savings (GJ/yr).

ED_{old} = Annual electricity demand by the old equipment (GJ/yr)

$ED_{efficient}$ = Annual electricity demand by the new or more energy efficient equipment (GJ/yr)

The ProKilowatt method

ProKilowatt is a sector-wide program initiated by the Swiss Federal Office of Energy (SFOE), subsidizing EE measures that are not economically viable (payback period above 5 years for process measures and 9 years for infrastructure). Energy Service Companies (ESCOs), consultancies and other actors can propose programs and projects to SFOE in a competitive tender call procedure. Once a program or project is accepted, the process of EE measure implementation is monitored. According to the new ProKilowatt approach, effective since January 2016, 40% of the total investment is granted as subsidy for the implementation of the retrofit measure if the age of the replaced equipment is less than 50% of its technical lifetime; and the subsidy amounts to 15% of the total investment if the replaced equipment has exceeded its technical lifetime [10]. ProKilowatt applies the following criteria (Equation 7) to define the subsidy level if the age of the replaced device is equal to or between 50% and 100% of its lifetime. The subsidy that ProKilowatt provides can be understood as the compensation for the additional costs for energy efficiency, i.e. as economic additionality.

$$EI = 40 - 15 \times \left(\frac{A}{0.5 \times L} - 1\right) \qquad (7)$$

ProKilowatt estimates energy savings by the following equation:

$$ES = (ED_{old} - ED_{efficient}) \times 0.75 \qquad (8)$$

where 0.75 is the reduction factor correcting for the autonomous technological change in future [10].

EPA metrics

The EPA outlines a simple and an advanced method to monitor EE costs and energy savings in case of equipment replacement. The simple method involves total investment costs (sum of purchase cost and installation cost of the new equipment) and energy savings as determined by Equation 6 in the calculation of specific costs. According to the advanced method, the cost difference between the new and the standard equipment should be added to the remaining present value of the existing machine in order to account for the EE (energy-relevant investment costs; see Equation 9). It is clear that the simple method does not single out the additionality effect, while this is the case for the advanced method. We therefore consider the advanced method as the method of choice (if data availability does not represent a constraint).

$$EI = PV_{old} + I_{efficient} - I_{standard} \qquad (9)$$

where:

PV_{old} = Remaining present value of the old equipment (CHF)

$I_{efficient}$ = Total investment cost of the efficient equipment (CHF)

$I_{standard}$ = Total investment cost of the standard equipment (CHF)

The advanced method further recommends the sum of Equations 10 and 11 be used for estimating the total energy savings for the retrofit measures (early replacement):

$$ES_{dur} = ED_{old} - ED_{efficient} \qquad (10)$$

where:

ES_{dur} = Energy savings by efficient equipment compared to old equipment during the remaining lifetime of the old equipment (lifetime 'L' - current age 'A') (GJ/yr).

$$ES_{aft} = ED_{standard} - ED_{efficient} \qquad (11)$$

where:

ES_{aft} = Energy savings after the remaining lifetime of the old equipment (when the new equipment is considered to replace a standard equipment) (GJ/yr).

$ED_{standard}$ = Annual energy demand by the standard equipment (GJ/yr)

In order to calculate the cost-effectiveness of the retrofit measures by Equation 1-3, the annual benefit 'B_y' is calculated as the sum of 'ES_{dur}' and 'ES_{aft}' multiplied by the respective energy prices for the years during which the measure would remain in operation after implementation.

Case study: motor retrofit

Situation

In order to demonstrate the application of the various approaches to account for additionality elucidated above, we selected a case from the database provided by EnAW[34]. The selection was made because most of the required information was available for this particular case only. In the selected case, a 45 kW motor of efficiency class IE2[35] was installed in 2010 for a milling application. The motor operates for 6000 hours per year while the load factor is unknown. In view of the European Commission (EC) directive (No 640/2009), from 2015 onwards all newly installed motors should be of efficiency class IE3 [11], which can be understood as the standard technology today, while the most efficient commercially available motors are of class IE4. In order to show the effect of additionality, a hypothetical case is assumed where a 5 year old IE2 motor (in operation between 2010 and 2015, with a remaining lifetime of 10 years) is to be replaced with the most efficient type, i.e. IE4.

Electricity demand by motors and price

In order to apply the aforementioned approaches (see Section: Accounting for additionality), the annual electricity demand of the old (IE2), standard (IE3) and new/efficient (IE4) motor and their respective prices need to be determined. Table 1 presents the annual electricity demand of each motor efficiency class, determined by the following equation:

$$ED_m = \frac{0.0036\,(SZ \times OP \times LF)}{\eta_m} \qquad (12)$$

where:

ED_m = Annual electricity demand by motor 'm' (GJ/yr)

SZ = Performance of motor which is 45 kW in this particular case

OP = Annual operating hours which are 6000 in this particular case

LF = Load factor which is assumed 75% at or above which motors work efficiently [12]

η_m = Efficiency of motor specific to each class, taken from [13,14]

0.0036 = Conversion factor from kWh to GJ

[34] EnAW provides final energy savings and total investment costs, as well as brief descriptions of each implemented measure which are often very general. The description of the selected case was more elaborate, which made it possible to extract the information necessary for this study.

[35] Since 2009, the EE of electric motors is classified according to standard IEC 60034-30-1, which distinguishes between standard (IE1), high (IE2), premium (IE3) and super-premium (IE4) efficiency motors [11].

Table 1 Annual electricity demand and price of each motor efficiency class

Motor class	Electricity demand (GJ/yr)[36]	Total investment cost (CHF)[37]
IE2 (old)	783	4605
IE3 (standard)	774	5610
IE4 (efficient)	764	6950

The purchase cost of motors by efficiency class (against the rated power 45 kW) is taken from the data given by 'Topmotors' [15]. For this specific case, total investment (purchase cost + installation costs) from the data is found to be a factor 1.07 higher[38] than the purchase cost. The purchase cost of the IE3 and IE4 motor is multiplied by this factor in order to estimate the total investment cost. Table 1 also presents the total investment costs of each motor efficiency class.

Salvage value

Ideally, once a motor has surpassed its projected lifetime, it should be replaced immediately, though this is not always the case in reality. For example, an electric motor energy efficiency program called 'Easy'[39], carried out under the ProKilowatt scheme, revealed that 56% of the analyzed motors (total 4142 motors in 18 industrial and infrastructure facilities) were much older than their expected lifetimes and several had been in operation for nearly double that time [16–18]. This indicates that for the private companies there is some value of the old motor left even after the projected lifetime is over. To account for this, a salvage value (SV) of 15% is assumed as the base case. The value is assumed based on standard ProKilowatt practice, according to which a measure is entitled to not more than 15% subsidy if the age of the old equipment is beyond its expected lifetime [10]. However, the choice of salvage value brings a lot of uncertainty and can largely influence the overall cost-effectiveness of the measure. Since the choice of salvage value is specific to each company and motor, a sensitivity analysis of the specific costs was also done in this study for the possible minimum and maximum salvage value of 5% and 50% respectively.

[36] Based on efficiencies of electric motors (4-pole) according to IEC 60034-30 [13,14].
[37] Installation costs are included.
[38] The factor is specific to this particular case only and does not reflect other cases where the motor replacement can be very complex and expensive, hence resulting in higher installation factors.
[39] 'Easy' is a financial incentive program aiming to reduce energy consumption of industrial motor systems used in Switzerland with energy efficiency measures [16–18].

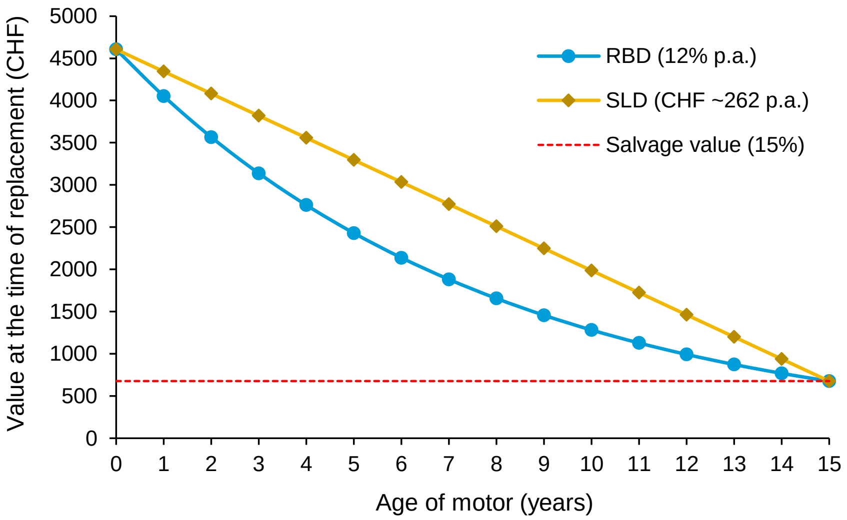


Figure 1 Depreciated and salvage value of the old IE2 efficiency class motor

Remaining value of the motor

Since the value of the motor depreciates with time, its present value (to be used in Equation 9, advanced method) needs to be calculated for the year in which it is replaced. In order to estimate its value, a simplified method of straight-line depreciation (SLD) could be used, according to which a fixed amount is depreciated each year from the initial value of the device at the time of installation [19]. However, it is often argued that the value of the asset, especially for the manufacturing plants, depreciates quickly in the early years compared to the period closer to the end of lifetime (reducing-balance depreciation (RBD) [6]. According to RBD, the value of the device depreciates by a fixed percentage each year instead of a fixed amount [19]. Both approaches were tested in this study. Remaining values of the motor over the years based on both RBD and SLD methods are shown in Figure 1 and are calculated by Equation 13 and 14 respectively.

$$PV_{old} = I_{old} \times (1 - \frac{d}{100})^A \qquad (13)$$

where:

d = Depreciation rate per annum i.e. 18%, 12% and 4% for the salvage value (SV) of 5%, 15% and 50% respectively at the end of the expected lifetime

A = Year of depreciation equivalent to the age of the motor being replaced

$$PV_{old} = I_{old} - (A \times D) \quad (14)$$

where:

D = Fixed amount depreciation per year which is calculated by the following equation

$$D = \frac{I_{old}}{L} \times (1 - \frac{SV}{100}) \quad (15)$$

Results and discussion

Figure 2 shows the comparison of the specific costs calculated by different approaches for this particular motor retrofit example. If the total investment costs are considered, i.e. not accounting for additionality (simple method), the measure emerges as cost-*in*effective. However if EnAW, ProKilowatt and advanced (base case with salvage value 15%) approaches are applied, the measure becomes economically viable. The comparison clearly shows that the cost-benefit analysis based on total investments leads to underestimation of the economic benefits and has the tendency to mislead decision and/or policy makers. Hence, accounting for additionality is the first step towards correctly estimating the cost-effectiveness of an EE measure.

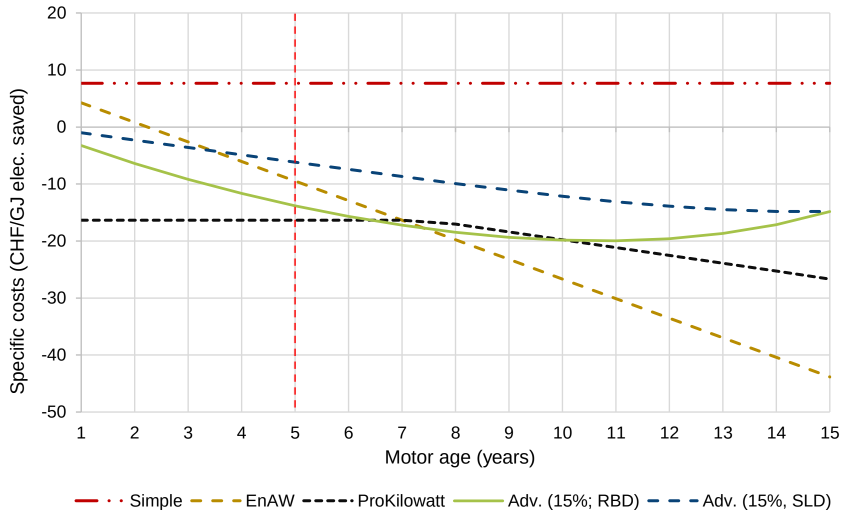


Figure 2 Comparing specific costs of the motor retrofit measure calculated by different approaches (IE2 motor if replaced by IE4 motor after X years of its completed lifetime)

The EnAW approach accounts for additionality in a simplified manner, i.e. considering only the age of the old equipment at the time of replacement. The ProKilowatt approach can be considered better than EnAW as it takes into account both the age of the motor and the technological improvement However, the approach does not make a difference in additional costs if the age of the old equipment is less than half of its lifetime and it applies a simple estimate to account for autonomous technological change, i.e. by reducing 25% of the annual energy savings every time (see Section: The ProKilowatt method). This is understandable because ProKilowatt criteria avoid too much detailing for the participants yet accounting for additionality in a rational way.

The comparison in Figure 2 shows that, for the given situation (IE2 motor if replaced by IE4 motor after five years of its completed lifetime; see Situation), the specific costs calculated by the advanced, EnAW and ProKilowatt methods range from -6 to -16 CHF/GJ for a replaced motor aging 5 years. The decision about the method providing the most accurate results at the fifth year also remains inconclusive. We hence find that the differences in specific costs among all the methods become large. The slope of the EnAW approach is found to be relatively steep compared to the other approaches. The ProKilowatt method also shows a gradual decrease in the specific costs after the seventh year (which represents approximately half of the old motor lifetime). On the other hand, advanced methods show the specific costs (after the 7th year) to be more than those calculated by the ProKilowatt and EnAW methods, indicating an over-estimation of the cost-effectiveness by the two programs.

It should be noted that the motor retrofit measure is found to be more expensive for the higher (50%) salvage value (advanced methods), while for the low (5%) salvage value, the measure becomes highly cost-effective (see Figure 3). In other words, salvage value at the end of a motor's lifetime plays a critical role in defining the cost-effectiveness of the motor. Since the parameter is highly influential and, at the same time, very challenging to estimate, it is difficult to conclude whether the ProKilowatt approach is over- or under-estimating the cost-effectiveness of the measure. Moreover, from the datasets received from the EnAW and ProKilowatt programs, it is observed (where possible) that most of the time (nearly 80%), the age of the replaced motors (early replacements) was more than or equal to half of their expected lifetime. This is logical because companies would not replace relatively new motors unless they were damaged or there were substantial benefits associated with the change, e.g. improved operability or advantages due to altered boundary conditions. Since the specific costs calculated by the EnAW approach are the lowest (for motor ages close to the expected lifetime), it is safe to conclude for this case study that the approach taking into account only the age of the replaced motor (e.g. EnAW) over-estimates the cost-effectiveness of the measure in the second half of the lifetime.

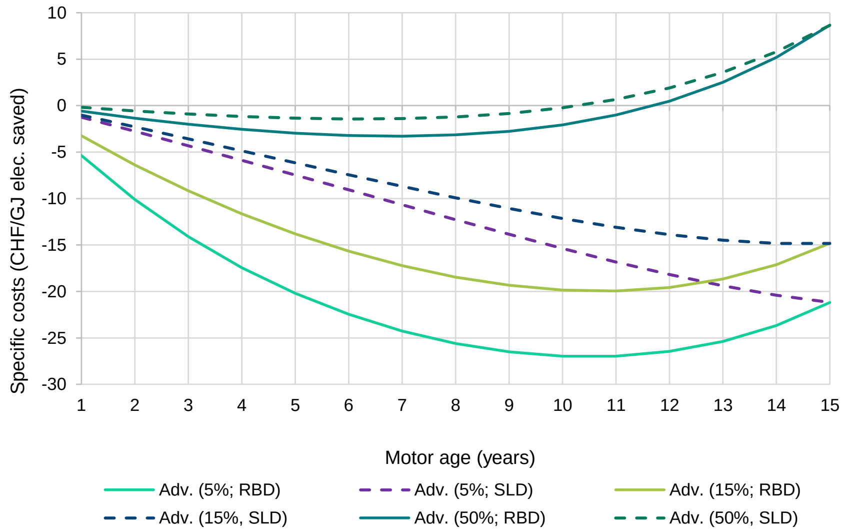
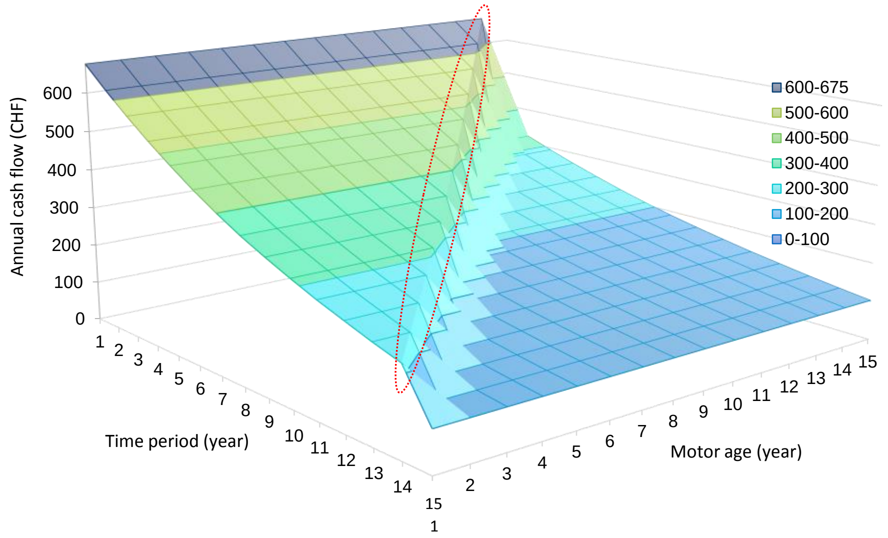


Figure 3 Comparing specific costs of the motor retrofit measure (replacing IE2 by IE4) calculated by advanced methods (RBD and SLD) with different salvage values i.e. 5%, 15% (base case) and 50%

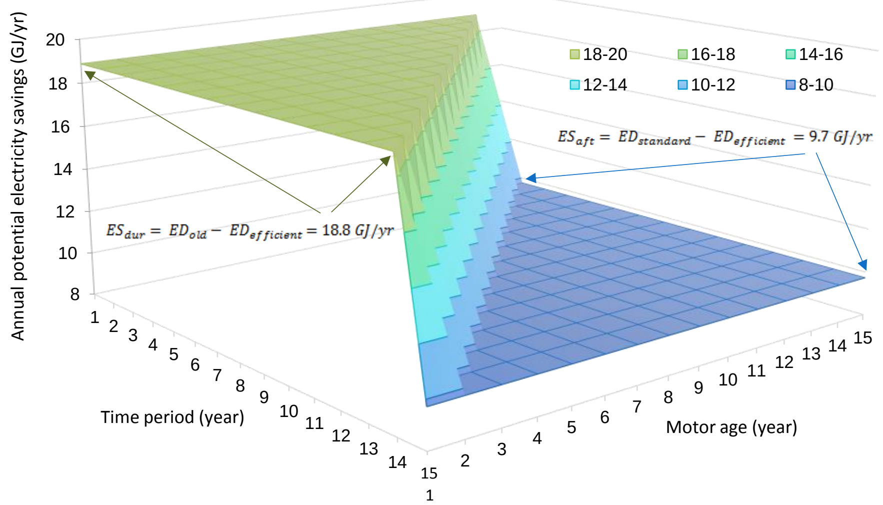
Another interesting feature in Figures 2 and 3 is the curve shape of the advanced methods, especially for RBD. The shape suggests that the specific costs decrease until a certain level is reached after which the costs start increasing, i.e. the measure becomes more expensive (while remaining cost-effective). This is explained with the help of Figure 4. As shown in Figure 4a, the annual discounted cash flows (see Equations 2 and 3) gradually decrease up to a point (red ellipse), after which they drop suddenly and smoothen out again at a low level. The sudden drop occurs due to the large difference in electricity savings during and after the lifetime of the old motor (see Equations 10 and 11) as shown in Figure 4b. This can be explained as follows: the reference technology for the remaining lifetime of the old motor is less efficient than the reference technology for the subsequent period in which the new standard is assumed as reference; this results in smaller energy savings and hence also smaller economic benefits in the second period compared to the first. This holds true for all cases depicted in Figure 3 but it is more visible for RBD than for SLD except for the case with high salvage value (i.e. 50%).

Moreover, the authors find the argument reasonable that the financial value of the manufacturing plant equipment depreciates quickly in the early years as compared to the term closer to the end of lifetime (RBD). Hence RBD can be considered a suitable approach. This leads to the conclusion that, from a company’s perspective, it is most profitable to change an old motor with a more energy efficient one once two-thirds of its lifetime has been reached[40]. This may not be true for motors that do not operate on a frequent basis and are in service only for a few hours annually (reflecting on a higher salvage value of the motor compared to motors used more frequently during a given time period; see Figure 3). However, if one considers that the effective lifetime of motors operating less frequently is larger than their projected lifetime, the conclusion may still hold true. The fact that the age of nearly 80% of motors replaced by the EE programs in Switzerland (EnAW) was more than or equal to half of their expected lifetime also partly justifies the conclusion.

[40] The precise timing at which the motor replacement is most profitable might vary depending upon the old motor efficiency class and its usage.



a)



b)

Figure 4 a) Annual discounted cash flows and b) annual electricity savings over the years for different levels of old motor (IE2 in this particular case) age at the time of replacement

Although advanced methods are more accurate and provide a better understanding of the EE measure, there are also challenges associated with the methodology that make its applications complicated. The major challenge is to define the reference standard technology for more complex systems such as compressors, pumps, fans etc. For example, compressors used in industry differ in terms of type (e.g. oil-injected or oil-free; with or without variable speed drive), capacity, number of stages, load factors and pressure requirements, which makes it difficult to define a standard equipment for comparison. In contrast, such standards exist for electric motors and could be applied in the case of motor replacement. Simplified methods are, therefore, more popular to account for additionality, however, the method of choice should be advanced retrofit where possible. Identifying standard technologies for electric motor driven systems can be an excellent topic for future research allowing better accountability for economic energy efficiency improvement potentials.

Conclusions

In this paper, a case of 45 kW motor retrofit is studied and the cost-effectiveness of the EE measure is analyzed based on different approaches accounting for additionality. The comparison shows that the chosen method very strongly impacts the results, i.e. by factors and potentially even resulting in opposite findings concerning cost-effectiveness of the EE measure. Choosing total investment costs may lead to the conclusion that the measure is not cost-effective while all other approaches result in the opposite conclusion (economically viable). In other words cost-benefit analysis based on total investments leads to underestimation of the potential and has the tendency to mislead the decision makers.

For slowly expanding manufacturing sectors in an industrialized country like Switzerland (limited growth, mature capital stock), the results show that the additionality approach based on age only overestimates the cost-effectiveness. The authors therefore recommend alternative approaches which allow to establish the uncertainty range of measure cost-effectiveness, while maintaining transparency. We emphasize more specifically on the advanced approach given by EPA for the cost-benefit analysis however, the method may not always be applicable due to several constraints which primarily include the definition of the reference standard technology for diverse systems such as compressors, pumps, fans etc. Finally, it is concluded that the careful estimation of energy-relevant investments and electricity savings and their use in the cost-benefit analysis can reduce the large investment barriers which often limits implementation of EE measures in industry.

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References

[1] Stenqvist C, Nilsson LJ. Energy efficiency in energy-intensive industries—an evaluation of the Swedish voluntary agreement PFE. Energy Effic 2012; 5:225–41.

[2] Hayashi D, Krey M. Assessment of clean development mechanism potential of large-scale energy efficiency measures in heavy industries. Energy 2007; 32:1917–31.

[3] Gustavsson L, Karjalainen T, Marland G, Savolainen I, Schlamadinger B, Apps M. Project-based greenhouse-gas accounting: guiding principles with a focus on baselines and additionality. Energy Policy 2000; 28:935–46.

[4] Jakob M. Marginal costs and co-benefits of energy efficiency investments: The case of the Swiss residential sector. Energy Policy 2006; 34:172–87.

[5] US EPA. Understanding Cost-Effectiveness of Energy Efficiency Programs: Best Practices, Technical Methods, and Emerging Issues for Policy-Makers. 2008.

[6] Zuberi MJS, Tijdink A, Patel M. Techno-economic analysis of energy efficiency improvement in electric motor driven systems in Swiss industry. Forthcoming n.d.

[7] Stadt Zürich, Stadtentwicklung. Increased energy efficiency with a bonus for business customers. Zurich: n.d.

[8] EnAW. Der partner für klimaschutz und energieeffizienz. Zürich: 2014.

[9] Energie-Agentur der Wirtschaft. Von der Wirtschaft. Für die Wirtschaft. Seit 2001. - Track record n.d. http://www.enaw.ch/en/about-us/leistungsausweis-en (accessed November 30, 2015).

[10] BFE. Bedingungen für die Einreichung von Programmen 2017 2016.

[11] European Commission. Guidelines accompanying: Commission Regulations (EC) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC with regard to ecodesign requirements for electric motors and No 4/2014 of 6 January 2014 amending Regulation (EC) No 640/2009 2014.

[12] Kaya D, Yagmur EA, Yigit KS, Kilic FC, Eren AS, Celik C. Energy efficiency in pumps. Energy Convers Manag 2008; 49:1662–73.

[13] ABB. Technical note: IEC 60034-30-1 standard on efficiency classes for low voltage AC motors n.d.

[14] Technische Daten – Merkblatt 13: Wirkungsgrade 2014.

Can be downloaded at: http://www.topmotors.ch/Download/

[15] Kosten – Merkblatt 10: Motorpreise 2014.

Can be downloaded at: http://www.topmotors.ch/Download/

[16] Brunner CU, Werle F. Incentive program for motor systems efficiency in industry: First experiences from Easy in Switzerland, Alexandria, USA: 2011, p. 375–91.

[17] Werle R, Brunner CU, Tieben R. Swiss motor efficiency program EASY: results 2010-2014, New York, USA: 2015.

[18] Werle R, Brunner CU, Tieben R. `Easy` program for electric motor systems efficiency in Switzerland, Rio de Janeiro, Brazil: 2013, p. 482–93.

[19] Cody M. Further Mathematics. Pascal Press; 2006.

Audit Methodology for Motor Driven Systems with Reference to International Standards

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Abstract

An energy audit is a systematic analysis of energy consumption within a defined system in order to evaluate opportunities for improved energy performance. It is therefore potentially an effective instrument to detect optimisation potentials for existing motor systems running on-site. The saving potential in this area lies on average between 10-30%.

The target of the task "Energy Audits for Motor Systems", within the Electric Motor Systems Annex of the IEA, is to screen legal and normative requirements for conducting energy audits, develop an energy audit methodology coherent to most important international standards and to outline how already developed tools can help to fulfil the requirements of these standards. This will help energy auditors to detect and calculate the most important energy saving potentials in these systems by considering all relevant standards.

As a first step of this task information on the implementation of energy audit programmes in different countries was collected and analysed. As a second step, existing energy audit standards and standards and guidelines for the measurement of energy savings were analysed in order to see if they already stipulate requirements in this field. The analysis of the standards shows that for energy audits in motor driven systems, all requirements of the ISO 50002, which contains a lot of general information, are relevant. Furthermore, a lot of different standards and protocols consider motor driven systems already as major energy users and two standards concentrate on two different motor driven systems, compressed air and pumping systems. For most of the different audit steps specific information and requirements for motor driven systems is available, either in form of tools, guidelines, or standards.

In general, the energy audit standards analysed, lack the following information:

- Parameters for the first evaluation of energy saving measures (pre-screening)
- Calculation formulas for assessing the energy benefit of the implementation of certain energy saving measures (exception is the annex of ISO 14414)

Performance measurement protocols and guides already include motor driven systems as examples or have already specific guidelines for calculation of saving measures in this field.

In the next project phase, this analysis will serve as basis for the development of the energy audit methodology. This document will be structured along the stages of an energy audit according to ISO 50002 and will include organisational and technical tasks to be performed during the audit. For each step it will refer to the relevant standards, guides and tools. This paper gives a first summary of this upcoming methodology.

Introduction

Energy Audits are an excellent instrument to detect optimisation potentials for existing motor systems running on-site. Especially over-sized equipment, equipment without control, wrong control strategy, leakages, old equipment and inappropriate use and running time can be detected during an audit. Improvements to older motor driven systems have the potential to save between 10 and 30% of energy consumption and running costs, thus offsetting the investment for high efficient components within three to five years. [2, 3]

Furthermore, policy makers already identified energy audits as important instruments to reach climate and energy efficiency targets: The Energy Efficiency Directive of the European Union (published in 2012) foresees regular mandatory energy audits for large enterprises (definition see footnote for Table 1). The first audit for each company had to be performed between December 2014 and 2015. [4] The evaluation of these audits comprises only legal requirements.

But also standard organisations worldwide developed energy audit standards during the last years:

- On international level: ISO 50002 Energy Audits – Requirements with guidance for use, ISO 11011 Compressed air – Energy efficiency – Assessment, ISO 14414 Pump system energy assessment
- In Europe: The EN 16247 series, with audit standards for (industrial) processes and qualification of energy auditors
- In the US: ASME EA-2 – Energy Assessment for Pumping Systems, ASME EA-3 – Energy Assessment for Steam Systems, ASME EA-4 – Assessment for Compressed Air Systems

For fan systems no international audit standard was identified, the work therefore referred to [5], developed for New Zealand: "Fan System Audit Standard, A standard for the auditing of the energy efficiency of electric-powered fan systems."

Therefore, energy audits should be used as an instrument to increase the efficiency of motor driven systems on a broader scale.

The International Energy Agency (IEA) Technology Cooperation Programme "Energy Efficient End-use Equipment" (4E) is driving governments and industry to higher concerns for energy to be saved. Within 4E the "Electric Motor Systems Annex" (EMSA) has many functions: it serves as a platform for technical and policy exchange within the field of electric motor systems, it disseminates best-practice information and it aims to support standards and policy development processes to improve the energy performance of new and existing motor systems in both industrialized and developing countries.

The target of the task "Energy Audits for Motor Systems" within EMSA is threefold:

- to give an overview on legal and financial incentives for conducting energy audits,
- to perform an analysis of existing standards on energy audits and to give an overview which elements are relevant for motor systems within these standards and
- finally, give recommendations how to perform energy audits for motor driven systems using tools from the EMSA group with a special reference to international standards in this field.

This article provides a very comprehensive overview of a selection of countries where energy audits are mandatory or voluntary and which standards already set requirements for energy auditing in motor driven systems and gives a summary of a methodology for energy audits in motor driven systems.

Country Overview on Audit programmes

Table 1 shows selected information on the implementation of energy audit programmes in the member countries of the Electric Motor System Annex & Japan. It shows the size of companies covered by the programme and incentives for energy audits.

Table 1: Overview on energy audit programmes for member countries of the Electric Motor System Annex plus Japan [22]

	Overview and/or Main Requirements of Energy Audit Support Mechanism/Programmes/Regulation in Different Countries
Australia [6]	Energy Efficiency Opportunities Programme (EEO), closed in 2014: Mandatory assessing and reporting on energy use was mandatory for corporations with energy consumption of > 0.5 PJ (139 GWh) In 2012, the programme introduced voluntary participation for medium-energy users
Austria [7]	Mandatory energy audits for big companies acc. to Energy Efficiency Directive (EED)* Voluntary energy audit programmes: regional subsidised programmes
Denmark [8]	Mandatory energy audits for big companies acc. to EED Energy Saving Obligation Scheme (for Energy Utilities) provides energy audits Renewable energy for production process (subsidy for energy audits and implementation in SMEs) Voluntary Agreements (reimbursement of public service obligation tariff) with the following elements: implementation ISO 50001, conduct special investigations, implement EE projects
Japan [9]	Energy Conservation Law: obligation for business with energy consumption of > 1,500 kl oil equiv. (approx. 15 GWh): appointment of an energy manager, periodically report on energy consumption status, submit medium and long term plans, reduction efforts of 1% p.a. (energy manager conducts periodically audits) Energy Conservation Centre (ECCJ), funded by Japanese government: Voluntary energy audit programme for SMEs (free audits, voluntary improvement, confirmation of effect)
Netherlands [10]	Long-term Agreements on energy efficiency for Non Emission Trading Scheme and Emission Trading Scheme (LTA3, MEE): four year energy efficiency plans, annual report on measures and results; these companies are exempted for conducting mandatory energy audits (according to EU-EED) Green Deal (not directly for audits) Mandatory Energy Audits for large energy users not part of LTA3/MEE (EU-EED) Local regional programmes offering advice
Switzerland [11]	Target-Agreements (TA) for companies to save energy (act energy): target agreement, energy-check up, implementation of saving measures, monitoring and reporting; TA are also the basis for reduction of CO_2-tax and grid utilisation charge (depending on electricity costs as share of production costs)
United States	Technical Assistance Programs:

	Overview and/or Main Requirements of Energy Audit Support Mechanism/Programmes/Regulation in Different Countries
[12]	Better Plants Program: Sign a voluntary agreement to reduce energy intensity by 25% over ten years organisation-wide, develop energy use baseline, annual reports Former Save Energy Now LEADERS Program (Free and cost-shared audits) offered three days audit for companies with of > 500 BTU/year primary energy consumption (approx. 150 GWh) Industrial Assessment Centres, university based audits for SMEs (e.g. below 500 employees, energy bill 100,000-2.5 Mio USD): One or two days assessment; free of charge; Superior Energy Performance concentrates on ISO 50001 certification

*Definition of big companies in European Energy Efficiency-Directive (EED) [4]: A company with at least 250 full-time employees or an annual turnover of at least EUR 50m and an annual balance of at least EUR 43m calculated according to annual financial statements.

In the EU-countries covered by this analysis (Denmark, Netherlands & Austria), energy audits are mandatory for big companies according to the Energy Efficiency Directive. In Japan, organisations with high energy consumption have to prove reduction efforts, report their energy consumption and appoint an energy manager. In Australia, (until 2014) big companies had to assess and report their energy use.

In Denmark, Netherlands, Switzerland and the United States, energy audits are embedded in Voluntary Agreements. When joining, companies are obliged to set and fulfil certain targets and (to some extent), conduct energy audits.

Austria, Denmark, Japan, (partly Netherlands) and the United States have subsidy programmes for energy audits in small and medium sized enterprises. Switzerland has a programme for motor specific energy audits.

Energyauditstandards

For developing an energy audit methodology for motor driven systems, existing standards in this field have to be analysed in order to see if they already stipulate requirements in this field. Table 2 gives an overview of analysed standards. In the full report [22] all documents (and, in addition, protocols for measurement and verification) were analysed according to a uniform structure, for this article only the main relevance for the auditing of motor driven systems are summarized.

Table 2: Overview of analysed energy audit standards

International Standard	Name of Standard
ISO 50002	Energy Audits – Requirements with guidance for use
EN 16247-1	Energy audits - Part 1: General requirements
EN 16247-2	Energy audits - Part 2: Buildings
EN 16247-3	Energy audits - Part 3: Processes
EN 16247-5	Energy audits – Part 5: Competence of energy auditors
ISO 11011	Compressed air -- Energy efficiency -- Assessment
ISO 14414	Pump system energy assessment

ISO 50002 Energy Audits – Requirements with guidance for use [15]

The standard ISO 50002 Energy Audits-process requirements published in 2014 is the first standard for energy audits on international/worldwide level. This standard specifies the process requirement for carrying out an energy audit for the following stages: Energy audit planning, opening meeting, data collection, measurement plan, conducting the site visit, analysis, energy audit reporting, closing meeting.

In general, for all audit steps requirements are stipulated that are also relevant for energy audits in motor driven systems. The main information to be provided during an energy audit for motor driven systems is, e.g.:

During data collection:

- A list of energy consuming systems, processes and equipment
- Detailed characteristics of the energy uses, incl. energy performance data
- Monitoring equipment
- Design, operation and maintenance documents

For measurement:

- Definition of relevant variables
- Data measurement plan specifying how data measurement has to be done (incl. determination of uncertainty)
- Ensure that measurements, observations and past data are representative of operational practices (day, night, evening, weekend, seasonal differences)

For evaluating current energy performance and identifying opportunities:

- Evaluate design and configuration options to address system needs
- Operating lifetime, condition, operation and level of maintenance of the audited objects
- Existing technology in comparison to most efficient on market, BAT operational control and behaviours

EN 16247-3 Energy audits - Part 3: Processes [13]

For the European standard series for energy audits specific standards for processes, buildings and transport were published. On the ISO level no further standards in addition to ISO 50002 exist. Some points specified in the EN 16247-3 [13] in addition to ISO 50002 relevant for motor driven systems are mentioned here:

The aim of the field work is among others:

- To confirm the current operational conditions (set points) of utilities and the impact with energy use and consumption
- To collect relevant information from identification plates, runtime information, interviews with operators, etc.

When identifying opportunities, the following measures should be considered:

- Measures in order to reduce or to recover the energy losses; (e.g. reduction of leakage of compressed air, waste heat recovery);
- Replacement, modification or addition of equipment (e.g. variable speed motor);
- More efficient operation and continual optimisation (e.g. set point adjustment, maintaining);
- Behavioural change and improvement of energy management (e.g. metering).

Furthermore, examples of different energy efficiency opportunities are explicitly mentioned in the standard (e.g. leakage reduction in compressed air systems, installation of variable speed motors). [13]

ISO 11011 Compressed air - Energy efficiency – Assessment [14]

The ISO 11011 gives details on an assessment methodology and defines specific parameters for compressed air systems to be collected and their determination. In the Annex of this standard, pressure, flow and electrical test points are identified for the different parts of the system. Furthermore, tables for data collection for all elements of a compressed system - air supply, transmission and demand - are given in Annex C, D and E. Table 3 gives an overview of this information.

Table 3: Tables for data collection in the Annexes of ISO 11011 [14]

Part of the compressed air system	**Information to be collected**
Compressed air supply	Compressor information, after cooler, air receiver and air treatment. (Annex C)
Transmission	Piping system (e.g. material, length, diameter), air receiver: dryer, filtration and condensate drains
Demand	Compressed air waste (e.g. leak), end use application (e.g. average peak flow rate, operating pressure (min. max), air treatment (equipment), air receiver close to the point of use)

This standard has high requirements for data collection and analysis. Especially required is the data collection not only on the supply side but also in the transmission and demand system. The evaluation of the influence of pressure and airflow during different operating period types on the energy use is certainly a challenge for the average energy auditor. One highlight of the standard is the Annex with ready to use data-collection sheets. But it does not, as ISO 14414, give help for the first evaluation of possible energy saving measures and does not include calculation methods.

ISO 14414 Pump system energy assessment [16]

This standard includes some important information for an energy audit on-site and the analysis: The standard gives conditions associated with inefficient pumping system operations and help for pre-screening, which means selecting the pump systems for more detailed analysis. Furthermore, detailed data requirements to be collected from operators or manufacturer data sheets and some requirements for measurements are included. In addition, formulas for the calculation of energy savings are given.

Methodology for Energy Audits in Motor Driven Systems

This chapter gives a concise summary of the methodology for energy audits in motor driven systems, currently developed within the Electric Motor Systems Annex.

Acquisition and Planning

The acquisition phase is not considered in the energy audit standards as it is the phase before the energy audit, but it is already relevant for defining the scope of the audit afterwards. During the acquisition phase it is necessary to build a strong argument for top-management to finance an energy audit. For this, it is useful to do some preliminary evaluation of the company, to investigate the strategic goals of the company and check how efficient motor driven systems can support these. This information will help energy auditors for the energy audit planning and during the opening meeting.

Reasons for the energy audit can be: legal or financial incentives for energy audits or energy management systems, out-phase of refrigerants, down-time, that can be attributed to bad functioning of motors, high maintenance costs, quality issues of the product associated with motor control, capacity issues (e.g. too high temperatures in halls, compressed air pressure too low) or expected energy savings.

According to the energy audit methodology developed, the energy audit planning phase can be structured in two different parts, which can be seen in Figure 1.

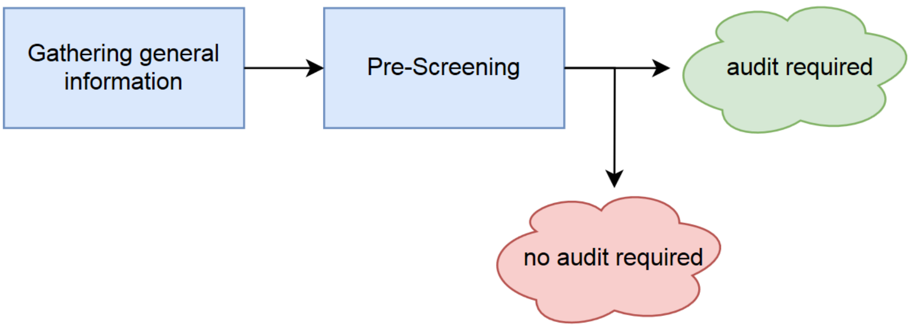

Figure 1: Different parts of the energy audit planning step

Firstly, general data of the company has to be collected: company address, sector, and number of employees, purpose for which motors are used, operating times, name and function of contact person. (See e.g. Annex A of ISO 11011, [14])

If seeking for potential energy savings will be the main issue, the saving potential should be estimated on a very rough level based on technical and financial data: The amount of electricity used in the company, the electricity price and total electricity costs. The share of electricity used by electric motors can give an estimate how much money is involved in the use of motors in this company. 70% of total electricity demand is used on average in production companies by electric motors [1]. The second indicator is the number of motors and their age; this can be answered by the question: When was the last major renewal electric or machinery? Based on this information the possible saving potential can be roughly estimated. Especially for this step "SOTEA", a free software-tool was developed by topmotors.ch in Switzerland. Table 4 below gives the required data.

Table 4: Required data input for SOTEA

Required Data	**Example**
General	
Tool-language	English
Currency	EUR
Turnover	1,000,000
Total number of workplaces	50
Factor of office workplaces	10 [%]
Electricity	
Use of electricity	100,000 [kWh/a]
Average price of electricity (present)	0.20 [EUR/KWh]
Annual costs of electricity	20,000 [EUR/a]
Last major renewal electric or machinery	1997

After the data entry SOTEA is able to calculate and estimate the energy efficiency potential of electric motor systems in the respective company. Based on this information the energy auditor and the company can decide if they want to proceed with the energy audit.

Opening Meeting

The opening meeting should be the first physical get-together between the energy auditor and the representative of the company. In this step, the energy auditor should inform the interested parties on the energy saving potential of the electric motor systems, define the audit scope, boundaries and methods and involve the right persons in the audit. Table 5 below is a checklist for the meeting.

Table 5: Relevant points for the opening meeting (based on [15])

Before the meeting	
Invite right representatives to the opening meeting	☐
Preparation of documents for the meeting	☐
During the meeting	
The energy auditor shall request the organization to:	
Convince the top-management	☐
Define scope, boundaries and methods of the energy audit	☐
Assign personnel to assist the energy auditor	☐
Ensure the cooperation of the affected parties	☐
Confirm any unusual conditions	☐
The energy auditor shall agree with the organisation on:	
Arrangements for access	☐
Requirements for health, safety and security	☐
Availability of financial resources	☐
Requirements and procedures to be followed for installation of measuring equipment	☐
Action plan	
An action plan for the assessment shall be developed	☐
Agreed by the assessment team and top-management	☐

In the methodology developed within the Electric Motor System Annex for each step some recommendations are summarized. As an example, recommendations for assigning personnel to assist the energy auditor the following list can be helpful:

- An assessor who has the electric motor system analysis competencies
- The host organization representative who has overall responsibility and ownership for the assessment
- Experts on the processes and the function of the system
- Experts on the maintenance practices of the electric motor systems
- Experts who can provide the team with cost data

(Based on [16], p. 9)

Data Collection

Before starting with the data collection it is useful to check the energy management system of the company to see which data is already available, useful information can be:

- List of energy consuming processes, systems and equipment (e.g. motors, pumps, fans)
- Historical and current energy performance
- Relevant variables influencing the energy consumption
- Previous energy audit studies
- Monitoring equipment and measurements
- Design, operation and maintenance documents
- (ISO 50002, 2014, p 8, [15])
- Training of relevant personal
- Decision process of implementation of energy saving measures

It is not possible to collect detailed data for all installed motor driven systems, therefore a two-staged process is recommended for data collection:

Firstly, for each motor general data should be collected within an Excel-spreadsheet. Table 6 is showing the required data for the first analysis:

Table 6: Data required for first analysis

Required Data	Example
Number of the motor (No.)	1
Year of construction	1999
Operating hours	3,000
Frequency converter available	no
Mechanical nominal power	100 [kW]
Number of poles	4

The next step is to rank the motors according to energy consumption, and select old motors with high energy consumption without control for a more detailed analysis. For the analysis of the existing electric motor driven systems with the focus on energy efficiency and potential on improvement measures the "Intelligent Motor List" (ILI+) developed by topmotors.ch can be used. In addition to the information given in Table 6, the energy auditor has to define the following criteria:

- Rate of realization of the maximal saving potential in % (e.g.: 50 %)
- Age, older than x years (e.g.: 15 years)
- Operating hours per year > x hours (e.g.: x = 3,000 h)
- Dimension of motors > x kW (e.g.: x = 10 kW)
- Motors without VSD (frequency converter)

- Application (pump, ventilator, compressed air system, cold system, others, etc.)

The ILI+ tool lists the most relevant motor driven systems based on the above mentioned criteria.

In the second stage of data collection detailed data for the selected systems has to be collected.

As an example, the following kind of detailed data is necessary for further analysis of pumping systems:

- Motor data (e.g.: coupling type, motor type (AC or DC), efficiency, manufacturer),
- Pump and control data (flow, shaft power, static or variable flow)
- Distribution system, (diameter, material, built in fittings)
- Liquid properties, (name, temperature, density, viscosity, presence of solids)
- Data of consumer and (pressure, flow requirement)
- Operating profile (hours per day, days per week, percentage of load…)

Measurement plan

In order to complete an energy audit, on-site data measurement might be necessary. It is recommended to establish an agreement of a measurement plan between the auditor and the organization. This plan is dependent on the target of the measurement.

According to the ISO 50002 the measurement plan should include the following points (for each point additional information from other sources are added):

- List of current and identification of additional measurement points
- Identification of any additional measurement points, this is depending on the purpose of the measurement. Measurement points can be on the supply side, in the distribution network or at end consumer side, see e.g. [14] for details.
- Associated measurement uncertainty. This is described by precision and confidence level. Unless stated otherwise, the confidence of meters stated is likely to be 95%. Some meters give the precision relative to maximum reading; therefore the precision of the actual metering might be lower. (for details e.g. for combined uncertainty see [21])
- Measurement duration: When considering the duration of baseline measurement, all typical periods of operation shall be measured [14, chapter 7.7.2]. The measurement should be done during a period where all other influence factors are known. (E.g. production rate, temperature inside and outside the building, employees in building). In some cases instant measuring can be enough, in most cases a measurement period of one week or ten days (to verify the first week's data) can be recommended.
- Data interval: Where dynamic events are to be recorded data required, a data interval of at least on order of magnitude less than the duration of the event being measured shall be applied (if a dynamic event in the system has a duration of one second, the data interval would have to be no greater than one tenth of a second or less, to characterize that event.) [14, 6.2.3]
- Representative time period: The required time period will vary according to the energy uses and processes involved. [15, Annex A.4.2] Typical periods are representative for planned or unplanned changes in production. Changes can be seasonal, based on the day of the week, market conditions, availability of raw material [14, chapter 7.7.1]. "If the operating conditions of the system are constant or only vary minimally in time, a snapshot of the operating conditions may be enough to assess the system." [16] If the system demand varies over time, the assessment team shall determine if the system needs to be monitored

over time and what time period is reasonable to get a representation of all operating conditions.

- Relevant variables according to ISO 50006 are quantifiable variables that impact energy performance. Examples are production parameters (production volume, production rate, or for motor systems: pressure, flow rate), weather conditions (outdoor temperature, humidity), operating hours, operating parameters. Where appropriate these data has to be provided by the organization. Other information necessary is e.g. the damper position. To select relevant variables regression analysis can be helpful, for details see [21]. For the following projects changes in power drawn should be the measured: Replacement of motors, fans and/or pumps, installation of frequency converters, reduction of pressure loss in distribution systems…For changes in control (e.g. installation of sensors to control pump and fan operation) and reduction of running time operating hours should be measured. Power drawn can be estimated on basis of supplier data in this case. (this refers to Option A according to IPMVP) [23]
- The responsibilities of the measurement should be clarified: In principle the auditor is responsible for the measurement. For the installation of the meters other persons can be involved (e.g. as specialized skills are required).
- According to ISO 11011, chapter 6.2.2., [14], measuring equipment shall be calibrated, verified or both at specified intervals or prior to use against measurement standards, if no standards exist, the basis used for calibration shall be recorded. Accuracy details should be mentioned in the report.

Site Visit

During the site visit the energy auditor checks the criteria for motor systems to be analysed further and completes the data collection sheets for the appropriate systems.

For example criteria for fans with saving potential are:

- Running without need
- Variable demand
- Significant changes to the system since installation (change of flow rate by more than 20%)
- Constant throttling
- Worn, eroded or broken blades
- Pressure loss across filters above certain levels
- Air is extracted from the whole hall (instead of specific location)
- No or insufficient maintenance plan

Data Analysis

After data collection the next step is the data analysis, which comprises three activities:

- Analysis of current energy performance
- Identification of improvement opportunities and
- Evaluation of improvement opportunities

For electric motor systems current energy performance of motor systems can be evaluated mainly by the following different indicators:

- Energy use, e.g. compared to other motor systems installed, can be used to identify significant energy users. It does not measure energy efficiency, as it considers total energy demand only.
- Specific energy: the disadvantage of this indicator is that it does not take account for base-load effects (and takes in account only one variable); therefore low load points have higher specific energy demand. On the other hand, this indicator can show that the control strategy for this motor system can be improved or that too big machines are used.
- Relationship of the energy consumption and the pump/fan flow rate (ISO 50006)

The following indicators can be used for on-site measurements and monitoring of energy performance (see Table 6):

Table 6: Indicators for current energy performance

	Indicator	**Source, State of the Art**
Compressed Air	[kW/Nm³] [Wh/Nm³]	ISO 50006 [17] Value should be below 120 Wh/ Nm³ for "normal" 7 bar systems; very good systems Wh/ Nm³ 80-100 Wh/ Nm³ [18]
Pumps	Specific Energy: P_{el}/Q [kW/(m³/h)] Efficiency of Pump $\eta_P = \frac{\rho \cdot g \cdot Q \cdot H}{P_{el} \cdot 367 \cdot \eta_M}$	ISO 14144 [16] Own Source (deviated formula) for pump efficiency (hydraulic power/power input to shaft)
Fans	$P_{SFP} = \frac{P_{el}}{\dot{V}_{Net}} = \frac{\Delta p}{\eta_{Ges}}$	Specific Fan Power in [W/(m³/s)] Value should be SPF class 4: 1,251-2,000 [W/(m³/s)] [19]
Cooling Systems	kWh/MJ	ISO 50006 [17]

*Symbol-Description:

η_P Efficiency factor of the pump [%]

P Density (e.g. water) [kg/dm³]

Q Flow rate [m³/h]

H Delivery head [m]

g Gravitational acceleration [m/s²]

P_{el} Electric power of the motor of the pump system [kW]

η_M Efficiency factor of the motor [%]

P_{SFP} Specific fan-power [W/m³s]

P_{el} Electric power of the motor of the fan system [W]

$\dot{V}_{Net}$ Nominal air volume flow of the fan [m³/s]

Δp Total pressure increase of the fan [Pa]

η_{Ges} Overall efficiency (fan, drive, motor) [%]

When identifying opportunities, the following measures should be considered (according to EN 16247-3 [13]):

- Measures in order to reduce or to recover the energy losses; (e.g. reduction of leakage of compressed air, waste heat recovery)
- Replacement, modification or addition of equipment (e.g. variable speed motor)
- More efficient operation and continual optimisation (e.g. set point adjustment, maintaining)
- Behavioural change and improvement of energy management (e.g. metering)

The evaluation of performance of an existing system requires extensive calculations. In order to assist technicians and energy auditors in system optimisation, the Danish Technological Institute developed the Motor System Tool within the Electric Motor Systems Annex. The tool is able to calculate the efficiency of different motor systems and provides technical support for selecting the optimal components. It calculates how the change in speed, of the operating points, or other elements affects the overall system efficiency. In addition the tool contains models for pumps, fans and compressors, electric motors and frequency converters as well as transmission types such as V-belts and combinations of those.

For the identification of improvement opportunities indicators for two important saving measures for pumping systems are shown in Table 7. Other saving measures for pumping systems include: control, reduction of head, reduction of flow, improvement of distribution system and maintenance.

Table 7: Example of indicators for saving measures [16, 19]

Kind of Saving Measures	Indicators for saving measure
Switch off Pumps	• Running (when not needed) on holidays, weekends, nights, too long before shift, finishes too long after shift, runs during breaks • Running continuously where loads are irregular (batch operations, irregularly used services, switch off one of a bank of machines) • Systems with multiple pumps where number of operated pumps is not adjusted in response to changing conditions
Replacement of Pumps	• Big pumps with long running times • Current flowrate differs more than 30% from nominal flow • Current head differs more than 20% from nominal head • Low Efficiency (below 60%) • Cavitating equipment, high maintenance requirements, noisy pumps, or piping

	• Constant throttling • Worn, eroded, corroded, distorted or broken impellers/vanes or wear rings

The evaluation of improvement opportunities should include the calculation of the cost savings of the most important improvement measures per technology. For the calculation of the energy saving measures in the energy audit methodology several examples will be published. Table 8 gives one example.

Table 8: Example of formula for calculation of energy cost savings

Title	Reduction of running time for pumps
Description	The first measure is to switch off pumps which are not needed. In addition the operating time of all pumps should be adapted to the actual required operating time. For example: time-, temperature-, pressure- and level control (level indicators) are simple control mechanisms for adjusting the operating time of the pumps to the process.
Formula	$\Delta C = P_{el} \cdot (t_{before} - t_{after}) \cdot c(E)_{el}$
Measurement plan	Measure running time and/or power drawn

*Symbol-Description:

ΔC Energy cost savings due to the reduction of the run-time of the pump system [€/a]

P_{el} Electrical power input to the pump system [kW]

t_{before} Current running time of the pump system [h/a]

t_{after} Running time of system after optimisation [h/a]

$c(E)_{el}$ Specific energy costs for electricity (el) [€/kWh]

For the financial evaluation of the energy saving measures usually experience of the energy auditor, list prices of suppliers or specific offers are used. For the evaluation the specific criteria defined together with the company (during the opening meeting) should be used. The EU-Efficiency Directive stipulates that life-cycle cost analysis should be used instead of Simple Payback Periods (SPP) in order to take account of long-term savings, residual values of long-term investments and discount rates. [4, Annex VI]

According to the ISO 50002 non-energy gains should be included in this analysis. Energy saving measures can contribute to the following topics: energy, maintenance, quality, productivity, financial (sales), environmental, health and safety. Table 9 shows non energy-gains which can be relevant for motor driven systems. These non-energy gains should be evaluated, if possible quantified together with the company representatives and included in the life cycle cost assessment.

Table 9: Non energy-gains relevant for motor driven systems [20]

Waste	Emissions	Operation and maintenance
Use of waste heat (e.g. chillers, compressed air, motors)	Reduced CO_2 emissions, (because of less electricity consumption)	Reliability Reduced wear and tear on equipment Reductions in labour requirements
Production	Working Environment	Other
Increased product output improved equipment performance Shorter process cycle times, Improved product air quality	Reduced noise levels Improved temperature control improved air quality	Decreased liability Improved public image Reducing capital expenditures Improved worker morale

ISO 50002 stipulates to recommend measurement and verification methods for use in post-implementation assessment of the proposed energy saving measures. In addition to the parameters associated directly with the system and saving measure (power and running time) other parameters have to be measured or estimated as well. See Table 10 and [21,23] for further details.

Table 10: Additional parameters to be measured or estimated for measurement and verification of energy saving measures in the field of motor driven systems [23]

Parameters	Examples
Independent variable	Operating time, production, required volume flow and pressure
Static factors	Number, capacity and usage model of all systems supplied (if relevant: production speed and production mix, system pressure change) Standard requirements for air quality (for fans)

Energy Audit Reporting and Closing Meeting

In the different energy audit standards the content of the energy audit report is stipulated.

1) Executive summary:

The executive summary shall provide an overview of the whole energy audit process. It is recommended to emphasize the economic benefits.

2) Introduction and facility information:

This section of the report should include a brief description of the background, the team and scope of the electric motor audit.

3) Description of system(s) studied in assessment and significant system issues:

The report shall include a detailed description of the specific motor systems. Supporting documentation, such as data sheets and handbooks, should be included if necessary.

4) Assessment data collection and measurements:

The methods used to identify and interview key facility personnel, obtain data, and conduct measurements shall be identified, including an overview of the measurement plan. The following relevant data should be included:

- Definition of system requirements and a determination of how system operation changes during the year (drawings, system process data)
- Electrical energy consumption data
- Other specific data relating to the motor driven systems such as pump total head, specific fan power, working pressure, flow, etc.
- Determination of operating hours of the motor systems
- Performance information of the motor system when available
- Measurement or estimation of system losses

Also information about data accuracy and the need for verification before the recommended projects are approved should be given in this section of the report.

5) Data analysis:

The outcome of the measurements and data analysis should be mentioned in the report. Any significant analytical methods, measurements, observations and results from data analysis form completed action items shall be documented.

6) If sufficient data exist, the assessment report shall contain the baseline of total annual energy consumption.
7) Performance improvement opportunities identification and prioritization
8) Recommendations for implementation activities
9) Appendices

Conclusion and Outlook

The analysis of the standards showed that for energy audits in motor driven systems all requirements of the ISO 50002, which contains a lot of general information, are relevant. Furthermore, a lot of different standards and protocols consider motor driven systems already as major energy users and two standards concentrate on two different motor driven systems, compressed air and pumping systems. For most of the different audit steps, ranging from audit planning to data acquisition and analysis and audit reporting specific information and requirements for motor driven systems is available, either in form of tools, guidelines, or standards.

In general, the energy audit standards analysed, lack the following information:

- Parameters for the first evaluation of energy saving measures
- Calculation formulas for assessing the energy benefit of the implementation of certain energy saving measures (exception is the annex of ISO 14414)

Performance measurement protocols and guides already include motor driven systems as examples or have already specific guidelines for calculation of saving measures in this field. As the measurement of energy savings have to be started before the implementation of saving measures, this information is important for the data collection during the energy audits.

Within the Annex Electric Motor Systems these standards and protocols and some tools are currently used for the development of an energy audit methodology for motor driven systems. This document will be structured along the stages of an energy audit according to ISO 50002 and will include organisational and technical tasks to be performed during the audit. For each step it will refer to the relevant standards, guides and tools and how they can be used during the audit process. In addition, it will include the following information:

- Technology-specific key indicators for the recommendations of energy saving measures
- Saving calculation methods in accordance with international protocols

References

[1] International Energy Agency (IEA)/OECD: World Energy Outlook 2016, Paris, 2016

[2] Paul Waide, Conrad U. Brunner et al.: Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems, International Energy Agency Working Paper, 2011

[3] Conrad U. Brunner, Rita Werle, Rolf Tieben: "Easy" programme for electric motor systems efficiency in Switzerland, In: Proceedings of the 8th International Conference on Energy Efficiency in Motor Driven Systems, 28 - 30 October 2013

[4] DIRECTIVE 2012/27/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2012

[5] Energy Management Association of New Zealand (EMANZ) (n.s.): Fan System Audit Standard, A standard for the auditing of the energy efficiency of electric-powered fan systems, website: www.emanz.org.nz, downloaded on 12.05.2017, at 10:16 am, source: http://www.emanz.org.nz/system/files/Fan_Systems_Audit_Std_v1.0.pdf

[6] Australia:http://eex.gov.au/energy-management/energy-efficiency-opportunities/; http://eex.gov.au/energy-management/energy-efficiency-opportunities/resources-energy-efficiency-opportunities-program/

[7] Austria:http://www.monitoringstelle.at/index.php?id=685; http://www.klimaaktiv.at/energiesparen/schulungen.html; http://www.klimaaktiv.at/energiesparen/betriebe_prozesse/beratung_foerderung/beratungsleist_bdld.html; http://www.klimaaktiv.at/energiesparen/betriebe_prozesse/technologieschwerpunkte.html;

[8] Denmark: European Commission: A Study on Energy Efficiency in Enterprises: Energy Audits and Energy Management Systems, European Union 2016; Order on mandatory energy audits for large enterprises

[9] Japan: http://www.asiaeec-col.eccj.or.jp/sector/com-resident/eneauditprog.pdf; http://www.eccj.or.jp/education/index.html; http://www.asiaeec-col.eccj.or.jp/law/pdf_fac_e/g-1.pdf; presentation: Energy Management Regulation & ESCO Industry Update in Japan, Nov. 2015 (Tetsuya Maekawa, JAESCO); personal communication: Tohru Shimizu, IEEJ

[10] Netherlands: European Commission: A Study on Energy Efficiency in Enterprises: Energy Audits and Energy Management Systems, European Union 2016; personal communication: Maarten van Werkhoven (TPA advisors); Ronald Vermeeren (RVO)

[11] Switzerland: Flyer act Energiespezialist www.act-schweiz.ch/de-wAssets/.../act_Flyer_Energiespezialist_web.pdf, act formular Akkreditierung; http://www.act-schweiz.ch/de/praxis/beraterliste.php; Information: Akkreditierung von KMU-Beratern der EnAW, Jan 2015; topmotors.ch; https://www.energieschweiz.ch/unternehmen/stromeffizienz/effiziente-kaelte.aspx ; https://www.energieschweiz.ch/unternehmen/stromeffizienz/effiziente-druckluft.aspx; personal communication: Marton Varga (act-energy), Armin Eberle (CEO, EnAW); Rita Werle (impact energy)

[12] United States: IAC: http://energy.gov/eere/amo/industrial-assessment-centers-iacs; Better plants: http://energy.gov/eere/amo/better-plants; CEA, CEAM: http://www.aeecenter.org/i4a/pages/index.cfm?pageid=4552; http://www.aeecenter.org/i4a/pages/index.cfm?pageid=4096

[13] EN 16247-3. Edition: 2014-07-01. Energy audits — Part 3: Processes

[14] EN ISO 11011 (2013): Compressed air - Energy efficiency – Assessment, Edition: 15.09.2013

[15] EN ISO 50002 (2014): Energy Audits – Process requirements, Edition: 14.01.2014

[16] EN ISO 14414 (2016): Pump system energy assessment, Edition: 15.02.2016

[17] EN ISO 50006 (2014): Energy management systems – Measuring energy performance using energy baselines (EnB) and energy performance indicators (EnPI) – General principles and guidance, Edition: 20.01.2014

[18] Kulterer K., Huber J., Ruther H., Oetiker H., Pucher C. (2015): Leitfaden für Energieaudits zur Optimierung von Druckluftsystemen, Austrian Energy Agency, klimaaktiv, Edition: 01.04.2015

[19] Kulterer K., Presch D., Geissegger G., Hofmann M. (2017): Leitfaden für Audits an Lüftungsanlagen, Austrian Energy Agency, klimaaktiv, Edition: 01.04.2017

[20] Worrel, E., Laitner, J., Ruth, M., Hodayah, F.: Productivity benefits of industrial energy efficiency measures, US EPA, Washington, DC, 2001)

[21] Efficiency Valuation Organisation: International Performance Measurement and Verification Protocol (IPMVP®), Washington, 2012

[22] Kulterer, K.: Energy Audits for Motor Driven Systems, Part 1, Overview of Programmes, Tools, Guides and Analysis of Standards and Protocols for Motor Systems Audits, Österreichische Energieagentur, Wien, 2016

[23] NSW Government, Office of Environment & Heritage: Measurement and Verification, Operational Guide: Motor, Pump and Fan Applications, NSW Government, Office of Environment & Heritage, Sydney, Dec. 2012

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Accreditation Program for Electrical Apparatus Service Centers: Planning, Implementation, and Success

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Electrical Apparatus Service Association (EASA)

Abstract

The Electrical Apparatus Service Association (EASA) has developed an international accreditation program for service centers based on the good practices in ANSI/EASA AR100 *Recommended Practice for the Repair of Rotating Electrical Apparatus* [1]. Since August 2014, this program, using independent third-party auditing, has evaluated service centers for evidence of compliance to assure that they are using the prescribed good practices to maintain efficiency and reliability during electrical and mechanical repairs of three-phase electric motors. At the present time there are nearly 100 accredited service centers in 7 countries in North America, Europe and Asia. This paper will detail the planning, implementation, and success of the EASA Accreditation Program and the positive impact it has had on accredited service centers and their customers.

Introduction

The concept for the EASA Accreditation Program (hereafter Program) came about in early 2012 at a meeting of the EASA Board of Directors. Board members had been hearing for years that customers of EASA member service centers were receiving feedback from some motor manufacturers, user groups, utilities and other sources that electric motors cannot be repaired without degrading efficiency, despite the conclusions of the 2003 EASA/AEMT rewind study (see Appendix A) [2].

Planning

The Board decided that rather than having outside entities doing so, EASA should be the recognized organization to offer a service center Accreditation Program on energy efficiency. Further, to be fair and equitable, participation in the Program would not require EASA membership. The initial target date for implementation of the Program was June 2013, however this proved to be too ambitious and the Program was launched in June 2014. One of the reasons for the longer time to implementation was that the scope of the Program was broadened from a focus on maintaining energy efficiency to also include maintaining the reliability of repaired electric motors.

An Ad Hoc Committee for Accreditation (hereafter Ad Hoc committee) of present and past Board members and EASA committee members was formed to create and implement the Program. Among the key considerations for the Program were:

- Limiting the initial scope to 3 phase squirrel cage induction motors
- Creation of a document to be used to provide specifications
- Creation of a document to be used to audit for conformance
- Identification and selection of independent 3rd party auditors
- Creation of a label to be affixed to conforming repairs
- Establishing processes for internal staff support and maintenance

The primary reasons for limiting the scope to 3 phase squirrel cage induction motors were that most energy-efficient motors above about 1 hp (0.75 kW) are this type, and initially limiting the Program scope would make it more manageable. Although it is possible that the scope may be extended to other motors such as 3 phase synchronous and direct current (DC) motors and generators, there are no active plans to do that at this time. Note that the present scope applies to all 3 phase squirrel cage induction motors; there are no minimum or maximum power ratings.

Preliminary work on a document that would provide specifications for conformance to the Program evolved from the concept of a relatively lengthy text document to the checklist used by the present Program. The committee found that the good practices that needed to be done already existed in the recommended practice ANSI/EASA AR100 [1] (Figure 1), supplemented by work-instruction style details in the Good Practice Guide (GPG) of the EASA/AEMT Rewind Study [2] (Figure 2).

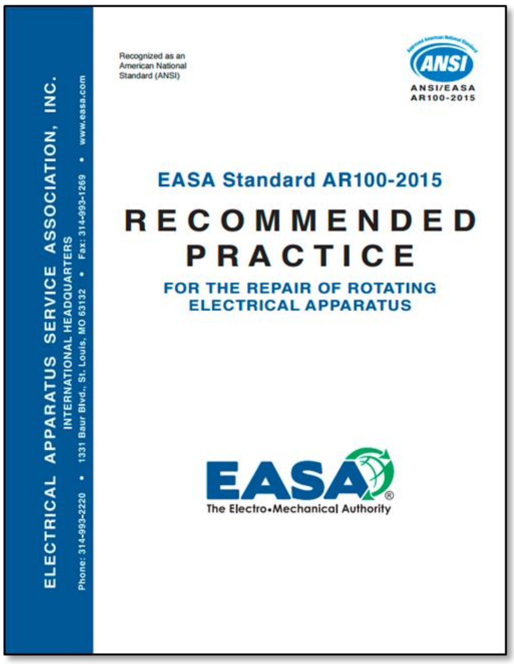

Figure 1: The cover page of ANSI/EASA AR100-2015

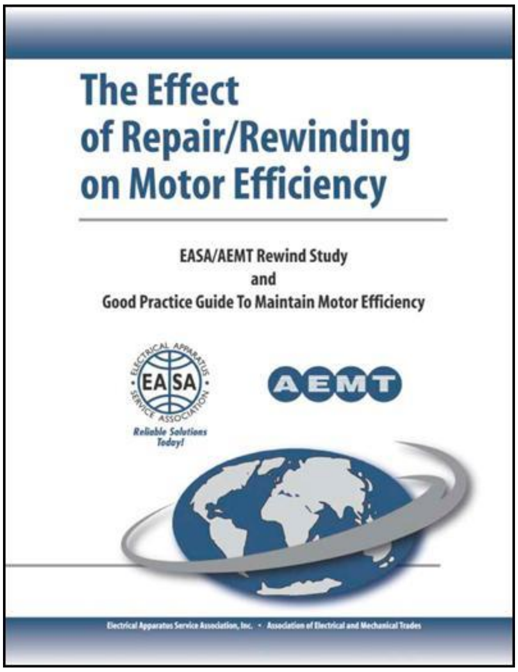

Figure 2: The cover page of the EASA/AEMT Rewind Study

Accreditation Program Checklist

Rather than duplicate much of what had already been written in AR100 and the GPG, it was decided to create an outline style document in the form of a checklist. In so doing, the checklist provided condensed statements of requirements, and a means to indicate that each requirement had or had not been met. Thus, the objectives of creating a document to be used to provide specifications, and a document to be used to audit for conformance, would be accomplished in a single document, the Checklist. The Checklist that was developed consists of 23 categories with over 70 total criteria. Three categories relate to functions indirectly associated with repairs, and the remaining 20 categories apply to specific repair functions. The Checklist categories and key criteria are in Table 1; and Table 2 is an example of a category with criteria.

Table 1: EASA Accreditation Program Checklist categories and key criteria

Category	**Key Criteria**
Housekeeping	Evaluates the cleanliness and orderliness of work areas and equipment in the service center since these are indicators of professionalism and a controlled (and safe) repair environment.
Training	Evidence of internal training of technicians is required; with external training encouraged, but not mandated. Technical training includes topics related to electric motor rewinding, machining, mechanical assembly or disassembly; and theory, principles, applications, failure analysis and design/redesign.
Internal audits	Annual internal audits are performed and documented. Annual internal audit reports are submitted to external auditor for review. If applicable, corrective actions for internal audit findings are taken and documented.
Identification and condition assessment	Among the requirements are that original nameplate data (if present) is recorded; incoming inspection findings recorded; primary apparent cause of failure determined and recorded; and repair records retained for at least 3 years.
Terminal leads, connectors and boxes	The terminal leads are labeled for identification; terminal lugs (if used) properly crimped; and terminal box integrity checked. Confirm terminal crimpers function checked at least quarterly for wear and proper crimp.
Cooling system	Internal and external cooling fans and cooling fan cover (if applicable) integrity is checked; and a check performed for damaged or missing cooling system components.
Shafts	Before and after repair shaft dimensions are recorded; shaft integrity checked; and shaft orientation (e.g., NEMA F1 versus F2) verified. Confirm outside micrometers calibration is current.

Bearings (ball, roller; sleeve)	Replacement bearings are equivalent to the original, or better suited to the application; original and replacement bearing numbers documented; as-received, and if rebuilt, post repair bearing fits documented; and if possible, the mode of failure documented. Confirm inside and outside micrometers calibration is current.
Lubrication	The service center is to have documentation indicating that the lubricant used in the motor is compatible with the customer's lubricant; and the service center is to identify the lubricant used in the motor.
Frame and bearing housings	Frame and bearing housing integrity is checked; a check performed for damaged or missing components; and parts are match marked in accordance with service center policy. Confirm inside and outside micrometers calibration is current.
Squirrel cage rotors	Check is performed for evidence of rotor damage or overheating; rotor is growler and/or single-phase tested; and if repaired, original electrical and mechanical characteristics are maintained. Confirm growler and ammeter are function tested.
Balancing	Dynamic balancing of the rotating element is to the level specified by the customer; or in the absence of a requested level, dynamic balance is to ISO quality grade G2.5 or better for machines rated 2500 rpm or slower, and to the level of grade G1.0 or better for machines rated above 2500 rpm; and original and final balance values are documented. Confirm calibration and functionality of balancing machine. Exception: Rotors of shaker (vibrator) motors do not need to be balanced.
Accessories	Check is performed for evidence of damaged or defective components; if replaced, components are identical with or equivalent to the original devices. Confirm calibration and functionality of associated test equipment.
Winding removal and core integrity	Core testing is performed before burnout or other equivalent process, and after winding removal, and the results documented. Evaluation assessment of core acceptability (watts per lb (kg) and temperature rise) is documented. Burnout oven has part temperature control set to 700 °F (370 °C) or less; water mist and analog or digital recorder are functional.
Rewind data (specification)	Details of as-received winding are documented; data is verified for accuracy; and winding changes made to maintain or improve efficiency of a rewound motor are documented.

Stator windings, insulation system, conductors and coils	Voltage rating and insulation class of winding system are equal to or greater than the original unless redesigned by agreement with, or at the instruction of, the customer; coil extension lengths are not to exceed original; and winding wire area per amp is at least equal to original. Confirm calibration and functionality of associated equipment including outside micrometers and verification of winding machine turns counter.
Winding impregnation	Windings of rewound motors are preheated, varnish/resin treated and cured in accordance with varnish/resin manufacturer instructions; bake oven temperature control set in accordance with varnish/resin manufacturer instructions; and varnish maintenance tested in accordance with manufacturer instructions. Confirm calibration and functionality of temperature meters.
Winding insulation and coil tests	Stator winding insulation resistance and winding resistance are tested and results documented; and stator winding surge comparison test is performed and results documented. Confirm calibration and functionality of associated equipment including megohmmeter, ohmmeter, milli-ohmmeter, and surge tester.
High-potential tests	New and reconditioned windings and accessories are high potential tested and results documented. Windings and accessories of windings not reconditioned are insulation resistance tested and results documented. Confirm calibration and functionality of megohmmeter and high potential tester.
Bearing insulation	If applicable, bearing insulation is insulation resistance tested and results documented. Confirm calibration and functionality of megohmmeter.
No load tests	No-load running test using test panel is performed at rated voltage. No-load currents and voltages, and vibration levels, are measured and documented. Evaluation assessment of acceptability is documented (e.g, "OK to ship".) Confirm calibration and functionality of associated equipment including voltmeter, ammeter, and vibration meter.
Finish and handling	Motor is packed or packaged in a manner suitable for the form of transportation to be used. Oil-lubricated motors are shipped without oil, and the need for lubricant clearly identified. Motor is externally clean and painted (if applicable).
Calibration	Proof of current calibration to applicable national standard is available for all applicable instruments. Proof of current certification for gauge blocks (if applicable) is available. Calibration requirements apply to all instruments included in the Equipment List.

Table 2 is an example of the criteria for one of the 20 repair categories. The blank spaces in the second column are used to indicate satisfactory or unsatisfactory findings (score) during an audit.

Table 2: Checklist criteria for winding removal and core integrity

	Score	Checklist item
Criteria:		Core testing is performed before burnout or other equivalent process, and after winding removal, and the results documented. Evaluation assessment of core acceptability (watts per lb (kg) and temperature rise) is documented.
		Burnout oven has part temperature control set to 700 °F (370 °C) or less; water mist and analog or digital recorder are functional.
		If core test losses increase more than 20% between the before and after winding removal tests the core is repaired or replaced.
		Parts are oriented and supported in oven so as to avoid distortion.
		Check is performed that core slots are clean and free of sharp edges or particles.
		Core teeth are not splayed, i.e., flared at ends of slots.
Equipment:	∅	Confirm calibration and functionality of associated equipment.
		Temperature meter
		Water mist (functionality)
		Analog/digital recorder
		Core tester (wattmeter, ammeter, and voltmeter integral with tester)
		or Loop test with separate/standalone:
		Wattmeter
		Ammeter
		Voltmeter

Source references: AR100-2.5, 3.1.1, 3.3, 4.2.7 GPG 3.2-3.4, 5.1, 7.3.2-7.3.4, 7.4

Audits

Another major element of the Program was the identification and selection of independent 3rd party auditors. The committee was already aware of two independent firms in the US that performed audits to verify that electric motor repairs maintained motor efficiency. Since many reliability requirements are also related to maintaining energy efficiency, it was clear that these two firms were candidates to provide external auditing for the Program. A third auditing firm, located in Canada, was also known to the committee by virtue of having been an auditor for the former EASA-Q quality management program.

The committee developed a Request for Proposal (RFP) to be sent to potential external auditing firms and the three firms that were identified submitted proposals that were accepted by the committee. After the Program was implemented, a fourth auditing firm, located in the United Kingdom, completed the RFP and the committee accepted them as an auditor.

Part of the plan with the Program was to make certain that the independence of the auditing firms was not compromised. To that end the committee established that business dealings between auditing firms and service centers were strictly between them. Further, EASA's role would be record-keeping to verify that Program integrity with issues such as audits was confirmed through service center and auditor documentation.

The role of EASA would also be to manage and maintain the overall program; and to the degree possible, assure that non-accredited service centers did not claim to be accredited. To aid service centers, end users and others, the EASA website would provide a list of accredited service centers (www.easa.com/accreditation). Firms that are accredited also would receive a logo for use on their websites and company correspondence. Figure 3 illustrates the logos for EASA member and non-EASA member service centers.

Figure 3: Accreditation logos for EASA member and non-member service centers

Accredited repair labels

Recognizing that motors repaired by an accredited service center that met the requirements of the Program should be identified, the committee decided that a label on each qualified repaired motor would be appropriate. Initial discussion favored a metallic plate because of its durability. However, attaching such plates could be difficult, and producing the metal plates would be relatively expensive. The final decision was to use a paper-like adhesive label with a special coating to increase durability. Figures 4 and 5 illustrate repaired motor labels for use by EASA member and non-EASA member service centers, respectively.

Figure 4: Accreditation label for EASA member service center repairs

Figure 5: Accreditation label for non-member service center repairs

Working with EASA staff the committee determined that staff would maintain the day-to-day operation of the program. This included maintaining a website page (www.easa.com/accreditation), maintaining copies of all internal and external audits, notifying service centers when their renewal audits were approaching overdue status, invoicing service centers for participating in the Program, and verifying that audit reports were complete. Long term modifications to the Program would be turned over from the Ad Hoc committee to the EASA Technical Services Committee when the Ad Hoc committee decided its work was complete. (Note: This transition occurred in June 2016.)

Implementation

As mentioned earlier, the Accreditation Program was launched in June 2014. The first service centers were accredited in August 2014. At present (July 2017) there are 98 accredited service centers located in 7 countries on 3 continents; and 25 more applications have been submitted.

Among the steps taken to implement the Program were posting of information on the EASA website (www.easa.com/accreditation) so that interested service centers could obtain details about the Program. The website also provides access to documents, downloads, and links needed for participation in the Program, including:

- Explanation of the Accreditation Program
- Application form with instructions
- Most current Accreditation Program criteria checklist and explanations
- List of EASA approved auditors with contact information
- Current list of Accredited Service Centers

During the first months of the Program a series of frequent questions were identified and 15 of these questions and their answers were added to the website as "Frequently asked questions". A few minor technical modifications were made to the Program requirements. An example of a technical change that was made was not requiring a calibrated ammeter for a growler test (Figure 6) of a rotor because the test assessment is based on the relative change in ammeter current, not the absolute value.

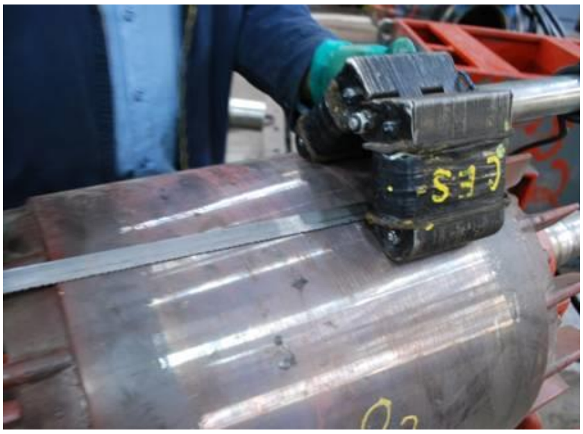

Figure 6: Growler test of a rotor.

Because the Program uses ANSI/EASA AR100 as its primary source the Checklist was revised effective August 1, 2016 to reflect changes in AR100-2015. As with the initial modifications to the Program Checklist there were few changes. However, the requirements for winding testing were expanded to require insulation resistance testing, lead to lead resistance measurement and surge testing. Although surge testing was optional with the prior (2010) version of AR100, all of the accredited service centers already had calibrated surge testers as part of their calibrated equipment list.

The Ad Hoc committee had estimated that external 3rd party audits of service centers should be able to be accomplished in one day, and that has turned out to be the case. The only external audit that required the auditor to be on site more than one day was due to the service center combining the Accreditation Audit with an audit to another standard offered by the auditor. Further, all of the service centers that were audited were eventually approved by the auditors. The most common reasons for delays in accreditation were lack of calibration of all required equipment, and in a few cases the need to procure new conforming equipment.

The audit process for the Program begins with an on-site audit by an EASA approved external (independent 3rd party) auditor. Upon successful completion of that audit the service center is accredited by EASA. The Program then requires service centers to perform an annual internal audit within 60 days of the first and second year anniversaries of the initial and subsequent accreditation cycles, with the external 3rd party auditor returning to perform the on-site audit within 60 days of the third year anniversary of the cycle. At the present time, all of the initial first year and most of the second year internal audits have been completed by the accredited service centers and accepted by the external auditors. The next series of external audits will begin in August 2017 initiating another 3 year audit cycle for the applicable service centers.

Impact

To measure the impact of the Program on accredited service centers, a brief survey was sent to a sample of them consisting of a wide breadth of geographic locations and a large diversity of firm size as measured by number of employees. The 3 questions in the survey are below, along with some of the service center responses.

Question #1: How has the Accreditation Program improved your internal business operations (e.g., more efficient, more productive, safety, morale)?

Service center responses:

- By adopting EASA accreditation we found that our employees are in a much better mood since they have a go or no-go on everything; and this also increases efficiency as they normally no longer need to get approvals from management on how to move forward.
- An economic saving is that by following the same procedures for all repairs this helps with the efficiency of work flow, making the employee's job simpler and less stressful.
- We tackled each of the [Accreditation Checklist] 23 sections one at a time giving our employee's a chance to comment on what they saw as opportunities for improvements. What came out of that were dramatic changes not only in the quality of our repairs but also a new level of employee engagement. They have become obsessed with not just doing things right, but understanding what this means to motor reliability. It was a tipping point for our business as we implemented 120 process improvements of which 72 were over and above what was needed in preparation for accreditation.
- We saw a large drop in warranty and other quality issues almost immediately. The interesting part was this wasn't just on accredited motors (0 in a little over two years) but across the board we dropped from 3% to 0.4% [warranty versus total number of repairs] on all repairs.
- Accreditation has become a foundational morale builder, as highly skilled craftsman literally put their "heart and soul" into their work, using a 3rd party internationally accepted reference in defining their quality. Accreditation created an internal, objective positive feedback loop. Craftsmen have become more confident, experience personal growth and actually require less supervision.
- Having a good quality system that covers industry standards and requirements cuts down on rework. Clear procedures cut down on wasted time and rework as well. Accreditation is an excellent program and even if you have to invest quite a bit in equipment to meet the standards, the payback would be just as quick because the impact of the Program would be greater.
- Continuous improvement is a big deal for us. Accreditation has helped us to maintain and reestablish the fact that we are following consistent processes and procedures to provide high-quality motor repair. Our employees have benefited from having clear guidelines laid out to them on performing procedures according to best practices in the industry.

Question #2: How has the Accreditation Program improved relationships with customers (e.g., increased customer confidence and trust in your work)?

Service center responses:

- Accreditation, in conjunction with our educational efforts [outreach to customers], has strengthened our pre-existing relationships. The trust placed in our work has been justified by the accreditation.
- When we talk with customers and tell them what we are doing with their motors they are somewhat surprised that a "small shop" (7-9 people) would be doing these things.
- The Accreditation Program has been a great marketing tool for us. It helps to convey to our customers what they are getting or not getting in a repair, especially the customers that do not have a specification.

- Because many customers were not aware of either EASA standards or the Accreditation Program we have been working to educate customers via joint presentations by our sales and engineering staff. As a result of these awareness efforts customers now have greater trust and confidence in our company and in our repairs. Customers have also found that our having accreditation brings value to the repair equation and differentiates us from our competition.
- Accreditation is definitely a selling point and a way to build trust with customers. We have customers that appreciate the fact that we are continually looking for ways to improve and advance our operations for their efficiency and reliability benefit. This definitely helps us sell ourselves as partners.
- Our electric motor repairs increased by 16% in the first year of the Program, while in previous years our electric motor repairs had shown single digit growth. Two significant new customers were attracted due in part to the Program which was a 'door opener'.
- Accreditation has helped us build trust with our customer base. In fact, the idea of a third party quality process audit, with specific expertise in both the mechanical and electrical components of the electric motor repair process, genuinely resonates with many of our important industrial customers.
- Accreditation has helped our company demonstrate evidence of our hard work and high standards. With these high standards our customers have gained access to motors that last longer, perform better, and that prove reliable following repair.

Question #3: Has the Accreditation Program provided any economic (e.g., increased business volume) or other benefits?

Service center responses:

- Economically, we have been successful in persuading several water agencies (who were not active customers) to adopt EASA Accreditation as a necessary qualification of repair bidders.
- We found that in a two year period the failure rate was 5% less on repair versus new product.
- We can supply customers with a proven quality repair with documentation and an equal or longer warranty period [than a new motor]; so a repaired product with good "bones" saves money and the environment by recycling.
- We have picked up some additional work outside of our normal service area because some users feel that if we are involved in "Doing The Job Right" and "Best Practices" that are part of the accreditation process, we have the skills and mind set to do their repairs correctly.
- During the first six months following accreditation, we were contacted by companies we had never done work for specifically stating that they needed to use an EASA accredited repair center for their motor evaluation.
- This process has been the single most important change in the history of our company. In only two years we couldn't have asked for a better return on investment.
- One of the main reasons we've stayed busy and profitable [in a weak economy] is due to the effort we've put into these programs to ensure that we're putting out high-quality work and are doing it efficiently.
- The reliability aspect of the Program has been the main driver and not the energy efficiency aspects, which was surprising given the current vogue. Training of staff in the repair and rewinding of electric motors has also been a benefit.
- We have seen an uptick in business from customers that have critical processes reliant on large and expensive electric motors. We expect that we will continue to

find ways to improve as we go forward and hope to see the Program be a phenomenal success for us, EASA, and industry.

- The benefit of accreditation to us is that it shows that we are committed to providing leading-edge solutions for our customers, and that we bring more to the table than our competition. It is important that we communicate the benefits of this achievement to our customers and vendors.

Success

Among the successes of the Accreditation Program was the number of service centers that applied and became accredited. Although there are other certification-style programs for electrical apparatus service centers, none of them have near the 98 active participants (July 2017) in their programs.

Indications of the success of the Program were evident in the survey responses from the accredited service centers. Some of the most common positive points reported by service centers were:

- Improved morale of service center employees
- Fewer warranty issues for service centers
- More satisfied and loyal customers
- Customers had greater confidence in the reliability of repaired motors
- Customers had greater trust and confidence in the service centers
- Service centers attracted new customers because of being accredited
- Accreditation served to differentiate service centers from their competition

Note that each of the bullet list responses to the 3 questions in the survey are statements attesting to the success of the Accreditation Program.

Conclusion

The Accreditation Program basic elements are good practices that provide objective evidence that efficiency and reliability are maintained (or sometimes improved) in repaired motors; including mechanical rebuilding as well as electrical rewinding. This paper has detailed the planning, implementation, and success of the EASA Accreditation Program and the positive impact it has had on accredited service centers and their customers. The journey for the Program from concept to reality was handled by an Ad Hoc committee over a 3 year period. The fact that the Checklist developed by the committee required few changes speaks to the diligence of the committee.

Objective evidence that the Program results in maintain efficiency is provided in Appendix B, which indicates that the overall average efficiency of 7 motors from Accredited service centers that have been tested was an incremental change of +0.04%. Not only has the Program resulted in maintaining energy efficiency of the repaired motors, it has also maintained or improved their reliability. Further, the Accredited service centers have seen measurable improvements in internal business operations, improved and stronger relations with customers, and economic benefits such as increased business revenue and reduced internal costs.

By the time this paper is presented, the Accreditation Program will be in its 4th year, with a number of 2nd cycle (3 years to a cycle) external audits having been completed. An update will be provided.

References

[1] *Recommended Practice for the Repair of Rotating Electrical Apparatus*. Electrical Apparatus Service Association. (EASA), ANSI/EASA AR100. 2015.

[2] *The Effect of Repair/Rewinding on Motor Efficiency*. Electrical Apparatus Service Association. 2003.

Appendix A: EASA/AEMT rewind study

A.1 Summary of results

The 22 motors in the study were broken into 5 groups to address different repair scenarios. The testing was performed at the University of Nottingham (UK). See Appendix A.2 for details regarding verification of accuracy of results.

The first group consisted of six motors rated 100 - 150 hp (75 - 112 kW) with no specific controls on the winding removal and rewind processes. Initial results indicated average efficiency change of -0.6% after 1 rewind (range -0.3 to -1.0%). However, it was found that two motors had been re-lubricated during assembly, which increased friction loss. After this issue was corrected the average efficiency change was -0.4% (range -0.3 to -0.5%).

The second group had ten motors rated 60 - 200 hp (45 - 150 kW) that were rewound once using controlled winding removal and rewind processes. The average efficiency change was -0.1% (range +0.2 to -0.7%). One motor was subsequently found to have faulty interlaminar insulation as supplied. Omitting the result from this motor the average efficiency change was -0.03% (range +0.2 to -0.2%).

The third group of five motors was rated 100 – 200 hp (75 – 150 kW) and rewound two or three times using controlled winding removal and rewind processes. The average efficiency change in this case was -0.1% (range +0.6 to -0.4%) after 2 rewinds of 2 motors and 3 rewinds of the other 3 motors.

The fourth group was two motors rated 7.5 hp (5.5 kW) that were processed through the burnoff oven three times, then the windings were removed and rewound once using controlled winding removal and rewind processes. The average efficiency change in this case was +0.5% (range +0.8 to +0.2%).

The fifth and final group was one motor rated 300 hp (225 kW) with formed coils that was rewound once using controlled winding removal and rewind processes. The efficiency change for this motor was -0.2%.

The overall average efficiency change of the 22 motors in the study was +0.08% (range +0.8 to -0.7%).

The primary conclusion from the study was that motor efficiency could be maintained provided repairers adhere to the good practices detailed in the rewind study.

A.2 Accuracy of test results

To ensure accurate tests results, a 30 kW (40 hp) IEC motor was efficiency tested first by the University of Nottingham and then by three other test facilities. The other facilities were: U.S. Electrical Motors, St. Louis, Missouri; Baldor Electric Co., Fort Smith, Arkansas; and Oregon State University, Corvallis, Oregon.

Each facility tested the motor at 50 and 60 Hz using the IEEE 112 Method B (IEEE 112B) test procedure. All testing used the loss-segregation method (at no load and full load), which allowed for detailed analysis.

As a benchmark, the results were compared with those of round robin test programs previously conducted by members of the National Electrical Manufacturers Association (NEMA). Initial results of NEMA's tests varied by 1.7 points of efficiency; the variance subsequently was reduced to 0.5 points of efficiency by standardizing test procedures.

The range of results for round robin tests of the 30 kW (40 hp) motor in this study did not exceed 0.9 points of efficiency at 60 Hz, and 0.5 points at 50 Hz. These results were achieved without standardization and compare favorably with the 1.7% variation of the NEMA tests.

These results also verify that the test protocol for determining the impact of rewinding on motor efficiency is in accord with approved industry practice, and that the results obtained in this study are not skewed by the method of evaluation.

Appendix B: Efficiency test results for service center repaired motors

Table B1 provides the full load (100% rated load) efficiency test results for seven motors that were rewound and repaired by service centers and tested for efficiency by a National Voluntary Laboratory Accreditation Program (NVLAP) certified (US) laboratory. The motors were tested by the laboratory prior to rewind and repair, and re-tested after rewind and repair, with repair good practices in accordance with the Accreditation Program. Note that most motors were rewound and repaired one time, and some were rewound and repaired up to 12 times.

Table B1: Motor full load efficiency test results

Motor designation	Power rating	# of times rewound	Full load efficiency % before rewind/repair	Full load efficiency % after rewind/repair	Full load efficiency % change
A	10	4	89.0	89.5	+0.5
B	10	5	90.9	91.1	+0.2
C	30	1	93.1	93.2	+0.1
D	40	1	94.8	94.8	0.0
E	40	1	94.0	93.6	-0.4
F	50	12	91.2	91.1	-0.1
G	250	1	94.3	94.3	0.0

The overall average efficiency change of the repaired motors was +0.04% (range +0.5 to -0.4%).

4E EMSA Policy Guidelines for Motor Driven Units: pumps, fans and compressors

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Abstract

The 4E Electric Motor Systems Annex (EMSA) Policy Guidelines for Motor Driven Units (MDUs) investigates policy options for harmonizing standards and regulations for MDUs, specifically for pumps, fans and compressors.

Motor systems are responsible for 53% of global electric energy consumption, or 10,700 TWh per year. Of this, energy use by pumps, fans and compressors account for around 70%. The study therefore focuses on pumps, fans and compressors. It covers the main global economies, accounting for 85% of global electricity use, including China, the European Union and the USA.

Part 1, published in October 2016, describes existing standards and regulations. Part 2, to be published in September 2017, will provide recommendations for advancing standards and regulations and their alignment.

Many regulations for MDU-components (like motors, pumps) build on international IEC and ISO standards to define testing methods and performance classifications. In some cases countries adopt these standards without change into national standards and legislation, in other cases countries make alterations depending on specific national circumstances.

Differences in product definitions within national Minimum Energy Performance Standards (MEPS) regulations hinder analyses and international comparisons of coverage, metrics and efficiency levels. In current MEPS the efficiency of the target application (e.g. pump, fan) is within the scope and is required to be measured. The other components, if present and if included in the scope, are in most cases either accounted for by default values and/or calculated values. This does not lead automatically to encouragement of the most efficient MDUs. Calculation and test methods show some small and other larger differences, including aspects like specification of load and other parameters.

This project investigates potentials for aligning product definitions, scope, testing methods and metrics for setting MEPS for pumps, fans and compressors. A uniform methodology can advance international comparisons of coverage, metrics and efficiency levels and reduce barriers to trade, enhancing international competition and higher efficiency of products.

4E EMSA

The IEA 4E Electric Motor Systems Annex (EMSA www.motorsystems.org) is a collaboration of six governments under the 4E Energy-Efficient End-Use Equipment (www.iea-4e.org) Technology Collaboration Programme of the International Energy Agency (IEA). The goal of EMSA is to help governments develop and implement policies for a successful market transformation towards more efficient electric motor systems. EMSA serves as a platform for policy and technical exchange.

EMSA promotes opportunities for energy efficiency in motor systems by disseminating best practice information worldwide since 2009. It supports the development of internationally aligned test standards and policies to improve the energy performance of new and existing motor systems.[41]

EMSA works on different levels to promote market transformation of motor systems:

- On a global level, for the international alignment of standards for testing and efficiency classification
- On a national level, for the development and implementation of successful policies
- On a company level, to promote energy audits and energy management that also encompasses motor systems
- On a personal level among professionals interested in issues around efficient electric motor systems, with a world-wide network of close to 5000 contacts in 75 countries.

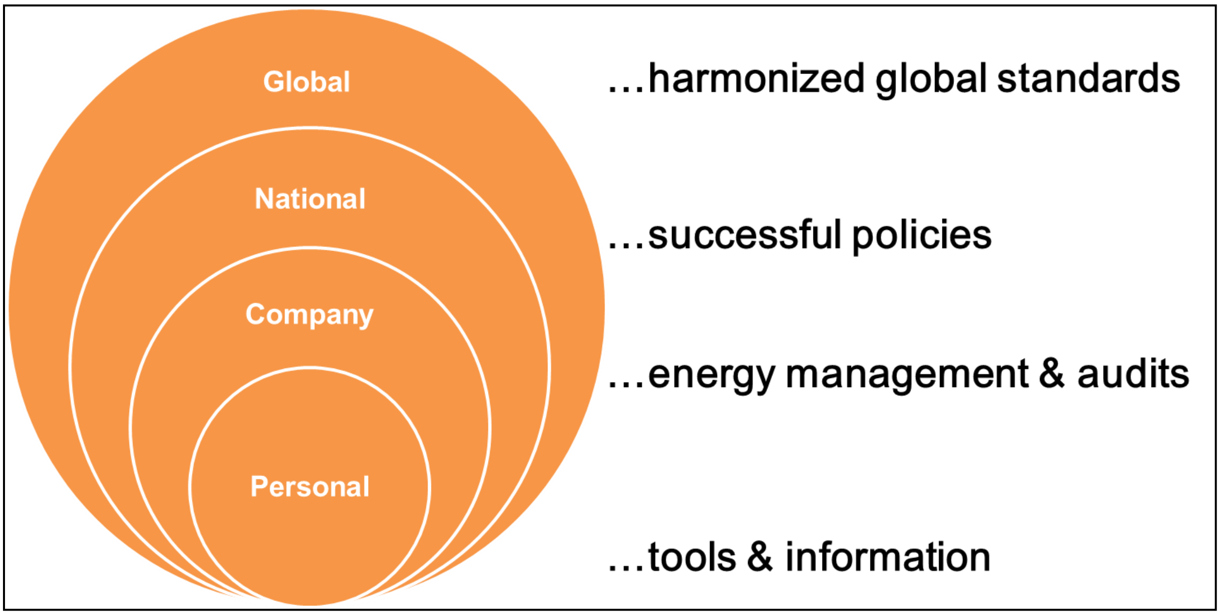

Figure 1 EMSA works on different levels to reach global market transformation of efficient electric motor systems

The 4E EMSA has published the following reports so far:

- EMSA Motor MEPS Guide (2009)
- EMSA Motor Policy Guide - Part 1: Assessment of Existing Policies (2011)
- EMSA Policy Guidelines for Electric Motor Systems - Part 2: Toolkit for Policy Makers (2014)
- 4E Energy efficiency roadmap for electric motors and motor systems (2015)
- 4E EMSA Policy Guidelines for Motor Driven Units - Part 1: Analysis of standards and regulations for pumps, fans and compressors (2016).

Policy Guidelines for Motor Driven Units

In 2015 4E assigned EMSA the project "Policy Guidelines for Motor Driven Units", to review opportunities for international alignment of standards and regulations concerning motor systems and system components. With this research 4E EMSA wants to:

[41] For an overview of EMSA's activities, see the EMSA Policy Brief: www.motorsystems.org/files/otherfiles/0000/0177/0_emsa_pb_20150917.pdf

- Understand the current status and differences in standards and MEPS concerning product definitions, scope, metrics and efficiency levels used
- Contribute to their future alignment
- Stimulate market development towards efficient motor driven units with well aligned international standards and advanced national performance requirements.

The project consists of two parts:

1. Part 1: Analysis of existing standards and regulations in important global economies
2. Part 2: Recommendations for advancing and aligning standards and regulations

Part 1 was published in October 2016 at the Motor Summit 2016 (www.motorsummit.ch) in Zurich. It contains a detailed description of existing standards and national regulations with MEPS for pumps, fans and compressors and summarizes their differences. Inputs were provided by experts within EMSA and 4E as well as external experts in the framework of a survey. The full report and an executive summary are available for download at: www.motorsystems.org.

Part 2 will be published in September 2017. The analysis will focus on opportunities for aligning and improving standards, serving as a common basis for regulations across the globe for efficient motor driven units. It will provide recommendations for advancing standards and regulations and their alignment. Special attention will be given to investigate energy efficiency principles that can be applied in one common methodology and metrics for the three major Motor Driven Units compressors, fans and pumps.

Part 1: Analysis of standards and regulations for pumps, fans and compressors

Part 1 of the 4E EMSA Policy Guidelines for Motor Driven Units (MDUs) describes existing standards and regulations.

As shown in **Figure 2**, a Motor Driven Unit converts electrical power into rotational mechanical power and may consist of the following individual components: variable frequency drive, electric motor, mechanical equipment (e.g. gear, belt, clutch, brake, throttle) and a driven application (e.g. pump, fan, compressor, transport).

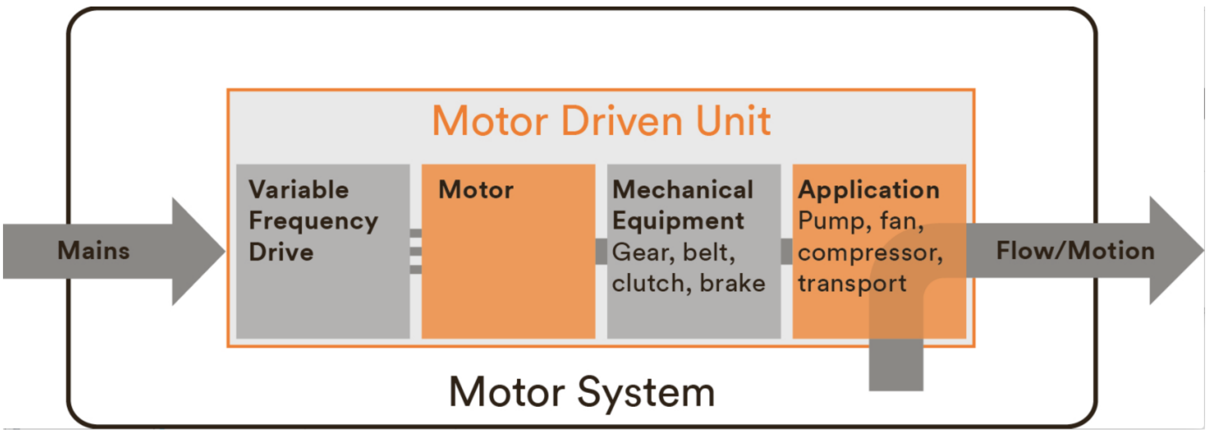

Figure 2 Motor Driven Unit definition (MDU). The orange boxes are components that are always part of a MDU.

Motor systems are responsible for 53% of global electric energy consumption, or 10,700 TWh per year. Of this, energy use by pumps, fans and compressors accounts for 70% (see **Figure 3**) [2]. This study therefore focuses on pumps, fans and compressors.

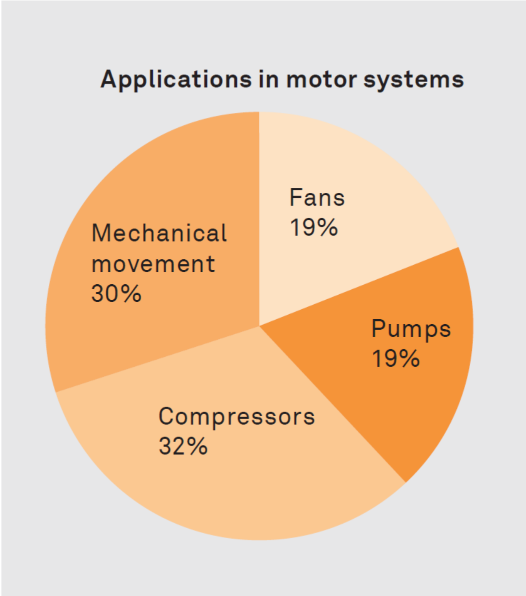

Figure 3 **Estimated share of global motor electricity demand by application [2]**

An optimised MDU with energy efficient individual components matched together to meet the required task and load is able to yield energy savings of 20% to 30%, estimated at up to 4,100 TWh per year globally in 2030 [1] [3].

Part 1 of the study covered the following main global economies, accounting for 85% of global electricity use: Australia, Brazil, Canada, China, European Union (EU28 plus Switzerland, Norway and Turkey), India, Japan, Korea, Mexico, New Zealand, Russia, Saudi Arabia, South Africa and USA (see **Figure 4**).

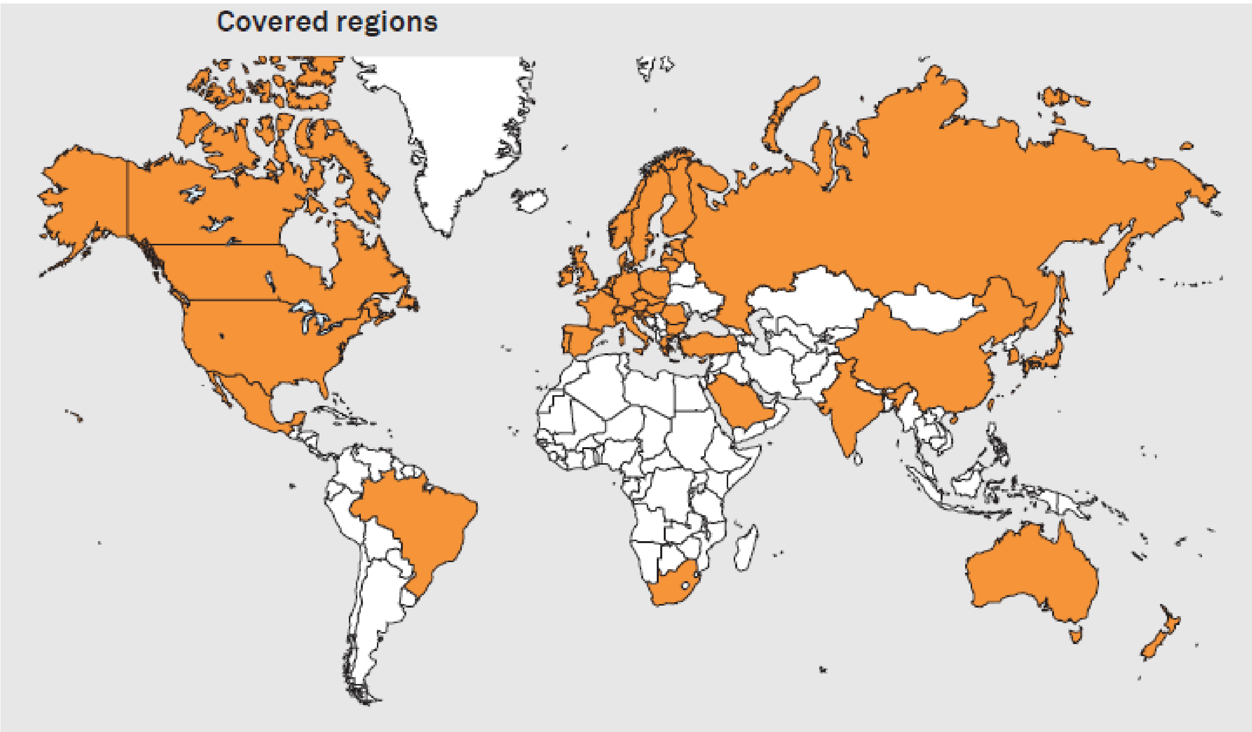

Figure 4 **Regions covered in Part 1 of the Policy Guidelines for Motor Driven Units**

The analysis shows that as of 2016 (see **Table 1**):

- 11 of the 14 countries studied have MEPS for motors. These countries account for 76% of the global electricity use of motor systems.
- 4 countries have MEPS for pumps, covering 60% of the global electricity use of motor systems.
- 3 countries have MEPS for fans, covering 43% of the global electricity use of motor systems.
- 1 country has MEPS for compressors, covering 28% of the global electricity use of motor systems.

Region (ranked by electricity use of motor systems)	MEPS: yes / no *)				Electricity use **)
	Motors	Pumps	Fans	Compressors	
China	y	y	y	y	28.3%
USA	y	y	(y)	(y)	15.6%
EU28 ***)	y	y	y	(y)	15.0%
India	n	n	n	n	5.0%
Japan	y	n	n	n	4.4%
Russia	n	n	n	n	4.1%
Korea	y	n	y+	n	2.7%
Brazil	y	n	n	n	2.5%
Canada	y	(y)	n	n	2.3%
Mexico	y	y	n	n	1.4%
South Africa	n	n	n	n	1.2%
Saudi Arabia	y	n	n	n	1.0%
Australia	y	(y*)	(y)	n	1.0%
New Zealand	y	n	n	n	0.2%
Electricity use (%) ****)	76%	60%	43%	28%	**85%**

Notes

) (y) = under development; (y) = swimming pool pumps; y+ = domestic small fans;

**) % of global electricity use of motor systems, based on total electricity consumption (IEA 2014) of each country and its 5 major sectors;

***) Including Norway, Switzerland and Turkey

****) % of global electricity use of motor systems in countries with MEPS, April 2016

Table 1 Overview of existing policies for MDUs with MEPS in main economic regions (Source: CLASP's Global S&L Database, April 2016; World Bank 2014; IEA 2014; Appendix II of the report)

Many regulations for MDU-components (like motors, pumps) build on international IEC and ISO standards (see **Table 2**) to define testing methods and performance classifications. In some cases countries adopt these standards without change into national standards, in other cases countries make alterations depending on specific national circumstances. International standards for complete MDUs are not as advanced as for MDU-components and the need for further work in this area is evident.

IEC-Standards		
Standard	Topic	Stage
IEC 60034-1:2010	Motor scope and tolerance	Published, revision pending 2017
IEC 60034-2-1:2014	Motor testing	Published
IEC TS 60034-2-3: 2013	Converter-fed motor testing	Published as Technical specification, revision pending
IEC 60034-30-1:2014	Efficiency classes for motors online (IE-code)	Published
IEC TS 60034-30-2	Efficiency classes for motors driven by converters	Draft Technical Specification (DTS)
IEC 61800-9-1	Efficiency classes and testing for converters and motors with converters and their driven applications	Final draft international standard (FDIS)
IEC 61800-9-2	Efficiency classes and testing for motors, converters and motor plus converters	Final draft international standard (FDIS)

ISO-Standards		
Standard	Topic	Stage
ISO 9906:2012	Rotodynamic pumps – Hydraulic performance acceptance tests – Grades 1, 2 and 3	Published
ISO 4409:2007	Pumps: Hydraulic fluid power – Positive-displacement pumps, motors and integral transmissions – Methods of testing and presenting basic steady state performance	Published
ISO 12759:2010	Fans – Efficiency classification for fans	Published, under revision
ISO 5801:2007	Industrial fans – Performance testing using standardized airways	Published
ISO 5802:2001	Industrial fans – Performance testing in situ	Published
ISO 16345:2014	Water-cooling towers – Testing and rating of thermal performance	Published
ISO 1217:2009	Displacement compressors – Acceptance tests	Published
ISO 5389:2005	Turbocompressors – Performance test code	Published
ISO 917:1989	Testing of refrigerant compressors	Published
ISO 11011:2013	Compressed air – Energy efficiency – Assessment	Published
ISO/ASME 14414: 2015	Pump system energy assessment	Published

Table 2 **Relevant IEC and ISO standards for Motor Driven Units**

Major findings of Part 1

- **Products**: the differences in product definitions and/or categorisation of products within national MEPS regulations hinder analyses and international comparisons of coverage, metrics and efficiency levels.
- **Scope**: in all MEPS the efficiency of the target application (e.g. pump, fan) is within the scope and is required to be measured. The other components, if present and if included in the scope, are in most cases either accounted for by default values and/or calculated values. This does not lead automatically to encouragement of the most efficient MDUs.

- **Metrics** and **methodology**: efficiency may be defined by "input/output" or through "efficiency-indices" relative to a reference MDU. Calculation and test methods show some small and other larger differences, including aspects like specification of load and other parameters.
- **International comparison** of the product efficiency levels within national MEPS of MDUs per country is very difficult, due to the different product parameters used.

Although regulators typically examine existing MEPS from other regions in the preparation of new or revised regulations, there appears no structured way of co-ordinating intelligence or closer alignment between regulators on aspects like product definitions and metrics.

For pumps, fans and compressors above 5 kW, many countries find it easier to define and implement individual component regulations. To develop and implement regulations for a MDU as a system consisting of several components is much more complex, and the enforcement of such regulations is also challenging.

Part 2: Potential alignment of standards and regulations

In Part 2 of the 4E EMSA Policy Guidelines for Motor Driven Units (MDUs), the study focuses on the three main economic regions China, EU and USA which have implemented or are in the process of establishing regulations for fans, pumps, compressors.

In the framework of three dedicated workshops held in February 2017 with technical experts from the EU, China and the USA, the following issues have been investigated in detail for each of the MDU type, see figure 5:

1. Product definitions and scope of regulations (Minimum Energy Performance Standards)
2. Testing standards
3. Metrics used

This includes an analysis of the actual used definitions in the regulations, the used definitions in the related standards if applicable, as well as the testing standards and the metrics. Differences are identified and an analysis will be made of the potential actions for alignment. As well as an assessment of the potential benefits, and actions needed to harvest these benefits. Finally the potentials for a more generic applicable metric will be investigated.

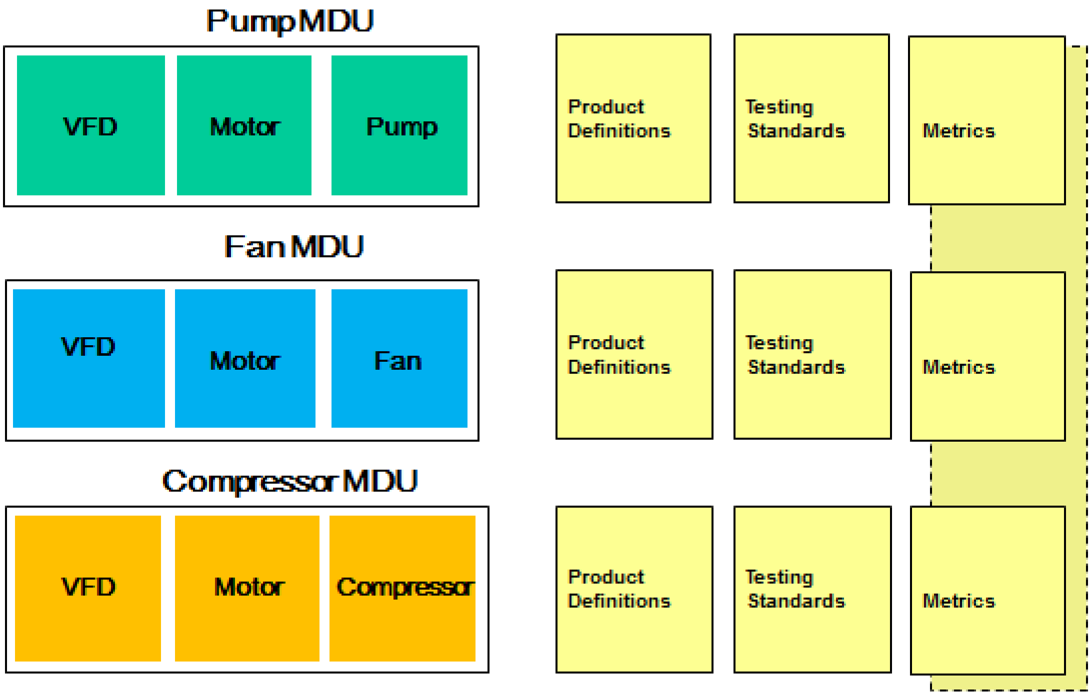

Figure 5 Methodology for seeking alignment of standards for pump, fan and compressor Motor Driven Units

The analysis is currently ongoing with the results and final publication expected for October 2017 [4]. At EEMODS 2017 the first results will be presented.

Acknowledgements

The authors would like to acknowledge all contributions by experts, regulators, industry representatives and other stakeholders to the project.

References

[1] Maarten van Werkhoven, Rita Werle, Conrad U. Brunner: 4E EMSA Policy Guidelines for Motor Driven Units - Part 1: Analysis of standards and regulations for pumps, fans and compressors, October 2016, available at: www.motorsystems.org.

[2] Paul Waide, Conrad U. Brunner et al.: Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems, International Energy Agency (IEA), Paris France, 2011. Updated global energy consumption data based on IEA statistics for 2014.

[3] IEA World Energy Outlook 2016, November 2016.

[4] Maarten van Werkhoven, Rita Werle, Conrad U. Brunner: 4E EMSA Policy Guidelines for Motor Driven Units - Part 2: Recommendations for further alignment of Standards and regulations for pumps, fans and compressors, to be published in October 2017.

Method for Assessing the U.S. Industrial and Commercial Motor System Markets

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Abstract

In 2015, the U.S. Department of Energy (U.S. DOE) initiated a Motor System Market Assessment (MSMA) of the current stock, electricity consumption, and cost-effective energy savings opportunity for motor systems in U.S. commercial building and industrial facilities. Led by Lawrence Berkeley National Laboratory (LBNL), the assessment is currently underway with field assessments being conducted at over 300 industrial and 150 commercial facilities across the U.S.

This paper will provide an update on the progress of the MSMA, focusing on the method for executing the field assessments. It will discuss the development of the statistical sample frame for ensuring a representative sample is conducted. This will include a review of U.S. industrial and commercial building energy consumption and facility characteristics underpinning the sample frame. The paper will also present the framework and questions for the field assessment. This will include a review of the tablet-based field assessment survey instrument being used to ensure consistency in the field assessments across all the facilities assessed. This paper will conclude with a summary of the planned data analysis and presentation, as well as expected next steps. This paper builds upon previous papers presented at EEMODS 2013 and 2015 and provides an update to the international motor system community on this significant undertaking in the U.S. It is hoped that by presenting the method at EEMODS, transparency in the MSMA methodology and process will aid other countries and regions seeking to conduct similar assessments.

Introduction

The development of advanced motor system technologies and the design of successful energy efficiency policies related to motor systems require information on the installed base of motor systems and their performance. But, collecting and analyzing information to estimate the installed base of motor systems and their performance relative to best technology and best maintenance practices requires considerable resources. As a result, there are limited assessments of this type available.

In the United States, the most cited assessment of industrial motor systems using field information was implemented by the U.S. Department of Energy (U.S. DOE) in 1995 as part of the then-U.S. DOE Motor Challenge Program. The results were published in 1998 and in a final report in 2002 in The United States Industrial Electric Motor Systems Market Opportunities Assessment[42] (2002 Assessment) and led to a greater understanding of motor system energy consumption and improvement opportunities, and also provided detailed, disaggregated information on these motor systems to government, manufacturers, and utilities [1].

For motors used in the commercial building sector, there is also a dearth of information. Primary research on the installed base of motors is even older than those for industrial motor systems. One of the more recent reports is from 1999, Opportunities for Energy Savings in the Residential and Commercial Sectors with High-Efficiency Electric Motors, and uses secondary sources to estimate the installed base [2]. Since these reports are

[42] Originally published in 1998, and republished in 2002 with minor corrections

the only U.S. national-level assessments of commercial motor systems, they remain influential despite being outdated.

These reports do not reflect the current industrial and/or commercial building motor system energy consumption or efficiency opportunity in the U.S. Moreover, both the industrial and commercial building sectors have changed substantially, as have motor system technologies. Many recent studies on motor system energy efficiency improvement potential have noted the lack of current and comprehensive information on motor system energy use and consumption as a limiting factor to their findings [3-5]. This lack of information affects a broad range of stakeholder groups in the U.S.:

- Component, motor, and motor driven equipment manufacturers do not have dependable information on markets
- Motor system users have no data to compare their systems against comparable systems
- Governments must rely on outdated information to target research and development opportunities and policy measures
- Energy efficiency program managers and electric utilities cannot accurately direct their programs

This information gap creates a barrier to the adoption of efficient motor system technologies and best practices in the U.S. To address these concerns, the U.S. DOE initiated a new Motor System Market Assessment (MSMA) in 2015, led by Lawrence Berkeley National Laboratory (LBNL). This paper overviews this MSMA and provides details on the study's objectives, scope, and methods. This new report will help all stakeholders, including motor systems component manufacturers, package equipment manufacturers, policymakers, and researchers better assess the installed base of motor systems, their energy consumption, and the opportunities for cost-effective energy efficiency improvement in the U.S.

Overview of US Motor System Market Assessment Update

Objectives:

The objectives for the two tasks of the MSMA are:

1. Motor System Field Assessments:
    - Develop a detailed profile of the stock of the motors and motor systems in commercial and industrial facilities in the U.S., including a profile of motor system purchase, maintenance, and operational practices
    - Analyze the opportunities (by various segments) for improved energy efficiency through implementation of efficient motors, control technologies, system optimization, and operation & maintenance practices
2. Supply Chain Assessment:
    - Evaluate the state of the global supply chain that supports motor and drive technologies

This paper will focus on the first task.

Scope and Method:

The MSMA will cover the following sectors within the U.S.:

- Manufacturing sector as categorized by the Manufacturing Energy Consumption Survey (MECS) and also the municipal wastewater treatment sector
- Commercial building sector as categorized by the U.S. DOE's Commercial Building Energy Consumption Survey 2003 (CBECS)

These sectors covered by the new MSMA are an expansion of the sectors covered by the 2002 Assessment, which did not include commercial buildings or municipal wastewater treatment.

Motor systems in the assessment will include those driven by polyphase motors 1 horsepower (0.746 kW) and greater regardless of end-use (e.g., compressed air, pumping, fan). Large (i.e., greater than 50 horsepower or 37.3 kW) motors observed of any type will also be included. The "motor system" includes the drive and controller, the motor, power transmission, motor driven equipment, and distribution system.

The MSMA was initiated in 2015 and the results are expected to be released by the end of 2018. Site visits for the Motor System Field Assessment task will be conducted primarily during 2017.

U.S. DOE **Interest**

The U.S. DOE Office of Energy Efficiency and Renewable Energy's Advanced Manufacturing Office is funding the update of the MSMA to increase awareness of motor system energy efficiency and cost saving opportunities through improved operation and maintenance practices and also advanced motor systems technologies. The U.S. DOE wants this report to identify research and development needs that will drive increases in motor system energy efficiencies, and enable a more competitive U.S. motor system manufacturing equipment industry.

The balance of this paper will outline the method for completing each of the objectives of the first task. This paper builds off past LBNL/DOE EEMODS papers in 2013 and 2015 [6, 7].

Sample survey:

The MSMA will rely on field assessments of a statistically representative sample of U.S. industrial and commercial building motor system energy consumption. Field assessments of industrial and commercial facilities will be conducted to determine the motor system energy consumption at the facilities and the results will be rolled up to the national level. The number of industrial and commercial facility field assessments is capped at 300 and 150, respectively. The allocation of field assessments within these caps was carefully chosen based on the estimated motor system energy consumption within each subsector. Within each subsector, field assessments are allocated based on facility size as estimated based on total number of employees for the industrial subsectors and square footage for the commercial building subsectors. While motor system energy consumption by facility size would be a better metric to allocate field assessments within each subsector, this information is unavailable. As a result, number of employees and square footage are being used as proxies for facility motor system energy consumption. Geographic location is also considered, but not as a primary strata. As much as possible, field assessments are allocated across the U.S. within each subsector to try and avoid any regional bias.

The industrial and commercial building sectors were categorized into subsectors such that they align with the categorization used by the U.S. DOE when gathering data for MECS and CBECS. MECS and CBECS are surveys conducted by the U.S. DOE every four years to estimate the energy consumption by subsector and end-use in the U.S. The data for MECS and CBES is collected through surveys completed by facilities. MECS and CBECS were chosen for the subsector categorization since they are also being used as the sample frame; high-level results from the MSMA will be compared to MECS and CBECS data to validate the accuracy of the MSMA findings. For both MECS and CBECES, the U.S. DOE follows the North American Industrial Classification System, commonly referred to as NAICS, for its subsector categorization. Table 7 and **Table 8** shows the categorization of the industrial and commercial building subsectors used in the MSMA based on MECS and CBECS categorizations. The municipal wastewater treatment sector is also being evaluated for the MSMA, but is not part of either MECS or CBECS. In total, 38 subsectors are being evaluated for the MSMA.

Table 7: Industrial subsector categorization used in MSMA (based on MECS)

Industrial		
Food Products	Printing and Related Support	Machinery
Beverage and Tobacco Products	Petroleum and Coal Products	Computer and Electronic Products
Textile Mills	Chemicals	Electrical Equipment and Appliances
Textile Product Mills	Plastic and Rubber Products	Transportation Equipment
Apparel	Nonmetallic Mineral Products	Furniture and Related Products
Leather and Allied Products	Primary Metals: iron, steel, ferroalloy	Miscellaneous
Wood Products	Primary Metals: other	Municipal Wastewater Treatment*
Paper and Allied Products	Fabricated Metal Products	

*Not part of MECS, but is being evaluated in the MSMA

Table 8: Commercial building subsector categorization used in MSMA (based on CBECS)

Commercial Building		
Education	Lodging (includes nursing)	Public Order and Safety
Food Sales	Mercantile: Retail (other than mall)	Religious Worship
Food Services	Mercantile: Enclosed and strip malls	Service
Health Care: Inpatient	Office	Warehouse and Storage
Health Care: Outpatient	Public Assembly	Other and Vacant

Motor system energy consumption was estimated for each subsector using MECS 2010 and CBECS 2003[43] data. MECS 2010 breaks out energy consumption by end use for each subsector. Although motor system energy consumption is not reported as an individual end use, it was assumed to be the sum of the following MECS' end use break-outs: process cooling and refrigeration, machine drive electric, and facility HVAC electric. Similarly, CBECS does not breakout motor system energy consumption as a separate end-use. It was assumed to be the sum of the following CBECS' end use breakouts: cooling, ventilation, refrigeration, and other. For the municipal wastewater treatment subsector, the estimate of motor system energy consumption was based on estimates from the Electric Power Research Institute of total electricity consumption [8]. It was assumed that approximately 67% of all electricity consumption for the subsector was for motor systems [9]. Field assessments were allocated among the subsectors based on the estimate of motor system energy consumption. When allocating field assessments, the industrial and commercial building sectors were considered separately, with municipal wastewater treatment considered as part of industrial. Also, the minimum number of samples for any subsector was forced to be 7. This was done to ensure that an accurate representation of each subsector is assessed. Finally, 9 assessments were left unassigned to any subsector to allow for flexibility in project execution.

Once the sample allocation by subsector was determined, the establishments within each subsector were broken down into three categories of size: small, medium, and large. For the industrial sector, these categories were defined based on the number of employees within each subsector as reported in U.S. County Business Patterns. For the commercial building sector, the categories were defined using CBECS data on square foot per establishment. The bounds for each category were defined individually for each subsector. The bounds were established such that each category would have 1/3 of the subsector's motor system energy consumption.

Figure 6 shows the number of field assessments for each industrial subsector, including municipal wastewater treatment. It also shows the break out of field assessments by size category. Figure 7 shows the number of field assessments for each commercial building subsector with the breakout of field assessments by size category as well.

[43] Since the development of the sample frame, the U.S. DOE has released CBECS 2012. This updated report will be used when validating the findings of the MSMA

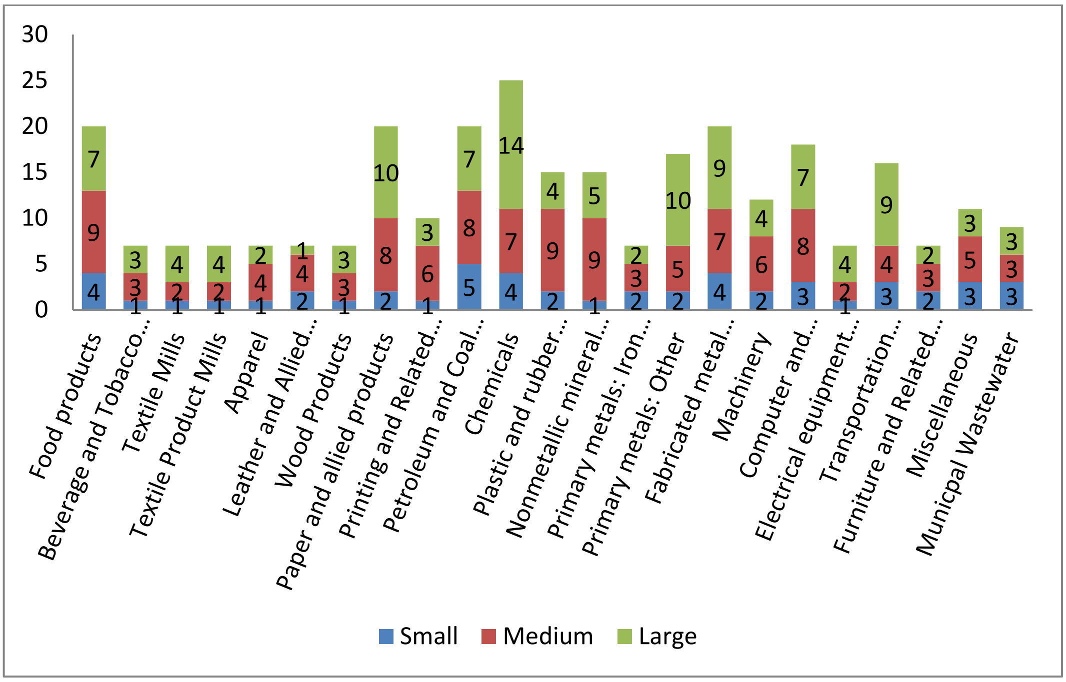

Figure 6: Field assessment allocation for each industrial subsector (including municipal wastewater) and breakout of field assessments by facility size based on number of employees

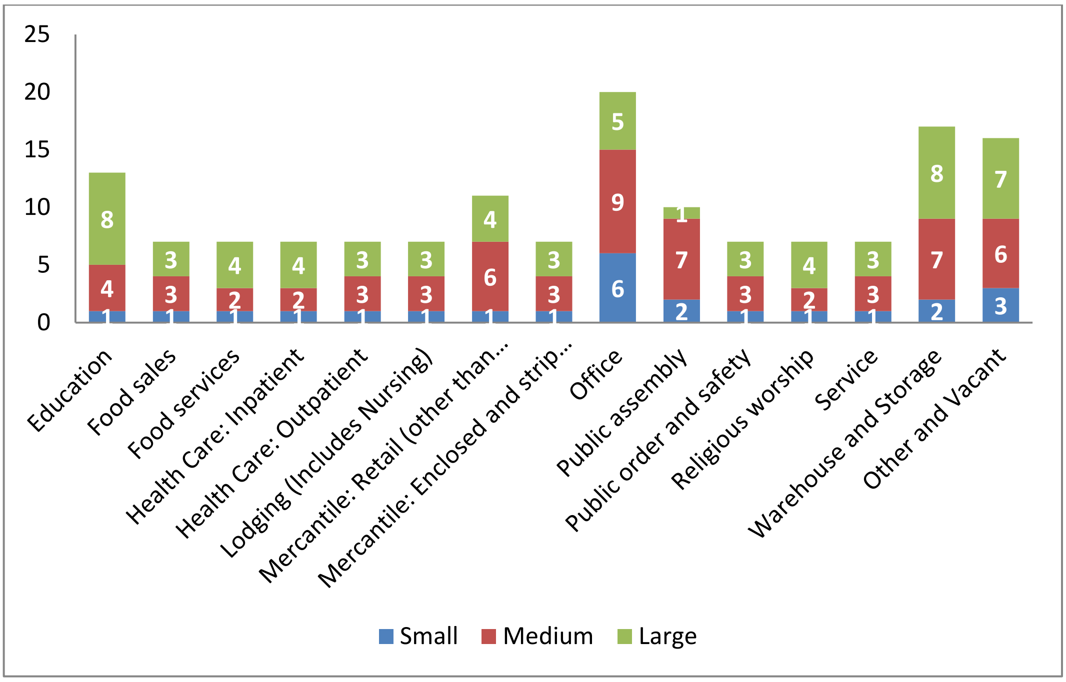

Figure 7: Field assessment allocation for the commercial subsectors and breakout of field assessments by facility size based on establishment square footage

Geographic location is used as an implicit stratum. An attempt will be made to spread the field assessments allocated within a subsector across four regions within the U.S.: the Northeast, Midwest, South, and West. The percent of field assessments to be conducted within any subsector and region is determined by the percent of motor system energy consumption for the subsector within that region compared to the total motor system energy consumption for the subsector. However, when allocating the field assessments for each subsector, preference will be given to ensure an accurate representation based on size over geographic region.

With the field assessment allocations determined, directories of industrial and commercial facilities in the U.S. were used to select potential facilities for recruitment. These directories include company/facility name, number of employees, and address. A list with ten times as many facilities needed to meet the MSMA caps was developed. The over-selection of facilities for recruitment is to accommodate an anticipated 10% recruitment success rate, i.e. 10% of facilities selected for a field assessment will agree to one. Facilities on the list will be contacted through utility or other program partnership connections (e.g. participation in a federal voluntary energy efficiency program such as the U.S. DOE's Better Building, Better Plants program). If no existing connection is available, the facilities will be contacted directly.

Field Assessment Plan:

The MSMA uses field assessments of U.S. industrial and commercial facilities to meet its objectives. The field assessment consists of three components:

1. An overall evaluation of how motor systems are managed across the facility, and basic information to characterize the facility's energy consumption.
2. An evaluation of general name plate information, purpose, and basic operational characteristics of all 3 phase AC and DC motors greater than 1 horsepower (0.746 kW).
3. For motor systems driven by a motor >20 horsepower (14.9 kW) and operating >2000 hours annually, a "checklist" of maintenance, load matching, and driven equipment information was developed to evaluate the potential for energy efficiency improvement.

The field assessments are conducted through a combination of onsite interviews and field observations. The field assessments are carried out using a tablet-based computer. Use of a common platform ensures consistency in the field assessments conducted across all facilities.

The field assessments are intended to be conducted in a day, with allowance for a second day for very large facilities (e.g., petroleum refineries, iron and steel mills). It is estimated that 100 motors can be evaluated by the field assessment team in a single day. For many commercial buildings and small to medium size industrial facilities, there will be less than 100 motors greater than 1 horsepower (0.746 kW) and all motors can be assessed in a single day. However, larger facilities will likely have more than 100 motors. In these cases, an onsite sample is developed based on electricity consumption. A general survey is conducted (usually through review of an equipment list or interview) to estimate the size (horsepower), operating hours, and process line/purpose for all motors. The overall motor system energy consumption is determined using this information and a facility-specific cap is set on the number of motors that can be assessed. Motors and associated systems are then selected to populate a representative sample of the facility's motor systems based on electricity consumption by size and process line/purpose.

The following sections will briefly outline the questions asked in each of the three field assessment components.

Facility-Level Evaluation:

The intent of the facility-level evaluation is to understand facility characteristics related to motor systems and motor system management and maintenance practices. This portion of the field assessment may be done offsite, before the site visit.

Facility characteristics assessed include description of facility output (if industrial), total revenue generated at the facility, square footage and number of buildings, total number of employees, and an estimate of the total number of 3 phase motors greater than 1 horsepower (0.746 kW) at the facility. This section of the field assessment will also evaluate facility-level energy consumption information, including total annual energy and electricity consumption and cost, peak electric demand, and facility power factor. The facility-level annual electricity consumption information is critical as it is used to:

- Validate the total estimated electricity consumption for motor systems at the facility
- Validate the use of employees to estimate facility size in the statistical sample development. If the size categories developed based on employees corresponds to a size categorization based on electricity consumption, then the use of employees to estimate facility size in terms of motor system energy consumption is validated. Otherwise, corrections can be made to the statistical roll-up of the results.

As part of the facility-level evaluation, motor system energy management practices will be reviewed to understand how motor purchases and energy efficiency improvement decisions are made at the facility. This includes identifying the person at the facility responsible for motor system efficiency and purchase decisions. An evaluation of basic energy management for motor systems is also made, including if energy efficiency is part of procurement and design of systems, how energy efficiency opportunities are identified, training on motor system efficiency, and use of energy efficiency/performance indicators for motor systems.

An evaluation of motor system maintenance practices is also included in the facility-level evaluation. It will seek to understand how the facility generally maintains its motor systems. The evaluation will review practices such as motor and equipment maintenance protocols, including how often motor systems fail at the facility, and motor repair/replace policies. The evaluation also seeks to understand motor and equipment maintenance history, including the percent of motors, pumps, fans, and compressed air systems undergoing routine maintenance procedures. These include rewind, bearing replacement, shaft alignment, and belt maintenance for motors; impeller, wear ring, mechanical seal, mechanical seal/packing, and/or bearing repair or replacement for pumps; lubricant replacement and filter replacement, air filter replacement, and condensate trap inspection for compressed air systems; and cleaning and bearing lubrication or replacement for fan systems. The motor system maintenance practices evaluation also seeks to evaluate the preventive maintenance procedures at the facility, including motor inspections, leak maintenance, and evaluations of the air and liquid distribution systems. It also seeks to assess the general condition of these distribution systems.

General Evaluation of Motors:

The intent of the general evaluation of motors in the field assessments is to enumerate and characterize motors one horsepower (0.746 kW) and greater in use at the facility and estimate their annual electricity consumption. Three basic categories of information are collected:

1) Motor nameplate information: The evaluation will collect as much nameplate information as possible. Recognizing that many nameplates are either inaccessible or illegible, essential information that must be determined includes motor manufacturer, size (horsepower), and some indicator of energy efficiency level. The latter may be determined through the identification of a NEMA efficiency label or by estimation based on size and age.
2) Purpose: The evaluation will seek to determine the purpose of the motor. The end use equipment, its size, and associated process will be identified. Also, the annual operating hours and load will be estimated.

3) Load matching: The evaluation will seek to determine how the motor matches load. It will seek to determine if the load varies, and to what extent (i.e., how often does it operate under certain load factors). For varying loads, the evaluation will understand how the motor system matches load. This includes assessing if the motor system uses a VFD, throttle, bypass, multiple motors, dampers, or some other load control technology.

Motor System Checklists:

For pump, fan, compressed air, and refrigeration systems driven by a motor greater than 20 horsepower (14.9 kW), checklists developed for the MSMA to better assess the current energy efficiency level are used. These checklists will be used to categorize the system based on its opportunity for energy efficiency improvement.

The size cut off of 20 horsepower (14.9 kW) was selected using the results from the 2002 Assessment. The 2002 Assessment documented the number of motors, operating hours, and energy consumption for motors by size range. In the current MSMA, a target was set to evaluate at least 80% of motor system energy consumption through the checklists. With this target and the information from the 2002 Assessment, it was determined that motor systems driven by motors greater than 20 horsepower (14.9 kW) comprised 85% of the total industrial motor system energy consumption. Therefore, this cutoff was selected. It requires an evaluation of 15% of the industrial motor population by motor count. For consistency, the same cutoff was used for the commercial building sector.

The checklists for pumps and fans are similar. They both review the nameplate information of the fan/pump, where possible, and the purpose of the fan/pump. They both seek to better understand load control, by assessing if the fan/pump is operating alongside another fan/pump, the position of any valves, throttles or dampers, and if the load is monitored. Finally, maintenance and energy efficiency awareness are also evaluated. The maintenance history is evaluated, along with the considerations used to select the fan/pump.

The compressed air checklist is different than the fan/pump checklist in that it is conducted on the entire compressed air system, whereas the fan/pump checklist is conducted on individual fans/pumps. Nameplate information is collected for each compressor that is part of the compressed air system. The air intake is evaluated, including use of colder air when possible and use of filters. The other components of the compressed air system are also documented including receiving tanks, dryers, and pressure controllers. Load/pressure is evaluated including typical loads, load matching capabilities (including ability to match outlier loads), and load reduction capabilities. The compressed air demand is evaluated, including identifying the end-use purpose and requirements and opportunities to reduce end use demand through actions such as leak maintenance and reducing pressure requirements. Finally, the compressed air checklist assesses maintenance procedures, including excessive pressure drops, meeting manufacturers' requirements for maintenance, conducting energy efficiency assessments, and implementation of a preventative maintenance program.

Similar to the compressed air checklist, the refrigeration system checklist is conducted on a whole chiller system. The checklist determines the nameplate information for all chillers in the system. It seeks to determine the system efficiency by evaluating the cooling end-use, operating parameters (e.g., flow, supply/return temperature, set points), refrigerant type, evaporator system, and heat rejection method. It seeks to evaluate the control system by determining characteristics such as the approach temperature, sequencing strategy, discharge/suction pressure and whether this is allowed to float, and the inclusion of various energy efficiency components such as VFDs and active defrost management. Finally, the checklist evaluates the maintenance practices on the system including adjusting the control strategy and set-points, inspection of components, and use of a preventative maintenance program.

The field assessments were piloted at a sample of 11 industrial and commercial facilities in 2016. The experiences from these pilots drove improvements to the field assessment procedures. Initially, onsite measurements of voltage and current for several motor systems were included. The purpose was to determine the load on the motor systems, as well as line imbalance and power factor. However, the process of measuring voltage and current proved to be very time consuming due in large part to adorning the required safety equipment. Further, many electrical lines are inaccessible, require significant effort to access, or are too large/immobile for a current transducer. Moreover, the resulting information was not very reliable. The measured load factor was only for a snapshot in time and not necessarily representative of the annual load factor. It was determined that the time required to take measurements would be better used collecting basic motor system information from more motors. Therefore, the field assessments do not include current and voltage measurements. Other improvements to the field assessment included reducing the number of questions to which the facility staff routinely did not have answers, in particular specific maintenance questions. Also, the ability to duplicate information for identical motor systems was built into the field assessment tool.

Desired Analysis Results

The information collected through the field assessments will be analyzed to develop national, sector, and subsector findings on motor system energy consumption, opportunity for energy efficiency improvement, and energy-related motor system operational characteristics. The results will be published in a report, expected to be released in 2018. The analysis will seek to inform the following overarching objectives:

1) Summary of the installed motor system base in the U.S. commercial building and industrial sectors, providing insight into installed motor system identifying information and overall energy consumption
2) Characterize energy management practices in U.S. industrial and commercial facilities, including but not limited to design, operations, and maintenance of the installed motor and motor system base
3) Assessment of the practical energy efficiency and electric demand potential utilizing existing and advanced technologies and practices and their potential impacts on production
4) Comparison of the current installed motor system base to the results of the 2002 Assessment

The results will be divided into key and detailed findings. See Rao et al (2015) for a summary of these [7].

To meet these desired assessment outcomes, analysis of the field assessment results will be made on an ongoing basis. A pause in the field assessments will occur once 10% are completed. This will offer the opportunity to develop preliminary findings. This may lead to additional changes to the field assessment plan. These changes may be to improve the field assessment plan to ensure the determination of the desired results can be stated with statistical certainty (i.e., within a specified confidence interval), eliminate field assessment questions that are not providing useful information, or further investigate preliminary results that were unforeseen during the MSMA planning.

Conclusion

This paper overviewed the U.S. DOE-initiated and LBNL-led MSMA that is currently developing a detailed profile of motor system energy consumption, operational and maintenance practices, and potential for energy efficiency improvement for the U.S. industrial and commercial building sector. By sampling facilities, the MSMA provides a much needed comprehensive assessment of motor system use in the U.S. The results will remove the current knowledge gap that has hampered policymakers, manufacturers, and researchers seeking to improve the energy efficiency of the motor systems in the U.S. industrial and commercial building sectors.

Through providing insight into the current state of motor system energy use and consumption in the U.S., it is hoped that the MSMA will lead to greater and sustained penetration of operational and maintenance best practices and the adoption of advanced technologies for commercial and industrial motor systems, saving substantial amount of energy and costs, and improving reliability. Further, the MSMA will build upon the success of the 2002 Assessment by identifying areas of potential improvement for U.S. motor systems, and hopefully spurring the motor system community to research, develop, and deploy new technologies, practices, and policies to meet the today's motor system challenges. Benefits derived from MSMA may also serve as a motivating factor for other countries to initiate similar motor system assessments. Others countries may benefit from leveraging both the approach and the lessons learned from MSMA. The results from the MSMA can be combined with the results of other motor system assessments, allowing for greater knowledge sharing and benchmarking of motor system energy efficiency and opportunity worldwide.

Acknowledgment

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References

[1] USDOE (United States Department of Energy). 2002. *United States Industrial Electric Motor Systems Market Opportunities Assessment.*

[2] ADL (Arthur D. Little, Inc.). 1999. *Opportunities for Energy Savings in the Residential and Commercial Sectors with High Efficiency Electric Motors*. Prepared for: United States Department of Energy.

[3] IEA (International Energy Agency). 2007. *Tracking Industrial Energy Efficiency and CO2 Emissions.*

[4] IEA (International Energy Agency). 2011. *Energy Efficiency Policy Opportunities for Electric Motor-Driven Systems.*

[5] McKane, A. and A. Hasanbeigi. 2010. Motor System Efficiency Supply Curves. United Nations Industrial Development Organization (UNIDO).

[6] Rao, P., A. Hasanbeigi, and A. McKane. 2013. "A Framework to Survey the Energy Efficiency of Installed Motor Systems." In *Proceedings of the 8th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS), Rio de Janeiro, Brazil, October, 2013.*

[7] Rao, P., Sheaffer, P., McKane, A., and Paul Scheihing. 2015. "Assessing Energy Efficiency Opportunities in US Industrial and Commercial Building Motor Systems", *Energy Efficiency in Motor Driven Systems 2015,* Helsinki, Finland. September.

[8] EPRI (Electric Power Research Institute). 2013. *Electricity Use and Management in the Municpal Water Supply and Wastewater Industries*. EPRI, Palo Alto, CA.

[9] Aghajanzadeh, A., Wray, C., and A. McKane. 2015. *Opportunities for Automated Demand Response in California Wastewater Treatment Facilities.* Lawrence Berkeley National Laboratory, Berkeley, CA.

Historical evaluation of performance of induction motors sold in Brazil between 1980 and 2016

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Abstract

The three-phase induction motor was the main element of increased productivity in the second industrial revolution in the late 19th century in Europe and the United States. Currently it is the main load in the world's electrical systems, reaching up to 65% of the demand, as in the case of Brazil. The minimum energy performance standard for three-phase electric induction motors with rotor in a squirrel cage was established in Presidential Decree No. 4508 of 2002, and later in Ministerial Directive No. 553 of 2005. This decree may be considered the first national document on the establishment of a minimum energy performance standard for electric motors sold in Brazil. This study aims to analyze the performance of electric motors manufactured in and imported to Brazil between 1980 and 2016.

The study evaluates the changes in performance that occurred in electric motors after the implementation of Ministerial Directive No. 553 of 2005 showing that the legislation resulted in significant positive impacts. More than 500 engines with nominal frequency of 60 Hz and nominal power between 1 and 250 HP were analyzed. In the analyzed period between 1980 and 2016, the electric motors of 5 HP accumulated average gains of 9.9%. As for 200 HP motors, the accumulated average performance increased 3.1%. The data was collected in the Laboratory of Electrical Machines at the Institute of Energy and Environment, University of Sao Paulo.

The energy context

Global and national energy scenario

In the last decades of the 20th century, population growth accelerated sharply. According to United Nations – UN prospects, the world population reached 7.349 billion people in 2015, and is projected to reach 11.2 billion in 2100 [1]. In the 1970s, the period of the first major oil shock [2], the world population was approximately 3.6 billion 2100 [1], which means that the world's population had doubled in 45 years. As shown in figure 1, energy consumption also increased, however, well above the increase in population. Between 1973 and 2014 the world's electric energy consumption deriving from various primary sources increased by 388% according to The International Energy Agency [3].

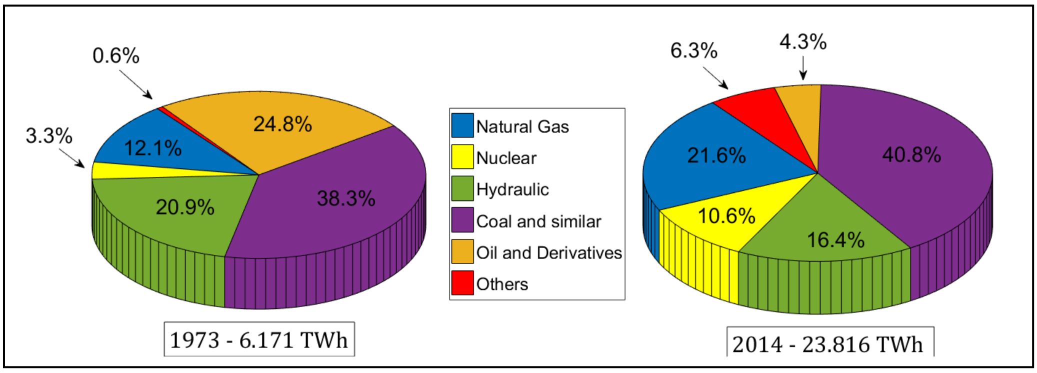

Figure 1– Primary energy sources for conversion to electricity, 1973 vs. 2014

The distribution of energy demand among the primary sources presented in figure 1 shows that the use of renewable energy sources, such as hydroelectric, has a percentage growth, however it is smaller than the growth of fossil and nuclear energy around the world. Coal continues to be the principal primary source of electric power in the world.

With the advent of the industrial revolution, mankind's energy consumption in the last two centuries has been intensive, sponsoring large gains in productivity worldwide, especially in countries with a strong industrial share of gross domestic product.

In the last two decades of the last century, a growing demand for energy has placed the change of conduct on the agenda, both in public policies as well as in the degree of awareness and demand of the organized population. In the field of public policies an intense discussion has begun, that development can be more sustainable and the energy sector is at the center of the discussion.

The electric energy sector is a participant in this process, mainly due to the negative effects on the environment and the population close to the enterprises, caused by large projects. In view of the above context, it has become attractive to research and implement ways of performing the same work with lower energy consumption. According to the Washington Energy Policy [4], "Energy Efficiency" is nothing more than the ability to use a smaller amount of energy to produce the same amount of illumination, heating, movement and other energy-based services.

Increasingly, energy efficiency has become a point of reference in discussions of energy production and demand, both at national and global levels, and today it has a central role in environmental policies, focusing on combating climate change, as the reduction of energy demand through energy savings. It is considered that energy efficiency points to a horizon of economic growth, reducing the need for large scale energy projects.

In order to reduce demand and consumption of electricity, it is necessary to identify and quantify the end-use of electricity in the current social organization segments as well as major electrical loads.

The end-use of electricity in Brazil

The end-use of energy in Brazil offers a wide range of possibilities due to the great diversity of need. Usually the processes demand: heating, cooling, movement, pressure, force and illumination among others. As shown in Figure 2, the Brazilian energy matrix is highly diversified.

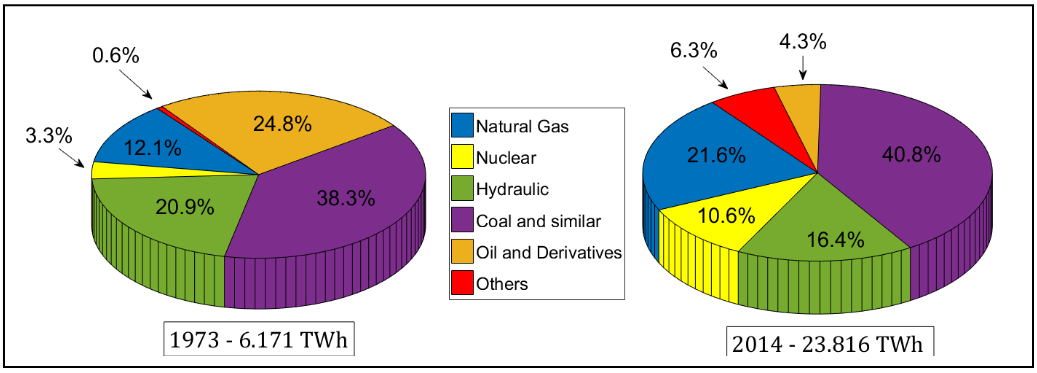

Figure 2 – Source of energy consumed in Brazil in 2015 in percentage

As the objective of this study is related to the performance of electric motors, it is important to stratify the energy consumption available in the form of electricity among the economic segments. Thus, according to Brazilian Energy Research Company - EPE [5], and as shown in Figure 3, electricity in Brazil is consumed predominantly in the industrial sector, which demonstrates the economic maturity of this sector.

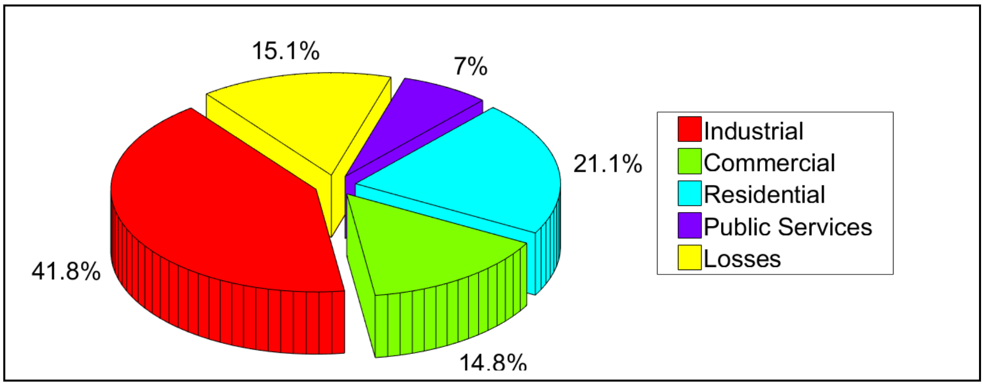

Figure 3[44] – Estimated representation of electricity consumption by sectors of the economy

Within all segments, there are predominant electric loads, those most commonly found being due to classical human needs as well as the needs of current production systems. In this perspective, we observe that motors are predominant as electric loads, directly corresponding to 46% of the average of electric loads in the world. It is also important to note that in electronic equipment there are also small electric motors for cooling and other functions. Within the 19% share of heat production are also heat pumps that are electrical motors, which proves the importance of electric motors for the production systems and for this organization of human life.

[44] In the industrial sector the transport and agriculture sectors and the energy sector's internal consumption are also included.

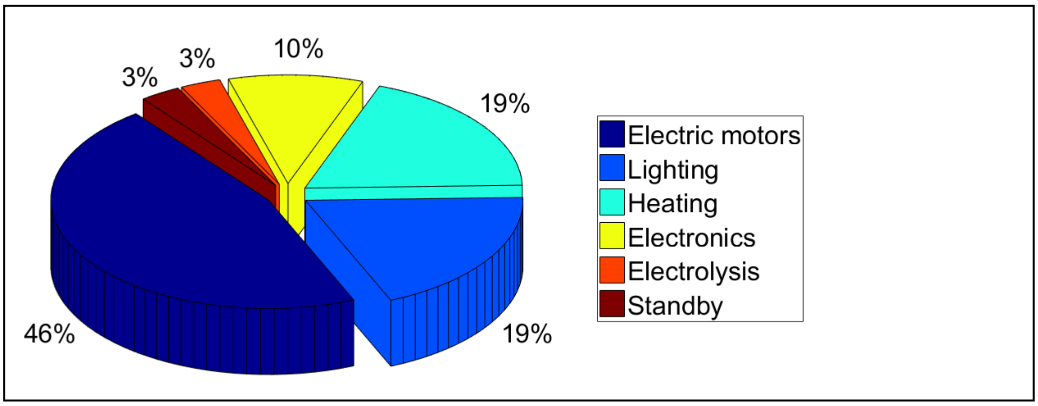

Figure 4 – Estimated share of electricity consumed by end-use in the world

The residential demand share represents 21% of the total consumption of the Brazilian electric system as shown in Figure 3. The most common types of end-use in Brazilian households are diverse and Figure 5 shows the household appliance demand stratified by end-use equipment.

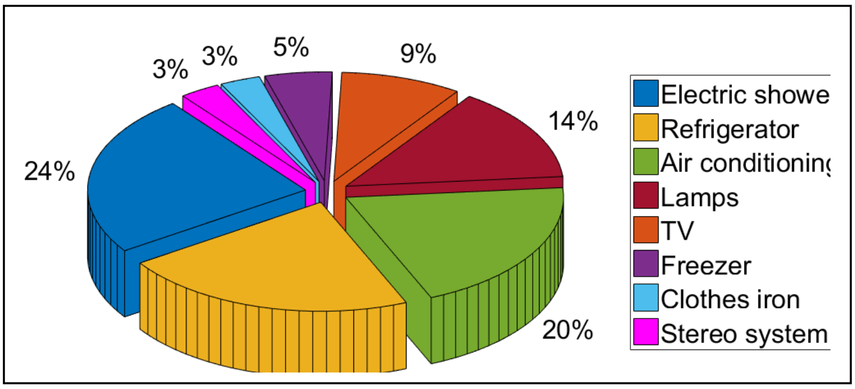

Figure 5 - Share of household appliances in the average residential consumption

It is possible to rearrange the presumed average Brazilian residential consumption in categories of end-use. Considering the use of TV's and sound equipment, as well as computers and others in the category of electronic equipment. Showers, irons, microwaves, electric ovens and etc., are heat production equipment. Consumption by light bulbs is classified as illumination. Consumption by refrigerators, freezers, environmental conditioning (in Brazil - air conditioner to remove heat), fans, washing machines, for example, are loads that operate with electric motors.

With these concepts and data from [6], Figure 6 was constructed, demonstrating that the predominance in residential consumption also is from electric motors, internally in household appliances.

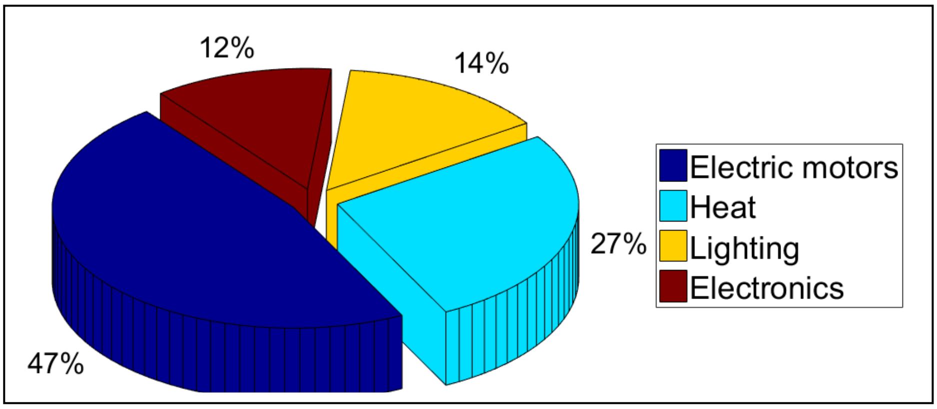

Figure 6 - Household participation in average residential consumption

On the average, the end-use of electricity in commercial and public buildings in Brazil occurs in a very similar distribution. In this way, the chart labeled Figure 7 was constructed. Where it is possible to observe the predominance of electric motors in air conditioners. This is due to the temperate climate and temperatures above 25º Celsius for most of the year.

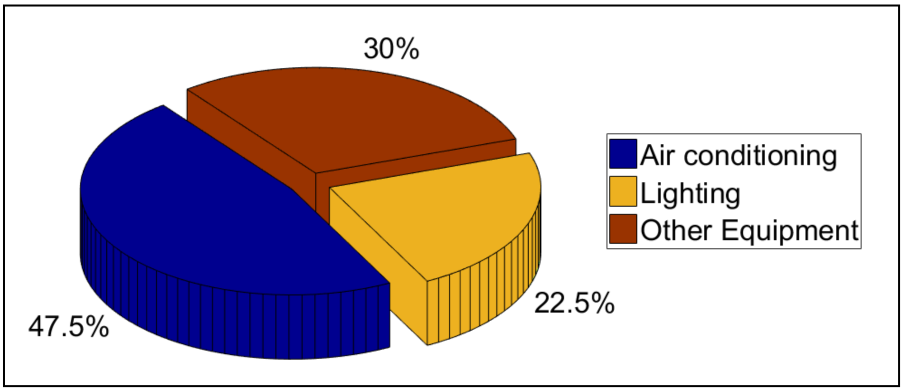

Figure 7 - Types of electricity end-use consumption in commercial and public buildings

In the Brazilian industrial sector, the average percentage of electricity consumed in relation to other sources is 17.2% [5]. Within the consumption of electricity in factories, Figure 8 shows the stratification of the four main possibilities of end-use of electricity in industries.

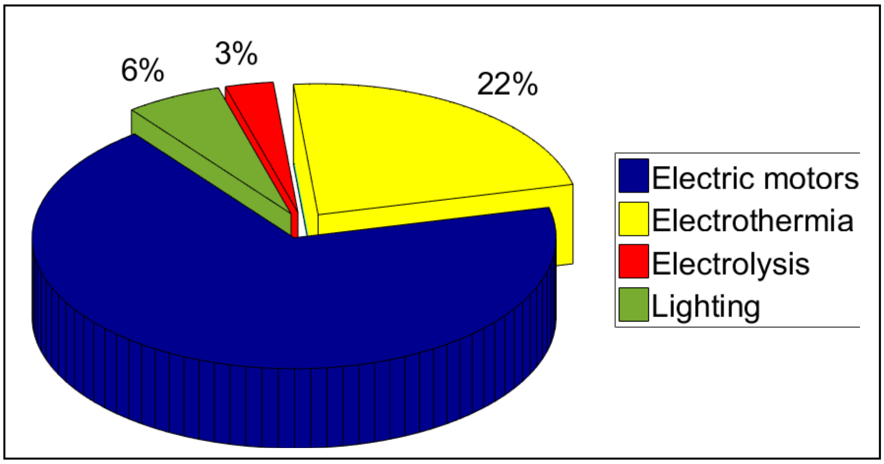

Figure 8 - Types of end-use of electricity in industrial consumption

In Figure 8 it is possible to observe the absolute predominance of electric motors in the Brazilian industrial percentage consumption, representing 68% of the electricity consumed by Brazilian companies. For this reason, specific legislation is needed to establish minimum performance for electric motors sold in Brazil.

Brazilian legislation

In the early 1980s, feeling the consequences of the global oil crisis. The Brazilian government initiated the first initiatives with the end-use of electricity. In 1985, the National Program for the Conservation of Electric Energy – PROCEL was installed. The first version is basically domestic instructions for rational use of electricity, avoiding waste [6].

In 1992 discussions about labeling electrical equipment began. In 1993, the PROCEL Seal was created, where manufacturers of electric motors voluntarily register with the program's secretariat, which is directly linked to ELETROBRAS - Brazilian Electric Utilities Company. The registration of electric three-phase induction motors with rotor in squirrel cage started in 1997.

In 2001, Brazil suffers with rationing of electricity and, in parallel, global discussions about the energy sector's importance for the reduction of greenhouse gases are advancing. Given this scenario, law 10295 which is known as the Energy Efficiency Law, was passed in October 2001. This law established that specific minimum performance regulations for end-use equipment must be created, aiming at reducing energy consumption and preserving the environment [7].

On December 11, 2002, Decree No. 4508 was published which establishes minimum levels of performance for three phase induction electric motors commercialized in Brazil [8]. The decree was elaborated with focus on the electric motors most commercially available in the market. They are: three-phase induction electric motors, industrial frequency 60 Hz or 50 Hz for 60 Hz operation, squirrel cage rotor, for voltage of up to 600 volts, having a rotation of 2, 4, 6 and 8 Poles, having shaft power between 1 HP and 250 HP, produced for continuous operation.

Decree 4508 created two categories of motors separated by performance. Conventional motors and high performance motors with slightly higher performance. Conventional motors are equivalent to category IE1 and high performance motors are equivalent to category IE2 internationally. Table 1 shows the minimum performance levels for the motor to be commercialized and also shows the level of performance that the motor needs to present to be characterized as high performance.

Table 1 - Minimum performance (%) as presented in Decree 4508

		STANDARD Poles				**HIGH PERFORMANCE Poles**			
HP	**kW**	**2**	**4**	**6**	**8**	**2**	**4**	**6**	**8**
1,0	0,75	77,0	78,0	73,0	66,0	80,0	80,5	80,0	70,0
1,5	1,1	78,5	79,0	75,0	73,5	82,5	81,5	77,0	77,0
2,0	1,5	81,0	81,5	77,0	77,0	83,5	84,0	83,0	82,5
3,0	2,2	81,5	83,0	78,5	78,0	85,0	85,0	83,0	84,0

4,0	3,0	82,5	83,0	81,0	79,0	85,0	86,0	85,0	84,5
5,0	3,7	84,5	85,0	83,5	80,0	87,5	87,5	87,5	85,5
6,0	4,5	85,0	85,5	84,0	82,0	88,0	88,5	87,5	85,5
7,5	5,5	86,0	87,0	85,0	84,0	88,5	89,5	88,0	85,5
10	7,5	87,5	87,5	86,0	85,0	89,5	89,5	88,5	88,5
12,5	9,2	87,5	87,5	87,5	86,0	89,5	90,0	88,5	88,5
15	11	87,5	88,5	89,0	87,5	90,2	91,0	90,2	88,5
20	15	88,5	89,5	89,5	88,5	90,2	91,0	90,2	89,5
25	18,5	89,5	90,5	90,2	88,5	91,0	92,4	91,7	89,5
30	22	89,5	91,0	91,0	90,2	91,0	92,4	91,7	91,0
40	30	90,2	91,7	91,7	90,2	91,7	93,0	93,0	91,0
50	37	91,5	92,4	91,7	91,0	92,4	93,0	93,0	91,7
60	45	91,7	93,0	91,7	91,0	93,0	93,6	93,6	91,7
75	55	92,4	93,0	92,1	91,5	93,0	94,1	93,6	93,0
100	75	93,0	93,2	93,0	92,0	93,6	94,5	94,1	93,0
125	90	93,0	93,2	93,0	92,5	94,5	94,5	94,1	93,6
150	110	93,0	93,5	94,1	92,5	94,5	95,0	95,0	93,6
175	132	93,5	94,1	94,1		94,7	95,0	95,0	
200	150	94,1	94,5	94,1		95,0	95,0	95,0	
250	185	94,1	94,5			95,4	95,0		

Decree 4508/2002 established February 28, 2003 as the cut-off date for sale of electric motors outside the minimum performance levels.

On December 8, 2005, the federal government of Brazil published Administrative Rule 553 establishing as minimum performance level the values indicated in the column "high performance" in table 1. Electric motors that do not meet the minimum level set in Decree 4058/2002 as “high performance motors” can, since 2009, no longer be sold in Brazil [9].

On September 4, 2009, the National Institute of Metrology, Standardization and Industrial Quality - INMETRO, published Ministerial Directive No. 243, which presents the mandatory requirements for the conformity assessment of three-phase induction electric motors, standardizing the national methodology for performance evaluation [10]. On December 08, 2010, INMETRO published Ministerial Directive No. 488, replacing 243. As of Ministerial Directive No. 243/2009 labeling of the aforementioned motors became mandatory [11].

There are three laboratories in Brazil that are accredited by INMETRO for elaborating performance evaluation of electric motors. The Electric Energy Research Center - CEPEL, located in the state of Rio de Janeiro and maintained by ELETROBRAS, the Electric Machines Laboratory at the Pontifical Catholic University - PUC, located in the state of Rio Grande Sul, known as LABELO and the Laboratory of Electric Machines at the IEE/USP - Institute of Energy and Environment of the University of Sao Paulo, being the first laboratory to perform this type of test.

INMETRO periodically carries out audits in the accredited laboratories, aiming to guarantee the quality of the result of the measurements. INMETRO is a member of the International Laboratory Accreditation Cooperation (ILAC), thus following worldwide standards of quality and reliability.

Institute of energy and environment

The IEE/USP - Institute of Energy and Environment was founded in 1902 under the name of the Office of Industrial Physics and Electrotechnics of the State of Sao Paulo. The purpose of the institution was to support a thriving national industry that expanded following the development policies of the time. The laboratory also acted as a school for the practical classes of the students at the Polytechnic School of Engineering in Sao Paulo.

In 1926 the laboratory was renamed Laboratory of Machines and Electrotechnics, being the first official Brazilian laboratory of standardization and equipment qualification tests, the objective being to serve the growing national industry. In 1931, it was renamed the Laboratory of Electrotechnics and its activities were eminently focused on providing services.

In response to the difficulties of importing equipment during World War II (1939-1945) and the consequent demand for the development of a national industry, in 1940, it became part of the structure of the Polytechnic School at the University of Sao Paulo, again changing its name to Institute of Electrotechnics (IE). In 1942 the first technical reports of tests of electric motors were realized, where quantities such as torque, performance and power factor were analyzed.

In the 1980s, Brazil was affected by the oil crises of the 1970s and the institute began to have concerns about the multidisciplinary field of energy, changing the name again, going through this new period being called the Institute of Electrotechnics and Energy, known nationally by the acronym (IEE).

In 2013, the IEE was renamed the Institute of Energy and Environment, keeping the acronym (IEE) where energy issues are discussed also with an eye to environmental issue.

Currently (2017), the Institute of Energy and Environment has already issued more than 80,000 technical reports since its foundation, of which approximately 21 thousand were electric motors. Thus being the institution that has been following the evolution of motors in Brazil the most, possessing a vast collection of performance tests on electric induction motors, making possible the development of this work [12].

Analyses of results

Between 1980 and 2016, the IEE Electric Machines Laboratory tested approximately 4280 electric motors. Of these, 95.8% were three-phase induction motors, representing the vast majority of the equipment tested. Figure 9 shows the rated power of three-phase induction electric motors tested in the aforementioned period.

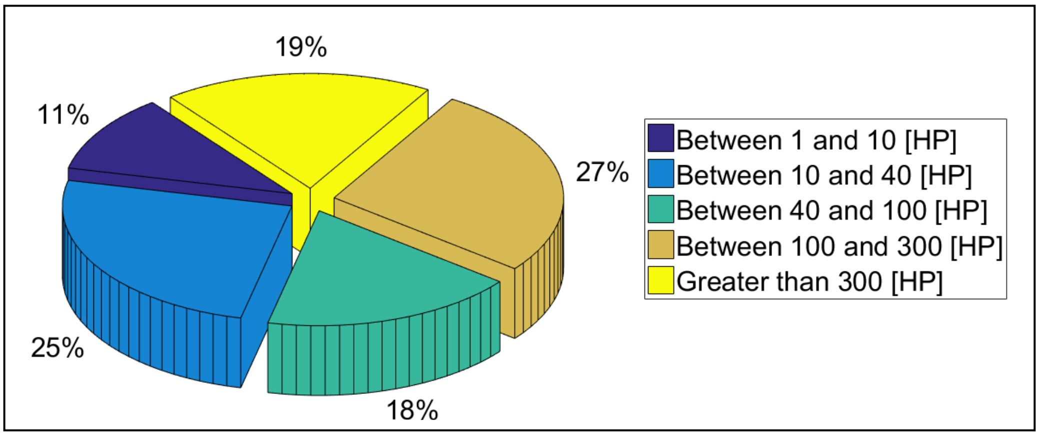

Figure 9 - Percentage of induction motors and their nominal power

In figure 9 one can observe that in the period between 1980 and 2016 there was a very even distribution of the percentages tested for each nominal power group. The group that presented the lowest percentage, only 11% of the total number of motors tested, was low nominal power between 1 HP and 10 HP. It is important to note that only three-phase induction motors are being accounted. In several industrial segments, for low nominal power drives, single-phase motors are used, which are not part of this research. This is the reason for the small number of induction motors of low nominal power, between 1 HP and 10 HP.

Medium nominal power motors (between 40 HP and 100 HP) and high nominal power (Over 100 HP) make up 64% of the total motors tested. This fact occurs because, in many cases, these motors represent a significant part of the industrial consumption, where the concern with the efficiency and reliability of the motors is fundamental.

The induction motors tested by the IEE are used for the most diverse possibilities of mechanical loads to be used in the industry and other sectors. Figure 10 shows the distribution of the motors tested according to pole numbers. It is possible to observe the predominance of 4-pole motors.

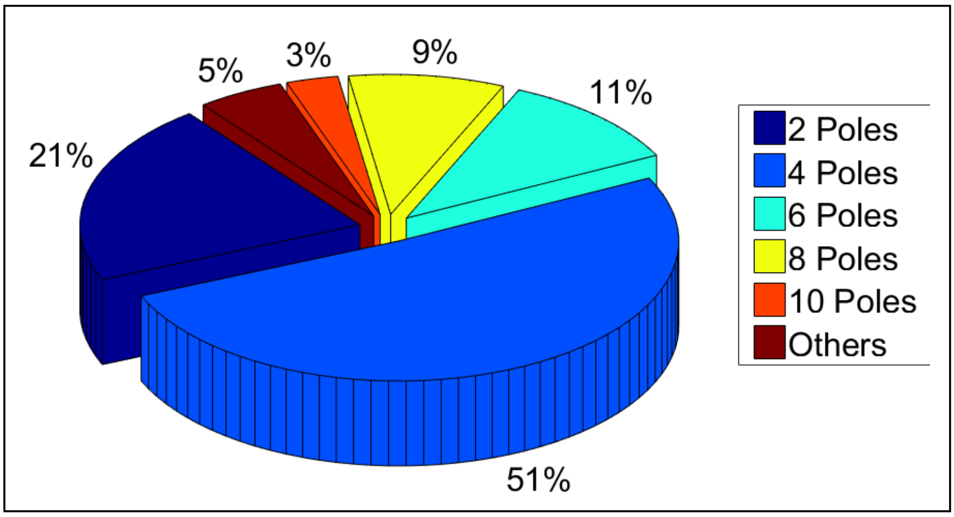

Figure 10 - Percentage distribution of researched induction motors grouped by number of poles

Figure 10 shows that 92% of the electric motors researched were in the 2 and 8-pole range. This confirms the fact that Decree 4.08 / 2002 and Ministerial Directive 553/2005 are limited to rotations corresponding to 2, 4, 6 and 8 poles.

A performance analysis of electric motors was performed using Decree 4508 / 2002 and Ministerial Directive 553/2005 as parameters. For this reason, only electric motors according to the following criteria were used in the research:

- Tests performed at a maximum voltage of 600 V (low voltage);
- Three-phase induction electric motors with rotor in squirrel cage;
- Motors tested at 60 Hz;
- Motors manufactured for continuous operation regime;
- Grouped according to the characteristics of N and H categories of ABNT NBR standard 7094/2000, equivalent to category A, B or C categories of the NEMA - National Equipment Manufacturers Association;
- 4-pole motors;
- Mechanical power between 1 HP and 250 HP.

According to figure 10, the electric motors with 4 poles are dominant in the sample of the test period (1980-2016), representing more than 50% of the total samples collected. For this reason, in this study the data analysis of 4-pole motors was explored.

Three classical rated powers were chosen to evaluate the performance trajectory: 5 HP, 50 HP and 200 HP. Being these nominal powers representative of the body of evidence used.

Figure 11 shows the performance increments of the electric motors tested at the IEE/USP, respecting the criteria established for the analysis.

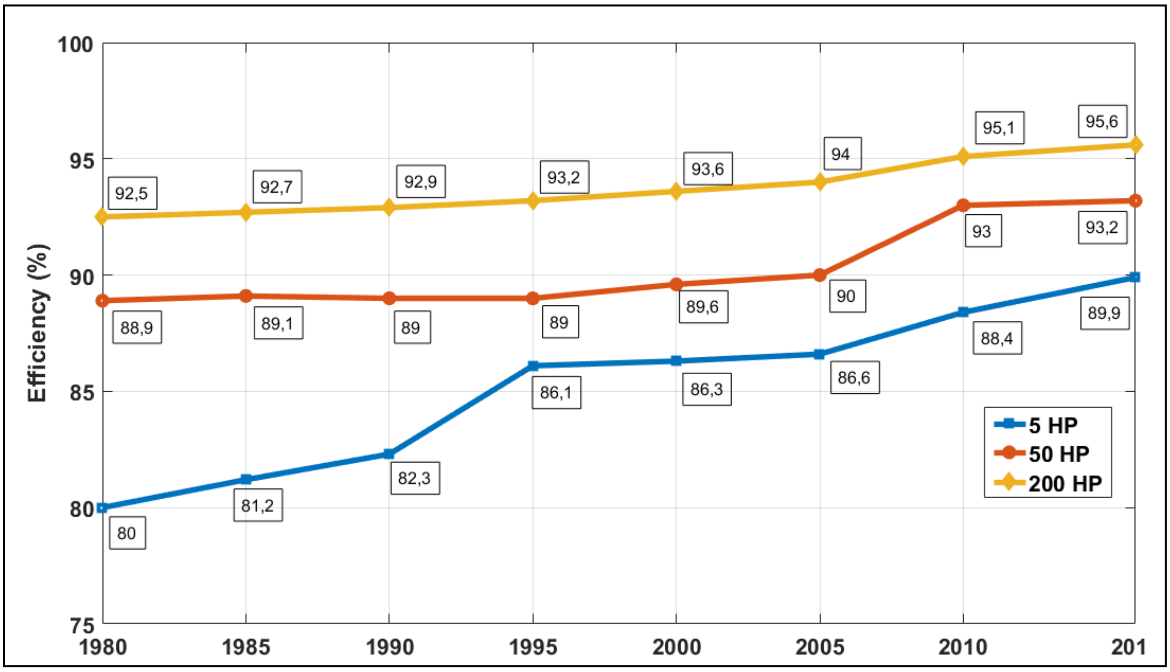

Figure 11 - Change in performance of 4-pole motors between 1980 and 2016

Figure 11 was constructed using a total of 163 4-pole electric motors tested between 1980 and 2016, considering 68 units of 200 HP, 54 of 50 HP and 41 of 5 HP. To determine the average performance per year, arithmetic mean was used.

In figure 11, it can be observed that the performance gains in lower nominal power motors were higher when compared to those with higher nominal power. The 5 HP motors accumulated average gains of 9.9% in the analyzed 36-year period. The 200 HP motors accumulated an average performance increase of 3.1%. This bearing in mind that higher power motors were already high performance due to the construction characteristics as well as the greater concern with maintenance of electricity in the use during their life cycle.

The 5 HP motors showed significant reductions in copper loss and iron loss. The group of 50 HP showed greater loss reduction in copper loss but small reductions of iron loss were recorded. The group of 200 HP, practically did not show any reduction of loss of iron loss, only copper loss. The additional losses, friction losses, ventilation losses and rotor losses did not show significant changes in the analyzed period. The changes were basically in the quality of the iron plates used in the construction of the stator and in the increase of copper mass used to construct the windings allocated in the stator.

During the period 1980-2016, concerns about the demand for electric power increased worldwide. Brazil participated in the discussions, implementing policies that contributed to the performance increase in end-use equipment.

As discussed, Decree 4508 / 2002 was the first document to establish minimum performance levels for electric motors, establishing "standard" and "high performance" categories. With Ministerial Directive 553/2005, only high performance equipment (Equivalent to category IE2 of IEC standard 60034-30-1 [7]) can be commercialized, effective as of 2009. For this reason, this work also evaluates the impact of Ministerial Directive 553/2005.

In Figure 12 the blue curve shows the average performance of the 4-pole electric motors tested between 1980 and 2000. The red (dotted) curve shows the minimum performance established by Ministerial Directive 553/2005. The green curve shows the average performance of 4-pole electric motors tested between 2011 and 2016.

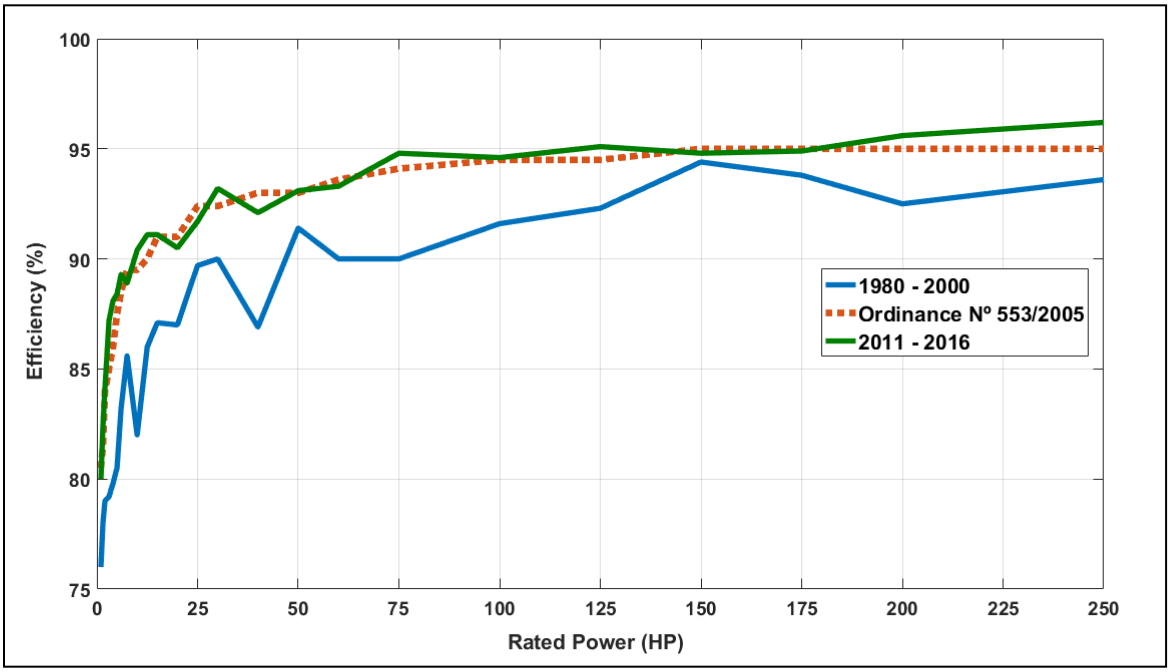

Figure 12 - Average performance of 4-pole motors tested before and after Ministerial Directive 553/2005

It can be observed that the implementation of Ministerial Directive 553/2005, changed the existing scenario. Where only a few manufacturers made high-performance electric motors available in their product list which were already in the international market. The manufacturers that operate in the Brazilian electric motors market have been forced to adapt to the new legislation in force. If we look at Ministerial Directive 553/2005 the dotted red line, and the average performance of the motors in the green curve, they are practically coincident, demonstrating the change of practice forced by the new legislation.

Figure 12 was constructed using arithmetic mean of the performance of 4-pole electric motors, presenting each nominal power standardized according to the directive. Several motors was with average below the minimum established by Ministerial Directive No. 488/2010. Some were still within the tolerance limit. Others were disapproved due to poor performance, which resulted in averages below the minimum established in Ministerial Directive 553/2005, as shown in table 2, numerically presenting the average performance calculated for each standardized rated power.

Table 2 - Minimum performances (%) presented in Decree 4508

HP	Kw	1980-2000	Directive 553	2011-2016
1,0	0,75	76	80,5	80
1,5	1,1	78	81,5	82,4
2,0	1,5	79	84,0	84,1
3,0	2,2	79,2	85,0	87,2
4,0	3,0	79,8	86,0	88,1
5,0	3,7	80,5	87,5	88,4
6,0	4,5	83,2	88,5	89,3
7,5	5,5	85,6	89,5	88,9
10	7,5	82	89,5	90,4
12,5	9,2	86	90,0	91,1
15	11	87,1	91,0	91,1
20	15	87	91,0	90,5
25	18,5	89,7	92,4	91,7
30	22	90	92,4	93,2
40	30	86,9	93,0	92,1
50	37	91,4	93,0	93,1
60	45	90	93,6	93,3
75	55	90	94,1	94,8
100	75	91,6	94,5	94,6
125	90	92,3	94,5	95,1
150	110	94,4	95,0	94,8
175	132	93,8	95,0	94,9
200	150	92,5	95,0	95,6
250	185	93,6	95,0	96,2

The performances highlighted in red were the averages found below the minimum stipulated in Ministerial Directive 553/2005 in the period 2011 and 2016.

In the universe of data used, we found 32 electric motor manufacturers. However, 4 companies alone represented 85% of the total equipment tested and one company alone represented 48%, according to Figure 13.

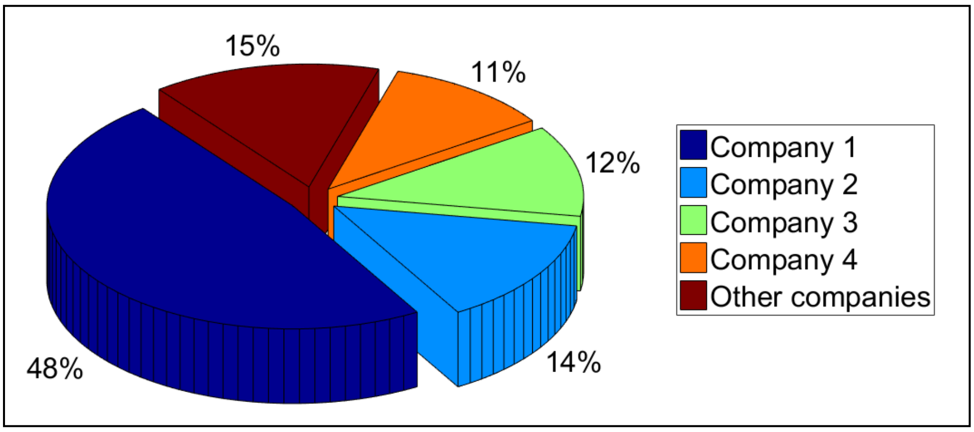

Figure 13 – Distribution of motors by manufacturer

Conclusions

The present study shows the performance gains of three-phase induction motors commercialized in Brazil between 1980 and 2016. It is possible to observe that for lower nominal powers the gains were significantly higher due to a larger margin for improvement in material and projects.

The standardization establishing the minimum level of performance of electric induction motors occurred relatively recently in Brazil. However, the positive results have already been identified in the present study. When analyzing the performance of electric motors before and after Decree 4508 / 2002 and Ministerial Directive 553/2005 entered into force, it is possible to observe that the electric motors industry has adapted to the new obligations to serve the Brazilian market.

There is room for improvements in the Brazilian legislation, following international standards. Today the current legislation is internationally equivalent to level IE2, making possible advancing to level IE3, which many countries of Europe and North America already have.

The Brazilian legislation is still not very comprehensive. It does not contain minimum performance for single-phase motors and for fractional motors, which are very present in the electricity end-use in residential, commercial and public service sectors, which, if added together, represent 43% of the total consumption of electricity in Brazil.

The article shows that a few companies are responsible for 85% of sales of electric motors in Brazil, which reinforces the idea of the state's need to determine minimum performance levels for these types of equipment, aiming at optimizing of the electric system.

References

[1] United Nations, “World Population Prospects, The 2015 Revision,” New York, 2015.

[2] T. Mayo e N. Nohria, Da Crise do Petróleo a Internet, 1 ed., Campus, 2008.

[3] Internacional Energy Agency, “Key world energy statistics,” Paris, 2016.

[4] National Energy Policy, “Report of the National Energy Policy Development Group,” Washington, 2001.

[5] EMPRESA DE PESQUISA ENERGÉTICA, “BALANÇO ENERGÉTICO NACIONAL,” RIO DE JANEIRO, 2016.

[6] PROCEL, “Pesquisa de posse de equipamentos e hábitos de uso, ano base 2005: classe Residencial Relatório Brasil - Sumário Executivo.,” Rio de Janeiro, 2009.

[7] Presidency of the Republic, LAW Nº. 10.295, OCTOBER 17, 2001., Brasília, 2007.

[8] Presidência da República, DECRETO Nº 4.508, DE 11 DE DEZEMBRO DE 2002, Brasília, 2002.

[9] Ministry of Mines and Energy, INTERMINISTERIAL ORDINANCE Nº. 553, OF DECEMBER 8, 2005.

[10] MINISTRY OF DEVELOPMENT, INDUSTRY AND FOREIGN TRADE, Ordinance Nº. 243, of May 21, 2015. NATIONAL INSTITUTE OF METROLOGY, QUALITY AND TECHNOLOGY-INMETRO, 2015.

[11] MINISTRY OF DEVELOPMENT, INDUSTRY AND FOREIGN TRADE, Ordinance Nº 488, of May 21, 2010. NATIONAL INSTITUTE OF METROLOGY, QUALITY AND TECHNOLOGY-INMETRO, 2010.

[12] J. L. COSTA DIAS e J. R. Cardoso, Os 120 anos da Escola Politécnica de São Paulo: mil razões para comemorar, São Paulo: Brasil Engenharia, 2014.

[13] International Electrotechnical Commission - IEC, IEC 60034-30: Efficiency classes of single-speed three phase cage induction motors, 2005.

[14] P. Waide e C. Brunner, “Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems,” Paris, 2011.

Is management a key driver of energy performance?

Rita Werle, Conrad U. Brunner

Impact Energy

Abstract

The Swiss research project "Management as a Key Driver of Energy Performance" (M_Key) aims to assess whether Energy Management (EM) positively influences decisions within companies for energy efficiency investment. The overarching objective of the project is to gain a better understanding of the determinants of energy efficiency investments.

M_Key targets large energy consumer companies in Switzerland with more than 0.5 GWh/a electric energy and/or 5 GWh/a thermal energy consumption in the industrial and services sectors.

The main research hypothesis is that EM significantly raises companies' perception of the strategic character of energy efficiency investments. Thus, EM is expected to induce positive decisions regarding energy efficiency investments and to ultimately increase the energy performance of a company.

The project runs for three years until the end of 2017. A quantitative and qualitative analysis was made during the following three phases:

1. Survey addressing approximately 3000 large energy consumers, with 305 valid responses
2. Interviews with 26 companies who responded to the survey
3. Case studies with 5 companies who were interviewed.

The results of the survey show that the level of EM in Switzerland in most companies is only moderate. The interviews were following up on the survey responses and getting a better understanding on how the EM system of the selected companies is being implemented and how it influences investment decisions. During the interviews, most companies mentioned laws and regulations and the support of the top management as an important determinant for investments into energy efficiency. The case studies focused on getting a detailed understanding of the energy efficiency measures effectively implemented at the companies, including optimization measures of electric motor systems. The evaluation and synthesis of the results of the three phases is still ongoing. This paper presents the findings of the project to date and focuses on the results of the case studies.

The M_Key research project is part of the National Research Programme "Managing Energy Con-sumption" (NRP 71) of the Swiss National Science Foundation (SNSF). Further information on the National Research Programme can be found at www.nrp71.ch.

Introduction

In many companies there is considerable potential to reduce energy consumption, but investments in energy efficiency often remain undecided, even though they may be highly profitable [4]. This is generally called the "efficiency gap". It is not sufficiently clear why companies are not implementing all the recognized economically feasible energy efficiency measures fully which could save them a considerable amount of money from lower energy cost and avoided CO_2-taxes.

The research project "Management as a Key driver of energy performance" (M_Key) is investigating through a detailed analysis of large companies in Switzerland whether EM significantly increases companies' perception of the strategic character of energy efficiency investments and ultimately increases their energy performance.

M_Key is led by INFRAS, a Swiss consulting company based in Zurich, project partners are the University of Neuchâtel and Impact Energy. M_Key is part of the National Research Programme "Managing Energy Consumption" (NRP 71) of the Swiss National Science Foundation (SNSF). Further information on the National Research Programme can be found at www.nrp71.ch.

The project targets large energy consumer companies in Switzerland in the industrial and services sectors with an annual consumption of more than 0.5 GWh/a electric energy and/or 5 GWh/a thermal energy.

Large energy consumers represent an important fraction of overall national energy consumption and are targeted with several specific policy instruments:

- Federal Act on the Reduction of CO_2 Emissions (2011) with a tax on CO_2 emissions
- National large energy consumer agreements to avoid CO_2 tax
- Reimbursement of electric grid surcharge for companies with high fraction of electric energy consumption in their gross value added (energy-intensive companies)
- Cantonal energy efficiency target agreements for large energy consumers.

The above policy instruments aim to motivate companies for entering into target agreements and committing to reducing their energy consumption. The target agreements are often coupled with financial benefits for the companies.

Theoretical framework

The theoretical framework of the project is based on research by Cooremans [2] [3]. According to this theoretical framework, investments within companies are implemented if they have a link to core business, i.e. if the investments are perceived as strategically important. An investment has a strategic character if it contributes to a durable competitive advantage of the company. A durable competitive advantage is characterized by the three dimensions cost, risk and value. Thus, if through an investment a company can reduce its costs, risks and increase its value proposition, the investment is likely to be perceived as contributing to a durable competitive advantage.

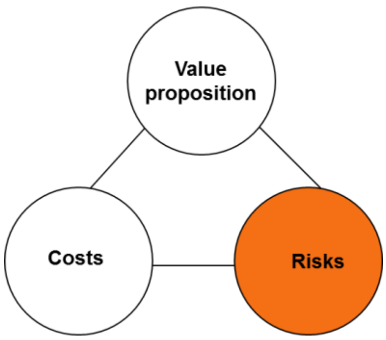

Figure 1 The three dimensions of competitive advantage [3]

The M_Key project builds on the hypothesis that the level of EM[45] has an influence on the perceived strategic character of energy efficiency investments. The higher the level of EM, the higher the perceived strategic character and therefore it is assumed that it is more likely that positive decisions are taken for energy efficiency investments. This leads to a better energy performance of the company (see **Figure 2**).

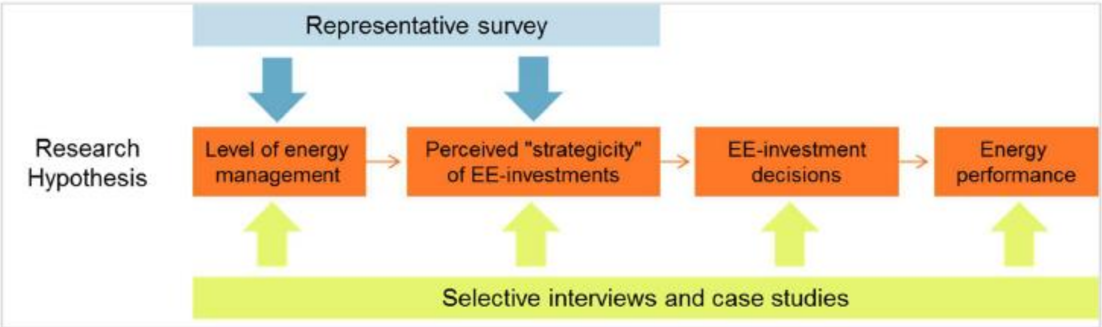

Figure 2: M_Key research model, methods and data collection

Research questions

To analyze the impact of EM, the project aims at answering the following main research questions:

- What are the determinants of EM level in for-profit companies?
- What is the level of EM in large energy consumer companies in Switzerland?
- Does the level of EM influence the perceived strategic character of energy efficiency investments?
- How does the perceived strategic character influence energy efficiency investment decisions?
- Does the level of EM significantly influence positive energy-efficiency investment decisions and therefore ultimately the energy performance of companies?

The project also looks at the effectiveness of the current national and local policy tools and measures in Switzerland and how these could be improved to encourage large energy consumers to implement more energy efficiency measures.

See the detailed research hypotheses in Table 1.

Research question	**Research hypotheses**
1) level of EM and its determinants	1.1 The level of EM in large energy consumers in Switzerland is generally low.
	1.2 The main determinants of the EM level are the company size, the company energy-intensity and the commitment or support of EM by the top management.
2) influence of EM on the strategic character of energy efficiency investments	2.1 The higher the companies' level of EM, the more strategic they perceive energy-efficiency investments to be.

[45] The term Energy Management is based on ISO 50001:2012. In the project a detailed quantification system is used to assess the level of EM within a company.

3) influence of the (perceived) strategic character on investment decision-making	3.1 The more strategic an energy efficiency investment project is perceived by a company, the better the chances for positive decision.
	3.2 The less strategic the investments, the more restrictive the financial criteria in the selection of investment projects.
	3.3 The number of energy-efficiency investments positively decided and realised depends mainly on the network relations/knowledge exchange within the sector.
	3.4 Increasing requirements from cantonal energy policies for large energy consumers and/or rising energy prices (in particular for electricity) positively influence energy-efficiency investment decision-making by companies.
4) influence of investment decision-making on energy performance, via positive energy-efficiency investment decisions	4.1 The higher the number of energy efficiency investments implemented, the higher the energy performance of a company (measured in energy-intensity terms).

Table 1 M_Key research questions and hypotheses

Methodology

The answers to the research questions are based on quantitative and qualitative data from large energy consumer companies in Switzerland, gathered through a mix of surveys, face-to-face interviews and a small number of case studies.

M_Key runs since 2015 until the end of 2017 in three phases (see Figure 3):

1. A survey among 3000 large energy consumers with 305 valid responses, led by the University of Neuchâtel.
2. Interviews with 26 companies, led by INFRAS.
3. Case studies with 5 companies, led by Impact Energy.

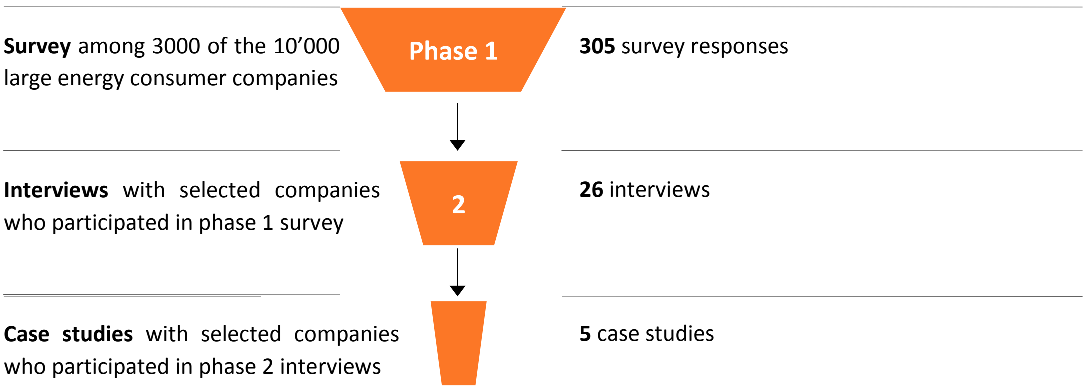

Figure 3: Three empirical work steps designed as focusing funnel

All three project phases have been finished, the project team is currently evaluating the overall results of the three phases.

Phase 1: survey

During the survey, answers were collected to a detailed questionnaire concerning the following main issues:

1. Characteristics of the company
2. Energy management within the company
3. Determinants of investments into energy efficiency
4. Evaluation of investments into energy efficiency
5. Public policy
6. Influence of investments into energy efficiency on the energy performance of the company

Out of the approximately 3000 companies who were invited to fill in the online questionnaire, 305 companies provided a valid response.

The level of EM of the companies was assessed based on their answers on a scale where they could reach between 1 to 23 possible points. The average score of respondents was at 10.2 points. Half of the firms have a score of 10 or below (median). This shows that the level of energy management in these companies is only moderate. No difference was observed between the companies in the industrial and services sectors. Approximately half of the respondent companies have designated an energy manager but all of them (except 14) manage energy issues on a part time basis only. **Figure 4** and **Figure 5** show the most important drivers and barriers for investing into energy efficiency.

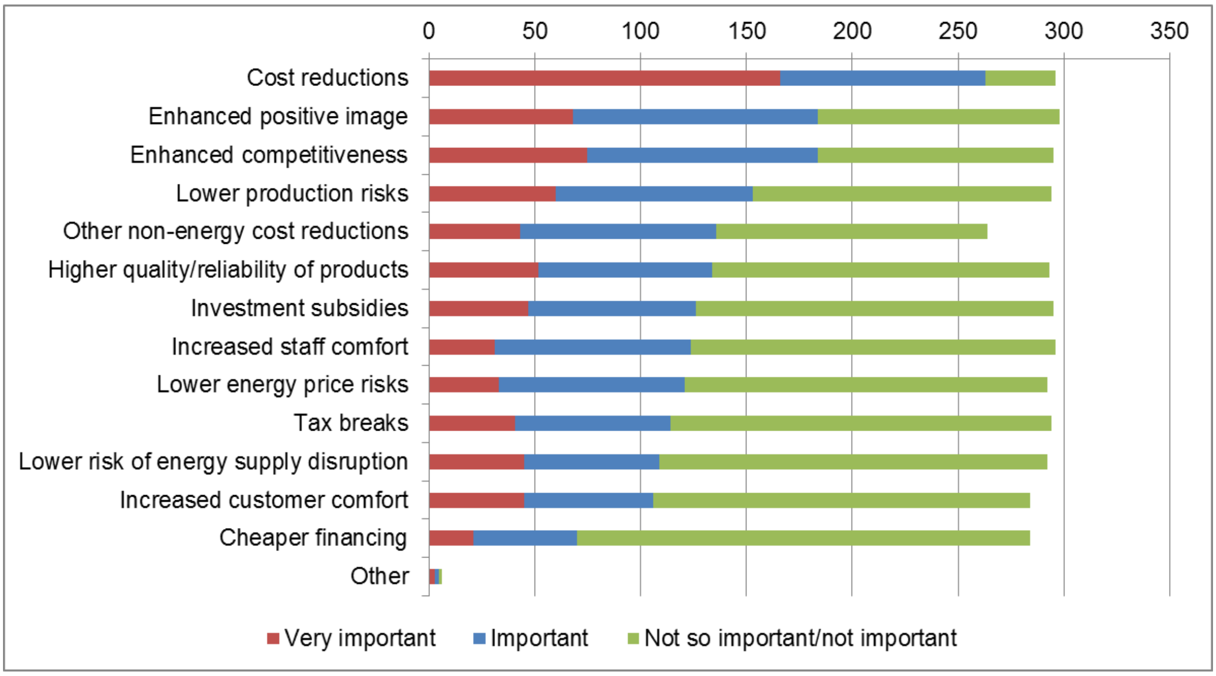

Figure 4 **Drivers of energy efficiency investments**

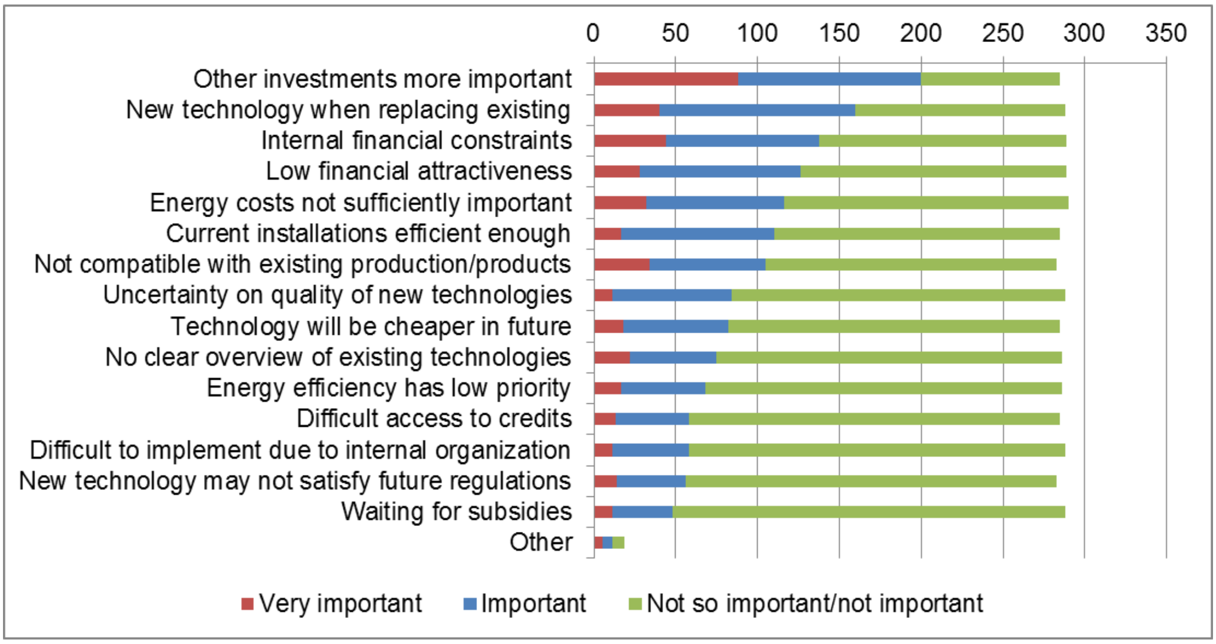

Figure 5 Barriers of energy efficiency investments

Phase 2: interviews

The interviews focused on the following questions:

1. Energy management: relevance, history, how it is organized today
2. Decision making process, including applied criteria
3. Influence of energy management on decision making
4. Impact of energy management on energy performance of the company
5. Potentials for improving energy management

The above questions were elaborated in an interview guide that was sent to the interviewed companies before the interview took place.

The face-to-face interviews were conducted with the energy managers in 26 companies, which have participated in the survey and agreed to be interviewed. Thereof, 18 companies are located in the German part and 8 in the French part of Switzerland. **Table 2** summarizes the characteristics of the interviewed companies, including the following information: level of energy management, size, sector.

Criteria		**German part**	**French part**	**Total**
Level of Energy Management*	"high" (19-23 points)	3	3	6
	"upper medium" (11–18 points)	9	0	9
	"lower medium" (6–10 points)	6	2	8
	"low" (0–5 points)	0	3	3
Size	> 10 GWh_{el}/a	5	4	9
	3–10 GWh_{el}/a	7	2	9
	0.5–3 GWh_{el}/a	6	2	8
Sector	Industry	11	6	17
	Services	7	2	9
Total		**18**	**8**	**26**

Table 2 - Characteristics of the interviewed companies

*The level of energy management was determined based on companies' responses to the survey questionnaire.

Figure 6 shows the most mentioned drivers for energy development by the 26 interviewed companies. Laws and regulations and the support of the top management were mentioned by most of the companies as an important determinant.

Figure 7 Most mentioned reasons and triggers for energy management development by the interviewees
Note: Font size indicates the number of mentions by companies.

Reasons for energy management development	Policy instruments / financial incentives	Sustainability policies / Corporate social responsibility (also SMEs*)	People (motivation and collaboration, involvement of top management)
Role of energy management in the decision-making process	A tool for: data collection / potential analysis / project ideas	Fact based argumentation for project proposals	Monitoring of energy efficiency projects' impact
Investment decision-making criteria	Profitability / Cost reductions	Priority of core business investments	Additional non-energy benefits
What determines the strategicity of energy efficiency investments?	Core business defines strategic relevance of investments	Sustainability policies and market demand (customer expectations, investors) can make energy efficiency more strategic	Finances are strategically relevant for companies. Low energy prices prevent energy efficiency measures from becoming more strategic

Table 3 summarizes the main findings and conclusions of the interviews regarding the research model.

Reasons for energy management development	Policy instruments / financial incentives	Sustainability policies / Corporate social responsibility (also SMEs*)	People (motivation and collaboration, involvement of top management)
Role of energy management in the decision-making process	A tool for: data collection / potential analysis / project ideas	Fact based argumentation for project proposals	Monitoring of energy efficiency projects' impact
Investment decision-making criteria	Profitability / Cost reductions	Priority of core business investments	Additional non-energy benefits
What determines the strategicity of energy efficiency investments?	Core business defines strategic relevance of investments	Sustainability policies and market demand (customer expectations, investors) can make energy efficiency more strategic	Finances are strategically relevant for companies. Low energy prices prevent energy efficiency measures from becoming more strategic

Table 4 - Summary of main results and conclusions from the interviews

*SMEs: small and medium-sized enterprises

Phase 3: case studies

Goal

Contrary to the interviews that wanted to clarify the level of the strategic character and the level and quality elements of EM, the questions asked in the case studies had three main goals:

1. Analyze and verify the energy efficiency investments
2. Identify who in the company is directly involved in energy efficiency matters
3. What is the effect of policy on energy efficiency and energy performance in the company.

By analyzing the energy consumption and cost data, the list of planned, realized and not-realized improvement measures of the company and with a "walk through audit" by two energy efficiency experts of the case study team, a qualitative analysis of the energy performance of the case study companies can be described [6].

The case studies do not deliver quantifiable nor representative results. They show the individual situation of the five companies with an in-depth qualitative analysis, allowing a closer "reality check" of the effect of all the national and cantonal programs, financial incentives and legal requirements.

Selection of companies

The following criteria were applied to choose the sample of the case study companies:

- Five companies which participated in the preceding survey and interview and agreed to be contacted for the case studies,
- Four companies located in the German speaking part of Switzerland and one located in the French speaking part,
- Different levels of energy management (a contrast with high/low was planned):
    - 2 companies with a high level of energy management
    - 2 companies with a low level of energy management
    - 1 company with a randomly chosen level of energy management,
- Within the case study sample, at least one occurrence of each of the following company sizes (defined by annual electricity consumption):
    - small: 0.5 to 3 GWh/a
    - medium: 3 to 10 GWh/a
    - large: above 10 GWh/a
- 2/3 of companies from the industrial sector, 1/3 of companies from the commercial sector.

In addition to the above criteria, it was aimed to conduct the case study with several people from the company on different hierarchical levels, with different responsibilities:

- One person at management level (decisions / financing)
- One person at technical management level (project planning and implementation)
- One person at operating level (production / energy manager)

For some - especially the smaller - companies, these different levels of responsibility were incorporated in one person.

In the end, as planned, the case studies were conducted with five companies and all of the above criteria could be met. The only difference occurred concerning the share of companies in the industrial and services sector. Instead of three companies from the industrial sector the sample included four such companies. This change was partly due to the fact that some companies who were contacted in the beginning declined to participate in the case studies, because of restricted availability of resources.

Table 5 summarizes the main characteristics of the case study companies and details regarding the contact person(s).

Table 5 Main characteristics of case study companies and details of contact person(s)

No.	Code	Region	Sector	Size	Level of energy management	Contact person/s
1	A	German	services	medium	4 (low)	1) head of building equipment, unofficial energy manager [T, O]
2	B	German	industry	small	9 (lower medium)	1) head of technology, unofficial energy manager [T, O]
3	C	German	industry	small	15 (upper medium)	1) energy manager, factory manager, member of the board [M, T, O]
4	D	French	industry	large	19 (high)	1) production, energy management, project planning and implementation [T] 2) head of manufacturing unit* [O] 3) energy purchase: gas, electricity, carbon certificates for Europe [O]
5	E	German	industry	large	19 (high)	1) factory manager, highest decision capacity on site [M] 2) head of energy management/electricity supply, head of energy team [T, O] 3) head of energy- and waste management, member of energy team [T, O] 4) head of manufacturing unit* [O]

Notes:
[M]: person at management level (decisions / financing)
[T]: person at technical management level (project planning and implementation)
[O]: person at operating level (production / energy manager)
*For both companies, heads of the manufacturing units representing the most significant production processes from an energy point of view took part in the case study.

Procedure

The procedure for conducting the case studies was as follow:

1. Before the on-site visit, each case study company received the case study guide with the questions of the case study which addressed the following issues:

1. Investment categories and budgets
2. Investment priorities
3. Investment decisions and implementation of measures
4. External and in-house know-how

5. Influencing factors
6. Energy efficiency improvements, status of implementation
7. Monitoring and quantification of energy savings and costs, ex ante and ex post evaluation
8. Reporting
9. Equipment maintenance practices
10. Role of public policy, opportunities and constraints, improvement potentials

In addition, companies were asked to provide the following information:

- Annual energy cost and consumption (electrical & thermal energy),
- List of implemented efficiency measures,
- Main elements of savings commitments (e.g. target agreement with goals, duration, intermediate results, status of target achievement),
- Incentivized measures, if any (financial incentives e.g. through federal public tenders, cantons, utilities, etc.).

2. During the visit on site, the case study questions and questions related to the previously supplied data on energy consumption and efficiency improvement measures were discussed. This was followed by a "walk through audit" of the company facilities.
3. After the visit on site, the minutes of the meeting discussion as well as a technical report with observations by the efficiency experts was made and verified by the case study company. The technical report captured the status of energy consumption, measures implemented and potential further savings not yet dealt with.

Results

Table 6 gives details on the characteristics of the five case study companies.

General data	A	B	C	D	E
Level of energy management	4 low	9 lower medium	15 upper medium	19 high	19 high
Sector	services	industry	industry	industry	industry
Type of ownership	family-owned	family-owned	several private owners	shareholders (company on stock market)	shareholders (company on stock market)
Product	photos, books, calendars, phone cases	cosmetics	yeast	aluminum sheet metal	pharmaceutical, chemical
Degree of competition in the sector	not so high	not so high	not so high	not so high	very high
Number of employees on site	168	110	30	500	2'700
Location of company top management	on site	on site	on site	USA	Switzerland, different location
Energy intensity (Energy cost/turnover)*	2-3%	1%	1.1%	10%	7-12% **
Energy cost **(million USD/a)**	0.5	0.2	0.2	12.9	57 to 78 ***
Energy consumption GWh/a **(thermal/fossil)**	Gas 1	oil 0.4 wood 0.7 total 1.1	gas 2.8	gas 184	gas 466 steam (waste) 86 total 552

Energy consumption GWh/a (electric)	3.3	0.7	2.3	77	492 +48 own production total 540
Trend in production	continuous development of technology, additional products, overall increase	increase of production and shift to specialty products	amount constant in last 10 years, growing share of energy-intensive product	almost doubled since 2012	heavy fluctuation due to market demand
Trend in energy consumption	large fluctuations due to summer temperature and change of cooling technology	heat decreasing, electricity constant	constant in last 10 years	strong increase in the last 10 years, strong increase also in efficiency per production unit	heavy fluctuation
Energy manager	1 part-time	1 part-time	1 part-time	1 energy manager (part-time) plus team	1 energy manager (part-time) and team of 6 people

Table 6 **Details of the five case study companies**
*The definition of "energy intensity" is not used in the same way by the five companies: energy cost is compared to either total cost, turnover i.e. sales volume or gross value added. These data (total cost, turnover, gross value added) are kept confidential in most companies. Therefore the energy intensity values shown give an indication, however, the values are not directly comparable.
**Range in the last five years.

The results of the case studies are based on the answers of the five case study companies and are presented as "anecdotal evidence" with the main observations, analysis and conclusions of the research team as follow:

Investment categories and budgets, investment priorities

- If the energy-intensity of a company is high, it has an inherent motivation for keeping its energy costs low and invest into energy efficiency. This makes it build up qualified internal staff dealing with energy efficiency issues.
- Energy efficiency does not appear to be a priority when deciding on investments; however, it is considered in all investment types.
- The category "energy efficiency investment" exists in two out of the five case study companies with dedicated budgets. In the other three companies a general budget for all investments is available. The general budgets correspond to the order of magnitude of the energy intensity of the companies (between 3% to 14% of the gross value added). The dedicated energy efficiency budgets are much smaller (0.1% to 0.3% of turnover or gross value added).

Investment decisions and implementation of measures

- The energy manager plays a crucial role, especially in small and medium-sized enterprises (SMEs). If he is supported by top management, he has a much easier task compared to the situation when he is not. All energy managers worked on a part time basis with respect to energy efficiency issues and had other responsibilities on the side.

External and in-house know-how

- SMEs favor to depend on external expertise to complement their scarce internal know-how while larger enterprises are reluctant to engage external specialists, as they claim to know the best their internal processes.

Influencing factors

- The companies pay a relatively low electricity and gas price. This is a disincentive for energy efficiency improvements. The larger enterprises purchase energy from the European market. Their sole decision criteria is low price, it seems that purchasing e.g. certified renewable energy sources is not on their agenda. In addition, in the CO_2 balance of the companies CO_2 emissions stemming from electricity generation and imported electricity are not taken into account.

Energy efficiency improvements, status of implementation

- A focus on fossil energy savings was observed. This can be explained by the Swiss CO_2-emission reduction policy. In Switzerland electricity generation is almost CO_2-neutral (nuclear and hydropower), therefore companies can reduce their CO_2 emissions mainly through decreasing their fossile energy demand (i.e. thermal processes). Energy efficiency measures in the field of electric energy were less present.
- While all five case study companies are located in rural areas, transport issues only entered their energy and environmental rationale in the case of two companies. One company delivered the raw materials for production via railway transport and the other tracked and accounted for the CO_2 emissions for employee transportation.
- While the companies claimed that the low hanging fruits of profitable energy efficiency measures have been implemented and they now have fewer opportunities, the walk through audit showed further savings potentials which could be looked at. This has to do with the setup of the target agreements that the companies enter into. Usually, the savings target and efficiency improvement measures are identified at the beginning of the commitment period. However,

throughout the commitment period of 5 to 10 years the list of measures is not being reassessed. This means that certain equipment is not being looked at or by the time it is, it is often deemed not economically replaceable.

Monitoring and quantification of energy savings and costs, ex ante and ex post evaluation, reporting

- Monitoring and especially the verification of savings remains a challenge. All companies reported that the results of energy efficiency improvements were as planned. However, it is questionable how they came to this conclusion. Usually for specific measures the engineers make an a priori estimate of the cost and the energy savings. After the implementation of the energy efficiency improvements they can relatively easily check the cost, but not the energy savings. They generally assume that it actually happened according to plan. None of the companies had a strict and systematic savings verification policy for all significant energy efficiency improvements. Some companies were equipped with measuring instruments (the higher the level of energy management, the more likely). Few used measuring equipment before and/or after energy efficiency measures.
- Before / after comparison is challenging. Changing energy prices, changes in production (output volume, product type and quality), weather and climate changes (summer or winter), etc. affect the energy consumption and eventual energy and cost savings. A disproportionate large effort is necessary to recreate the same conditions in two different points in time (before and after implementation) and to determine the influence of these individual factors.
- None of the five companies was able to establish a "Key Performance Indicator" (KPI) to easily compare multi-annual results across all of their products. They mentioned the change of production volume and the characteristics of the individual products (with different energy demand in production) that do not allow a global KPI, comparable over time. If KPIs were established it would be much easier to evaluate progress of energy efficiency improvements.

Role of public policy, opportunities and constraints

- In the case study companies, the Swiss policies have in all cases triggered actions for implementing energy efficiency measures and are therefore an important driver. This was particularly visible in the SMEs. At the same time, the reception by the companies is mixed: many admit that the policies helped in implementing efficiency improvements, however, they were perceived not so enthusiastically, rather as an imposed obligation that comes with an administrative effort. The largest company explicitly expressed strongly favoring market mechanisms freely regulating the market instead of public authorities through policies. All case study companies stressed the importance of keeping administration efforts associated with policies and especially financial incentives at the lowest possible level.
- The goal-setting aspect of the target agreements is helpful to convince company management for energy efficiency improvements. Once the company commits to its goals, there is a certain obligation to fulfil them (instead of postponing or abandoning investments).
- All companies reached their agreed targets easily. None of them complained about severe measures and costly investments.
- While large energy consumers and energy intensive users benefit from financial exemptions/reimbursements, these benefits should be coupled to more stringent energy efficiency improvement requirements.
- The large enterprises benefiting from financial incentives said that they would have implemented the energy efficiency improvements anyway, only stretched during a longer time period (free-rider effect). Incentive programs do not seem to

reach SMEs due to a lack of information. A central, coordinated and transparent approach, including a central point of information for such programs is missing.

- SMEs experience the implementation of energy efficiency improvements more challenging than larger companies. They expressed interest for more support concerning the following areas:
    - Qualified external know-how for initial analysis and identification of potentials (partially or entirely subsidized) as well as the implementation of energy efficiency improvements and follow up.
    - Training of energy managers.
    - Information on relevant financial incentives.

Energy efficiency performance in relation to level of energy management

The research team made a qualitative evaluation of the level of energy performance of the five case study companies, based on the "walk through audit". Two independent experts who conducted the audit gave a rating to 13 questions (see Table 7) which forms the basis of the qualitative analysis. This was compared to the level of energy management, as determined during the survey (phase I, based on the answers of the companies).

[redacted]										
Nr	Question	average	average	average	average	average	average	min	median	max
1	Are all thermal processes and their energy efficiency potential analyzed?	6.5	6.5	8.5	7.0	8.5	7.4	6.5	7.0	8.5
2	Are all electric processes and their energy efficiency potential analyzed?	5.0	5.0	4.0	3.5	6.5	4.8	3.5	5.0	6.5
3	Is the implementation of the cost effective thermal efficiency measures planned systematically?	6.0	5.0	7.0	4.5	7.0	5.9	4.5	6.0	7.0
4	Is the implementation of the cost effective electric efficiency measures planned systematically?	4.5	4.0	2.5	3.5	4.5	3.8	2.5	4.0	4.5
5	Fraction of thermal measures implemented?	5.0	5.0	7.0	4.5	7.0	5.7	4.5	5.0	7.0
6	Fraction of electric measures implemented?	3.0	4.0	3.0	4.0	5.5	3.9	3.0	4.0	5.5
7	Do they have a good plan* for fossil measures for the next 5 years?	4.5	3.5	5.0	5.5	5.0	4.7	3.5	5.0	5.5
8	Do they have a good plan* for electric measures for the next 5 years?	3.5	3.5	2.0	4.5	5.0	3.7	2.0	3.5	5.0
9	Does the energy manager give the impression of being competent?	5.0	7.5	8.5	7.0	8.0	7.2	5.0	7.5	8.5
10	Did the company use external experts?	7.0	7.5	6.5	4.0	3.0	5.6	3.0	6.5	7.5
11	Did the company take individual measurements before a machine was changed?	3.0	2.5	5.0	5.0	6.5	4.4	2.5	5.0	6.5
12	Did the company take individual measurements after a machine was changed and compared with the outset?	2.5	2.5	4.5	4.5	6.5	4.1	2.5	4.5	6.5
13	Are the calculations for the effect of the energy efficiency measures shown in their plan plausible?	4.0	5.5	2.5	5.5	6.5	4.8	2.5	5.5	6.5
average		**4.6**	**4.8**	**5.1**	**4.8**	**6.1**	**5.1**	**3.5**	**5.3**	**6.5**
percentage		46%	48%	51%	48%	61%	51%	35%	53%	65%

Table 7 Qualitative rating of the level of energy efficiency performance of the case study companies (10: best; 1: worst)

*a good plan for measures for the next five years is defined as complete, comprehensive, systematic, credible.

Note: Overall, three experts were engaged: one expert evaluated all five companies, one four, one only one company. All experts had only a short briefing for their task and no communication between each other for the individual evaluation and rating. The three experts had a fairly good overall match of their average rating of the five companies and the 13 questions: the result differed by +11% and -18%. The research team did not consider this as major fault of the qualitative analysis.

Figure 8 shows that while the range of the level of energy management of the five case study companies is quite wide (between 4 and 19 points out of 23 points), their level of energy efficiency performance remains in a relatively narrow band (between 4.1 and 6.1 out of 10 points). The comparison shows no clear specific pattern between these two criteria. Also, the sample of the case studies is not large enough to plot any conclusions being representative for a larger group of companies.

Two companies (A and B) clearly started during the case study that they started to analyze their energy consumption and identify efficiency improvement measures in response to their large energy consumer obligations under cantonal law. They did not deal with improving their energy efficiency before. This shows that policies have an effect and can move companies within a short period of few years to a favorable level of energy efficiency performance, comparable to the level of companies with a high level of energy management, and significantly better compared to the status with no or very little efficiency improvements before.

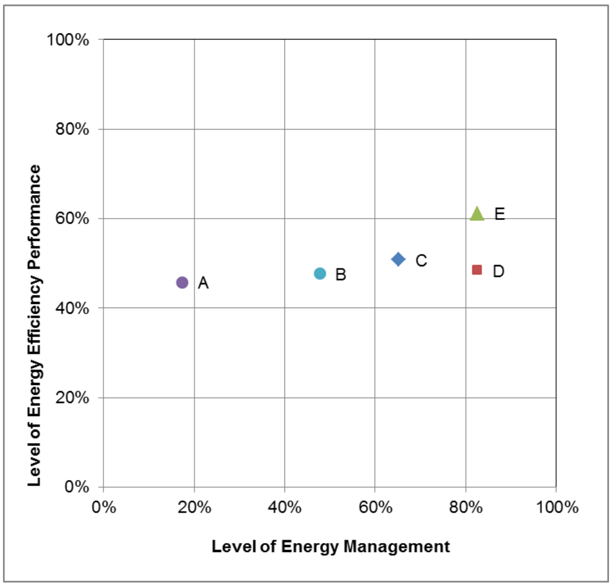

Figure 8 Comparison of level of energy efficiency performance with level of energy management

Main conclusions from the perspective of the case studies

The "efficiency gap" especially observed in large industrial consumers has stimulated research in the decision making process and energy management of companies.

The findings show that several factors play a role in decisions for energy efficiency improvement measures and whether companies perceive energy as strategically important. The main determinants include policies (laws and regulations), role and responsibilities of the energy manager, support by top management, energy intensity and investment priorities.

The case studies have clearly shown that the Swiss policies have a tangible effect and successfully move companies to a considerable level of energy efficiency performance.

The level of energy management seems to be a manifestation of the importance companies attribute to energy issues. Energy management appears to serve as an operational filter, creating more transparency on potential energy efficiency measures, delivering reliable, fact-based data and information as a basis for investment decisions, leading to increased trust and ultimately to increased support for energy efficiency improvements.

The overall evaluation and synthesis of the results from the three project phases is ongoing and will be available until the end of 2017.

Acknowledgements

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References

[1] Catherine Cooremans: Les déterminants des investissements en efficacité énergétique des entreprises: dimensions stratégique et culturelle de la décision d'investir. Université de Genève. Thèse, 2010

[2] M_Key project team: M_KEY – Management as a Key Driver of Energy Performance, Inception Report, 2015. Interim final report, not published.

[3] Catherine Cooremans, Rita Werle: M_Key Management as a key driver of energy performance, eceee Industrial Summer Study 2016, Berlin

[4] Rolf Tieben, Rita Werle, Conrad U. Brunner: EASY- Lessons learned from four years of the Swiss EASY audit and incentive program, Energy Efficiency in Motor Driven Systems EEMODS 2015, Helsinki

[5] Rita Werle: Energy management and training for industrial energy optimization, Motor Summit 2016, Zurich

[6] M_Key final project report, currently internal working document, to be published in October 2017.

The Motor Systems Tool – A new level

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Abstract

After the successful presentation of the Motor Systems Tool at previous EEMODS conferences in both Washington D.C. and Rio de Janeiro, and following the well-attended workshops in both Zürich and Utrecht, it shall be a great pleasure to present the latest developments of the Motor Systems Tool at the EEMODS '17 in Rome, Italy.

The main goal of the task III - Outreach in the 4E EMSA project is to upgrade the capacity of motor system users all over the world, by utilizing tools and guides etc. making everything easy accessible as online content. One approach to achieve this goal is the Motor Systems Tool.

The Motor Systems Tool, which was developed with full support from Danish public means, did at the launch in 2011 present a new, impartial calculation tool in which the efficiency of complete motor systems is calculated. The aim was to create a tool which can be easily handled, gives good technical support for choosing the correct combination of elements when creating the optimal motor system and is available for a broad audience.

Since the latest presentation at EEMODS '13 development of the tool has taken place, and with the recent start of a parallel Danish project, even more development has been secured looking forward to the coming EEMODS conference in Rome. The focus of the coming developments will be a more integrated evaluation in terms of Eco-design requirements, including the expected extension of the scope of the motor regulation, new motor technologies, elaborate application calculation, energy evaluation and finally an improvement of the usability of the tool. The Tool also have focus and future integration of the latest developments within the international standardization of power drive systems (IEC 61800-9 series).

The presentation will show and demonstrate the latest developments of the Motor Systems Tool with a few calculation examples combined with discussions of the models used.

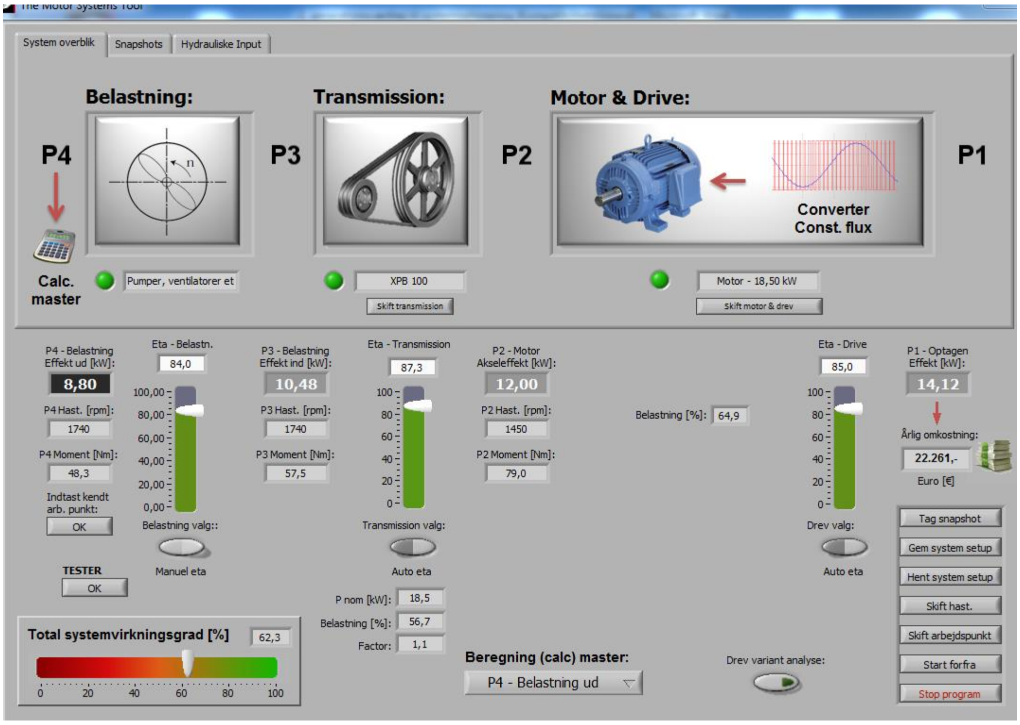


Figure 1 – Main screen of the MST-Tool, spring 2017

Introduction

Optimizing motor driven systems is about choosing the right components and getting them to work well together - thereby achieving maximum energy efficiency of the entire system.

In the Motor Systems Tool a system is defined as the entire system from the wall outlet to the power delivered by the application, for instance a pump that delivers hydraulic power such as P_4, in Figure 2.

A motor driven system by definition consists of the following four components:

- The driven machine – load (pump, fan, compressors, conveyor belts etc.)
- The transmission – if any (belt, gear, gear motor etc.)
- The motor
- A possible drive (soft starter, frequency converter or other VSD equipment)

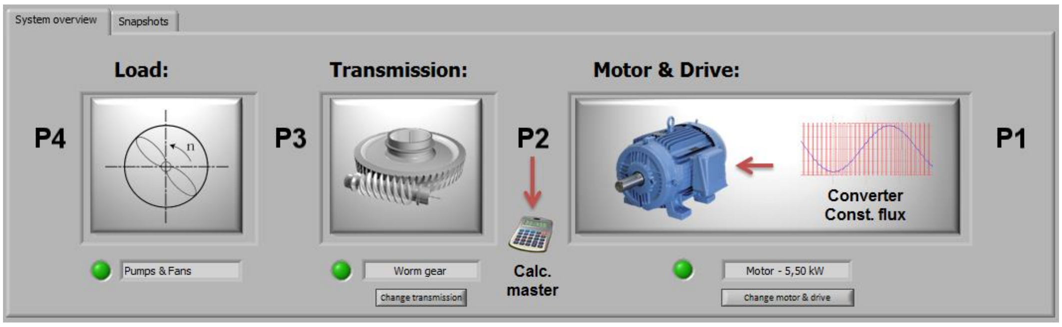


Figure 2 – Potential components of a motor driven system

Basic build up

The heart of the MST-Tool basically consists of simplified models of standard components all giving the efficiency at a specific duty point based on the input speed and load, Eta $_{(n, T)}$

Most of the models used are based on real life measurements during the last decade in former energy projects, carried out at the accredited laboratories of the Danish Technological Institute, in combination with the known theory of certain components, anonymous data from manufacturers, legislation rules, actual compliance testing, etc.

In many cases a variable speed and torque input makes the basis for a mathematical 3D "plane" which can be "simplified" and described as a certain equation with a number of variables involved. All of these mathematical models for each component are handled and calculated inside the MST-Tool dynamically.

This design allows the possibility for very easy documentation and extraction of existing models (for use in spread sheets), verification of models, and optimization and improvement of all the models.

The design of the "engine room" of the MST-Tool has always kept "the door" open for implementation of new models (e.g. new motor technologies, new components and so forth) which has now been utilized as several of the now standardized and accepted reference models from IEC 61800-9-2 [12] have now been implemented.

In the same sense the standardized mathematical models for partial load on motors driven by non-sinusoidal supply have also been implemented. These equations come from the now published IEC standard: IEC 61800-9-2 [12]

In general, it can be said that if any given component can be described by efficiency based on speed and torque, it can easily be implemented in the MST-Tool.

Figure 3 – Illustration of a standard model

Structure of the MST-Tool

A simple flow chart was carried out to define the program structure:

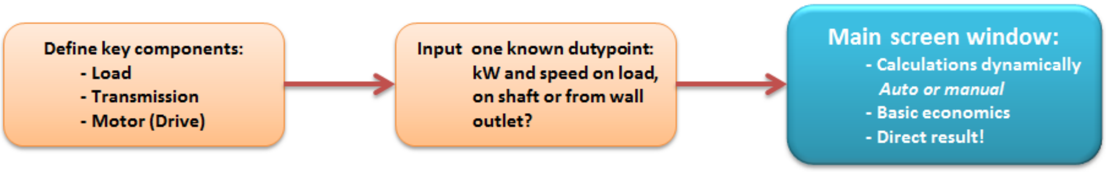


Figure 4 – MST flowchart

When selecting load and motor, the tool will provide suggestions if you're in doubt regarding your system. Quite often in real life the available information is limited.

In this way, you can get a very good estimation of your system performance – even with very little knowledge about your actual system.

Describing the MST-Tool

Step 1 – Selecting key components

First step of the tool is to pick the key components of the system. This is, as a minimum, a load and a motor, but it can also be a transmission (belt or gear) and a potential drive.

Load

Load is at this point in the program selected as a torque profile

(One of four different speed/torque relations)

Transmission

Transmission selection has proven to be somewhat impossible to simplify completely. The user has to have some knowledge of the transmission chosen. There are default values in the tool, but if not selected carefully, calculated values can be quite inaccurate. Included are transmissions (as of spring 2013), many different belt types, and three gear models (helical, worm and bevel)

Motor

If known the user can input the actual motor nameplate data but when such information is not available, the user can choose a standard size motor. As of spring 2013 the table from the present IEC 60034-30-1 definition of IE1, IE2 and IE3 can be selected (1 through 500 horsepower, 50 Hz).

Potential drive

After the selections made above the user must input the method by which the motor is connected. The options made available are:

- Direct on-line (D.O.L.)
- Soft starter
- Frequency converter
  - Constant flux or automatic energy optimization (AEO) These models are based on actual measurements combined with a 2001 PhD study from Aalborg University [3]
- Reference converter
  - Based on models from IEC standard [12]

Step 2 – Input of a duty point

All calculations inside the MST-Tool are based on only one duty point. The user is free to choose this duty point, based upon equipment design and operating criteria, anywhere from wall outlet P_1 to actual load P_4. But it is vital to emphasize that all calculations originate from this one point!

Step 3 – Main Screen of the tool

Having overcome these few steps the user is now presented with the main screen of the Motor Systems Tool and already by now a qualified “guess” of the total system efficiency:

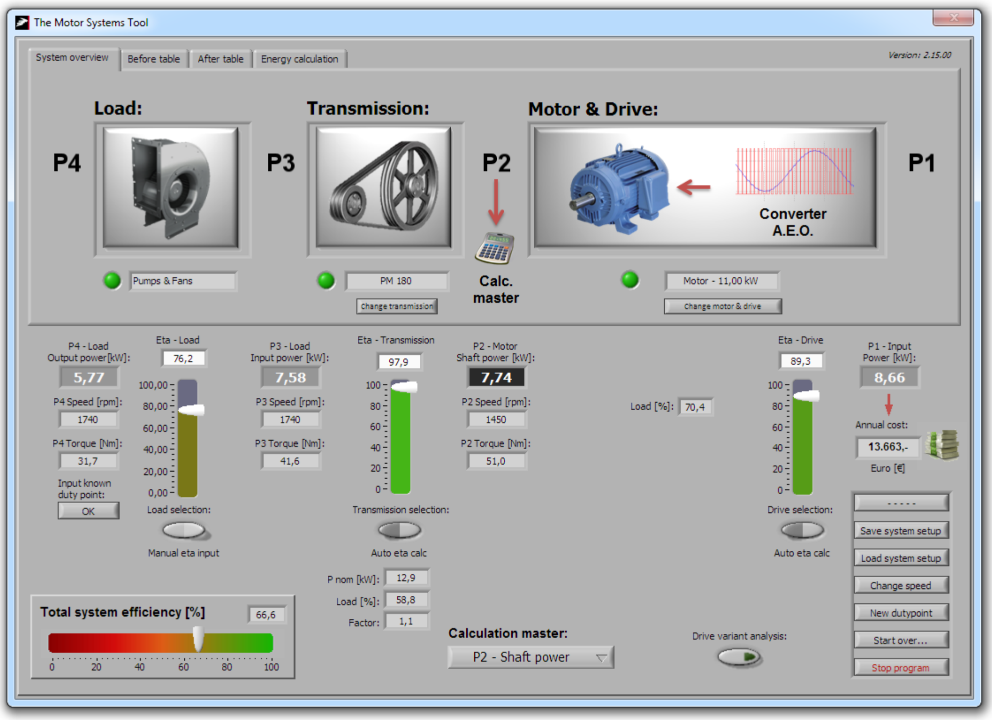


Figure 5 – Main screen of the MST-Tool

The top third of the main screen is a representation of the choices previously made. The lower two thirds show the calculated efficiencies of the respective components, the kilowatt powers in all of the split points of the entire chain, P_1 through P_4, and finally a presentation of the total system efficiency in the duty point selected.

In the illustrated example the total efficiency is calculated to approximately 67 %.

(Calculated from the known duty point P_2 = 7.74 kW)

Below each kilowatt indication, values like speed, torque and load percentage are also shown.

If desired the calculated efficiency of a certain component can be overridden manually.

From this screen, it's possible to calculate and document both before and after situations when for instance a user wants to see the difference between an IE1 and an IE3 motor in a given application. For this purpose, the tabulators "Before table" & "After table" are used.

From the main screen of the MST-Tool a lot of different features and functions are available.

Input and ideas on how to fill out these, can be found in both formerly published papers on the tool and on the 4E EMSA web page – see reference table in the back of this paper.

The motor model

The model for standard 3 phase cage induction motors used inside the MST-Tool was originally a simplified mathematical description of a standard shape for efficiency in the whole range of motors (0.75 kW through 375 kW) The Danish Research Institute – DEFU have made a mathematical expression based on the motor nominal efficiency, the nominal power and a constant (alpha) which is dependent on motor size. This gives the following shape of efficiency as function of load where maximum efficiency is achieved somewhere around 70 – 80% load:

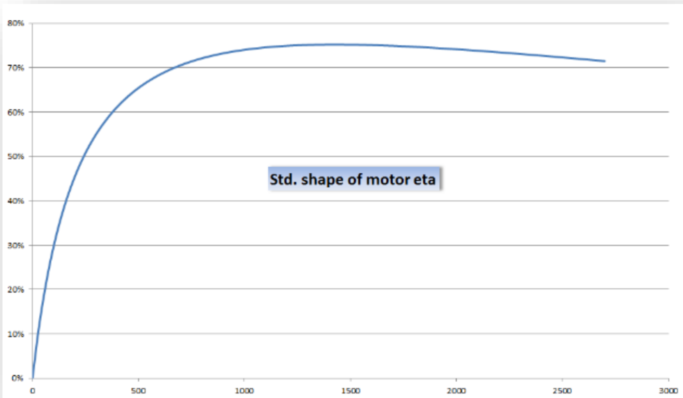


Figure 6 – Standardized shape of motor efficiency vs. load

When the shape above is combined with the nominal values for efficiencies on motors, which today is provided by the standard IEC 60034-30-1 [11], a reasonable loss definition of motors is thereby achieved.

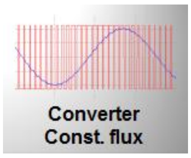
As an example, a 4 pole 2.2 kW IE2 motor must have an efficiency of 84.3% at full load.

Following the shape above this motor would then most likely have a slightly higher efficiency at 75% load (≈ 84.4%) – a lower at 50% (≈ 82.1%) – and significantly lower at 25% load (≈ 72.0%)

All the nominal values which are to be selected inside the MST-Tool comes from the tables inside IEC 60034-30-1 [11].

As of September 2017 the tables include IE1, IE2, IE3 & IE4 motors ranging from 0.12 kW to 1000 kW – 2 to 8 pole motors.

The converter model



The model inside the MST-Tool for frequency converters has until now been solely based on a Ph.D. study from Aalborg University, 2000 [3], where the impact on efficiency on converters was investigated when using automatic energy optimization (AEO) vs. scalar mode.

The study clearly showed the advantage of AEO mode on partial loads on all sizes of motors investigated:

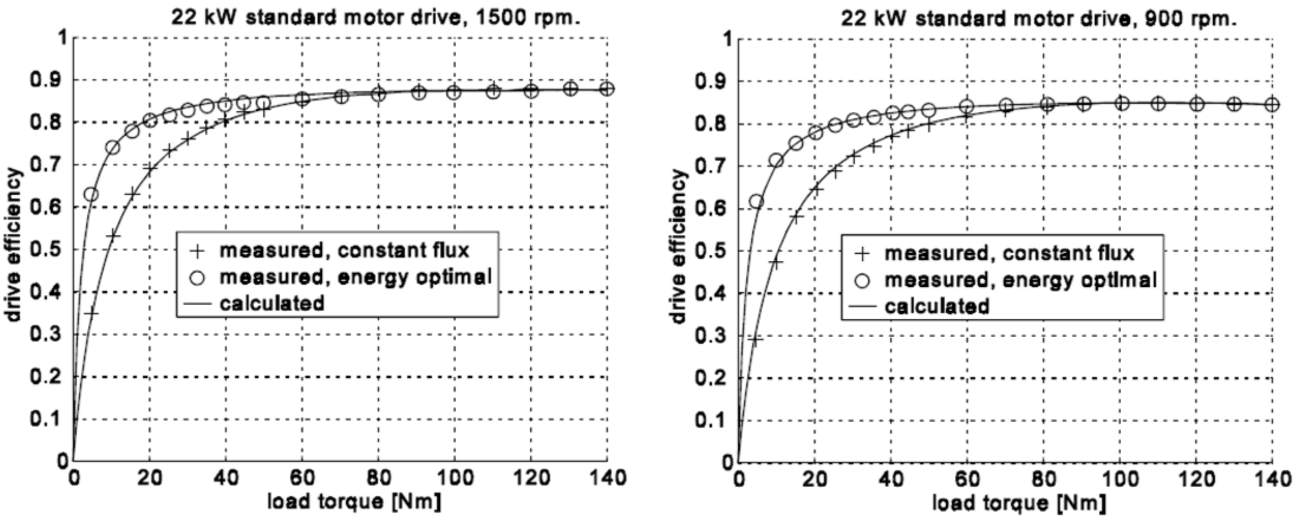


Figure 7 – Example of measured and calculated losses by Abrahamsen, anno 2000

Ever since the IEC in recent years have started to develop more “modern” standards taking technological development into account on especially drives and none sinusoidal driven motors, an increasingly number of models and equations have been developed to calculate the losses inside these units more precise.

In the now published IEC 61800-9-2 [12] two sets of equations for motor and or converter losses have been developed. These equations are now a part of the MST-Tool meaning that they can be selected as loss models, or rather, efficiency models for converters and motors in combination.

The first set of losses comes from annex A of the IEC standard and are referred to as the reference losses for both RCDM (Reference Converter Drive Module), RM (Reference

Motor) and RPDS (Reference Power Drive System). These are equivalent to the reference losses used inside the standard when classifying drive systems.

The second set of losses comes from annex D of the IEC standard. These tables have been developed based on an anonymous collection of actual measurements made by numerous motor labs worldwide on drive systems. The collected data provides solid basis for an interpolation scheme of losses based on seven known duty points to calculate "all" others.

A full elaboration of the interpolation scheme can be find in IEC 61800-9-2 [12]

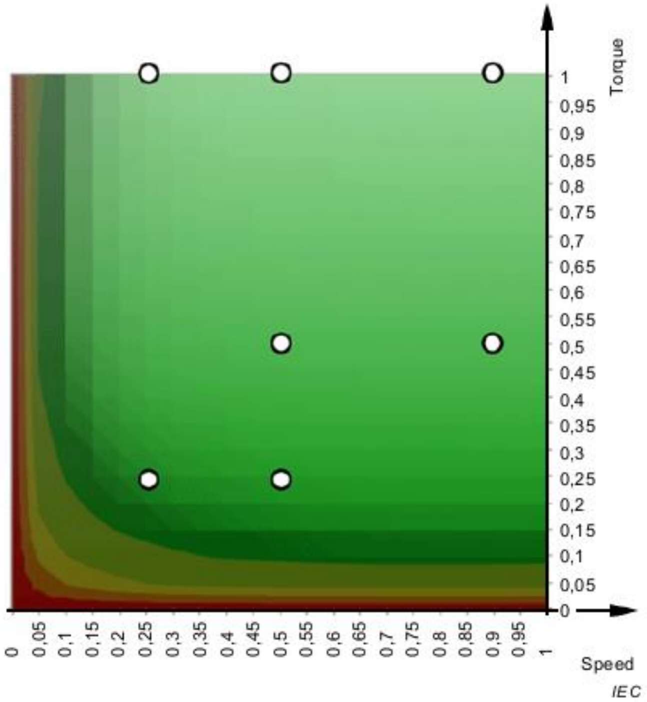


Figure 8 – The seven duty points from annex D in IEC 61800-9-2 [12]

Both new variants of reference losses can now be selected in the MST-Tool.

Application calculators

A new feature of the MST-Tool is an advanced application calculator in which several standardized end-user applications have been implemented.

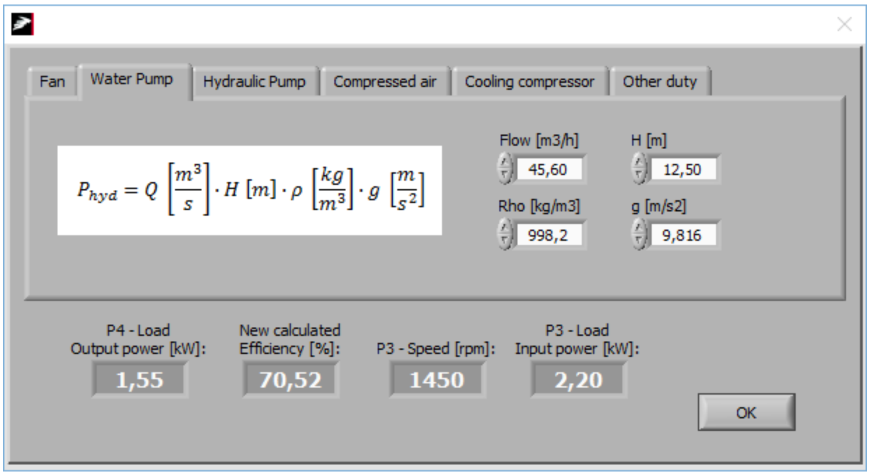


Figure 9 – Application calculator for water pump

In the water pump example above, known values for flow and head (+ some constants) are put in, and because MST know the shaft power of the motor, the efficiency of the actual pump is simple to calculate.

The general idea in the application calculator is to allow the user to input known values of an application into the MST-Tool, and from these have the tool calculate the total system efficiency.

The MST-Tool can calculate in both directions meaning that if shaft power from the motor is known, total efficiency is given. And if shaft power is unknown, a manual application efficiency can be put in.

An option to this variant is to put in a number of known duty points in the tool and have it interpolate automatically during calculations.

An example of this will be shown in the presentation at EEMODS'17.

Other examples of the application calculator can be seen here:

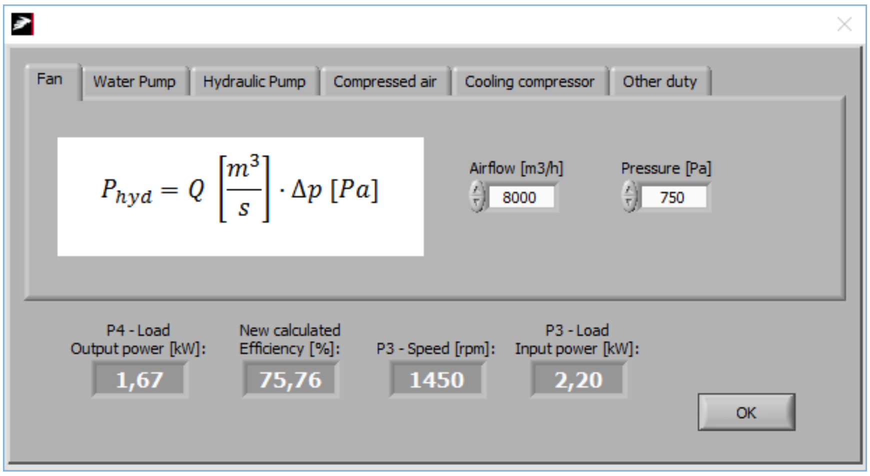


Figure 10– Application calculator for fans

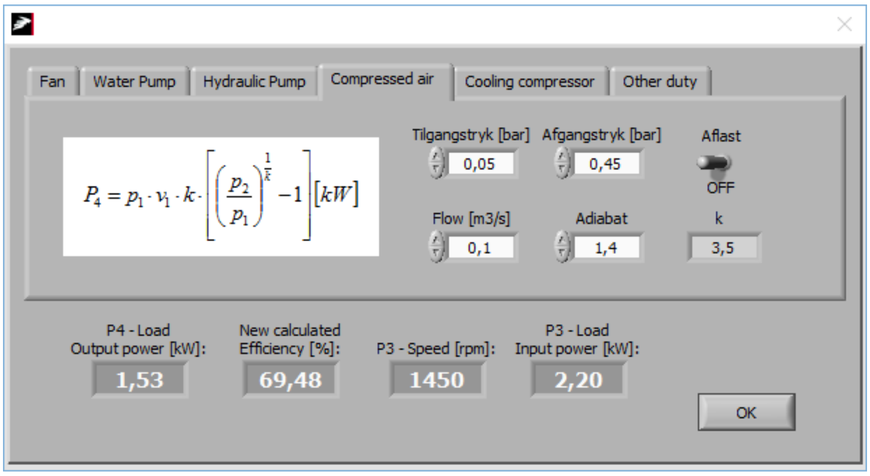


Figure 11 – Application calculator for compressed air

Additional languages

Another new feature of the MST-Tool is the additional languages now implemented in the tool. Since the original launch, Danish and English have been the only two languages but with the recent upgrade German and French have been added.

With this upgrade, it is the hope of the author that even more people will enjoy and use the tool.

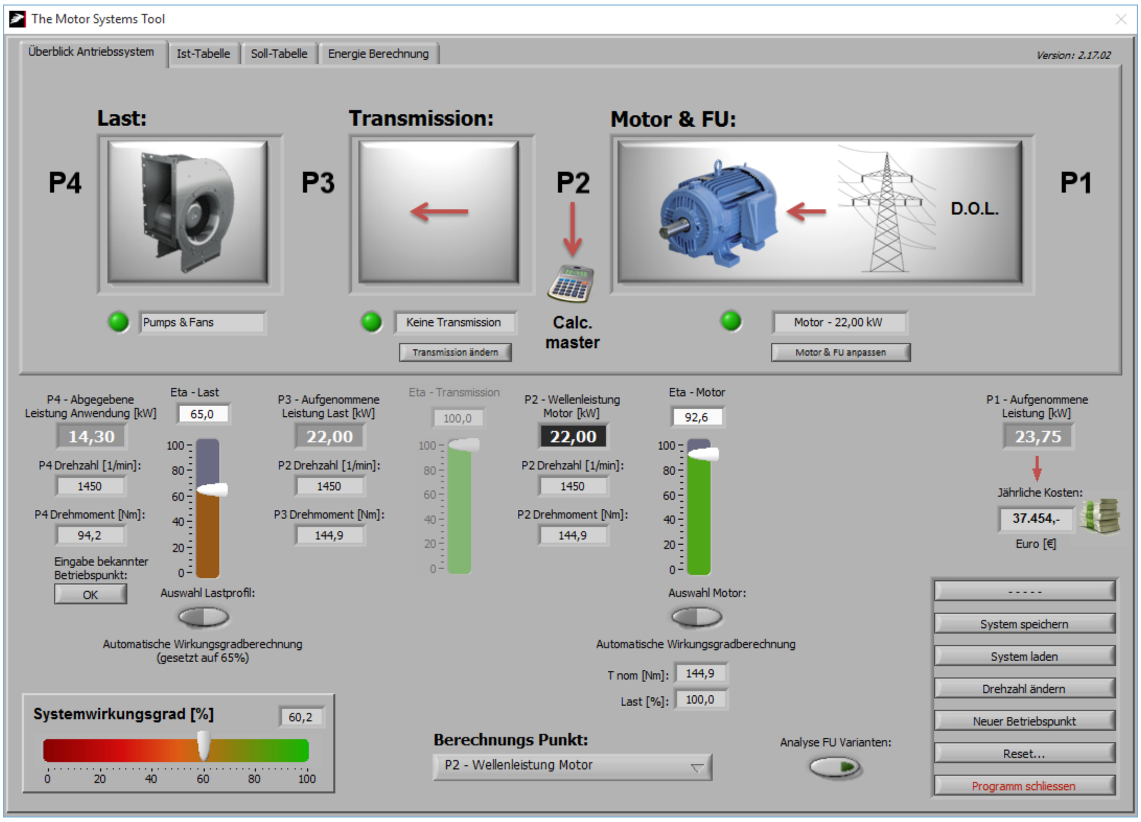


Figure 12 – MST-Tool main window – German language

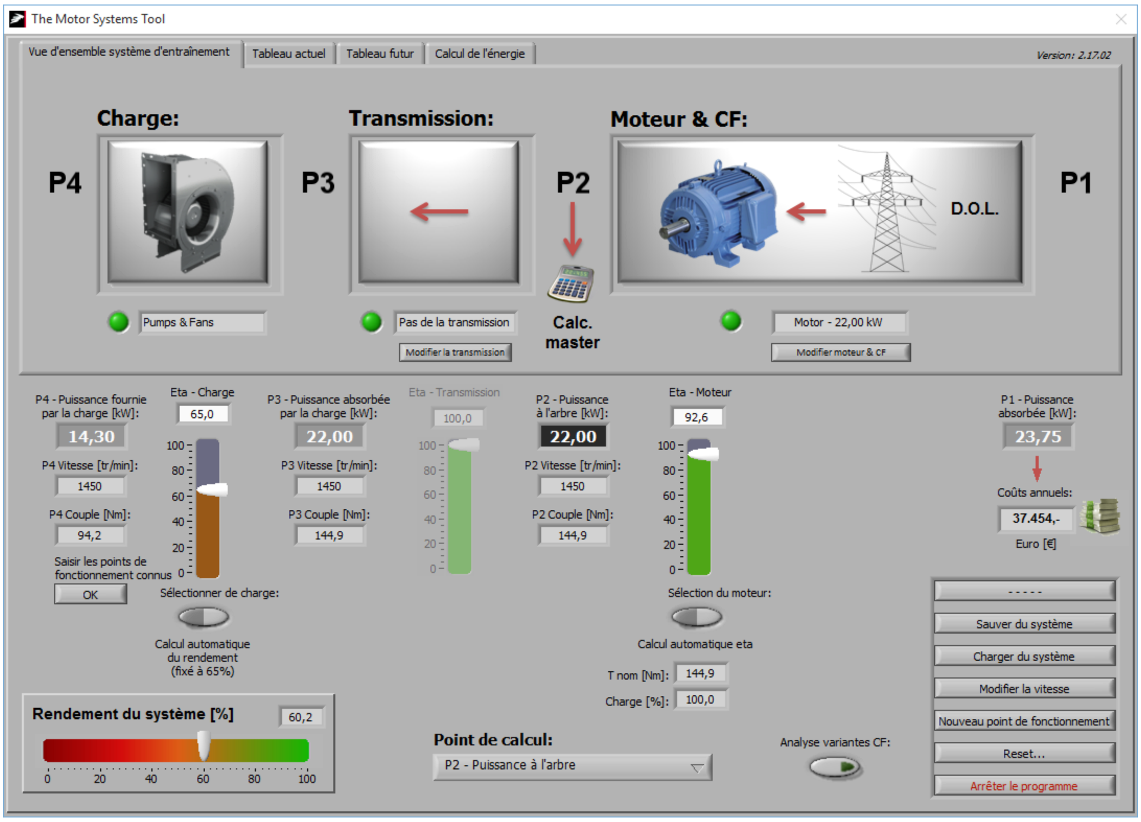


Figure 13 – MST-Tool main window – French language

Final comment

The MST-Tool has been available for download from the EMSA web page since September 2011 and ever since that time, the tool has been downloaded more than 2.000 times by unique downloads per Google statistics.

This fact emphasizes the interest and necessity of an impartial tool helping users to understand relations between components in a complete motor system.

The MST-Tool is by no means "perfect" or "finished" and many users will probably argue against the models used, the precision of the calculated efficiencies and the lack of inputs to make everything more exact. Despite this the tool still can provide a useful "guess" on a given efficiency in a given system which will be valuable to many.

There is room for improvement – for sure – and the on-going project in both Denmark [7] and the 4E EMSA project will ensure further development of the MST-Tool in the years to come. Furthermore, Danish Technological Institute has started co-operation with the Belgian University Howest which have done – and still are performing – quite a few measurements on gears, belts and drives. These results are also to be implemented in the MST-Tool.

Bullets:

The Motor Systems Tool is impartial using "self – made" standardized models for all implemented components, thereby helping to ensure that no specific products or manufactures are being favoured over others. This also means that results are general rather than exact.

The Motor Systems Tool is the obvious choice to use to inform and train not only engineers working in industrial plants but also energy consultants, original equipment manufacturers, trainers and teachers at schools and universities as well as government officials responsible for creating policy instruments.

Finally – The Motor Systems Tool is free of charge and it can be downloaded from the EMSA web-page http://motorsystems.org

The software comes in a self-extracting zip file and installs itself with a just a few clicks.

The only thing required is a registration on the EMSA page – for statistical purposes only

Summary of calculation models:

The present version of The Motor Systems Tool includes the calculation models below. The tool can handle any combinations of these.

Load:

4 variations of torque vs. speed: $T_{(n)} \sim n^{-1}$, $T_{(n)} \sim n^{0}$, $T_{(n)} \sim n^{1}$ and $T_{(n)} \sim n^{2}$

Transmission:

Direct coupled, belt drives and gear.

Motor & Drive:

Updated AC squirrel cage asynchronous motors 50&60 Hz models (IEC 60034-30-1), D.O.L., connected through soft starters, VSD constant flux and VSD with automatic flux optimization. Reference RCDM, RM & RPDS from IEC 61800-9-2 + Annex D interpolation model.

References

[1] Nielsen, Sandie B.:*The Motor Systems Tool – An outcome of the 4E EMSA project*
Paper 067 from EEMODS'11, Washington D.C., United States of America

[2] Nielsen, Sandie B.: *The Motor Systems Tool*
Paper and workshop at Motor Summit '12, Zürich, Switzerland
(http://motorsummit.ch)

[3] Abrahamsen, Flemming: Energy Optimal Control of Induction Motor Drives
Ph.D. study, Aalborg University, 2000

[4] Hvenegaard, Claus M.: *Small changes – Big savings!*
Paper from EEMODS'09, Nantes, France

[5] The Motor Systems Tool manual/quick guide – available at the EMSA webpage.

[6] EMSA webpage: http://motorsystems.org

[7] *2. Generation of the Tool for optimization of motor driven systems*, research project report (PSO 344-008). Carried out by Danish Technological Institute in cooperation with Lokalenergi, Lemvigh-Müller, Arla Foods, Leroy-Somer, 2012 -

[8] *Tool for optimization of motor driven systems*, research project report (PSO 341-014). Carried out by Danish Technological Institute in cooperation with Lokalenergi, Danfoss, Lemvigh-Müller and Arla foods, 2010-11.

[9] *System Optimization of Machine Systems Driven by Electrical Motors*, research project report (PSO 338-009). Carried out by Danish Technological Institute in cooperation with Lokalenergi, Danfoss, Lemvigh-Müller, A-Vent and Arla foods, 2008.

[10] *Den lille blå om Systemoptimering [The Small Blue Book on System Optimization]*, ELFOR [The Association of Danish Energy Companies], Jørn Borup Jensen (ELFOR). Henrik Lykke Lilleholt (Lemvigh Mühler). Claus M. Hvenegaard, Hans Andersen (Danish Technological Institute). 2005.

[11] IEC 60034-30-1: Rotating electrical machines: Efficiency classes of single-speed, three-phase, cage-induction motors

[12] IEC 61800-9-2

New technology needs new policy - From component to systems

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Abstract

The electric motor market has witnessed a big change in the last decade: both in structure, with company mergers contributing to an even more global market, in content with energy-efficiency policies, and in its economy with rising costs of material and variable electricity prices moving the market towards more energy-efficient products.

Recent technological developments have led to the introduction of very efficient motors, often referred to as Super- and Ultra- Premium Efficiency Motors, with efficiencies well above the IE3 level [1]. Cost-effective induction motors (IM) with efficiencies on and above the IE4 threshold are now widely available on the market and other advanced technologies have enabled manufacturers to produce motors that exceed the IE4 and IE5[46] efficiency limits. Driven by the expanding market penetration of Variable Speed Drives (VFD), introducing big energy savings in motor systems with variable load, there is a growing concern over their efficiency, both in operation, in full and especially in part-load and also in stand-by mode. First evidence shows that significant differences exist between the efficiencies of VFD in the market with similar functionality. Developments in power semiconductor technology allow for a significant reduction in the VFD losses of up to 60%, as well as a reduction of the motor losses.

The largest part of the energy savings is made available by the optimization of the entire motor systems (20-30%) [2] [3]. But still to date, Minimum Energy Performance Standards (MEPS) have been targeted due to legal limitations mostly at individual components. Difficulties arise in the standardization of measuring and classifying the entire motor driven unit (MDU). The methodology to describe energy efficiency requires a new approach to take into account that different components are made by different manufacturers and need to be assessed together. The larger energy savings achievable together has stirred concerns from manufacturers of the increased burden of compliance with several individual MEPS for components (motor, VFD, pumps, etc.) is leading to the launch a combined system standard on IEC and ISO level.

The two approaches for standardization and MEPS, components vs MDUs, must be carefully complemented in order to achieve the maximum energy savings and carbon emission reduction possible. This needs to be achieved without imposing disproportionate burdens on both manufacturers and market surveillance which will discourage industrial users to acquire high performant systems.

[46] IEC 60034-30-1:2014 defines efficiency classes IE1 to IE3. The new class IE5 is not yet defined in detail but is envisaged for potential products in a future edition of the standard. It is the goal to reduce the losses of IE5 by some 20% relative to IE4.

This paper carries out technical, economic and environmental analyses of introducing new policy measures (standards and MEPS) for both individual components and MDUs.

Recent technological developments

Growing governmental and industrial awareness towards the importance of energy-efficiency and its benefits, together with the global diffusion of countries with MEPS, has led to the development of motors with very high efficiency, well above the IE3 level, often referred to as Super- and Ultra-Premium Efficiency Motors (IE4 and IE5, respectively). Induction motors with efficiencies on and above the IE4 threshold are now widely available on the market and other advanced technologies (e.g. permanent magnet motors, synchronous reluctance motors) have enabled manufacturers to produce motors that exceed the IE4 and IE5 efficiency limits.

For fixed speed applications, three-phase induction motors are still the best option because of their reliability, efficiency and cost. They represent today, by far, the vast majority of the market of electric motors both in sales and running stock. Several strategies can be used to increase the efficiency of induction motors: advances in motor design (namely thermal and winding design), tighter tolerances, the use of superior magnetic materials, larger copper/aluminum cross-section in the stator and rotor to reduce resistance, use of copper rotors are just some of the techniques that contribute to lowering the losses in induction motors and allowing them to reach very high (IE4) efficiency levels [4] [5]. Other technologies have surfaced capable of starting direct-on-line (DOL) such as Line-Start Permanent Magnet Motors (LSPM) and DOL Synchronous Reluctance (SR) motors, but they still present some operational challenges, such as the starting charateristics which hinder their wide spread use.

On the other hand, in variable speed applications Permanent Magnet Synchronous Motors (PMSM) and SynRel motors can present themselves as an alternative to induction motors, rivaling in reliability and excelling in efficiency. Since these motors operate at synchronous speed they do not have losses in the rotor and are, therefore, capable of achieving very high efficiency levels up to IE5.

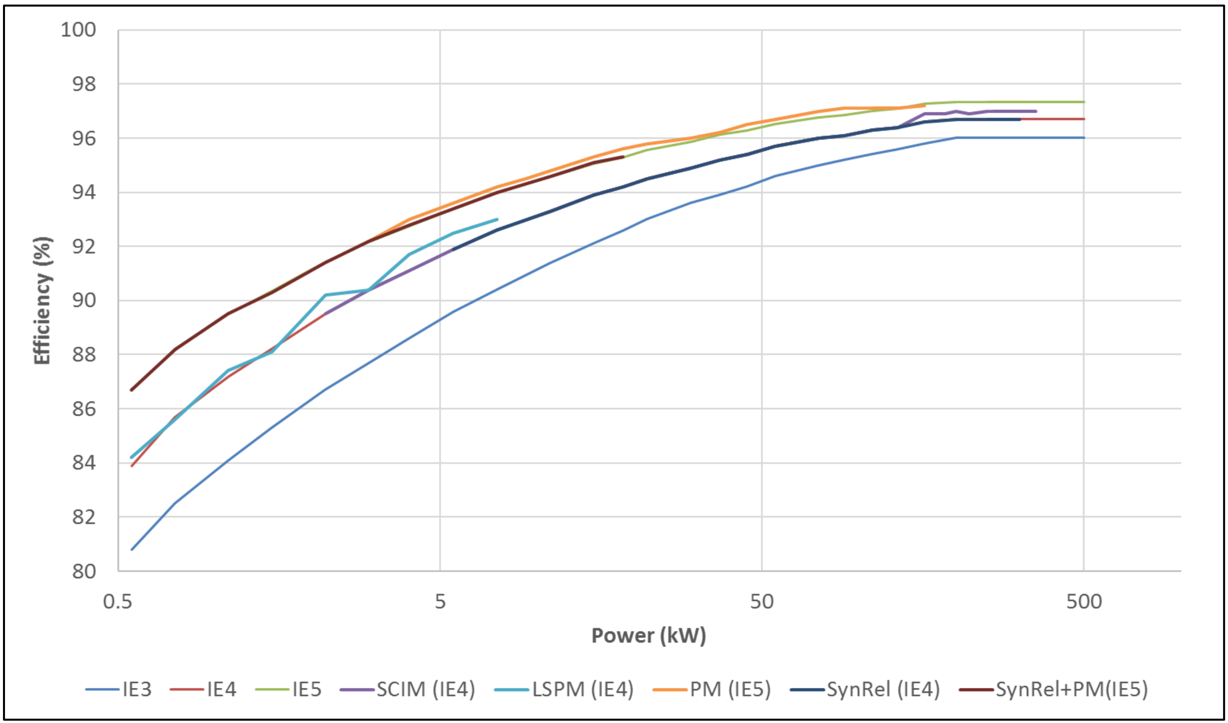

Figure 1 Efficiency of commercially available IE4 and IE5 motors (Source: ISR-UC, 2016 catalogue data)

The use of these technologies can also significantly reduce the overall weight and size of the motor meaning that less material is needed for its construction, including active materials.

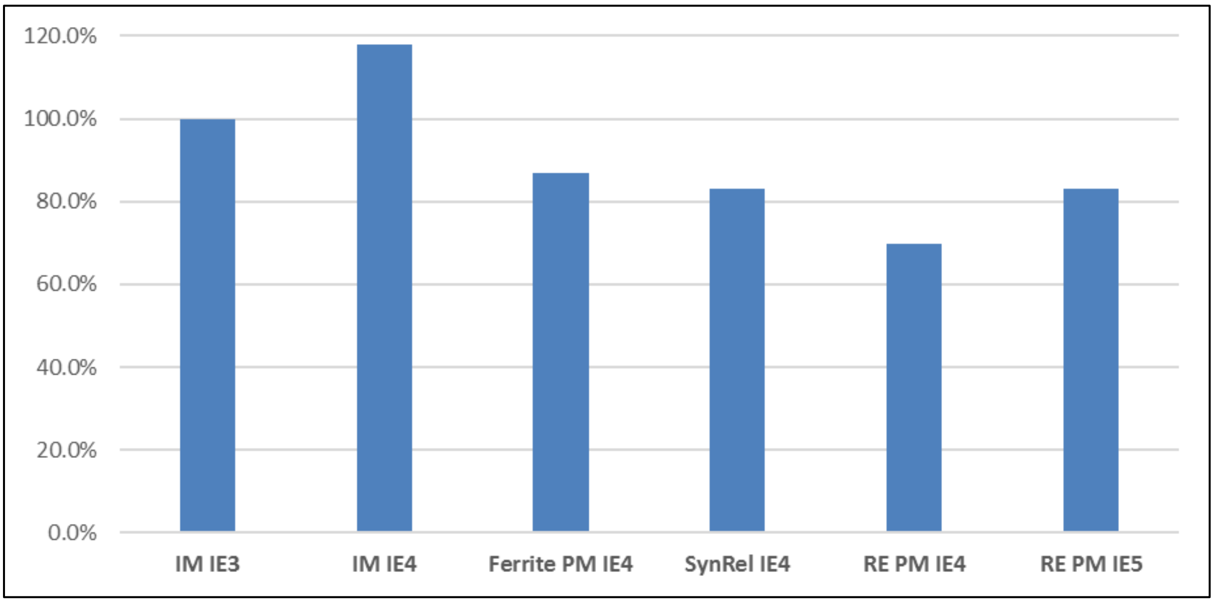

Figure 2 Relative Motor total weight (11 kW; 1500 rpm; aluminum frame; source: ISR-UC: catalogue data, 2016)

Because of the problems presented by the production of rare-earth alloy permanent magnets - (1) Price instability / uncertainty due to concentrated production of Rare Earths, (2) the limited supply of Dysprosium (Dy) and (3) the environmental impact of mining and refining these elements - some manufacturers have started production of motors using alternative technologies and materials, such as:

- Reduced-Dy magnet technology (e.g. Hitachi's dysprosium vapor deposition diffusion technology).
- Recycling (limited by economic feasibility).
- Development of new magnetic materials (some not yet commercially available): Iron Nitride, Samarium Iron Nitride, Cerium and Manganese-based compositions, magnetic nanoparticles and Iron Lithium Nitride [6].
- Much less costly and widely available Ferrite Magnets.

The increasing use of Variable Frequency Drives (VFD) for application with variable loads has also led to the increased awareness of its energy losses: in the VFD in operation, in standby and the further losses in the motor caused by non-sinoidal power supply. VFD energy consumption depends on the losses in the control circuits: motor control, network connection, Input/Output (I/Os), logic controllers and particularly in the output-switches (30-50%). These losses may vary depending on the capabilities of the VFD.

Recent developments in power semiconductor technology and materials, such as GaN (Gallium Nitride) and SiC (Silicon Carbide), can reduce the losses in VFDs (both switching and conduction) by over 50% [7]. These technologies have had their cost decline due to their wider market penetration and economy-of-scale effects.

Another important contribution to the overall energy loss of VFDs is their standby and control power consumption which can also vary widely as can be seen in **Figure 3**. In IEC 61800-9-2, a standby and control loss of 50 W is included for all VFDs which makes for very low efficiencies in the small size segment of 0.12 kW and up to 2 kW.

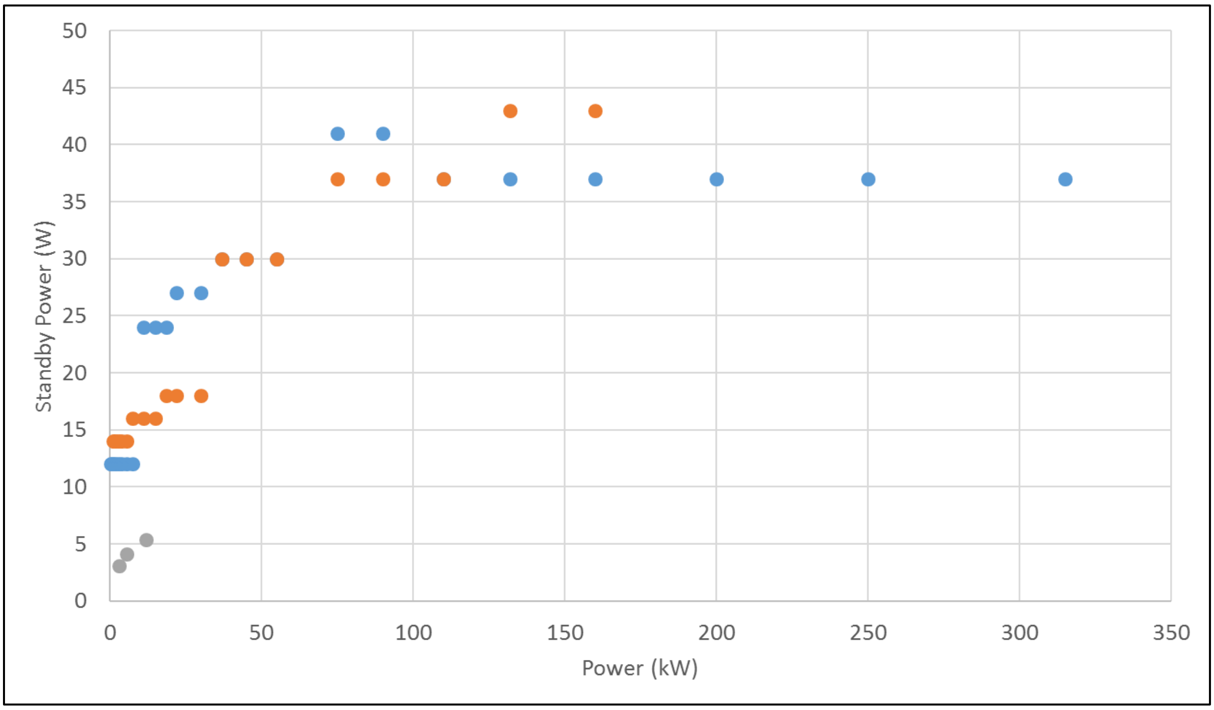

Figure 3 VFD Standby Losses (Source: ISR-UC, manufacturers' data, 2016)

Energy savings in Motor Driven Units

Savings from components

Motor systems (**Figure 4**) are made of individual components that work together to produce mechanical movement. Besides the motor there is the need for several groups of components: equipment for supplying it with power; optional electrical / electronic controls for starting and speed variation; components for mechanically transmitting motion to the driven equipment; the driven equipment itself; and optional mechanical controls and process components. Each of these parts of the system, when present, will have losses which when compounded determine the overall system efficiency.

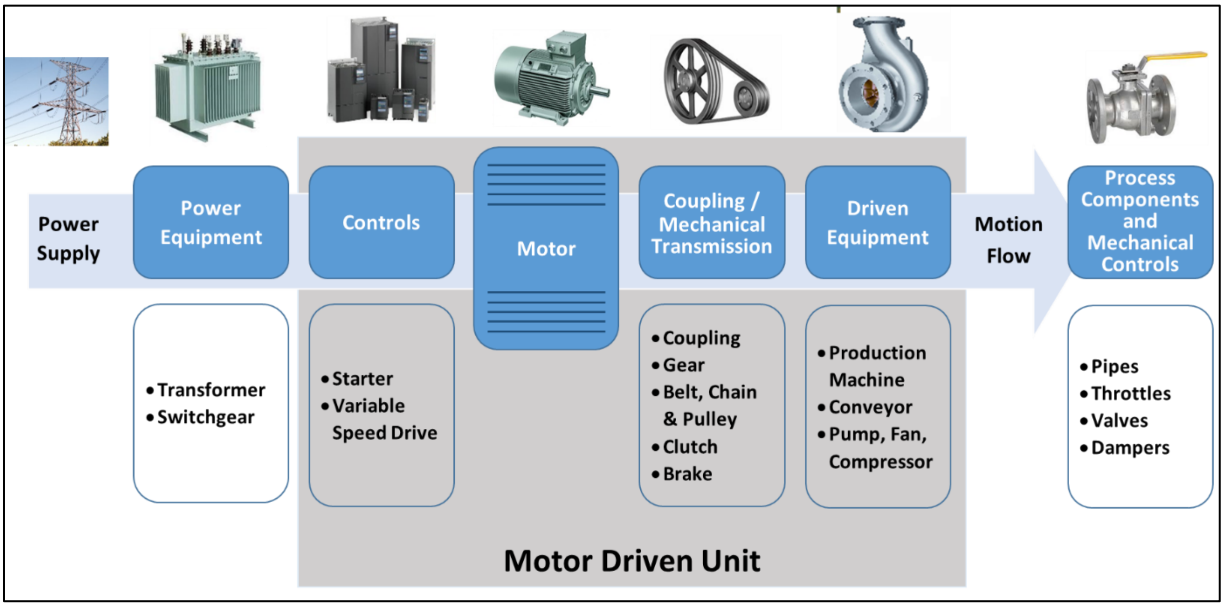

Figure 4 Example of motor system including Motor Driven Unit (Source: ISR-UC)

Savings from system integration

Although component efficiency is important, it is the total process control strategy which offers the highest energy savings potential. In the design of motor systems it is essential to precisely identify the mechanical load requirements (torque-speed characteristics) under a variety of operating conditions (e.g. starting/breaking, steady-state, variable load, on/off, etc.) and then ensure that the best control strategy is used to deliver over the entire operation cycle the desired torque and speed with the maximum efficiency.

In **Figure 5**, the main strategies to reduce the energy consumption in motor systems are depicted, namely, the reduction of power loss in the energy conversion process (motor & converter efficiency increase), reduction of motor & converter output power (reduction of load torque by means of process friction/loss reduction, counterweights use, output speed reduction, etc.), and re-use of stored kinetic and/or gravitational potential energy (energy regeneration for direct use in other motors & converters, injection into the mains grid and/or common DC bus, and/or energy storage in supercapacitors/batteries) [8] [9].

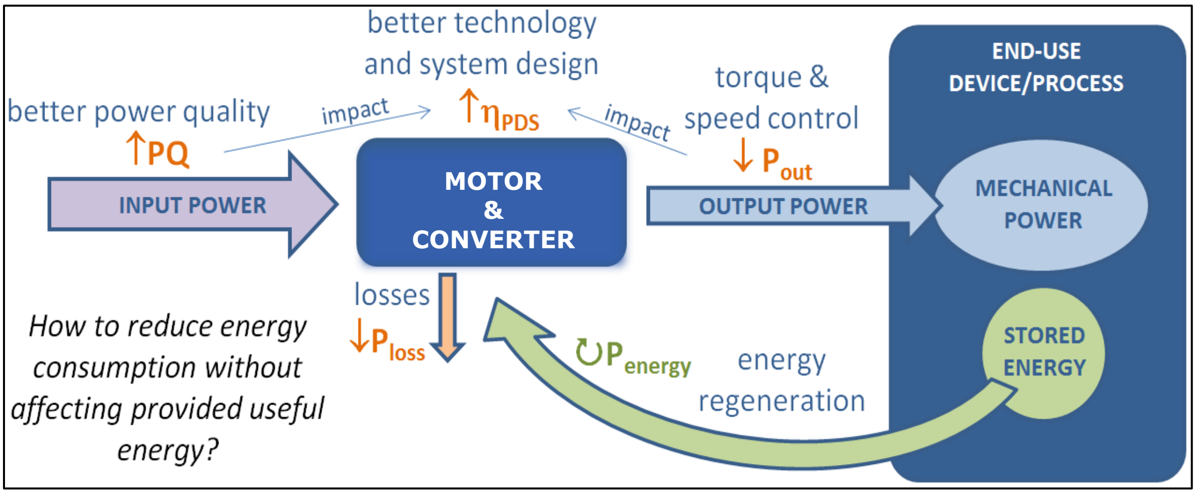

Figure 5 Strategies to reduce energy consumption in Electric Motor Systems (Source: ISR-UC, [8])

Optimized process control using sensors to closely match the output of the motor driven unit to the exact process needs (e.g. matching fan speed to the output temperature in a heat exchanger) as well as the use of regeneration can sometimes save a much larger amount of energy as using high-efficiency components. Loads with a high potential for regeneration include cranes, lifts, and traction/motion control.

Standardization and regulations for motor driven units

Standards

Motors

The International Electrotechnical Commission (IEC) with its 60034 standards series has set electric energy related international standards for low voltage motors (< 1 kV) between 0.12 kW and 1000 kW operated at 50 and 60 Hz. Both the testing standards and the efficiency classes are aligned and updated regularly. The process of harmonization of testing standards between IEC 60034-2-1, CSA 390 and IEEE 112 B has proven successful for fixed speed motors. The publication of the standard IEC 60034-30-1 [10] for harmonized efficiency classes (IE-code) in 2009 has been a global success story.

Lately, with the market success of variable speed applications and first proposals in 2009 [13], also converter fed motors are included in the testing procedure and efficiency classification. For a converter-fed motor a reference converter has to be defined because converters and motors are often not made by the same manufacturer. Agreement has been reached in IEC on the 7 relevant testing points with torque and speed (see **Figure 6**) as well as on the respective interpolation method [14]. With this, all potential operating points of the motor, the VFD and of the application can be easily calculated and verified by tests. But, the efficiency rating proposed for converter fed motors in IEC 60034-30-2 is so far based only on one single operating point: 90% speed and 100% torque of the motor. This does not allow to properly rate a converter with a motor in their typical field of part load operation.

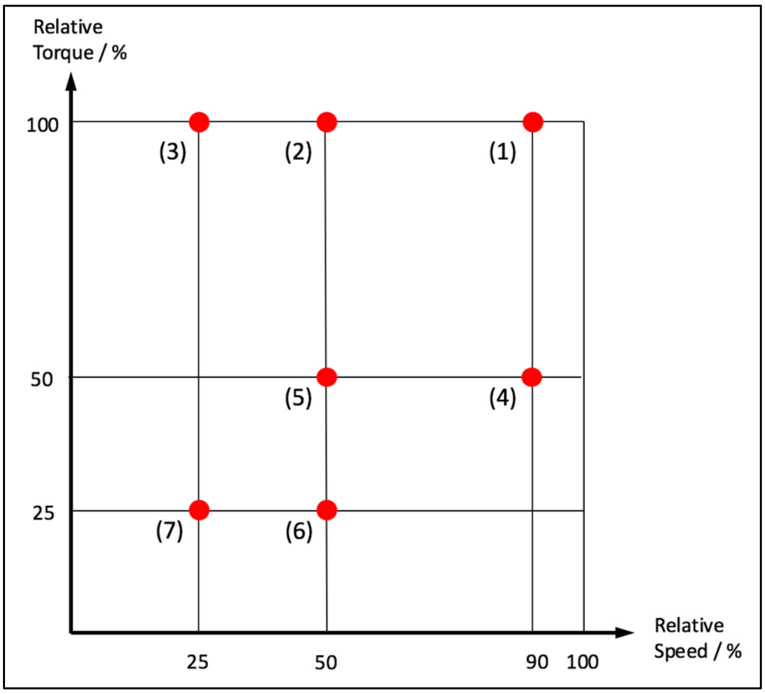

Figure 6 edition Standardized operating points (Source: IEC 60034-2-3 [15], 2, 2017) draft

Table 1- List of IEC energy relevant standards for rotating electrical machines [11]

IEC standard	Date of publication, edition	Title
IEC 60034-1	2017 ed.13	Part 1: Rating and performance
IEC 60034-2-1	2014 ed. 2	Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)
IEC TS 60034-2-3*	2013 ed. 1	Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors, currently under revision
IEC 60034-30-1	2014 ed. 1	Part 30-1: Efficiency classes of line operated AC motors (IE-

		code)
IEC TS 60034-30-2*	2016 ed. 1	Part 30-2: Efficiency classes of variable speed AC motors (IE-code)

*) TS Technical Specification

The introduction of variable speed applications and new motor technologies (Permanent Magnet PM, Switched or Synchronous Reluctance SR) requires an update on testing procedures to include the necessary VFD and to rate the variable speed performance. This task has not yet been completed in IEC. It has launched a broad discussion on how the full and partial load losses in the VFD and the further losses in the motor have to be accounted for in the efficiency classification.

Another subject has not yet been dealt with are efficiency classes for Medium and High Voltage motors (above 1 kV). They are usually larger than 500 kW and are not made in large series. They tend to have slightly larger losses than LV motors but they do not need the respective voltage transformation and therefore do not have these transformation losses.

Variable frequency drives (VFD)

The introduction of variable speed operation with frequency converters changes the picture. The interaction of the VFD and the motors is complex. The advantages of converter use, especially in square torque applications (closed loop pumps, fans), is manifold. Extra losses of the converter at full and partial speed are not the only disadvantage. The motor itself suffers from the Pulse-Width-Modulation-induced non-sinoidal feeding and thus has a reduced efficiency.

The new IEC 61800-9 series is about to clarify standards for variable frequency drives. This means that both the testing standard and the efficiency classes for VFDs are be published in the same document. The testing standard is encountering some problems because the manufacturers of motors and VFDs are often not the same. This means that a "reference converter" has to be defined that will provide for repeatable and accurate efficiency test results. Earlier studies have shown that there are efficiency differences between products of different manufacturers. Therefore, an efficiency classification is necessary. Discussions with industry show that not all types and products of VFD can easily reach the predetermined testing condition. Also, the combined effect of a VFD and the motor are addressed. The current draft IEC standard has not been able to come up with a rating of efficiency at partial load which would be the critical operation point. The efficiency rating is done only in one point: at 90% speed and 100% torque of the motor. The ongoing revision for edition 2 might also reconsider the current analytical model which is based on an old analysis by one manufacturer. It is also desirable to agree that efficiency classes for motors, VFD and their combination are expressed as efficiency (input/output in %) and not only as an absolute loss (W) which is very difficult to compare.

Table 2 List of IEC energy relevant standards for adjustable speed electrical power drive systems [12]

IEC standard	Date of publication, edition	Title
IEC 61800-9-2	Published 2017, edition 1	Adjustable speed electrical power drive systems - Part 9-2: Ecodesign for power drive systems, motor starters, power electronics & their driven applications - Energy efficiency indicators for power drive systems and motor starters, publication expected in mid-2017. Revision (edition 2) has started

Motor Driven Units - the challenge for standardization

The integrated MDU has opened a new field for efficiency standards of mechanical performance of applications in pumps, fans, compressors that is dealt with by the International Organization for Standardization (ISO). Some small products (i.e. circulator pumps, exhaust fans, cooling compressors) include the motor, the application (pump, fan, compressor, etc.) and a VFD into one integrated package manufactured by one producer. This makes for easy testing and performance standards with the resulting efficiency equal to the mechanical output divided by the electrical input (%).

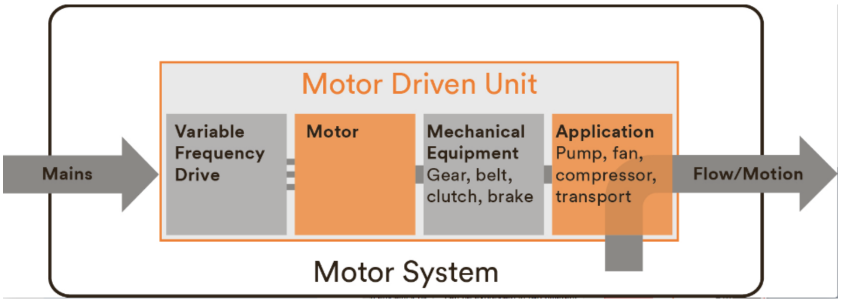

Figure 7 Definition of Motor System and Motor Driven Unit (Source: 4E EMSA 2013)

But, this integrated package is not the case in applications above 2 to 5 kW where the three components are often manufactured by two or even three different producers and assembled only on the factory floor. In such a case both the individual components, their interaction and the entire MDU have to be tested and eventually classified. This system efficiency η_{System} can be expressed in two different ways for the example of a pump MDU that lead to the same result:

$$\eta_{System} = \eta_{VFD} * \eta_{Motor} * \eta_{Pump}$$

or

$$\eta_{System} = (P_{Output} + \Sigma\ (P_{Loss\ VFD} + P_{Loss\ Motor} + P_{Loss\ Pump})\ )\ /\ P_{Input}$$

This calculation for the system efficiency does not yet solve the entire problem: usually the three major components are not independent, that means the addition of their losses does not return a complete result. As mentioned above, the VFD reduces the efficiency of the motor. This has to be accounted for by either an addition loss term or by a combined VFD-motor efficiency.

Table 3 List of selected energy relevant ISO standards for pumps, fans and compressors

ISO standard	Date of publication	Title
Pumps		
ISO 9906 ISO/ASME* 14414	2012 2015	Roto-dynamic pumps -- Hydraulic performance acceptance tests -- Grades 1, 2 and 3 Pump system energy assessment
Fans		
ISO 5801 ISO 12759	2007 2010	Industrial fans -- Performance testing using standardized airways Fans -- Efficiency classification for fans
Compressors		
ISO 1217 ISO 5389	2009 2005	Displacement compressors — Acceptance tests Turbo-compressors -- Performance test code

*) ASME American Society of Mechanical Engineers

The logical next step is to include motors and VFD together with the application in the performance standard, both for testing and efficiency classification. This needs a much closer cooperation between IEC in electrical and ISO in mechanical performance standards than the current attempts. This, and the fact that three major components are involved, increases the complexity of the MDU and makes standardization more complex.

In the IEC 61800-9-1 a first version of a possible methodology for MDUs that has been drafted (based on the earlier Cenelec standard EN 50598-1). It defines the relative power losses of the MDU in order to calculate the system energy efficiency for the whole application.

Table 4 New draft IEC standard for Motor Driven Units

IEC 61800-9-2	Published 2017, edition 1	Adjustable speed electrical power drive systems – Part 9-1: Ecodesign of power drive systems, motor starters, power electronics and their driven applications – General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi analytic model (SAM)

Regulations

National regulations for industrial products, mainly for minimal performance requirements, are usually based on international standards where scope, metrics, methodologies of comparison of performance, efficiency tests, etc., are described in detail. Regulators are at ease when there is an established and widely accepted, globally harmonized standard as a base for a national regulation. Usually the regulation describes additionally only the scope, sets the Minimal Energy Performance Standard (MEPS) and the timeline of entering into force of the respective level of the requirements. It can also stipulate procedures of products (or systems) for check-testing, declaration and registration, etc.

In the three major industrial regions (China, Europe, USA) that in 2014 are responsible for 59% [16] of global electricity use for motor driven systems a fairly large number of component regulations for testing and efficiency classification of motors exist. A somehow shorter list exists for applications like pumps, fans and compressors. The list of countries that include advanced products and technologies (VFD, PM or SR motors) in their regulation is very short. The list of countries that also include regulations for entire MDUs (that are not small integrated and packaged units) is so far nonexistent because the respective IEC and ISO standards are not available yet.

The problem with energy performance requirements of MDUs is complex:

Currently the individual components of a MDU are regulated; the entire MDU is not regulated (with the exception of circulators in Europe and pumps in the US). This means that their interaction escapes the vigilance of the regulator. As we have seen above in the discussion of standards, the interaction includes some complexities in both the widely used partial load situation and the further losses in the motor when driven by a converter.

Industry obviously prefers the way small integrated and packaged products are tested and regulated ("wire to water", "wire to air", etc.) to be used also for larger assemblies: only output and input under rated load are measured in the laboratory, noted and checked. This makes assemblies of components impossible to be tested because they meet only on the factory floor. Physical performance testing in a factory is not possible as precisely as in a laboratory under controlled and repeatable conditions. Also, this leaves the field wide open to the industrial user to mix less performing together with higher performing components in order to meet a minimum requirement. This cannot be the goal of a regulator on the mid and long range.

In the European Ecodesign Directive the principle is included that a pump or a fan that is integrated into another product (like a washing machine or a refrigerator) has to comply with its respective MEPS also when the entire appliance has labels and MEPS to comply with. Industry has called this unnecessary burden "double regulation". Market studies in fans have shown that to exclude the fans built into other products a very large portion of products would never be checked and will remain on low efficiency levels.

Conclusions and recommendations

The challenge for standards in IEC and ISO

The hope is to eventually solve the problem of the large effort for testing and efficiency classification of MDUs by calculation and simulation. If the performance of an individual product and its interaction with another component in a MDU can be described in an easy way by a registered simulation program then the physical test would not be necessary anymore. This simulation needs to involve a series of coordinated standard operating points for a VFD (V, A, cos φ, harmonic content), a motor (torque and speed) and an application (for instance in a pump head and flow), a clear definition of the respective components and a weighted average of the performance at standardized operating points that fits both square and linear torque applications with different annual part load profiles. The simulation program needs to be verified by tests and calibrated according to a necessary international standard.

In the USA the Department of Energy has recognized the Alternate Efficiency Determination Method (AEDM) [18] for motors based on an accredited and third party verified simulation program. IEC is discussing whether an AEDM needs some special definition in any of the existing (or in a separate new) standards for motors. The subject has not yet been discussed as a simulation program for motors with converters and entire MDUs.

The challenge for regulators

Regulators need to consider that on one hand they want to have a transparent market moving unhindered towards more efficient components and MDUs. On the other hand they cannot impose check testing and registration programs without considering the burden and cost for manufacturers in testing, labeling and compliance documentation and certification. The IEC System of Conformity Assessment Schemes for Electrotechnical Equipment and Components (IECEE) as a certification program [19] for motors is certainly a first move in the right direction.

References

[1] Novatorque, "NovaTorque Premium Plus Motor Brochure," 2014. [Online]. Available: http://www.novatorque.com/downloads/NovaTorque-Overview-Brochure.pdf.

[2] R. Werle, C. U. Brunner, R. Tieben: Swiss motor efficiency program EASY: results 2010 - 2014, in: conference proceedings, ACEEE Industrial Summer Study, Buffalo NY, USA, 2015.

[3] M. van Werkhoven, R. Werle, et al., IEA 4E Technology Network: Energy efficiency roadmap for electric motors and motor systems, Paris, France, 2015

[4] A. de Almeida, J. T. E. F. Ferreira and J. Fong, *Standards for efficiency of electric motors - Permanent magnet synchronous motor technology,* Vols. 17, n.1, pp. 12-19, 2011.

[5] A. De Almeida, F. J. Ferreira and G. Baoming, "Beyond Induction Motors – Technology Trends to Move Up Efficiency," *IEEE Transactions on Industry Applications,* vol. 20, no. 3, pp. 2103 - 2114, 2014.

[6] Z. Wang, Y. Enomoto, H. Tokoi, A. Komura, T. Obata and K. Soma, "Development of IE5 High Efficiency Motor with Iron-base Amorphous Magnetic Cores," in: conference proceedings EEMODS'15, Helsinki, Finland, September 2015.

[7] K. Vogel and A. J. Rossa, "Improving Efficiency in AC drives: Comparison of Topologies and Device Technologies," in: conference proceedings PCIM Europe 2014, Nuremberg, Germany, 20 – 22 May 2014.

[8] F. J. T. E. Ferreira and A. T. De Almeida, "Energy Regeneration and Output Power Reduction in Electric Motor Driven Systems," in: conference proceedings IEEE/IAS 52nd Industrial and Commercial Power Systems Technical Conference (I&CPS), Detroit, USA, 2016.

[9] F. J. T. E. Ferreira and A. T. De Almeida, "Energy Regeneration and Output Power Reduction," in: conference proceedings IEEE Industrial & Commercial Power Systems, 2016.

[10] IEC 60034-30-1 (Ed.1): Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code), International Electrotechnical Commission, Geneva, Switzerland, 2014.

[11] IEC Technical Committee 2 (TC2): Rotating Machinery (32 participating countries, 16 observer countries).

[12] IEC Subcommittee 22G (SC22G): Adjustable speed electric drive systems incorporating semiconductor power converters (22 participating countries, 19 observer countries).

[13] A. de Almeida, C.U. Brunner, P. Angers, M. Doppelbauer: Motors with Adjustable Speed Drives: Testing Protocol and Efficiency Standard, in: conference proceedings EEMODS 2009, Nantes, France 2009

[14] M. Doppelbauer: Interpolation procedures for the determination of losses and energy efficiency of electrical machines, in: conference proceedings EEMODS 2015, Helsinki, Finland, 2015

[15] IEC 60034-2-3, Committee draft, 2017 (confidential)

[16] M. van Werkhoven, R. Werle, et al., IEA 4E EMSA: Policy Guidelines for Motor Driven Units, part 1, Zurich, Switzerland, 2015

[17] World Energy Outlook 2016, OECD/IEA, Paris, France, 2016

[18] B. Finley: AEDM, in: conference proceedings of Motor Summit 2016, Zurich, Switzerland, 2016

[19] D. Delaney: IECEE, in: conference proceedings of Motor Summit 2016, Zurich, Switzerland, 2016

Energy Efficiency in Compressed Air Systems – A review of energy efficiency potentials, technological development, energy policy actions and future importance

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Abstract

Compressed Air Systems (CAS) play a key role in all kind of production processes, as compressed air is remaining to be the key energy carrier in a broad range of applications. Since the first studies on energy efficiency and energy consumption of motor driven systems about 20 years ago, significant changes and actions occurred. After the EU study on compressed systems in the European Union, published in 2001, a number of national action have taken place, for example in Germany and Switzerland, to realize the energy savings in CAS not only to reduce energy consumption and related emissions but also to strengthen competitiveness of the industry. Since the studies had been undertaken, the EU had been enlarged from 14 to now 29 countries, leaving a lot of open questions in regards to the current status of motor driven systems in the EU. Also countries outside the EU, for example the US, and Asia, are trying to improve CAS with a number of different measures.

The introduction of a new energy efficiency classification scheme for electric motors together with minimum energy performance standards (MEPS) for electric motors have triggered also improvements in the production of compressed air, however still the losses in the system such as air leakages or pressure drops play typically a more important role in the efficiency of the whole system but remain widely untapped.

To support the increased uptake of more efficient technologies, programs providing financial support for the replacements of compressors and other cross cutting technologies had been introduced for example in Germany and Switzerland.

Compressed air as a service also received a lot of attention after the liberalization of the electricity market but has been cut back when the focus moved back to the competition on electricity prices rather than energy services. So insights are given into the structure of the compressed air service market and the barrier associated to service models.

Introduction

At the end of the 90ies, the EU with its 14 Member States where aware that energy consumption and energy efficiency will play a key role in the competiveness of the European Industry, with rising energy prices challenging the European Industry. It was at that time, the EU launched a significant number of studies on electric motors and motor driven systems to get insights into the overall consumption figures throughout Europe and the related energy efficiency potentials [1–6]. When the work moved from the motor to the motor systems such as pumps, compressed air, fans and refrigeration it became obvious, that the major savings in such system will not be in the motor but in the system aspects. Typical economic saving potentials identified in these studies where between 15 and 30 %.

Despite these high economic savings potentials, industry showed significant reluctance to implement related measures. Based on this experience the European Commission launched the Motor Challenge Program, which still exists today, to reduce the barriers for implementation, however today only a small number of people know about it and it might be worth considering new action to support the achievement of the energy efficiency target within the EU.

In the area of CAS, Germany and Switzerland had been very active in country specific joint actions based on a broad campaign to inform and support energy efficiency measures in CAS.

However, 20 years later it is time to look back and to analyze the achievements and the shortfalls that still need to be solved.

Since then the EU has introduced the 2020 targets for energy efficiency, which had further strengthened to improve energy efficiency by 27%. The recently published winter package of the EU is proposing even to strengthen the energy efficiency target to 30% for 2030 and to more clearly put energy efficiency first, which was out of focus due to a concentration on renewable energy policies.

The current paper tries to analyze the status quo in regards to consumption, savings potentials and uptake of energy efficiency measures in CAS.

Importance of energy efficiency in Compressed Air Systems

The first comprehensive study on CAS in the EU-14 was published in 2001 by Radgen & Blaustein [1]. Based on data collection in France, Germany, Italy and the Netherlands, the authors calculated the electricity consumption in CAS and identified an economic savings potential of 32.9 %. The largest saving opportunities had been attributed to air leakages, waste heat recovery, the overall system design and control systems to improve part load behavior of the systems.

Since then, very little fieldwork has been done to broaden the basis for a better forecast and extrapolation of energy consumption to the Eu-28 or other parts of the world. In the US comparable efforts had been undertaken to deepen the insight by the compressed air challenge [7].

In the framework of the Ecodesign directive air compressors had been looked at underlining that there has been little work undertaken to better understand the utilization and energy consumption of CAS in Europe [8]. The EuP studies are focusing on sales data of compressors, however the prodcom classification does not allow to get all the relevant and required data. Currently an follow up study on oil free compressors and low pressure compressors are underway [9].

The recent EuP study on compressors are however highlighting that the compressor as the product is not the main source of poor system efficiency. Still there seem to be a lack of knowledge and a lack of efforts to improve the energy efficiency of CAS.

The Compressed air campaign in Germany (Druckluft effizient, 2002-2006) [10] and in Switzerland (Effiziente Druckluft; 2005-2008) [11] as well as a broad number of activities around the world for producing information material on how to improve the energy efficiency of CAS can be identified. So there remains little doubt on the potentials and opportunities in CAS but better insights are required to update the technical possibilities based on the overall technological development as well as on the overall benefits for companies and the society as a whole.

Energy consumption of Compressed Air Systems

Obtaining country specific energy consumption data for CAS is a difficult task and is not often addressed in scientific publications. The general problem with the existing publications is the fact that all publications are taking a reasonable number of assumptions because of the lack of a reliable database.

Fleiter & Eichhammer [12] started by gathering information on electricity consumption of industrial sectors in several countries. Since most countries do not differentiate electricity consumption by end users, these allocations had to be estimated. The authors note that these estimations, especially for developing countries have to be analyzed with care due to special factors such as usage of combustion engines and a higher share of manual work. The energy consumption calculated in this study is shown as blue bars in *Figure 45*.

To evaluate the findings of this study, a number of other studies addressing this aspect are analyzed [13–21] and compared to the results, typically giving values only for single country (orange bars in *Figure 45*). The quality of those sources varies significantly. For example, McKane & Hasanbeigi (2010) [17] published a comprehensive report on energy efficiency in motor systems. Compressed air consumption form a part of this study. It analyzes the country specific energy consumption of compressed air allocated to industrial sectors in the USA, Canada, the EU, Thailand, Brazil and Vietnam. To determine the compressed air use by sector, McKane & Hasanbeigi conducted a literature review and used additional input by six compressed air experts to estimate the actual consumption.

An example for sources with limited quality of the foundation of the results is Mehke [14], dealing with the energy consumption for compressed air in India. The publication is more a sales pitch of a company active in the field of compressed air metering rather than a robust analysis. Mehke presents a table for energy consumption of CAS in India by sectors. There is no explanation, how the data was collected or which sources were used. The energy consumption for compressed air in India by Mehke (~ 88,000 GWh/a) and Fleiter & Eichhammer (~ 19,000 GWh/a) differ by a factor of 4.5.

Comparisons of data from different sources illustrate the difficulty of the missing database for CAS worldwide. Using the publication by Fleiter & Eichhammer as a reference, the deviations range from -40 % for Russia to + 385 % for India. While there are only minor deviations in the proclaimed consumption for the EU (+4 %), a deviation of 60-80 % applies for the USA, Japan, Brazil and Thailand. The three countries/regions with the highest energy consumption for compressed air generation are China, the EU and the USA.

In addition there will be a rather different growth path in the US and Europe compared to China, India and Asia. Whereas in the developed world there will be typically a stagnation of consumption or even a reduction where as in developing countries still an increase should be envisaged, therefore data on installed stock should be used carefully and only together with the indication of the base year.

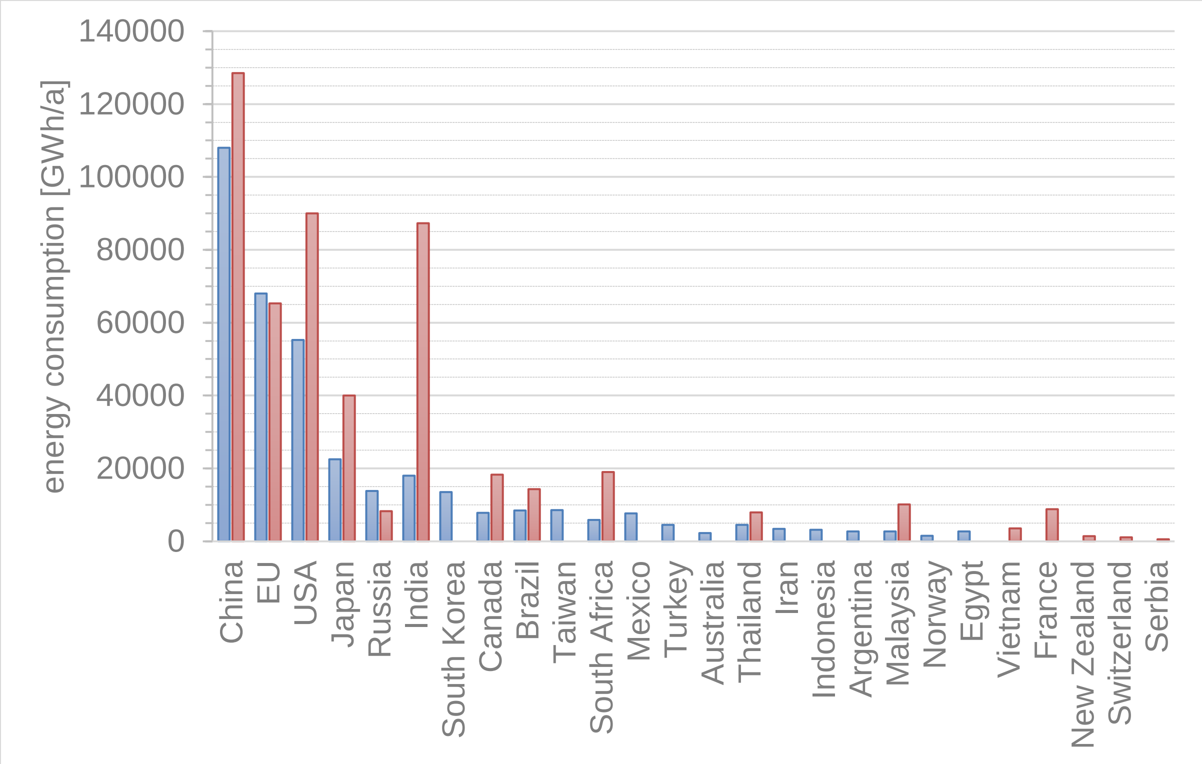

Figure 1: Energy consumption for compressed air generation in selected countries; blue [12]; orange [13–21]

An interesting fact is that two major publications on the country specific energy consumption of CAS concern Switzerland, although it has a low energy consumption compared to the main consuming countries. The first publication was conducted by Gloor in 2000 [22]. To estimate the energy consumption for compressed air in Switzerland, Gloor used a statistic on sold compressors in Switzerland from 1998. The in 1998 newly installed capacity is calculated and extrapolated on the total capacity of compressors in Switzerland. Gloor estimates the average overall full load hours to be 750 h/a resulting in an electricity consumption of 750 GWh/a, which represents about 1.5 % of the total energy consumption in Switzerland. In 2014 Lang together with representatives from the compressed air sector published a comprehensive study on the electricity demand for compressed air generation in Switzerland [20]. The study used a bottom up approach to calculate the energy consumption by sectors. For calculation, several classes for companies according to the amount of employees had been used. These classes have specified installed capacities for generating compressed air as well as full load and stand-by hours. The values for each class were determined using input of several experts. An advantage of this approach using different classes and different industries (19) is the ability to consider industry-specific working hours and capacities. This study is based on estimates from experts. Exact measurements or field data collection was not in the scope of this study. The calculation resulted in an energy consumption of 1,100 GWh/a for compressed air in Switzerland, however highlighting also the actual consumption range of 900 – 1,300 GWh/a. The comparison of both publications on Switzerland's energy consumption for CAS shows that even detailed analyzes have to rely on estimates by experts and can therefore can deliver quite varying results.

A study by Wünsch et al. examines the energy consumption of CAS in Germany by sectors [23]. Due to the lack of a reliable database, Wünsch et al. used a bottom up method to calculate the energy consumption for compressed air. The bottom up method uses characteristic values and typical operating hours to calculate/estimate the energy consumption for compressed air. *Figure 46* shows the results obtained by the study. The highest demand for compressed air is in other manufacturing industries, which covers all industries not named separately. The sectors with the highest demand are vehicle manufacturing and rubber & plastic. Reasons being the high degree of automation in the vehicle manufacturing and the high demand of compressed air for processes in the plastic industry. The share of electricity consumption for compressed air generation varies greatly between sectors. The lowest shares are identified to be in basic chemistry and chemical industry with only 1.8 %. High shares are found in rubber & plastic, glass & ceramics and stone & earth industries with up to 17 %. Results on the consumption however do not allow making any statements on the efficiency of CAS.

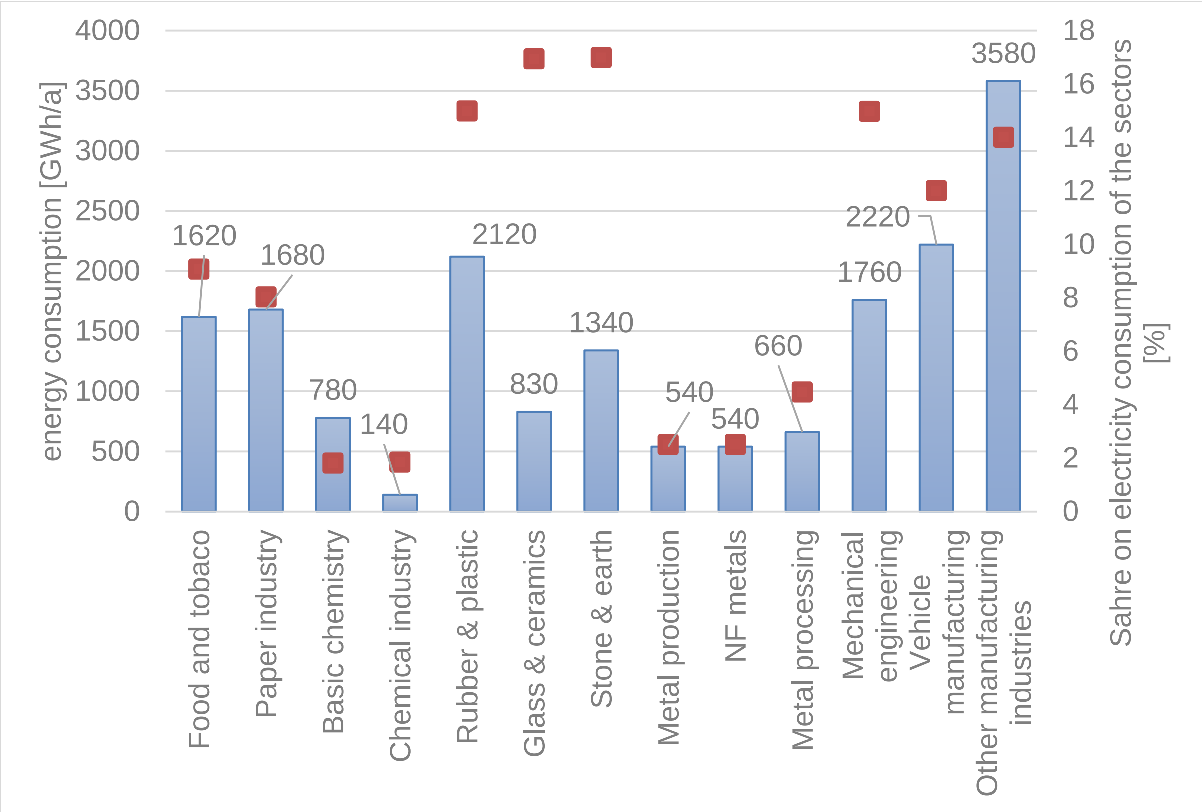

Figure 2: Energy consumption for compressed air generation in Germany (2008) by sectors [23]. Blue: energy consumption, orange: Share on electricity consumption of the sectors

Energy savings in Compressed Air Systems

Even if technical measures to improve the energy efficiency of CAS will be globally valid, the share to which extend technology improvements are already incorporated in the CAS vary significantly. Some factors will also be dependent on climate conditions or the average altitude of a country. Therefore it is important to look on energy saving potentials from a national rather than a global perspective.

Country specific energy savings Potentials

However, there are only a few publications on country specific energy savings potentials in CAS. A general problem stated by the authors of these studies is the lack of data. Most countries and even most companies do not record their energy consumption for compressed air generation. All of the studies have in common, that they are based on assumptions for consumption, energy savings and conditions of CAS.

A comprehensive study was published by McKane & Hasanbeigi in 2010 on the motor efficiency supply curves [17]. The scope of this study is the identification of energy savings potentials in motor driven systems, including CAS, for several countries/regions representing different levels of industrial development and varying sizes. The study analyzes the potentials in the United States, Canada, the European Union, Thailand, Vietnam and Brazil. For this study, McKane & Hasanbeigi conducted a literature review on the country specific savings potentials in CAS and more importantly interview respective experts to estimate those potentials due to missing data. However no indication is given on the number of the participating experts. Baselines for low, medium and high efficiency scenarios are developed. Typical efficiencies for these scenarios are calculated and assigned to the selected countries. Going on, the cost effectiveness of several efficiency measures is calculated and matched with the respective energy savings. This allows calculating a fictitious electricity price for the saved energy. As long as this price is lower than the actual electricity price, the measure is cost effective. A problem with this approach is that the electricity prices in a country can vary significantly depending on the overall consumption, the consumption structure as well as additional charges and levy's, so the electricity price can be different by a factor of more than two for different end customers. *Table 19* shows the economic and technical energy savings potentials in CAS for the evaluated countries. The difference between the technical and economic savings potentials increase with the level of industrial development. Low energy efficiency standard often go hand in hand with a lower development of the economy. In these countries typical low upfront cost (Investments) are an important decision factor. However, countries with high electricity prices like Brazil typically have higher economic potentials as the return on investment increases with high electricity prices.

Table 1: Economic and technical savings potentials in CAS based on [17]

Savings potentials GWh/a	**USA**	**Canada**	**EU**	**Thailand**	**Vietnam**	**Brazil**
Economic savings	20,344	4,707	18,519	3,741	1,609	6,069
Technical savings	28,403	7,498	24,857	4,381	1,970	6,762

The first comprehensive study on savings potentials for CAS in the EU by Radgen & Blaustein (2001) proclaimed economic savings of 32.9 % (= 26,320 GWh). It is important to keep in mind, that the EU had only 14 members at that time. The calculated savings by McKane & Hasanbeigi [17] are based on the EU with 27 member states. The difference in the calculated savings have multiple reasons. The study from 2001 already covers the countries with the highest energy consumption. The additional members only play a minor role. Since the release of the study in 2001, many government programs were launched to increase energy efficiency in CAS. A resulting increase of the average efficiency is highly probable.

Table 20 shows the top 3 cost effective energy efficiency measures for CAS according to McKane & Hasanbeigi [17]. The highest savings, with over 18,374 GWh/a are accounted to Leakage reduction and optimized systems controls. An interesting result of this study is that compressors with variable speed drive, which are mentioned in most other studies on energy efficiency in CAS, is highlighted as not being cost effective.

Table 2: Top 3 cost effective measures for energy savings in CAS [17]

Measures for energy savings in CAS		USA	Canada	EU	Thailand	Vietnam	Brazil	Total savings
Leakage reduction and system control optimization	[GWh]	7,073	1,867	6,190	986	444	1,814	18,374
Eliminate inappropriate compressed air uses	[GWh]	3,479	918	3,045	467	210	722	8,841
Install sequencer	[GWh]	2,825	745	2,684	562	213	866	7,895

The most recent study on energy savings potentials in CAS was published by Fleiter & Eichhammer in 2011 [12]. The results of that study are shown in *Figure 47.* The savings potentials are estimated and represent the cost effective potentials. The exact method used to obtain the published values is not explained in the publication. Comparing the energy savings potentials proclaimed by Fleiter & Eichhammer with the ones from McKane & Hasanbeigi, the weaknesses of estimating potentials become clear. For USA and Canada, the published savings potentials of both publications have only minor deviations. The savings potentials for Brazil published by Fleiter & Eichhammer (~ 4,000 GWh/a) is about 33 % less than by McKane & Hansanbeigi (~ 6,000 GWh/a). A similar situation occurs for the savings potentials in the EU. According to Fleiter & Eichhammer the savings potential is about 31,500 GWh/a, McKane & Hansanbeigi indicate only about 18,500 GWh/a. The deviation of these potentials is about 40 %.

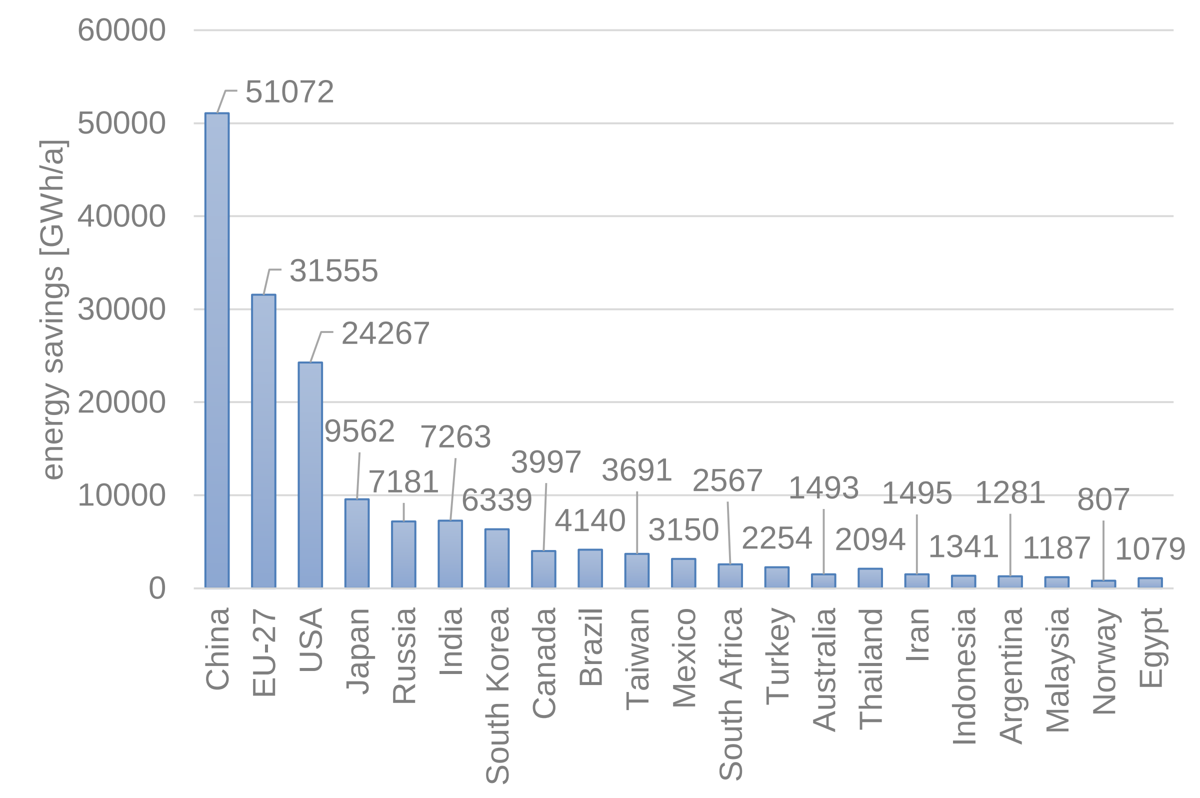

Figure 3: Energy savings potentials in CAS for several countries [12]

To illustrate the problems that accompany estimating energy savings potentials on a weak database, a comparison of two publications on the energy efficiency potentials for Switzerland is made. In 2000 Gloor estimated the savings potentials on 100 GWh/a [22]. The calculation for these potentials is kept very simple. Gloor estimates average cost effective savings potentials to be 25 % and calculates with an implementation rate of 50 % in the industry, thus resulting in 100 GWh/a. In comparison, Lang published a study on the electricity demand of CAS in Switzerland in 2014 [20]. This study evaluates the energy demand for CAS in the Swiss industry. As most publications on the energy demand and savings potentials in CAS, this study relies on estimations by experts. The energy savings potentials amount to 245 GWh/a and an additional potential of 255 GWh/a for using heat recovery. Adding up these savings, Lang indicates potential (cost effective) savings 5-times as high as Gloor. This comparison on the savings potentials in Switzerland clearly illustrates, that the problem with the studies on savings potentials is the lack of a reliable data for energy consumption and the actual condition of CAS in industry. Therefore much more real data collection is necessary to achieve more robust calculations. Reasonable assumptions have to be made for the calculations but results strongly depend on the assumptions selected by the authors of the studies.

Energy efficiency measures in Compressed Air Systems

There are many publications dealing with measures for increasing the energy efficiency in CAS. All these publications present more or less the same or similar suggestions.

Table **3** presents an overview of proposed energy efficiency measures, the most common being:

- Reduce leakage
- Reduce/avoid unnecessary pressure drops
- Lower system pressure

- Install/optimize compressor controls
- Install heat recovery
- Use variable speed drives

Table 3: Energy efficiency measures in CAS

Measures	**McKaine & Hasanbeigi [17]**	**Radgen & Blaustein [1]**	**Kaeser compres-sors [24]**	**Festo [25]**	**da Cunha [26]**	**Gloor [22]**
Reduce leakage	X	X	X	X	X	X
Minimize pressure drops	X	X	X	X	X	X
lower system pressure	X		X	X	X	X
Install sequencer / optimize compressor controls	X	X	X		X	X
Heat Recovery		X	X		X	X
Variable speed drive	X	X			X	X
Improve end use efficiency	X	X			X	
Predictive Maintenance program	X	X			X	
Replace compressor	X	X			X	
Zero loss condensate drains	X				X	X
Eliminate inappropriate compressed air uses	X					X
Optimize compressor intake conditions	X					X
Match air treatment to demand side needs	X	X				
High efficiency motors		X	X			
Improved system design		X				X
Optimize air dryers					X	X
Partly shut off compressed air		X		X		

Measures	McKaine & Hasanbeigi [17]	Radgen & Blaustein [1]	Kaeser compres-sors [24]	Festo [25]	da Cunha [26]	Gloor [22]
networks during stand-by						
Shorten hoses				X		
Several measures for more efficiency in pneumatics (e.g. energy recovery, lower weight, less friction, correct dimensioning, …)				X		

The majority of those publications can be classified in one of two categories: publications from manufacturers (e.g. compressors or pneumatics) and government-funded publications promoting energy efficiency in CAS.

Most manufacturers for compressors or pneumatics produced publication on energy efficiency in CAS for marketing purposes. However even if these publications are sales orientated, they provide relevant facts on the importance of energy efficiency in CAS. As the function often as a door opener with the clients they do not present wrong facts but may not inform about all relevant aspects. The target audience of these publications are project engineers and energy managers of companies, not scientists. An example for publications of that particular category is published by Kaeser compressors [24]. This specific publication gives simple formulas to calculate the energy costs of compressed air generation and leakages. *Figure 48* shows the actual costs for leakages at different leak sizes. In addition, heat recovery is discussed and a simple checklist describes potential actions to increase energy efficiency and the resulting saving potential. The three biggest potentials are heat recovery with up to 90 %, efficient compressor control with up to 45 % and leakage reduction up to 35 % additional savings.

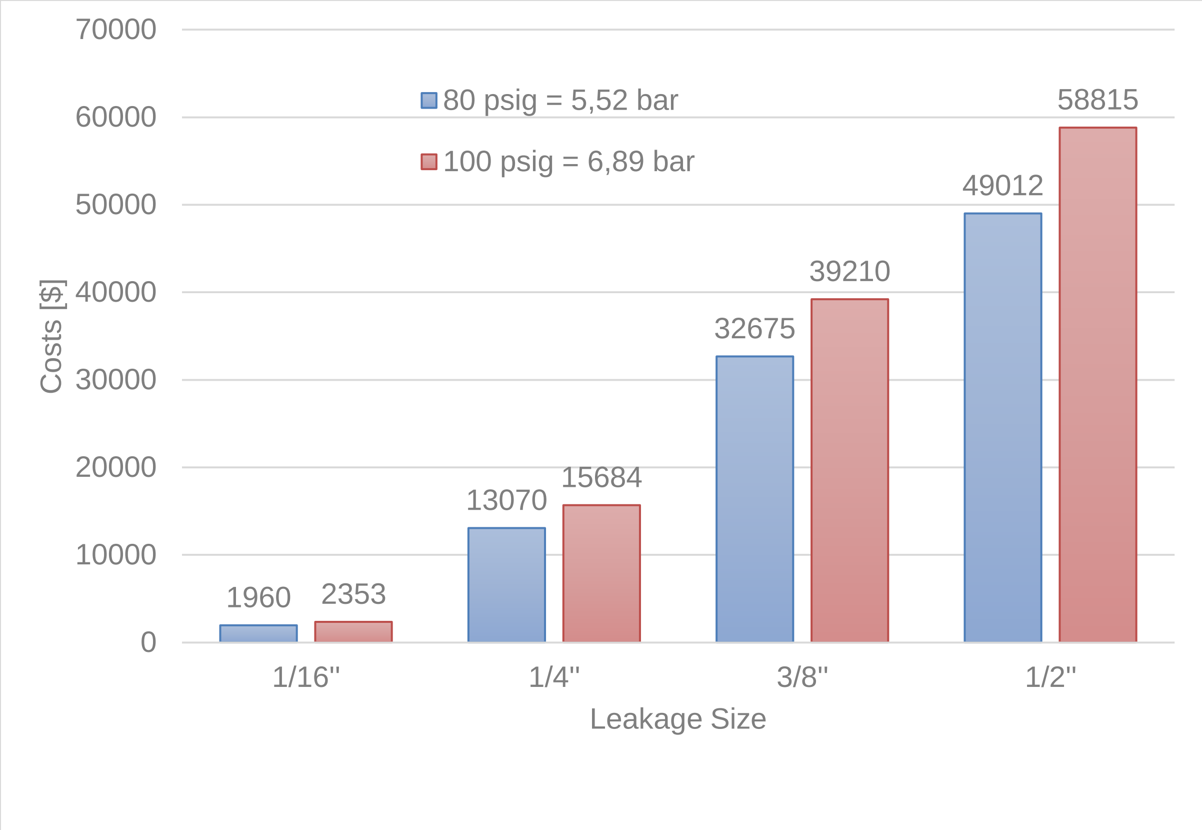

Figure 4: Leakage Costs at different pressures based on 8760 h/a and 0,1 $/kWh [24]

Another example for publications by manufacturers (pneumatics) is Festo [25]. The publication focuses on energy efficient pneumatics. Optimizing the compressed air generation and treatment is not part of this publication. However, it is very detailed about energy savings in pneumatics. Festo proposes several additional measures like the correct dimensioning of pneumatic cylinders, energy recovery on pneumatic cylinders or the shutdown of compressed air pipes during stand-by operation. Festo indicates the potential savings for different industries (see

Table **22**).

Table 4: Energy savings potentials for different industries on selected measures [25]

Measures	Description	Energy savings potentials in several industries		
		Automobile	**Food**	**Electronics**
Correct dimensioning	Smaller pneumatic cylinders	10%	13%	2%
Energy recovery	In pneumatic applications	3%	3%	3%
Shutdown of pipes during stand-by	-	8%	8%	8%

The interpretation of publications from manufacturers becomes obvious when such publications are analyzed. Manufacturers typically set their products and savings that could be achieved by applying them in the focus. So these articles are often biased towards the respective company/products. However, they show actual commercial products and are valid indicators for rough assessments on savings potentials, but typically overestimation the saving potential that could be achieved in the real application.

Most countries try to decrease their carbon footprint with a variety of measures. Many countries see energy efficiency as an important factor to achieve their goals. The average efficiency of CAS is low, thus potential energy savings are very high in these systems. However, the economic savings potentials are high, therefore typical non-financial barriers are hindering implementation of measures. This is one of the main reasons, why a number of different countries promote energy efficiency in CAS.

In 2000, the Swiss federal office of energy ordered a study on energy savings potentials in CAS in Switzerland. The results of that study were published by Gloor [22]. The study is divided in three parts and offers 26 measures for potentials savings. Those three parts are compressed air generation, compressed air distribution and compressed air consumers. Gloor does not calculate specific savings, but analyses and judges potential energy saving measures and there cost effectiveness. In the category of compressed air generation, Gloor describes several measures dealing with the actual compressors. He proposes the usage of variable speed drives and the maintenance of compressors (especially filters). In addition to that, higher-level controls, heat recovery and the reduction of system pressure is mentioned. To increase the energy efficiency in the distribution of compressed air, Gloor suggests increasing the pipe cross section, a regular exchange of filters and an adjusted air treatment. For the last category, compressed air consumers, Gloor suggests the substitution of certain processes and the reduction of leakages at couplings and hoses.

Another example for publications on energy efficiency in CAS by the government is Canada. In 2007, Natural Resources Canada published a guide for energy efficiency in CAS, written by Da Cunha [26]. This guideline covers several important aspects of compressed air. It educates for example about compressor types and controls, air treatment, misuses of compressed air as well as energy efficiency measures. Da Cunha discusses leakage, pressure drops, compressed air usage, heat recovery and air treatment as energy efficiency measures.

Da Cunha rates the energy savings by introducing heat recovery with 50-60 %. Comparing this value with the one published by Kaeser [24] (up to 90 %), a significant difference is noticeable. There are several reasons for that deviation. The calculation of energy savings due to heat recovery depends on the temperature level and whether air or water is used as the heat transfer medium. Up to 90 % savings are possible if air at a low temperature level is used (e.g. for heating). In the practical applications, many heat recovery systems are water based and work at higher temperature levels, thus resulting in lower energy savings. Another important factor is the heat demand. During winter, the recovered heat can be used for space heating. In summer, when the heat demand is low, the recovered heat cannot be used, so there are no energy savings. Using water as heat transfer medium enables the usage in low temperature industrial processes.

Da Cunha also presents data for the costs by leakage depending on the leak size (see *Table 23*). Leakages are permanent consumers, as long as the respective branch is not shut off during weekends/holidays or at night. Typical calculations of leakage costs use 8760 h/a as operating hours. The comparison of the extrapolated data (see *Table 23*) with the data from Kaeser, shows that for leak sizes of 1/2'', the costs are almost identical. Going on to smaller leak sizes, the deviations increase but show no linear behavior. For a leak size of 1/16'', the difference is about 60 %. This comparison shows a typical problem of these publications. The data on leakage costs is presented with little or no information on the actual calculation, boundary conditions and/or measurement setup.

Table 5: Leakage Costs at different leak sizes based on 0,1 $/kWh [26], [24]

Leak size	3 Shifts (8400 h) [26]	Da Cunha (extrapolated on 8760 h/a) [26]	Kaeser 8760 h/a (5,52 bar) [24]	Deviation in estimated costs
1/16'' (~1,6 mm)	750 $ (~709 €)	782 $ (~739 €)	1,960 $ (~1,852 €)	- 60 %
1/4'' (~6,4 mm)	11,990 $ (~11,332 €)	12,504 $ (~11,818 €)	13,070 $ (~12,353 €)	- 4.3 %
3/8'' (~9,5 mm)	26,980 $ (~25,500 €)	28,136 $ (~26,592 €)	32,675 $ (~30,882 €)	- 13.9 %
1/2'' (~12,7 mm)	47,850 $ (~45,225 €)	49,901 $ (~47,163 €)	49,012 $ (~46,323 €)	+ 1.8 %

Case studies on the implementation of energy efficiency measures in Compressed Air Systems

Energy efficiency, especially in CAS, is an important cost factor for companies. Since most of the life cycle costs of compressed air are caused by consumed electricity, optimizing CAS should be a top priority in companies and in the literature. However only few scientific papers are directly linked to the implementation of measures for energy efficient CAS.

In [27] Yang describes the implementation and the results of a compressed air audit in a Vietnamese company (footwear manufacturing). The company uses 8 compressors with total capacity of 1.4 MW. According to the study, the energy consumption for compressed air is 8 GWh per year. During the audit, the CAS was analyzed comprehensively. The audit focused on 9 different aspects: air treatment, pressure levels, pressure controls, heat recovery, load profile, end-use equipment, compressor package, filter and dryers and air leakages. Most examined aspects turned out to show acceptable performance, except leakage and pressure controls. The average identified leakage rate in the CAS of the company was 65 %. This leakage is equivalent to an energy consumption of around 4.8 GWh per year. The author suggests searching and repairing the larger leaks as well as educating the workers and thus decreasing the energy consumption to 3.9 GWh per year. The payback time calculated for leakage remediation as well as the relocation of compressors was about 5 months according to Yang.

Part of the German campaign "Druckluft effizient" (see informational campaigns for more details) is a measurement campaign for CAS in the industry. The results of that campaign were published by Radgen in 2004 [28]. Over 190 companies took part in the free audit of their CAS. Radgen evaluates the results of 40 of these audits. The study indicates a higher demand of compressed air is usually linked with a higher overall efficiency. Larger companies tend to have experts or trained staff for their CAS, while that is not the case in smaller companies. The average savings potential was about 18,000 €/a per company and independent from the saving percentage. The study also evaluates the reasons for the participation in the measurement campaign. Only 29 % state high energy consumption of the CAS as the main reason. Most companies plan to renew (43 %), expand (14 %) or experienced defects (21 %) with their CAS. This is a clear indicator of the lack of information on the energy efficiency in CAS.

However, there are several websites promoting energy efficiency in CAS, which present a variety of successful projects. Case studies can be found for example at [7,29–32]. All these publications have a similar structure. They are five pages at most and are written in a more colloquial style. The focus of these studies are the economic benefits through increased energy efficiency, most of the case studies show payback times of one year and less. A detailed calculation of the savings potentials is normally not included. Most of the reported data on energy savings and resulting economic benefits are estimates from experts. In the following a selection of case studies is presented in more detail.

The U.S. department of energy presents a project concerning the implementation of a leak management program at an automotive plant [33]. The goal of the project is to cut down the losses due to leakage. An energy team of volunteering workers at the company is formed. The baseline for the compressor operation is taken during production and holiday shutdown, to estimate the actual amount of leakages and to calculate potential energy savings. Leaks are then identified and fixed by the energy team. Furthermore, awareness for energy efficiency among the workers is aroused by several promotion measures. The result for the company has been a reduction of the annual energy consumption of 11.5% which was equivalent to savings of 560,000$ per year.

Another case study by the U.S. department of energy covers energy efficiency measures at a chemical company [34]. The company partnered with Tennessee Technical University to identify potential savings in their CAS. At first the baseline of the compressed air demand was measured. The report highlights significant amount of air leakage, ineffective dryers and poor performing compressors due to a lack of maintenance. As a result, the compressors and dryers had been repaired and a leak detection and repair program was established. These measures led to an annual energy saving of 413 MWh (about 31,000 $/a). The payback period was about one year.

A case study by Marshall [35] analyzes energy efficiency measures in a sawmill and a paper mill. As a starting point, a CAS audit was conducted. The audit showed leakages occurred with up to 35 % of the compressed air demand. Additionally, damaged air dryers as well as the lack of compressed air storage were identified. Next, leakages were detected and repaired, dryers were renewed or repaired and additional compressed air storage was added to the system. The resulting savings were 1,100 MWh/a or 125,000 $/a. The payback period was one year.

Federal promotion programs for energy efficient Compressed Air Systems

Due to climate change and the resulting agreements, most countries set goals for energy efficiency to decrease their total energy consumption. As shown in this paper, savings potentials in CAS are high and can be realized in a cost effective and financially attractive manner. Thus, countries launched a variety of programs/measures to promote energy efficiency in CAS. To promote energy efficiency in CAS countries rely on financial incentives, informative publications and laws/standards. This chapter gives an overview of programs/measures in several countries. It is not performing a comprehensive evaluation of all existing programs/measures worldwide.

Financial programs

Many countries introduced financial programs to support investments in energy efficient CAS. An overview of existing financial programs is given in *Table 24.* Due to the limited scope of this study, only three programs are presented here in more detail. The chosen countries are Switzerland, Germany and the United Kingdom.

Switzerland introduced a program, financially supporting the implementation of energy efficiency measures called the Swiss competitive tenders in 2010 [36]. The funding of the measures is based on an auction process focusing on cost effectiveness of the measures. Either individual measures within a single company can be supported or programs aiming at implementing similar measures at a number of different end users. Individual application can be made twice a year. In addition programs for CAS had been awarded funding under the competitive tenders, providing support with the implementation The program dealing with CAS (ProEDA2) is a three-step program [36,37]:

1. Preliminary analysis: Rough assessment of energy savings potential in the company including a visit at the company for 2-3 h
2. Detailed analysis: Measurement and evaluation of the compressed air consumption and generation for 1-2 weeks. Investment proposal for future actions concerning the energy efficiency in the CAS with a calculation on energy savings.
3. Implementation: Investment of the respective company in the proposed measures from step 2.

The grant is funding of 50 % for step 1, 25 % for step 2 and up to 20 % for the actual investment in step 3. The target group are companies with an installed compressed air capacity of over 18 kW. Companies with an energy consumption of over 500,000 kWh/a can apply for funding of leakage detection devices (up to 1,000 SFr.). The aim of ProEDA2 is to save 48 GWh/a of electricity within the 3 years of operation of the program.

Germany supports investments in energy efficient CAS as part of the support program for cross cutting technologies ("Förderung von Querschnittstechnologien" [38]). This program consists of two parts, the funding of individual measures and system optimization. As part of individual measures, investments in high efficient compressors, heat recovery and high level controls are funded with up to 30 % of the investment costs (maximum support per applicant is 30,000 €). The program also supports the purchase of ultrasonic sensors for the detection of compressed air leakages with up to 500 €. In addition, the overall optimization of CAS is funded under this program. To apply for funding, a detailed energy concept has to be developed by an energy consultant, showing minimum energy savings of 25 %. As part of system optimization, additional compressed air components can be funded, for example compressed air storage tanks, compressed air network components, etc. Funding is up to 30 % of the investment, with a maximum of 100,000 € and an additional 60 % of funding for consulting costs with a maximum of 3,000 €.

The United Kingdom established the "Energy Technology List" (ETL) as part of governmental funding of energy efficient technologies [39]. The ETL was established in 2001 and consists of products with a high energy efficiency. It is updated on a regular basis. Companies can apply for funding, if they invest in technologies that are included in the ETL. The funding are basically enhanced capital allowances. Enabling the companies to write off 100 % of the investment costs for those technologies in the financial year of the purchase. The maximum of annual investment allowances is limited to 200,000 £ per year. The following categories concerning CAS are on the ETL:

- Desiccant Air Dryers with Energy Saving Controls
- Flow Controllers
- Master Controllers
- Refrigerated Air Dryers with Energy Saving Controls

Informative programs

Many countries introduced information campaigns or produced information material to raise awareness for energy efficiency in CAS. An overview of existing information programs is given in *Table 6*. Due to the limited scope of this study, only three programs are presented in more detail. The chosen countries are Germany, Switzerland and the USA.

Table 6: Financial and informative programs on efficient compressed air

Country	Financial Program	Informative Program
Australia		Sustainability Victoria: Best practice guidelines [40]
Austria		Guide for compressed air [41]
Columbia		www.si3ea.gov.co/Portals/0/Gie/Tecnologias/aire.pdf
France		http://www.ademe.fr/guide-pratique-lair-comprime
Germany	Querschnittstechnologien Programm	www.druckluft-effizient.de
Ireland		Energy MAP [42]
Northern Ireland	Interest free energy efficiency loans	www.carbontrust.com/resources/guides/energy-efficiency/compressed-air/
Serbia		Guide for increasing energy efficiency of CAS [43]
Switzerland	ProEDA2	www.druckluft.ch
UK	Energy Technology List	www.carbontrust.com/resources/guides/energy-efficiency/compressed-air/
USA		www.compressedairchallenge.org
Wales	Interest free energy efficiency loans	www.carbontrust.com/resources/guides/energy-efficiency/compressed-air/

One of the most comprehensive programs called "Druckluft effizient" was active in Germany between 2001 and 2004. The campaign was a follow-up of the European study by Radgen & Blaustein [1] on CAS, that showed a lack of information on energy efficiency in CAS. The campaign consisted of the following parts [10]:

- Public relations: Placing the campaign in relevant media to raise awareness
- Information: Free online publications on energy efficiency in CAS
- Measurement campaign: Measurement of CAS in companies and development of individual measures to increase efficiency
- Award: Award for companies optimizing their CAS
- Demonstration unit: Used to illustrate typical problems in CAS
- Benchmarking: Online-based tool to compare CAS on energy efficiency
- Financing: Publications on contracting for compressed air

The final results of the achievements of the program (Agricola et al. [10]) highlight that over 50 % of companies that took part in the measurement campaign went on to implement the proposed efficiency measures. The campaign was discussed/mentioned in over 133 articles (more than 5 Mio circulation), which indicates the success of the campaign. The campaign ended in 2004, but the website with all information is still online (www.druckluft-effizient.de), even if the provided information is no longer updated or maintained.

Based on the success of the German campaign "Druckluft effizient", Switzerland commissioned a study to transfer the campaign to Switzerland [44]. In 2006, Switzerland launched their own campaign on energy efficiency in CAS. This campaign focused on the following aspects [45]:

- Information: Awareness raising for compressed air. Additionally, publications on the optimization of CAS, extension or replacement of existing CAS and green field compressed air installation are available free of charge
- Economic analysis: Focusing on life cycle costs instead of investment costs. Excel Tools for easy calculation of benefits from energy efficiency measures
- Benchmarking: Online-based tool to compare CAS on energy efficiency

Given the Multilanguage environment of Switzerland, all information is provided in French, German and Italian and some tools even in English. The original website www.druckluft.ch was merged into the overall website of the Swiss Energy Campaign "Energie Schweiz". After the first wave campaign at the end of the year 2000, there is currently running the second wave of the campaign with the updating of the information. The Swiss campaign is still on going and updates are made on the content.

Also in the USA an information campaign on energy efficient compressed air use is in place [46]. All of the information is placed on the website of the Department of Energy (Office of Energy Efficiency & Renewable Energy). The campaign focuses on the following aspects:

- Compressed air tools: AirMaster+ (free) enables to identify energy savings calculate life cycle and operating costs, etc.
- Compressed air training: Online Webcasts on the usage of the tools and Workshops on energy efficiency in CAS
- Qualified specialists: Contact data to find specialists for compressed air in the USA
- Compressed air case studies: Several case studies of compressed air energy efficiency projects
- Compressed air tip sheets: Short publications (1-3 pages) on multiple important topics in CAS (easy understanding)
- Compressed air technical publications: Detailed publications on energy efficiency in CAS

Another program by the USA is the compressed air challenge [7]. It offers similar information as the other programs, but offers additional training courses.

The target of all information campaigns in the different countries is to raise awareness for energy efficiency in CAS and to provide compressed air user with the information required to make informed choices for updating their CAS. All programs concentrate on the areas of the largest saving potentials. Another similarity is that all programs created simple tools to facilitate the calculation of potential savings. In addition, case studies can be found at all programs to see the ease of implementation of measures as well as the very positive cost benefit ratio for the measures in a real company environment.

Laws and standards

Laws and standards had been focusing in the past typically on health and safety issues. In the last years, requirements for energy efficiency had been introduced into the relevant laws to ensure the improvement of energy efficiency of products. Laws and standards for energy efficiency in CAS can be directly related such as minimum energy performance standards (MEPS) for compressors or indirect, like MEPS introduced for electric motors or fans. A summary of MEPS for electric motors in several countries is shown in *Table* 7. The MEPS in Europe require IE3 standard for applications of more than 7.5 kW. Most compressors used in the industry have at least a capacity of 18 kW and are thus required to use electric motors with an efficiency class of IE3 or higher to drive the compressor. In many other countries/regions, the legislation is similar to Europe with different limits or requirements. The reason behind this is to fade out less efficient electric motors by prohibiting their sale. In that way, the average efficiency of electric motors and subsequently the efficiency in CAS is increasing.

Table 7: Several country specific MEPS for electric motors [47]

Efficiency Classes	**Range for Country-specific MEPS**	**Country MEPS Regulation**
IE3	USA (0.75-375 kW)	US DOE 10 CFR Part 431, Effective 6/1/2016
	Europe 2015 (>7.5kW) 2017 (>0.75kW)	ErP Directive, Regulation 640/2009
	Canada (0.75-150kW)	Canadian EEA, CSA C390
	Mexico (0.75-375kW)	NOM 016-ENER-2010
	Korea 2015-2017	MOCIE/KEMCO
	Japan	Top Runner
IE2	Canada (15-375kW)	Canadian EEA, CSA C390
	Australia (0.75-190kW)	AS/NZS 1359:2004
	New Zealand (0.75-190kW)	AS/NZS 1359:2004
	Brazil	NBR 17094-1
	Korea	MOCIE/KEMCO
	Argentina	IRAM 62405
	China	GB 18613-2010
	Europe	ErP Directive, Regulation 640/2009
	Turkey	SMG-2012/2

A study by van Werkhoven et al. from 2016 analyzed standards and regulations on motor driven systems, including motors, pumps, fans and compressors [48]. The results of the study are summerized in

Table **8**. The study indicates that most regions/countries implemented regulations on electric motors, with India, Russia and South Africa having no regulations on motor driven systems. China is so far the only country that has implemented MEPS for compressors, the USA and the EU have MEPS for compressors under development.

The European Union is evaluation the introduction of MEPS for compressors under Lot number 31 and are covered by the eco-design directive. The status (February 2017) on compressors is, that the preparatory study on oil injected compressors has been completed and the final report being published [8]. Currently the draft final report for the extension of lot 31, covering oil free and low pressure compressors has just been released. [9]

Table 8: Overview of existing regulations for Motor driven systems in main economic regions [48] (X: regulations in place, D: regulations under development/evaluation, -: no regulations)

Region	**Presence of Regulations**				**% of global electricity use of motor systems**
	Motors	**Pumps**	**Fans**	**Compressors**	
China	X	X	X	X	28,3 %
USA	X	X	D	D	15,6 %
EU28	X	X	X	D	15,0 %
India	-	-	-	-	5,0 %
Japan	X	-	-	-	4,4 %
Russia	-	-	-	-	4,1 %
Korea	X	-	-	-	2,7 %
Brazil	X	-	-	-	2,5 %
Canada	X	D	-	-	2,3 %
Mexico	X	X	-	-	1,4 %
South Africa	-	-	-	-	1,2 %
Saudi Arabia	X	-	-	-	1,0 %
Australia	X	-	D	-	1,0 %
New Zealand	X	-	-	-	0,2 %
% Global electricity use by motor systems covered by regulations	76 %	60 %	43 %	28 %	85 %

According to the Kyoto protocol, countries are required to reduce their greenhouse gas emissions. As part of the Kyoto protocol, the clean-development-mechanism (CDM) was established. The CDM allows to invest in in emission-reduction projects in developing countries to earn certified emission reduction (CER) credits. The CERs can be traded and used to achieve the emission reduction goals of industrialized countries. The idea behind CDM is the lower costs for emission reduction projects in developing countries due to a lower average efficiency standard. Since the introduction of CDM in 2001, about 7760 projects (Feb. 2017) have been registered [49]. Two projects increased the energy efficiency in CAS in factories in Malaysia and Mexico. Additionally, there is a PoA (Program of Activities) for compressed air energy efficiency [50].

Technological development in Compressed Air Systems

Over the last decade, several technological developments in CAS took place. The developments cover a wide range from compressed air generation to air treatment and ongoing digitalization. A general problem is the lack of scientific publications on those developments. Scientific articles often focus on a specific problem, like the simulation of a screw compressor or the temperature distribution on the screws. General developments and practical applications are rarely described in these publications. However, the technological development is reflected in the constantly increasing energy efficiency of products sold on the market.

As an example, two scientific publications on technological development on compressed air generation are shortly analyzed.

Hsieh et al. [51] published a paper on the temperature distribution in rotors of oil injected screw compressors. They are proposing a mathematical model to calculate the temperature distribution in the screws of a screw compressor. Additionally experimental data had been collected to improve the accuracy of the mathematical model. The proposed mathematical model can be used to improve the geometry of screws in compressors, through a better estimation of deformation due to thermal stress.

A paper by Krichel & Sawodny [52] focuses on the dynamic simulation of oil-flooded screw compressors for compressed air generation The presented mathematical model for the screw compressor consists of four subsystems, the screws, the oil/air separator, the motor and losses. The resulting model is detailed enough to account for dynamic effects in real compressors, still enabling the use in more complex models with additional components.

Over the last decade, there is an increasing trend toward the use of oil-free compressors. All major manufacturers offer oil-free compressors. In general, oil-free screw compressors can be categorized by the utilized coolant. There are water injected and air or water-cooled screw compressors. The energy efficiency of water injected screw compressors is higher than for the indirectly cooled oil free compressors, because lower compression temperatures can be reached. Compared to oil injected or water injected compressors, oil free screw compressors have typically two stages with intermediate cooling. On the other hand, water injected screw compressors need a special corrosion protection (e.g. non-corrosive steel alloys or coatings) and typically have a shorter lifetime. Basic data and information on the different compressors can be found online on the websites of compressor manufacturers but typically, the provided data do not state the efficiency of the compressor but provide only data on air delivery and the size of the electric motor. Therefore, customers need to ask suppliers directly to obtain this important information.

Industrial processes that require oil free compressed air can be found for example in the food and pharmaceutical industry, where compressed air with contaminants of oil can lead to contaminated products causing health damages.

However even if processes are requiring oil free air, this can be provided with both types of compressors as air treatment is necessary in any case. Using oil-injected screw compressors requires a special treatment of the air downstream of the compressor. Usually oil separators are used for standard purity classes. To meet the requirements for high purity classes, additional filters (activated carbon) or catalytic devices have to be installed. Oil-free compressed air can also be generated using oil free compressors. In order to achieve high purity classes additional filters or catalytic devices have to be installed, depending on the oil concentration in the ambient air.

A general problem is the definition of oil free compressed air. The standard ISO 8573 regulates the purity classes for compressed air. Class 1 has to have an oil concentration below 0.01 mg/m³. The standard also included a class 0, however for the class 0 no exact limit for the acceptable oil concentration is defined, and so every value better than class 1 would be acceptable. An oil concentration of 0 mg/m³ is not possible. It should be kept in kind that oil free compressors compress ambient air, which typically contains contaminants. *Figure 49* shows the oil concentration in Ludwigshafen (Germany), as well as Centre Fr.-Ebert which is located in the city center of Koblenz (Germany) and the maximum oil concentration of class 1 compressed air [53]. This clearly illustrates, that under certain conditions an oil-free compressor is even not able to produce class 1 compressed air without additional air treatment downstream the compressor.

There are several case studies from companies switching from oil injected to oil free compressors like [54], but the technical information is often held to a minimum, as most of the case studies are "progress reports".

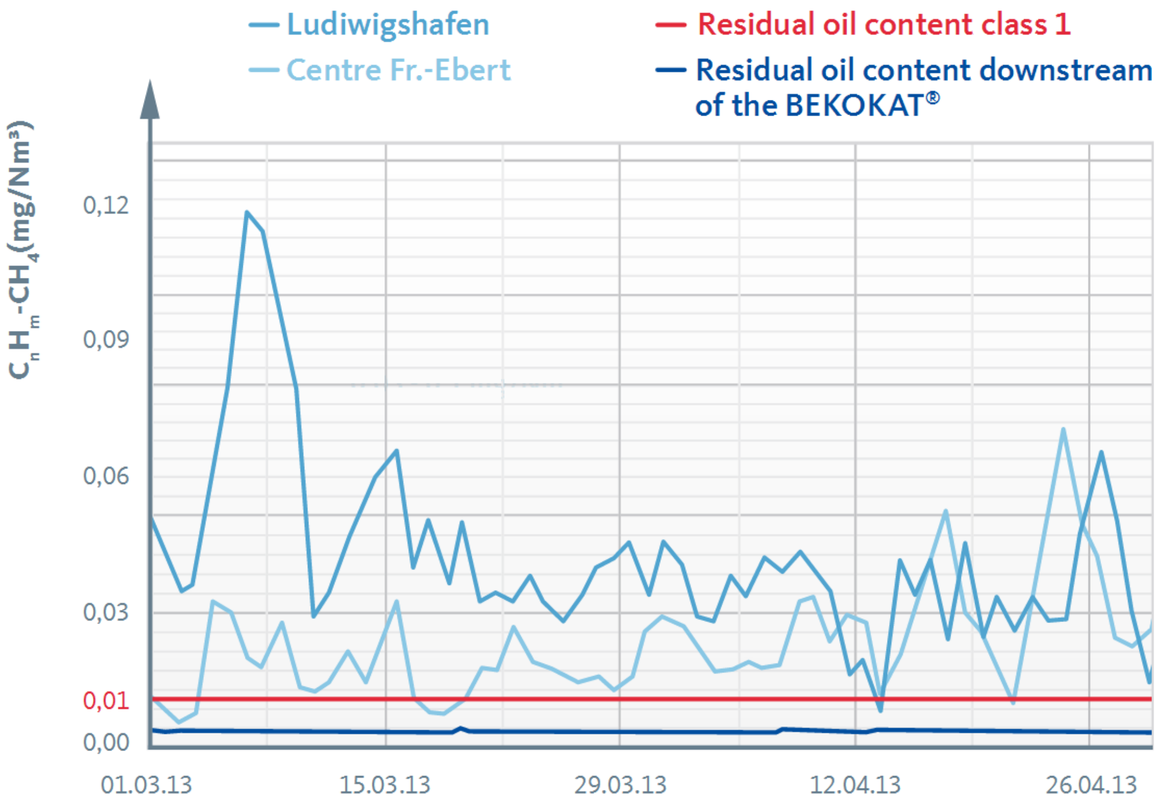

Figure 5: Oil concentration in ambient air and allowed oil concentration according to ISO 8573 class1 [53]

Compressed Air as a Business Model

Since the liberalization of the electricity market, energy services (e.g. for compressed air generation) caught a lot of attention. In 2001, Dudda et al. [55] published a guide on contracting for CAS. The publication aims at informing end users considering a contracting solution for their compressed air demand. The report explains the different types of contracting for compressed air and show advantages and disadvantages of the different business models.

Contracting models for compressed air services

The biggest share in contracting solutions has energy-supply-contracting with over 90 %. The customer buys compressed air with a certain quality directly from the contractor typically for a fixed price per m³. The contractor has to care about financing and maintenance of the compressed air generation. Normally, the price per m³ compressed air is composed of a basic price for financing, maintenance and operation and an operating price depending on the consumption of compressed air. The compressors and periphery for air treatment are owned by the contractor. An important advantage of this type of contracting is the high cost transparency, avoidance of own investments low investments and no need for trained staff for the operation. Paying per m³ in principle incites measures for energy savings in the respective company. Key disadvantages of energy-supply-contracting are rather long contract periods giving less flexibility and the challenge to correctly define the interface between customer and contractor. In most cases the outlet of the compressor station after air treatment is chosen as the interface, with the air meter being a key element for the cost allocation. If the interface is fixed at the outlet of the compressor station, the contractor has no incentive to optimize the compressed air distribution or to reduce leakages. So it might be possible to include the compressed air network and maintenance in the contract but this will required special efforts, as leakages might occur in core production processes where the customers do not want the contractor to be active. If electricity is not counted for but provide to the contractor free of charge, it would be necessary to add a guarantee for the specific energy consumption for the compressed air generation the contractor has to adhere. [55]

Another important contracting model, however with significantly smaller share of 6 % of the market, is performance contracting. The idea behind this business model is the financing of the contractor through energy efficiency measures. Performance contracting is mostly used when replacing old systems. The contractor calculates the revenue on the difference between the costs for compressed air generation of the old and the improved system. As a first step, the contractor does a comprehensive analysis of the initial state and potential energy savings. The responsibilities operation, plant engineering and investments in energy savings measures lies with the contractor. Typical advantages of performance contracting is the identification as well as assessment of energy savings potentials, low investment costs, and less trained staff required by the customer. Disadvantages are a high conflict potential due to estimations on energy savings and thus resulting costs and the difficulty of setting prices for the future, especially when compressed air requirements in terms of amount and quality change over time. [55]

Structure of the compressed air service market and barriers of contractors

A study by Radgen published in 2014 [56] analyzes the service market for compressed air in Germany. The annual market for contracting in Germany is only about 1 % compared to the market volume for compressors directly sold. The study is based on personal interviews with providers (contractors). The six considered contractors are compressor manufacturers, electricity supply companies (regional and supra regional) and service providers. Covered services of each provider are identified. Compressor manufacturers offer the most services since they already have a national wide service network and experts for measurements, planning and operating of CAS. Compressor manufacturers normally only consider their own products for compressed air services and their business structure is typically not suited for long-term contracts.

Supra regional electricity supply companies however cover fewer services, due to a lack of expertise in measurements, planning and operation of CAS. Those services are often outsourced to compressor manufacturers. Supra regional electricity suppliers profit from their contacts through power supply at the management level of potential customers.

Compressed air services is seen as an opportunity to expand their business after the liberalization of the energy market [56].

Regional electricity supply companies profit from their awareness level in their home region. Compressed air services are seen as an opportunity to expand their business supra regional. Specialized service providers have a broad understanding of compressed air needs in the industry and of CAS in general. They profit from the lack of qualified experience about CAS in many companies. However, their biggest obstacle is the low awareness level in the industry [56].

Additionally, the study analyzed the experiences of the service providers with contracting. Five out of six providers had made both positive and negative experiences with the business model. One particular company only made negative experiences and stopped offering compressed air services. The examined companies stated that there is massive price competition during acquisition. Acquisition is deemed vital by all interviewed service providers. The acquisition process takes a lot of time and is very expensive, because most "first evaluations" are free of charge to be able to present contracting opportunities to customers. Earnings are made through successful contracts, but the financial return depends on the actual contract period. As a consequence, companies need to have a sufficient capital stock to survive especially in the first years of service offers [56].

However, there are several barriers for compressed air services that are valid for all service providers. First, it has to be defined where the exact transfer point for compressed air is, e.g. after the generation and treatment, or between the network and the actual consumers. The measurement procedure for the compressed air consumption and the air quality has to be specified. In many cases, the customer has cheaper electricity prices than the contractor. The usage of the low prices has to be agreed by contract. Low electricity prices for the contractor can lead to less efficiency measures. Both parties can agree on certain efficiency standards. Since most contracts, especially with performance contracting are long-term, increasing energy prices or significant change of compressed air consumption can lead to conflicts between customers and contractors. Thus, necessary actions to be undertaken in these cases should be discussed in advance. [55,56]

Conclusion

This paper has analyzed the available information on CAS. Even if there has been a lot of awareness on CAS, there is a significant lack of credible and reliable data. For this paper, we have looked at energy consumption and energy efficiency measures as well as information campaigns and financial support schemes.

The country specific energy consumption for compressed air generation for several countries from different sources are presented and compared. The high uncertainty related to the determination of the actual consumption, which mostly relies on estimations, was highlighted by the comparison of different sources. Sectoral disaggregation for compressed air energy consumption had been presented for Germany, showing a strongly diverging role of compressed air in different sectors.

Furthermore, country specific energy savings potentials for CAS had been collected for this paper. A comparison of studies for Switzerland indicates the problems of obtaining a reliable database for compressed air energy demands and the deviations in the proclaimed potentials through estimations and changed boundary conditions. Since energy savings potentials in CAS are high, the major energy efficiency measures are presented in this paper. A comparison of different sources show deviations, because of the lack of reliable sources and the usage of practical values and "rule of thumb" estimations. The costs of compressed air for companies is a notable factor. Case studies present successful cases of implementing energy efficiency measures in several companies.

It can be concluded again, that average savings potentials in CAS are very high. As most countries have set goals for energy efficiency, tapping the cost efficient potentials from CAS should be high on the agenda. A non-comprehensive overview of governmental programs on energy efficiency in CAS had been given together with highlight from the information campaigns in Switzerland, Germany and the USA. Also countries aiming at triggering investment with financial programs in Switzerland, Germany and the United Kingdom. The status of minimum efficiency standards for compressors together with an overview of current laws and standards for electric motors and compressors had been presented.

Over the last decade, several technological developments in components of CAS took place. Since most research and development is done by manufacturers, results are rarely published. Thus, the paper highlights the need for more scientific papers on compressors and CAS, looking not only on technical details of single components but addressing the overall system for the provision of compressed air.

New business models for compressed air services may help to transform the market towards higher energy efficiency; however, energy services are facing significant difficulties to take up significant market shares.

References

[1] Radgen P, Blaustein E. Compressed Air Systems in the European Union: Energy, Emissions, Savings Potential and Policy Actions 2001.

[2] Keulenaer H de, Belmans R, Blaustein E, Chapman D, Almeida AT de, Wachter B de et al. Energy Efficient Motor Driven Systems … can save Europe 200 billion kWh of electricity consumption and 100 million tonne of greenhouse gas emissions a year; 2004.

[3] Almeida AT de, Ferreira F, Fonseca P, Chretien B, Falkner H, Reichert J et al. VSDs for Electric Motor Systems; 2001.

[4] Almeida AT de, Fonseca P, Ferreira F, Guisse F, Blaise J, Clair E et al. Improving the Penetration of Energy-Efficient Motors and Drives; 2000.

[5] Birks J. Energy Audit Procedures for Electric Motor Systems; 2000.

[6] Radgen P (ed.). Market study for improving energy efficiency for fans. Stuttgart: Fraunhofer IRB Verl; 2002.

[7] Compressed Air Challenge. Compressed Air Best Practices; Available from: https://www.compressedairchallenge.org/library/.

[8] van Elburg M, van den Boorn R. Electric motor systems / Compressors ENER LOT 31. Brussels; 2014.

[9] van Elburg M, van den Boorn R. Preparatory study on Low pressure & Oil-free Compressor Packages 2017.

[10] Agricola A, Radgen P, Zelinger M. Druckluft effizient Abschlussbericht; 2005.

[11] BFE Schweiz. Energieeffizente Druckluftanlagen; Available from: www.druckluft.ch.

[12] Fleiter T, Eichhammer W. Energy efficiency in electric motor systems: Technology, saving potentials and policy options for developing countries; 2011.

[13] Bashmakov I, Borisov K, Dzedzichek M, Gritsevich I, Lunin A. Ressource of energy efficiency in russia: scale, costs and benefits 2008.

[14] Mehke S. Compressed air metering; Available from: http://www.greenbusinesscentre.com/EES2010/Presentations/Compressed/Mr%20Suhas%20Mekhe,%20Forbes%20Marshall.pdf.

[15] Qin H, McKane A (eds.). Improving Energy Efficiency of Compressed Air System Based onSystem Audit; 2007.

[16] Sullair. Fundamentals of Compressed air systems; Available from: https://www.nipsco.com/docs/default-source/commercial-industrial-docs/compressed-air-1.pdf.

[17] McKane A, Hasanbeigi A. Motor Systems Efficiency Supply Curves; 2010.

[18] Seslija D, Ignjatovic I, Dudic S, Lagod B. Potential Energy Savings in Compressed Air Systems in Serbia 2011.

[19] Cai M, Kagawa T. Design and Application of Air Power Meter in Compressed Air Systems 2001.

[20] Lang T. Elektrizitätsbedarf dür die Druckluft in der Schweiz 2014.

[21] CEREN. Le gisement d’économies d’énergie dans les opérations transverses de l’industrie; 2010.

[22] Gloor R. Energieeinsparungen bei Druckluftanlagen in der Schweiz 2000.

[23] Wünsch M, Seefeldt F, Schlomann B, Fleiter T, Gerspacher A, Rohde C et al. Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008: (Auswertung für das Jahr 2008); 2012.

[24] Kaeser Compressors. Energy Savings in Compressed Air Systems 2010.

[25] Festo. Effizienz@Festo 2014.

[26] da Cunha I. COMPRESSED AIR: Energy Efficiency Reference Guide; 2007.

[27] Yang M. Air compressor efficiency in a Vietnamese enterprise. Energy Policy 2009;37(6):2327–37.

[28] Radgen P. Druckluft effizient: Messkampagne bestätigt Einsparpotenziale der EU-Studie zu Druckluftsystemen; 2004.

[29] Smith R. Compressed air best practises; Available from: http://www.airbestpractices.com/.

[30] U.S. Department of Energy. Compressed air Systems: Case studies; Available from: https://energy.gov/eere/amo/compressed-air-systems.

[31] Fraunhofer-Institut für System- und Innovationsforschung. Druckluft effizient; Available from: http://www.druckluft-effizient.de/dokumente.html.

[32] University of Northern Iowa. Compressed Air case studies; Available from: https://iwrc.uni.edu/compressed-air/case-studies.

[33] U.S. Department of Energy. Implementing a Compressed Air System Leak Management Program at an Automotive Plant 2000.

[34] U.S. Department of Energy. FUJIFILM Hunt Chemicals U.S.A. Achieves Compressed Air System Energy-Reduction Goals with a Three-Phased Strategy 2011.

[35] Marshall R. Tolko's Paper Mill and Sawmill Save $125,000 per Year; Available from: http://www.airbestpractices.com/industries/paper/tolkos-paper-mill-and-saw-mill-save-215-000-year.

[36] Phillips R. Swiss Competitive Tenders for Promoting Efficient Motor Systems. 9th International Conference on Energy Efficiency in Motor Driven Systems 2015.

[37] Enerprice Partners AG. Druckluftprogramm ProEDA2; Available from: http://www.enerprice-partners.ch/proeda2.

[38] BAFA. Förderung von Querschnittstechnologien: Einzelmaßnahmen; Available from: http://www.bafa.de/DE/Energie/Energieeffizienz/Querschnittstechnologien/querschnittstechnologien_node.html.

[39] Department of Energy & Climate Change. THE ENERGY TECHNOLOGY LIST: Call for Evidence; Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/484663/ETL_Call_for_Evidence.pdf.

[40] Sustainability Victoria. Best Practise Guide: Compressed Air Systems; Available from: www.sustainability.vic.gov.au/-/media/resources/documents/services-and-advice/business/srsb-em/resources-and-tools/srsb-em-best-practice-guide-compressed-air-2009.pdf?la=en.

[41] LandesEnergieVerein Steiermark. Ratgeber Druckluft für den Praxiseinsatz: Ein Handbuch für die Instandhaltung; Available from: https://portal.ea-stmk.at/documents/20181/25550/Druckluftratgeber.pdf/8a91ff4f-0d83-4eb1-802e-d3425ebf5e3d?version=1.0.

[42] Sustainable Energy Authority of Ireland. Energy Awareness: compressed air; Available from: http://www.seai.ie/EnergyMAP/Energy_Awareness/Implement_your_campaign/3_Plan/Topic_Planner/Compressed_Air/.

[43] Seslija D. Guide for increasing energy efficiency of compressed air systems; 2008.

[44] Radgen P, Stadelmann B. Vorarbeiten zum Start der Kampagne Druckluft effizient Schweiz und begleitende Arbeiten zum Aufbau eines Druckluftkompetenzzentrums 2004.

[45] Radgen P. From Awareness Raising to Implementing Actions - The Swiss campaign Efficient Compressed Air. EEMODS'07 Conference Proceedings 2007:763–74.

[46] Office of Energy Efficiency & Renewable Energy. Compressed Air Systems; Available from: https://energy.gov/eere/amo/compressed-air-systems.

[47] Delaney D. NEMA and IECEE GMEE "Global Motor Eenergy Efficiency" Program. EEMODS'13 Proceedings.

[48] van Werkhoven M, Werle R, Brunner C. Policy Guidelines for Motor Driven Units: Part 1: Analysis of standards and regulations for pumps, fans and compressors; 2016.

[49] UNFCCC; Available from: https://cdm.unfccc.int/Projects/index.html.

[50] UNFCCC. Compressed Air Energy Efficiency PoA; Available from: https://cdm.unfccc.int/ProgrammeOfActivities/Validation/DB/07IVK61B3YJZ830VFI148O40OB8BTQ/view.html.

[51] Hsieh SH, Shih YC, Hsieh W-H, Lin FY, Tsai MJ. Calculation of temperature distributions in the rotors of oil-injected screw compressors. International Journal of Thermal Sciences 2011;50(7):1271–84.

[52] Krichel S, Sawodny O. Dynamic modeling of compressors illustrated by an oil-flooded twin helical screw compressor. Mechatronics 2011;21(1):77–84.

[53] BEKO Technologies. BEKKOKAT: catalytic technology for hydrocarbon-free compressed air; Available from: http://www.beko-technologies.com/fileadmin/downloads/brochures/bekokat/bekokat_int.pdf.

[54] Bopp M. German Lab Relies upon WATER-INJECTED OIL-FREE AIR COMPRESSOR; 2016.

[55] Dudda C, Radgen P, Schmid J. Contracting Finanzierung Betreibermodelle: Leitfaden für die Anwendung bei Druckluftanlagen 2004.

[56] Radgen P. Air Compressors or Compressed Air: Harvesting the Benefits. In: Lay G, editor. Servitization in Industry. Cham: Springer International Publishing; 2014, p. 91–107.

Integrated national program on Electric Motor Systems

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Abstract

Regulations on efficient products and energy efficient production have made Dutch enterprises in industry and commercial sectors active on improving their energy efficiency and decreasing their overall CO2-emissions. Dutch government and ngo's though signal that the pace of progress is too low; more effective measures are needed in order to be able to reach the internationally agreed CO2 emission goals set for the near future.

Efficient motor systems can have a great impact on achieving these goals. Research shows a savings potential of 9.1 TWh, equaling 19.8% of energy used by motor systems in industry and commercial, and 11% of the electricity use in Dutch industry and commercial sectors by implementing efficient motor systems (related to medium sized motors and a simple pay back time of 3 years).

In the Netherlands the government and several market parties (the 'supply chain') work together on designing tools and policies to increase the awareness and implementation of efficient motor systems through the so-called Knowledge Network on motor systems. It builds on the energy efficiency programs in place like the Long Term Agreements (LTA) program for large industries and the Environmental Management Law, applicable to all energy using enterprises.

Different policy elements are integrated with focus on increasing the overall capacities of market parties in terms of manpower and knowledge – through educational programs and training, raising the level of awareness of the savings potential of efficient motor systems through communications and events, and develop enablers to tackle some of remaining barriers signaled. Including adequate surveillance and enforcement by government and access to funding of investments in efficiency measures by esco's and end-users.

The EU minimum energy performance standards for pumps, fans and compressors - although still targeted at the individual components – are used to intensify the attention for energy efficiency and the need for a focus on motor systems within industry and OEMs.

This integrated approach is a very cost effective way to lower the national energy demand and to increase the level of sustainability on a national and company level. And, last but not least, it also increases the level of economic activities with a factor 7 (at the level of end users and supply chain).

1. Introduction – Industrial energy policy in the Netherlands

Dutch government has a long standing focus on securing energy supply and stimulating energy efficiency in industry, buildings, transport and dwellings through specific policy programs. The main programs are the LTA/LEE agreements, including the EED companies, the Sectoral Measure-lists for SME's, and the overall environmental enforcement activities on Energy Efficiency, with the Environmental Management Law as overall basis.

For many years large energy consumers in the industrial sector are involved in the Long-Term Agreements "LEE and LTA3". These instruments (hereafter covenants) have been designed to set clear energy efficiency targets for industry and at the same time give the individual companies the freedom to plan and implement the most economic saving measures at their own planning and speed, fitting their individual economic and technological circumstances. In short the participating companies have to implement a energy management system, conduct energy audits every 4 years and submit an energy action plan, and finally report to the government each year on the results.

Other non participating companies are addressed with different policy tools. For large energy users the European Energy Efficiency Directive (EED) sets comparable targets including an energy audits and submitting an energy action plan to the local government.

For medium sized companies the government has developed a number of "measure-lists" per sector; these lists contain a set of mandatory energy saving measures that each company has to implement when the simple payback time is below 5 years. Examples of such measures are applying LED lighting in buildings, automatic shut off of certain fan systems, etc.

However despite these dedicated policy programs the lack of consistency in policymaking on energy efficiency and sustainable energy in the Netherlands has led to a relative poor performance the last decade compared to other European countries. Despite some dedicated efforts the transition to a more sustainable energy system stagnated. By 2013 the share of renewable energy sources (in 2013) had reached a level of only 4.5% in total energy consumption. Since not one coalition government completed its full term, the energy policy did change quite frequently, which negatively affected the policy's effectiveness [1].

The Netherlands is committed to EU obligations to increase its share of renewable energy consumption to 14% by 2020. Furthermore, massive efforts are necessary to realize the required saving in final energy consumption (100 PJ in 2020) to meet the EU Energy Efficiency Directive. 100 PJ equals the annual energy consumption of approximately 1.5 million Dutch households.

To overcome these flaws and to secure the goal of 100 PJ reduction by 2020 (in EU) the government together with 40+ Dutch ngo's have developed a "Agreement on Energy". This Agreement on Energy for Sustainable Growth (2013) marks the start of the transition to a sustainable future in The Netherlands. The specific goals are:

- an average energy efficiency savings of 1.5% per year (adding up to a reduction of 100 PJ by 2020):
- 14% share of renewable energy in the Netherlands' total consumption of energy by 2020.
- Creating at least 15.000 additional jobs by 2020, of which a significant number to be created in the next years.

By the end of 2016 the Ministry of Economic Affairs together with the partners of the Agreement on Energy decided to intensify the implementation of activities on energy efficiency and sustainable energy in order to secure to 2020 targets. For industry one targeted focus area is efficient electric motor systems.

2. Efficient Electric Motor Systems in the Netherlands

Electric motor systems (EMS) are a key technology in industry. Motor systems are applied for all kind of production systems, utilities like pump, fan and compressor systems and transport. Around 69% of the electricity use in Dutch industry is attributable to electric motor systems [6]. Research and projects show that system optimization and best available drive technology can deliver reductions of 20 - 30% in pumps, fans and compressors in heating, cooling and ventilation systems, and industrial handling, processing and production systems.

The policy instrument "Green Deal" is an accessible way for companies, other stakeholder organizations, local and regional government and interest groups to work with the Dutch government on green growth and social issues. The aim is to remove barriers in order to help sustainable initiatives get off the ground and to accelerate this process where possible. In the last 3 years a Green Deal Efficient Electric Motor Systems was designed concerning electric motor driven systems in the industrial sector ('Green Deal Efficiente Elektrische Aandrijfsystemen') [3].

The Ministry of Economic Affairs has asked the Dutch Energy Centre Netherlands to assess the results of this Green Deal and to assess the potential of efficient motor systems on the Netherlands.

Research shows that the potential savings are substantial and amount to 9.1 TWh (equals 33 PJ) of electricity if all driven systems within the industrial and commercial sector are optimized. This relates to 11% of the total electricity consumption of these sectors and 8% of the total national electricity consumption. See tables 1 and 2.

	Replacement by IE3, > 0.75 kW	IE3 + VSD for pump, fan, compressor systems (var. load)	IE3 + VSD + system optimisation pump, fan, compressor	IE3 + system optimisation other systems	IE3 + system optimisation all systems
			1	2	(weigh.av. 1 and 2)
Industry	3,1%	10,6%	25,0%	17,5%	22,2%
Commercial	4,3%	9,7%	15,0%	9,6%	14,0%
Weighed Average	3,4%	10,3%	21,4%	16,2%	19,8%

Table 1 Energy savings potential by different measures in Dutch motor systems [3]

	Total electricity use	% electric motor systems	Savings motor systems	Savings potential motor systems	Savings potential motor systems
	TWh	%	%	TWh	%
Industry, inclusive energy and water	47,0	69%	22,2%	7,2	
Commercial	35,8	38%	14,0%	1,9	
Total Industry + and Commercial	82,8	56%	19,8%	9,1	11%
Total Netherlands	115,0				8%

Table 2 Energy Savings in industry and commercial sectors in Netherlands [3]

The Green Deal focuses on a specific segment within these sectors, the so called LTA companies with 'Long term agreements' with the government, and companies for which participation in the European Union Emissions Trading System (ETS) is compulsory. Therefore, the Green Deal covered 38% of the existing savings potential. The direct results of the Green Deal program are 19 GWh savings as a intermediate result in 18 concrete projects [4].

Importance of governmental support and enforcement to social parties and organizations

The International Energy Agency (IEA) dedicated in its 2016 World Energy Outlook a separate chapter to energy efficiency and electric motor systems. The analyses has been made based on and composed out of research by IEA 4E EMSA, IEA and other sources, and is based on three scenario's for energy supply and demand world wide [5].

The analyses show the importance and potentials of efficiency improvements in electric motor systems worldwide. It is estimated that by 2040, the annual global electricity savings for motors and motor systems could reach up to 3,050 TWh per year[47] equaling 24% compared to a policy following business as usual, see figure 1. The savings in industry, buildings and agriculture account for 4,950 TWh per year (24%), but due to electrification the transport sector will show an increase of 1,900 TWh per year. The IEA estimates these savings based on the implementation of a set of policies including applying systems optimization, ambitious minimum energy performance standards, increased energy tariffs, adequate enforcement activities and more.

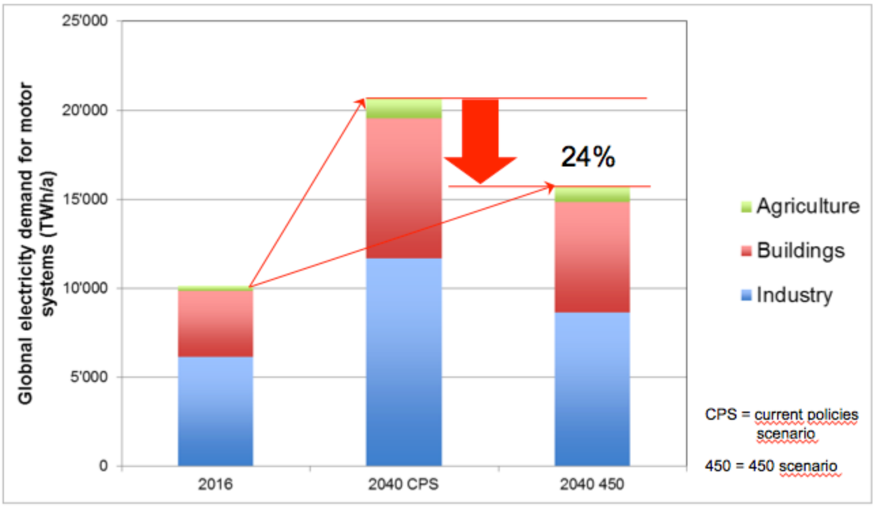

Figure 1 Potential efficiency improvements in electric motor systems worldwide [5] [8]

3. Knowledge network on Efficient Motor Systems

In the Netherlands the government and several market parties (the 'supply chain') work together on designing tools and policies to increase the awareness and implementation of efficient motor systems through the so-called Knowledge Network on motor systems.

Analysis of the market for electric motors systems and components and maintenance of industrial equipment in the Netherlands shows that for a successful acceptance of efficient electric motor systems all market parties have to get involved [6]. As a result of this government broadened the focus of their activities on efficient electric motor systems from end-users alone towards addressing all parties in the supply chain in a 'knowledge network on efficient electric motor systems' (KEMS). Three main Dutch trade associations, the FEDA – manufacturers, suppliers of motors and components, the UNETO-VNI – technical service and maintenance companies, and HPG – pump manufacturers and suppliers, have joined the network. Fourth partner is the Dutch Enterprise Company RVO.nl a branch of the Ministry of Economic Affairs.

The network works along a 3 year program, with main activities being capacity building in the market, with industrial end-users; knowledge transfer on national and international tools and developments – e.g. on standards and regulation like the EuP-regulation on energy efficient motors, fans and pumps. Specific tools and best practices and factsheets

[47] Comparing the Current Policies (CPS) scenario to the "450" scenario (maximising the global temperature rise to 2 C by 2050)

are brought to industry and other organization involved in the efficiency of motor systems.

The EU minimum energy performance standards for pumps, fans and compressors - although still targeted at the individual components – are used to intensify the attention for energy efficiency and the need for a focus on motor systems within industry and OEMs.

Dedicated projects are initiated and executed in cooperation with the companies of the network partners. Such as a pilot on 'marketing of motor system' addressing Small and Medium sized companies. Workshops are being organized for specific industrial sectors e.g. chemical industry, plastics, food and water companies on potential and actions for improving efficiency of production. Also a best practice on motor systems is available and a specific web based tool (scan) both aiming to address the potential savings of a single motor application as well as steps towards optimizing all motor systems in a complete production plant. Overall goal is to raise the awareness of its potential and to guide to help the interested person towards partners, sources to initiate action.

Mentioned before the Green Deal on motor systems has been initiated from within the KEMS and executed by a selection of 30+ front running member companies. The program has been executed in 2.5 years time and has resulted in concrete energy savings of 19 GWh (per year) and a number of outreach activities including workshops, events and fact sheets [4].

The network combines three business associations, 500+ members companies form the supply chain, and is open for further cooperation. International cooperation through partner RVO is an important asset for the involved parties and is covered through IEA 4E EMSA, with Australia, Austria, Denmark, Switzerland and United States, as well with organizations as IEA, SEAD en UNIDO.

4. Integrated Program on Motor Systems 2017 - 2020

The potential benefits of efficient motor systems are well addressed through different sources, i.e. practical evidence through the Green Deal projects, and international and national evidence from different well-known entities. International and national regulation which sets minimum energy performance requirements for motors, fans and pumps are in place, and in revision, as well as under development for compressors systems.

Research and experience shows also that extra effort – from government, supply chain and industry, has to be made in order to harvest and secure the savings possible with EMS. For this the KEMS together with Dutch Enterprise Agency and Economic Affairs have developed an approach with the following main elements:

1) Market: enforcement, marketing and capacity building

Starting point is to increase the awareness of the actual legal requirements on energy efficiency in combination with awareness of the potential benefits of efficient motor systems. Partners will work on dedicated and regular communication through workshops, articles and projects a/o events.

Special focus will be on the development (or integration) of an standard motor systems audit by which industry and enforcement agency know that the potential measures have been identified and to a agreeable level been implemented.

At this moment the pilot EPT (Energy Performance Test; EPK in Dutch) has been developed with the same scope and coverage (meaning replacing an actual check by enforcement authorities themselves) [6]. A parallel example of the concept has been demonstrated recently in the Netherlands in the commercial buildings sector. New regulation demands that within 5 years (2023) all commercial buildings must have a "C-label" as a minimum, which is an efficiency level for energy use in kWh.m2/year. If the building does not comply, it cannot be let from that date. As a result of this regulation commercial banks launched a special investment fund of appr. 1 billion euro to enable the improvement of the current building stock, as a first enabling step for the sector.

2) Training and Audits

Establishment of an acknowledged preferably certified audit scheme which offers transparency to all parties involved. Being industry, enforcement officers, management and technical officers. Deployment of a motor systems audit program in combination with a training program for industry and service industry (consulting).

The increased awareness in the market as well as from the side of the enforcement authorities will create an increasing demand for audits and sound business cases. And will enable industry to meet the minimum requirements set by the government.

Benefits will be multiple: companies get an extra tool for their communication on sustainability and energy efficiency, towards clients, public and local government. And the economic impact will be substantial as well with the people and equipment involved in these activities.

3) Finance, Energy Investment Allowance and Monitoring

The 3rd element is focusing on enabling factors, addressing finance (sources) and subsidies (discount) and providing evidence of the actual savings (monitoring).

In the slipstream of the audits and the elaboration of sound business cases the (lack of) funding of the investments can give serious draw backs. Experience shows that in some cases the lack of funding can be a barrier to actually invest in efficiency improvements. In many cases investments in energy efficiency do have to compete with other investment proposals more directly related to e.g. extra production capacity, quality improvements. These latter proposals can have a more strategic impact than those related to EE only [4].

In parallel and with a focus on ‘industrial energy efficiency’ a number of parties have started a project to define and test business models, where suppliers as a service deliver the audit, the business case and take care of the implementation and operation – mostly for a limited period of time. And as second element the partners will develop a market place and/or fund for financing the actual business cases. Providing the business models, including the underlying legal, financial and technical models, will enable market parties to apply these concepts. Without this the smaller companies in the supply chain who do not have the resources and or manpower to deal with not be able to serve their industrial customers.

Innovative measuring and monitoring is under development within several Dutch companies as well as with some large motor manufacturers. The application of different types of sensors together with the development of algorithms for different concepts of maintenance opens the door to new services enabling more focus and concrete results on optimizing motor systems towards lowest total cost of ownership. A few pilots are under way in the Netherlands.

Finally the certified audit as well as ‘system improvements’ will be proposed for uptake in the the existing energy tax allowance. Companies get a 10-15% reduction on their initial investment by this.

The proposed planning is 3.5 years [9]. In this period the expected results will be the direct participation of 100 medium to large industrial companies, leading to a savings potential of 1.0 to 2.2 PJ[48]. Indirectly the initiative can influence a larger audience of 20.000 companies.

5. Conclusions

[48] Calculation based on practical results from earlier projects, e.g. from the Green Deal EMS 2012-2015; but with addition of a more integral implementation per company (i.e. addressing all relevant motor systems in a company and implementing the economical viable business cases) with applying systems optimization.

Different policy elements are integrated with focus on increasing the overall capacities of market parties in terms of manpower and knowledge – through educational programs and training, raising the level of awareness of the savings potential of efficient motor systems through communications and events, and develop enablers to tackle some of remaining barriers signaled. Including adequate surveillance and enforcement by government and access to funding of investments in efficiency measures by esco's and end-users.

This integrated approach is a very cost effective way to lower the national energy demand and to increase the level of sustainability on a national and company level. And, last but not least, it also increases the level of economic activities with a factor 7 (at the level of end users and supply chain).

Involvement is needed from the main stakeholders, i.e. the government, main actors from the supply chain and the industrial end-users to work together on these ambitious and realistic goals.

Glossary

LTA Dutch covenant for long-term agreements on energy efficiency agreements

LEE Dutch covenant for large industrial companies that are obliged to participate in the Emissions Trading System of the European Union (https://www.rvo.nl/sites/default/files/2MJAP1227_Results_Long-term_agreements_2011_november_2012_v2.pdf)

EED EU Energy Efficiency Directive (https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive)

SME Small and Medium Enterprises

LED Light Emitting Diode assembled into a lamp

Coalition Dutch government formed by a combination of 3 up to 5 political parties.

ngo's Non-governmental organization; a nonprofit organization that is independent of governments and focuses on an assumed social interest.

UNETO-VNI Trade organization of installation and electromechanical maintenance companies

FEDA Trade organization of suppliers of Electric Motors, Drives and Automation Engineering

HPG Dutch Pump Manufacturers Group

KEEA Dutch Knowledge Network for Efficient Electric Motor Systems

IEA International Energy Agency

IEA 4E EMSA IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment – Electric Motor Systems Annex

EMSA Electric Motor Systems Annex - Annex to IEA 4E

RVO Netherlands Enterprise Agency, part of the Ministry of Economic Affairs

SEAD Super-efficient Equipment and Appliance Deployment. SEAD is an initiative under the Clean Energy Ministerial (CEM) and a task of the International Partnership for Energy Efficiency Cooperation (IPEEC)

UNIDO United Nations Industrial Development Organization

EuP regulation Energy using products regulation based on the EuP Directive (2005/32/EC)

References

[1] SER, The Agreement on Energy for Sustainable Growth, 2013

[2] Van Werkhoven, M., et. al.: Green Deal EEA, in conference proceedings: ECEEE 2014, Arnhem The Netherlands, 2014

[3] Sipma J. et. al. ECN, Het besparingspotentieel van Elektrische Aandrijfsystemen in de Nederlandse industrie en dienstensector (in Dutch), April 2017

[4] Van Werkhoven M., Green Deal – Results and lessons learned in 2 years of cooperation of industry and government in the Dutch Green Deal program on motor systems, EEMODS 2015

[5] IEA, World Energy Outlook, Paris, 2016

[6] RVO.nl, Efficient Electric Motor Systems (Krachtenveldanalyse - in Dutch), Utrecht, 2010

[7] Evaluatie EPK-pilot; Wesselink et. al., (in Dutch), November 2015

[8] Van Werkhoven M., Werle R., et al, Workshop presentation, Brussels, March 2017

[9] Van Werkhoven M., et al, KEEA plan 2017-2020, Zoetermeer, April 2017

Harmonization of Policies for Energy Efficient Motors in West Africa and Beyond

Patrick Blake (UN Environment) and Steven Kukoda (International Copper Association)

Abstract

The paper describes the benefits and process for regional harmonization of policies on energy efficient motors and motor systems in West Africa. The approach builds upon the achievements that UN Environment had with the ECOWAS Centre on Renewable Energy and Energy Efficiency (ECREEE) in harmonizing policies for energy-efficient on-and off-grid lighting that started in 2012, and an array of projects on air conditioners, refrigerators, motors and transformers around the world.

Over the next 15 years, the energy consumption of electric motors in West Africa is expected to increase by over 150%. This projected growth is largely expected due to positive circumstances such as increased economic activity and GDP growth, which correlate to increased use of motors. However, electric motors and motor systems can put a strain on the electricity grid and the economy if inefficient motors are used. Currently, no countries in the region have minimum energy performance standards for motors or motor systems. Products with outdated technologies permeate these markets.

The Economic Community of West African States (ECOWAS) should implement regionally-harmonized policies for electric motors that are based on international best practices. Harmonization helps lower compliance and implementation costs for programme administrators, suppliers, and ultimately, consumers. Stakeholders benefit from the reductions in trade barriers and the choice of goods available with the larger economies to which they are harmonized.

1. Introduction

U4E helps developing and emerging markets quickly and comprehensively transition to energy-efficient electric motors and motor systems, and other appliances and equipment. The initiative draws upon lessons learned from helping more than 60 countries move away from inefficient lighting, and an array of projects on air conditioners, refrigerators, motors and transformers around the world. These efforts are making a positive impact for over one billion people around the world.

UN Environment leads U4E, with funding from the Global Environment Facility and steadfast support from the UN Development Programme, CLASP, the International Copper Association, the Natural Resources Defense Council, and an array of partners. Partner manufacturers include ABB, Osram, Philips Lighting, Arçelik, BSH Hausgeräte GmbH, Electrolux, MABE, MEGAMAN, and Whirlpool Corporation. Partners support U4E with technical expertise to inform the adoption of model policies, market intelligence, capacity building, and outreach.

U4E has a particular focus on general purpose, three-phase, medium-size induction motors and the systems that are driven by these motors, which comprise 10 per cent of the stock but account for 68 per cent of energy used by motors[49]. There is considerable international policy experience with this range of motors, and best practice examples are readily available for adaptation and replication by developing countries. Once experience has been gathered with regulating these motors, policies are typically expanded to cover additional motor sizes and types, other parts of the motor system (which is more

[49] IEA, 2011. Energy Efficiency Policy Opportunities for Electric Motor-Driven Systems

complex but offers considerably larger energy savings potential), and the repair of existing motors that are already in use.

Most developed countries are well underway in the transition to energy-efficient electric motors and motor systems. However, many developing and emerging economies are just starting to explore such opportunities. A well-designed set of policies can help transform these markets by enabling them to leapfrog past out-dated technologies to superior, cost-effective alternatives. Otherwise, consumers and business unnecessarily face higher electricity bills, utilities struggle to meet excessive demand for power, governments are burdened with additional economic development challenges, and the planet suffers from worse pollution and greenhouse gas (GHG) emissions.

U4E has developed Country Savings Assessments for 150 developing and emerging economies on the respective financial, climate, and energy benefits of transforming their markets (these and other resources are available at http://united4efficiency.org). The assessments show energy savings from motors in these countries could reach 300 TWh per annum in 2030, with a savings of 200 Mt of CO_2 emissions (equivalent to the annual electricity generated by approximately 60 coal-fired power plants with a capacity of 1,000 MW)[50].

West African countries have prioritized action on energy-efficient motors within the ECOWAS Energy Efficiency Policy, which was published in 2015. The Energy Efficiency Policy calls for the development of initiatives to develop energy-efficiency through electric motors and motor driven systems.

In West Africa alone[51], the U4E's Country Savings Assessments show over 1,000 GWh of electricity could be saved annually by 2030 if energy efficient motors were used. These savings are equivalent to $300 million in reduced electricity bills providing business owners with increased profits to invest in new business opportunities. In addition, the market transformation will assist West African Countries in meeting their climate targets by reducing 400,000 tonnes of CO_2 emissions.

[50] Weighted carbon emissions factor for electricity used by motors in these 150 countries is 750 g/kWh as assessed by U4E.

[51] ECOWAS countries include: Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo.

2. Integrated Policy Approach for Market Transformation

While the technologies, stakeholders, and challenges differ for each products, there are consistent elements needed to successfully achieve a market transformation. U4E utilizes an *Integrated Policy Approach* involving each of the following elements in its projects:

- **Standards and Regulations** that define which equipment is blocked from the market (those that do not meet minimum energy performance standards (MEPS), which equipment may be recognised for meeting performance and quality requirements, how to test the equipment, and other aspects. Standards and regulations are essential to the success of market transformation, and therefore are the cornerstone of the U4E Integrated Policy Approach.
- **Supporting Policies** that ensure the smooth implementation of standards and regulations and achieve broad public acceptance. Supporting policies include labels that endorse the performance of the equipment or allow for easy comparison of performance between competing products. Consumer awareness campaigns are also used to help purchasers make more informed decisions about the total cost of ownership of the equipment and to modify behaviour (e.g. encouraging the timely repair of equipment by certified technicians).
- **Finance and Financial Delivery Mechanisms** that address the barrier of higher upfront costs of efficient equipment through fiscal incentives such as grants, rebates and tax-relief, or by extending credit lines, partial risk guarantees, loans, bulk procurement opportunities, equipment leasing through financial intermediaries, and services through energy service companies.
- **Monitoring, Verification and Enforcement (MVE)** that track which equipment is sold in the market, test the equipment to ensure that claims of performance are accurate, and to prompt corrections by those that fail to comply. Otherwise, incentives intended for efficient products may reward sub-standard alternatives and non-compliant equipment will enter the market. This results in an uneven playing field, penalising manufacturers who comply with the requirements. Moreover, poor quality equipment that is advertised as energy-efficient will disappoint consumers who may opt to avoid performance considerations in the future.
- **Environmental Sustainability and Health** considerations, given the hazardous wastes (e.g. lubricating grease) found in motors, the risks for workers during motor manufacturing and repair, the recycling opportunities for many components that can be diverted from landfills, and the need to get end-users engaged to facilitate waste collection and processing.

3. Regional Harmonization and Collaboration

U4E encourages regional blocks of countries to harmonize policies and collaborate whenever practicable, as it offers multiple benefits. For example, countries can lower administrative and compliance costs by minimizing duplication of testing, coordinating on the inspection of products as they cross borders, and requiring the same information on equipment labels. Trade barriers can be lowered and purchasers can benefit from better prices and selection of goods that might not otherwise be available in a smaller market that is differentiated from its neighbors.

Cooperation between national governments and major stakeholder groups enables sharing of model approaches and lessons learned, exchanging data, and use of common facilities (e.g. test laboratories) and resources (e.g. similar outreach campaigns). Many efficiency programmes are initiated each year at local, national and regional levels, which can inadvertently cause confusion if not informed of related activities that are underway elsewhere.

The following approaches help foster regional cooperation:

- Conduct roundtables and other consensus-building activities to reach agreement about particular issues, policies, guidelines, standards, and related subjects;
- Identify liaisons in each government, civil society and industry to be designated points of contact;
- Establish bilateral activities to demonstrate the benefits of joint activities; and
- Conduct regular in-person and online events to share experiences and information.

For promoting energy-efficient products, regional cooperation can include:

- Developing a regional efficient product roadmap to identify areas of cooperation and ways to share resources and build regional markets for efficient products;
- Establishing or harmonizing specifications and standards that include energy performance and quality criteria;
- Coordinating monitoring, verification and enforcement activities (e.g., mutual recognition of test results, verification of labeling compliance, linking networks of test professionals); and
- Other pooling of resources and strategic use of available structures and capacities.

4. Lessons Learned from Lighting

U4E's resources, partners and expertise on electric motors and other products around the world can be put to great use in West Africa, where U4E has an excellent network and track record of experience fostering regional collaboration on lighting. Before U4E got involved in the region in 2012, only Ghana had national MEPS for lighting products. There were many communication campaigns to inform consumers of the benefits of energy efficient lighting in various countries, but without MEPS, incandescent lamps continued to flood into these markets.

U4E partnered with the ECOWAS Centre for Renewable Energy & Energy Efficiency (ECREEE), which supports the region's goals for sustainable infrastructure development. The experience yielded multiple insights that could be incorporated in future work on electric motors and motor systems, including:

- **Importance of high-level commitment:** The project fell under the larger framework of the ECOWAS Policy on Energy Efficiency that targeted the phase-out of inefficient incandescent bulbs by 2020. The project benefitted from high-level commitment at the ministries of energy the encouragement of other stakeholders to take action.

- **Country driven:** Thematic Working Groups were established at the outset to develop and contribute inputs to the regional efficient lighting strategy. In line with the *Integrated Policy Approach*, the groups covered the following topics:
    - Minimum energy performance standards: Chaired by Senegal
    - Supporting policies and mechanisms: Chaired by Ghana
    - Monitoring, Verification and Enforcement: Chaired by Cote d'Ivoire
    - Environmentally Sound Management: Chaired by Nigeria
- **National champions:** Steady progress was due in many aspects to Senegal's championing of the project and rallying other countries to continue through the final Regional Efficient Lighting Strategy.
- **Regional collaboration:** The working groups included a diverse range of experts across the region[52]. Commonalities and differences across the countries were readily explored. Experiences were shared by countries that already developed other types of national policies.
- **Multi-stakeholder:** The process included a presentation of the draft Regional Efficient Lighting Strategy for civil society representatives and manufacturers. Their perspectives were incorporated with an effort to maximize the benefits and minimize concerns, where possible.

5. Recommendations for West African Collaboration on Electric Motors and Motor Systems

An absence of energy-efficiency policies can result in the entrenchment of inferior motors. Since motors have long lifetimes, sometimes 20 years or more, the lack of policies locks-in electricity waste for decades. Factories and businesses are less competitive as they spend more money than necessary to power their equipment while competing with energy conscious companies elsewhere in the world. Utilities that already struggle to meet electricity demand face unnecessary strains on the grid as additional inefficient motors enter the market.

U4E has also just released Policy Guides for each of the five products, including one for electric motors and motor systems. This resource could be readily applied in West Africa, and other regions around the world. The content was developed based on expert insights from over 20 organisations, ranging from motor manufacturers and industry associations to environmental groups, academia, and governments. This balanced cohort offers credible guidance to address common questions. Key recommendations for policymakers include:

Key recommendations for policymakers:

- Adopt mandatory MEPS for general purpose, three-phase electric induction motors with two, four or six poles; rated output between 0.75 kW – 375 kW (i.e. 1 HP to 500 HP); rated voltage up to 1,000 Volts at 50 Hz or 60 Hz; and continuous duty operation.
    - Level IE2 (defined by IEC 60034-30-1) is recommended as a starting point for countries that produce motors domestically.
    - Level IE3 (defined by IEC 60034-30-1) is recommended as a starting point for countries that import all motors.

[52] Customs authorities, Ministries of Energy, Ministries of Environment, Ministries of Finance, Ministries of Trade and Industry, Rural Electrification Agencies, Standardization Agencies and utilities

- Collaborate with other countries in the region to harmonise standards according to international best practices and to share resources and lessons learned.
- Require that all motors feature IEC 60034-30-1 conformant nameplates.
- Conduct targeted outreach and training to inform, educate, and gain the support of key stakeholders.
- Aim to implement a MVE regime within the national legal framework in time to coincide with the adoption of MEPS, and ensure accurate and reliable measurement of the energy efficiency of motors as prescribed by IEC Standard 60034-2-1.
- Encourage adoption of best practices (e.g. per ANSI/EASA AR100 or the specifications of the Consortium for Energy Efficiency) in shops to yield professional repairs so motors meet their original performance.
- Use voluntary supporting policies to enhance the efficiency of motor driven units and the overall motor system.
- Consider regulating motor driven units after sufficient experience has been gained with the implementation of mandatory MEPS for motors.
- Assess existing sources of finance and conduct market analysis to understand financial barriers so that applicable delivery mechanisms are in-place to support voluntary actions (e.g. encourage the purchase of motors with higher efficiency than MEPS, early-replacements of inefficient motors, upgrading motors systems).
- Establish collection and recycling mechanisms for motors that have reached the end of their useful life, as the cast iron, steel, aluminium, copper, stainless steel and brass parts that constitute more than 98 per cent of the material content are fully recyclable.

6. Conclusions

Most developed countries are well underway in the transition to energy-efficient motors. However, many developing and emerging economies are just starting to explore such opportunities. A well-designed set of policies can help transform these markets by enabling them to leapfrog past out-dated technologies to superior, cost-effective alternatives. U4E has a proven approach, suite of resources, and expert partners that are transforming markets around the world. West African states have strong potential to build upon their successful work on energy efficient lighting to accelerate the transition to superior electric motors and motor systems.

Influence of Production Processes on the Efficiency of Electric Drives and Measures for its Optimization

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Abstract

Electric Drives perform an enormous contribution to solve current challenges of mankind: Electric generators supply regenerative energy from wind, water or biomass; electric traction drives move cars, trains, boats and soon planes without emission, noise and exploiting precious fossil fuels; and primary electric motors enable the automation of manufacturing, logistics, services and private life. Their efficiency is of utmost importance not only for the consumption of energy and vice versa for the effort to cool the losses, but also for their needed installation size, weight and material usage, for their performance and finally for their total cost of ownership. Therefore, generations of engineers strove creatively for optimizing the design and control of electric motors and drives. However, the immense portion of inefficiencies which are caused by imperfect manufacturing procedures was scientifically not comparably elaborated up to now. Thus, the purpose of the submitted paper is to present a structured overview of the entire production process of electric machines and power electronics and their influence on energy efficiency. Detailed measures developed to minimize the losses especially caused by mechanical friction, ohmic resistance, eddy currents in electric steel, magnets and induction bars, and even skin respectively current displacement effects will be introduced and their improvement potential will be discussed. Finally, the establishment of a European joint effort for a research laboratory on production technologies for electric drives will be proposed.

1. Introduction and objectives

The different process steps during manufacturing of electric drives influence the running characteristics and especially the efficiency and the quality of the end-product. Commonly utilized machining and processing methods for the used materials of the drive's components such as motor and power electronics often lead to undesired characteristics of the electric drive. Parasitic effects like induced noise, harmonic torque or additional losses, just to mention a few, can be caused by inaccurate manufacturing with high tolerances and deviations and by the production processes themselves. The chain of deterministic and stochastic individual effects summarizes to the whole drive system.

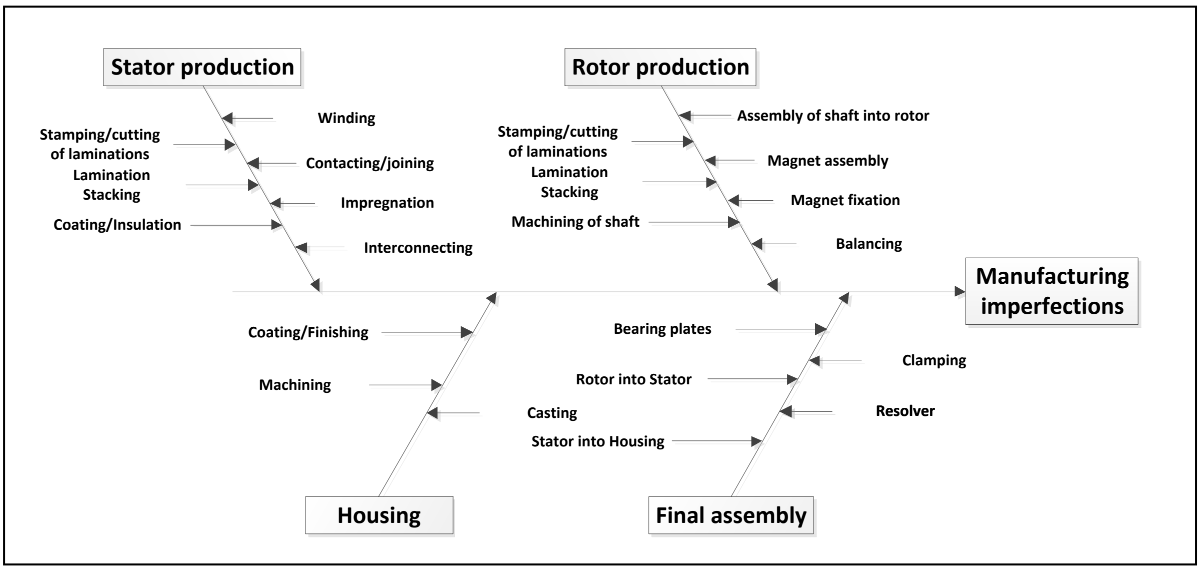
The presented paper gives a short overview over the production processes of rotational electric drives with the focus on the error-sensitive permanent magnet synchronous motors in order to create a basis for further investigations in the area of production-related deviations and their influences on the whole drive system. It is necessary to determine their effects on the performance of the drive and their propagation in the whole system by taking into account the interactions between the single process steps. This will be done in future research projects.

2. General overview of manufacturing imperfections in electric drives production

The production of rotational electric drives has to be divided into four general fields (see Figure 1): Manufacturing of the machine housing, stator and rotor production as well as the final assembly of all components. The stator production steps together with the processes for the manufacturing of the housing in general are similar for all mentioned motor types in this paper. However, there are some exotic stator constructions such as the flux switching machine [16] or the intelligent stator cage drive [17], which will not be further dealt with in this paper. The individual process steps and the sources of manufacturing imperfections will be described in detail in the next chapter. Depending on the machine type, there are general differences in the processes of the rotor production and the final assembly. Within electric excited synchronous motors (SM), commutator machines and induction motors (IM) with slip-ring rotor, the rotor manufacturing steps and the consequent manufacturing imperfections are quite similar to those of the stator manufacturing process chain. Solid rotor IM can be further divided into smooth solid rotor and squirrel cage rotor. The latter can be divided further according to their rotor type into aluminium and copper squirrel cage, where the material of the cage defines the process steps of the rotor production. The low melting point of aluminium allows for efficient mass production of rotors though suffering from the lower electrical conductivity of the cage material resulting in lower efficiency. [1] Copper cages can be assembled by soldering together coppers bars with short circuit rings during assembly in a laminated iron core or as cast copper rotors with laminations. The latter brings some challenges due to the high melting point of the cage material. In contrast, smooth solid rotors for IM benefit from simple manufacturing restricted to the chipping process of the rotor iron and thus high mechanical durability. However, the conductivity of the rotor iron is poor in comparison with aluminium or even copper [1], [2].

Aside from electric excited synchronous motors, manufacturing of permanent magnet synchronous motors (PMSM) meets further challenges especially due to magnet assembly and magnetizing. In addition, the magnetic interactions between the magnet bodies, the magnetized rotor and other ferromagnetic material complicates the handling of several motor parts. Furthermore, these interactions require advanced handling strategies within the magnet assembly and fixation processes to ensure the exact end position of the magnet on the surface of the rotor. Next to imperfections in magnet position, magnet bodies suffer from deviations in the magnetizing vector. The effects of these imperfections on the running characteristics of PMSM were investigated in several studies, such as [18] and [3]. Chapter 4 addresses these challenges of rotor manufacturing more detailed.

Figure 1: Influences on manufacturing processes of PMSM



3. Influences of stator production processes

Laminations

The iron core of rotor and stator consists of laminations of electrical steel insulated against each other in order to reduce eddy current losses. For manufacturing of the single lamination sheets, cutting techniques such as laser or water jet cutting, rotational cutting or stamping are utilized. Laser cutting brings in a huge amount of heat into the cutting edge according to the process parameters influencing the microscopic material structure with negative influences on the iron hysteresis losses. An Example for advanced laser cutting is the remote laser cutting process providing cutting speeds of 80 m min^{-1} on 0,5 mm thick stainless steel at 5 kW laser power [24]. Stamping processes have a similar effect by plastic deformation of the cutting edge. In addition, tool wear brings in additional imperfections in terms of geometry deviations.

To create the end geometry of the lamination stack, a stacking process, and in several cases also a joining process, are required. The latter can be integrated into the stamping process which causes electrically conductive interconnections between the single sheets increasing eddy current losses. Also other cutting processes like laser cutting or water jetting can cause these negative effects by creating a cutting burr at the edges. Joining techniques such as clamping or welding also cause interconnections between the single sheets. In addition, thermal processes cause microscopic material changes increasing hysteresis losses. [19], [11]

Table 1: Eddy current losses caused by different stacking technologies [19]

Manufacturing processes	**Losses for one stator tooth at 400 Hz and 1 T** **in W**	**Reduction of η in %** **For a sample machine with 15 kW at 6000 min-1**
Welding	Up to 19,7	Up to 1,4
Stacking by stamping	2,6	0,23
Stamping burr of 50 µm	0,1	Not measurable

A method for reducing eddy current losses to a minimum (only stamping burr can occur) is the baking enamel system. Drawbacks are process time and lower operational temperatures compared to the Methods mentioned in Table 1.

Great influence on the magnetic properties of the lamination stack has the amount of internal stresses. Investigations show a rise of the required field strength by factor 1,7 to reach the same magnetic flux comparing stresses of 8 N/mm² with a stress free iron core. [23]

Insulation and Impregnation

The insulation inside an electric drive has to fulfil different tasks: Firstly, an electric insulation between the stator core and the windings has to be established. This is for utmost importance especially with higher voltages. Further, the ground wall insulation has to maintain a good thermal conductivity between the windings and the stator core, in order to ensure a sufficient heat dissipation and thus a higher power density. Materials used for ground wall insulation are insulation papers, powder coatings or tape insulation. To support this heat transfer, an additional impregnation of the windings is required in order to eliminate air inclusions with lower thermal conductivity. As further tasks for the impregnation, mechanical fixation and protection against environmental influences have to be mentioned. Processes for impregnation can be dipping or dripping impregnation or complete vacuum casting of the whole stator. [10]

The quality of these processes has a great impact on the power density of the electric machine, since air encapsulations and other errors negatively influencing the heat dissipation from the coil into the stator core can cause thermal damage to the stator.

Winding technologies

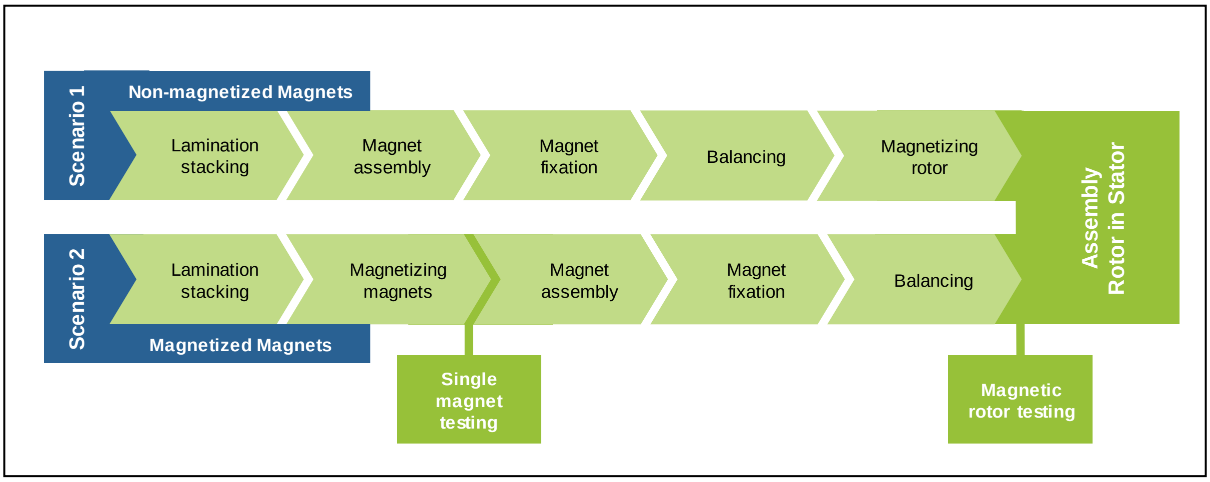
Several winding technologies, such as draw in winding, needle winding, or single coil linear winding face new technologies like hairpin, solid bar or stator cages. The aim is to increase the copper fill factor inside the stator slot while reducing skin and proximity effects which diminish the effective conducting cross-section of the wire/conductor. Consequently, manufacturing imperfections of the winding processes can lead to a lower fill factor and thus lower power output of the whole machine. In addition, stresses on the insulating layer of the copper wire can cause damage and thus areas of lower insulation capability. This reduces the voltage resistivity of the stator. [15]

Joining resin insulated copper wires

In order to establish an electrical contact at the end of the insulated copper wires of the windings, a special joining process has to be performed. The first requirement is the removal of the insulation layer, often made of polyimide, before applying a contacting element e.g. a cable lug. Therefore, different techniques can be used. The two process steps removal of the insulation layer and joining of the wires to a contacting element can be done either sequential or in the same step. For sequential processes, laser brazing, brushing, sandblasting or thermal removal by a flame can be used. When it comes to combined processes, the thermal crimping process is most commonly used. This process has advantages in process time, however, suffering from high tool wear. The main influences of the joining process are electric resistance of the joining and mechanical stability against tensile forces. [14]

4. Influences of rotor production processes

Permanent magnet rotor production scenarios



Magnets

Magnets show imperfections in case of geometrical measurements and magnetic parameters [20]. Several studies showed the impacts of deviations of the magnetic moment vector [18] and of geometrical deviations [4]. For instance, [4] performed a design of experiments to address manufacturing tolerances (in this case the magnet thickness) to cogging torque and back-electromotive-force. These tests were performed using different stators and thus influences caused by stator imperfections could not be detected and separated from the magnetic deviations.

Magnet Assembly

Magnet assembly has to be divided into different scenarios: First, the rotor topology defines the required assembly movements of rotor and magnet body. These topologies can be distinguished between surface mounted permanent magnets (SPM) and integrated permanent magnets (IPM). Second, the time of magnetization has enormous effects on the complexity of handling. The assembly of non-magnetized magnets allows for easy pick-and-place or collect-and-place operations with a lightweight gripper and short process time. Manufacturing imperfections such as misplaced magnets away from the target position can be reduced to a minimum during the handling and placing operation especially with automated magnet handling since there are no magnetic interactions creating lateral force on the magnet and the gripper. In contrast to that, handling of magnetized magnets requires high gripping forces and stiff constructions of the assembly system to ensure the required precision of the magnet's target position. As an additional problem factor during magnet assembly of magnetized magnets, the commonly used adhesive fixation process for magnets has to be mentioned. Depending on the adhesive system, different curing processes are necessary, influencing the assembly process. Magnetized magnets have to be held in place until the adhesive has cured to a certain degree able to fix the magnet's position against magnetic forces, when there are no holding structures integrated into the rotor's lamination stack. [7]

Magnetization

As mentioned above, magnetizing can be done at different time spots of the rotor assembly process chain. Magnetizing the whole rotor after magnet assembly (in-situ magnetization) and balancing can bring benefits in process time due to an easier magnet assembly process (see above) and a reduction of process steps in comparison to magnetizing single magnets. Further, polarity errors among single magnets are eliminated. As a major drawback the need for a rotor variant specific magnetization fixture (so called magnetization head) with high invest cost has to be mentioned. In addition, angular errors while positioning the rotor inside the magnetization head can occur resulting in wider pole gaps depending on the rotor design (not relevant with gapless rotor designs [21]). [12] [13] An effect not yet stated with figures in detail, is the saturation of the rotor iron during magnetization resulting in lower polarisation of the magnets. This was seen during experiments.

Magnetizing single magnets allows for 100% testing of the magnets and controllability of proper saturation of each magnet. In addition, it is possible to magnetize whole magnet stacks to save process time and energy. However, the process has to be carefully designed to ensure full saturation of each magnet within the magnet stack. [12]

Balancing

In [5] the cause for rotor imbalance is described as follows: Due to numerous different parts of a rotor assembly, such as shaft, laminations, magnets, centrifugal force protection and adhesive material, material inhomogeneity occurs. Imperfections in the insulation coating of the laminations or more specifc uneven coating layer thickness produce additional imbalance. During machining, stamping and/or cutting imperfections can be induced by wear of cutting tools, vibrations and general precision of the used tooling machines. Last, the assembly steps mentioned in the previous chapters of this paper are further sources of imbalance. For compensation, additive or subtractive balancing has to be performed leaving small residual imbalance. [5], [6]

5. Measures for optimization

Selective magnet assembly

To reduce imperfections caused by magnetic deviations among the magnet bodies and to ensure a homogenous rotor magnetic field, several approaches have been presented. [4] describes a method for selective assembly of rotor segments. This approach is based on single rotor discs with IPM. The magnetic field of the discs is getting measured and afterwards the optimum rotational and lateral position of the rotor to match the rotor stack is being calculated. This method enables for detecting magnet imperfections as well as imperfections caused within the magnet assembly process and allows in-situ magnetization of the single rotor discs. A drawback is the residual unevenness of the resulting rotor magnetic field due to missing 100 % tests of magnets before assembly and the large number of magnets within a rotor segment.

[8] addresses a 100 % test method for magnets within a magnet logistics and storage concept. This allows for fully automated geometrical and magnetic measurement of single magnets and includes a laser marking process. The magnet storage is represented by an automated warehouse system to reduce residual magnets out of specification. An algorithm calculates the optimum magnet position on the rotor's surface and according to this, a sequenced magnet stack is extracted out of the warehouse. A drawback of this concept is the additional process time and it is no solution for compensating assembly errors.

Compensating the magnetic imperfections gains even more importance with new motor concepts, such as halbach-rotors allowing to eliminate the heavy iron joke for the magnetic inference. This design uses different magnetization directions to eliminate the magnetic flux on one side and concentrate the flux in the air gap of the motor. A huge benefit is the higher power density due to a lighter rotor. Full elimination of the magnetic flux on the opposite side of the motor's air gap can only be assured by precise arrangement of the magnets with full compensation of the magnetic imperfections. [22]

For compensating rotor imbalance, two similar concepts were presented. [5] does a 100 % weighing of magnets before assembly with the same major drawback as [8] and is dependent of the quality of imbalance of the lamination stack and the tolerances of the magnet cavities in the rotor lamination stack. [6] can reduce the total imbalance significantly by premeasuring the imbalance of single rotor discs and arranging them in an optimum order and rotational orientation. However, a small residual imbalance cannot be compensated.

Compensation of magnetic field imperfections by single coil control

Fraunhofer IISB developed an integrated inverter drive for traction applications. In this development, each single tooth coil has a designated inverter, in this case a transistor full h-bridge. [9] With intelligent electronics, this can be used for compensating magnetic as well as stator manufacturing imperfections according to the rotational magnetic components of the whole drive.

6. Conclusion and Outlook

The presented paper gives a short overview of the challenges of electric drives production addressing influences of manufacturing on the quality of the electric drive. First, the process steps are introduced and brought into context with the process chain. This in turn is divided into stator and rotor manufacturing processes. The paper closes with some suggestions for compensating most of the rotor imperfections presenting different approaches of current research. In this topic further investigations are being performed giving detailed information about the dependencies of the presented imperfections with the performance of the drive regarding power density, energy efficiency, vibration and noise. Great importance for manufacturing is given to in-line test methods to ensure the highest possible quality during the whole production chain.

References

[1] H. C. Lahne and D. Gerling: Comparison of state-of-the-art high-speed high-power machines: Research study including a design example of a 50000 rpm induction machine. IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, 2015, pp. 003519-003524

[2] J. Huppunen: High-speed solid-rotor induction machine – electromagnetic calculation and design. Thesis for the degree of Doctor of Science, Lappeenranta University of Technology, Lappeenranta, Finland, 2004

[3] M. A. Khan, I. Husain, R. Islam and J. Klass, "Design of experiments to address manufacturing tolerances and process variation influencing cogging torque and back EMF in the mass production of the permanent magnet synchronous motors," 2012 IEEE Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, 2012, pp. 3032-3039.

[4] D. Coupek, A. Verl, A. Lechler, J. Aichele and S. Junker, "Defect reduction in the production of electric drives by downstream compensation and space-resolved inspection," 2014 4th International Electric Drives Production Conference (EDPC), Nuremberg, 2014, pp. 1-8.

[5] M. Peter and J. Fleischer, "Rotor balancing by optimized magnet positioning during algorithm-controlled assembly process: Selection and assembly of rotor components minimizing the unbalance," 2014 4th International Electric Drives Production Conference (EDPC), Nuremberg, 2014, pp. 1-4.

[6] B. Hofmann, M. Masuch, P. Kümmeth, J. Franke, P. Frey and M. Merklein, "In-line strategies and methods to reduce balancing efforts within rotor production for electric drives," 2016 6th International Electric Drives Production Conference (EDPC), Nuremberg, 2016, pp. 27-31

[7] J. Tremel, S. Kreitlein and J. Franke, "Production planning scenarios for manufacturing of electric drives," 2012 2nd International Electric Drives Production Conference (EDPC), Nuremberg, 2012, pp. 1-9.

[8] Meyer, A., Heyder, A., Kühl, A., Sand, C., Gehb, H., Abersfelder, S., Wangemann, S.: Concept for magnet intra logistics and assembly supporting the improvement of running characteristics of permanent magnet synchronous motors. Procedia CIRP, 2016, 43 356-361.

[9] H. Rauh, M. Hofmann, B. Eckardt, M. März: Radantrieb und Zentralantrieb – innovative Antriebskonzepte im Vergleich. Tagungsband ‚Haus der Technik - Trends in der elektrischen Antriebstechnologie für Hybrid- und Elektrofahrzeug (Expert Verlag)', München, 2011.

[10] B. Hofmann, S. Spreng, J. Franke and B. Maryniak, "Innovative and energy-efficient insulation technology for the production of electric drives," 2014 4th International Electric Drives Production Conference (EDPC), Nuremberg, 2014, pp. 1-5.

[11] M. Schneider, M. Hubert and J. Franke, "Influence of cutting edge on core loss induced through various manufacturing parameters," 2016 6th International Electric Drives Production Conference (EDPC), Nuremberg, 2016, pp. 186-192.

[12] A. Meyer, C. Nolte, C. Fischer, A. Sauerhöfer and J. Franke, "Increasing the energy efficiency of the impulse magnetizing process," 2016 6th International Electric Drives Production Conference (EDPC), Nuremberg, 2016, pp. 22-26.

[13] H. Schilp, P. Schlag and M. Kohnhäuser, "Optimized handling of permanent magnets within the mass production of electric traction drives," 2013 3rd International Electric Drives Production Conference (EDPC), Nuremberg, 2013, pp. 1-6.

[14] S. Spreng, T. Gläßel and J. Franke, "Adaption of the ultrasonic welding technique to the process of joining insulated copper wires with standardized tubular cable lugs,"

2015 IEEE 61st Holm Conference on Electrical Contacts (Holm), San Diego, CA, 2015, pp. 147-153.

[15] J. Hagedorn, F. Sell-Le Blanc, J. Fleischer, "Handbuch der Wickeltechnik für hocheffiziente Spulen und Motoren". Springer Verlag, Berlin, Heidelberg, 2016

[16] J. H. Kim, Y. Li and B. Sarlioglu, "Novel Six-Slot Four-Pole Axial Flux-Switching Permanent Magnet Machine for Electric Vehicle," in IEEE Transactions on Transportation Electrification, vol. 3, no. 1, pp. 108-117, March 2017.

[17] A. Greifelt, D. Gerling, O. Moros, A. Patzak, F. Bachheibl, A. Baumgardt: „ISCAD Intelligent Stator Cage Drive – application related economics oft he 48 V high-power drivetrain". IET 2016, June 24 – 27 2016, Sapporo, Japan, pp. 250-267.

[18] I. Coenen, C. P. Mbo'o and K. Hameyer, "Statistical evaluation of manufacturing tolerances in electrical machines by simulation and measurement," 4th International Conference on Power Engineering, Energy and Electrical Drives, Istanbul, 2013, pp. 506-510.

[19] E. Lamprecht, "Der Einfluss der Fertigungsverfahren auf die Wirbelstromverlsute von Stator-Einzelblechpaketen für den Einsatz in Hybrid- und Elektrofahrzeugen". PhD Thesis, Meisenbach, 2014, Bamberg, Germany

[20] Brela, M.; Meyer, A.; Mahr, A.; Gehb, H.; Berger, D.; Franke, J., " Selective Assembly of Permanent Magnets for the Optimization of Operating Characteristics of PMSM," in Electric Drives Production Conference (EDPC), 2015 5th International, pp.1-6, 15-16 Sept. 2015

[21] A. Meyer, A. Heyder, M. Brela, N. Urban, J. Sparrer and J. Franke, "Fully automated rotor inspection apparatus with high flexibility for permanent magnet synchronous motors using an improved hall sensor line array," 2015 5th International Electric Drives Production Conference (EDPC), Nuremberg, 2015, pp. 1-5.

[22] R. P. Praveen, M. H. Ravichandran, V. T. Sadasivan Achari, V. P. Jagathy Raj, G. Madhu and G. R. Bindu, "A Novel Slotless Halbach-Array Permanent-Magnet Brushless DC Motor for Spacecraft Applications," in IEEE Transactions on Industrial Electronics, vol. 59, no. 9, pp. 3553-3560, Sept. 2012.

[23] M. Schneider, M. Zahner, and H. J. Franke, "Kräfte- und Belastungsermittlung," *ZWF*, vol. 110, pp. 771–774, 2015.

[24] A. Dr. Wetzig and P. Herwig, "Remote Laser Schneiden Metallischer Werkstoffe," Dresden.

Learning Energy Efficiency Networks – how to accelerate the implementation of high efficient motor systems in industry

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Abstract

When starting energy efficiency networks (EEN) in industry in the 1990s in Switzerland and in the early 2000s in Germany, their initiators did not realize how effective this new policy instrument would turn out to be. This paper reports on the lessons learnt about the identification and implementation of high efficient motor systems in EEN. Ten to 15 companies regularly exchange their experiences on energy efficient solutions, set joint efficiency targets and perform a yearly monitoring of their efforts.

EEN have been implemented with great success in different policy settings: (1) as centrally organized instrument with a standard set by government, or (2) with an open standard, but a saving target set by government, or (3) as an open standard with a minimum specification. In every case, participation of companies is not obligatory, but encouraged by incentives or voluntary agreements.

The paper reports on the performance of regional EEN with more than 400 companies with regard to efficient motor systems as a segment of cross cutting technologies. Out of almost 1,800 profitable investments the results show:

- average yearly savings per investment: between 110 MWh/a (cold) and 360 MWh/a (ventilation);
- average profitability of the investments: 22.5 % (cold) and 45 % (compressed air systems).

In addition, participating companies have taken their own initiatives to improve their products' energy efficiency (e.g. high efficient ventilators, energy management and monitoring systems). Energy managers have asked their machinery suppliers to improve the energy performance of their products (machinery with high efficient motors).

1 Introduction – Large profitable efficiency potentials in unfavourable boundary conditions

Many national and international studies describe the existence of large profitable energy efficiency potentials in the industrial sector [1][2][3][4] and more specifically for electric motor systems [5]. This knowledge is not new and includes electrical motor systems. The fact has been reported since the 1980s in Europe or North America [6][7]. Energy efficiency has been described as the EU's biggest energy resource and one of the most cost effective ways to enhance the security of its energy supply and decrease the emissions of greenhouse gases and other pollutants [8]. Many European governments are now treating energy efficiency as a main driver of strategic development and CO_2 emission mitigation.

Our own empirical analyses of 400 energy audits concluded that more than 3,700 profitable energy efficiency investments with an average internal rate of return of 31 % should reduce the companies' final energy demand by around 10 % within four years [9]. The internal rate of return varies from 12 % (minimum rate) to more than 100 % in many cases. On average, the annual energy bill should be reduced by some €180,000 per participating production site (mostly industrial companies) and the energy-related CO_2 emissions should decrease by around 1,000 tonnes per year (Mai et a. 2016). Obviously, there has been no change in the situation observed 20 to 30 years ago [7]:

"Consulting engineers usually return from on-site visits in companies with substantial and profitable energy efficiency potentials that are easy to realize and usually have high rates of internal return."

In addition to this business economics' perspective, microeconomic aspects and even macro-economic issues may be important. A high density of energy efficiency networks – similar to today's situation in Switzerland [10] - will create additional business opportunities for companies in industry, construction, services, and the energy sector. Additional jobs in energy efficiency consulting, construction, manufacturing, banking, maintenance, and research will be created by raising the demand for energy-efficient solutions and reducing energy imports.

These multiple benefits of the energy efficiency approach as defined by the International Energy Agency (IEA) [11] represent a broad range of potential positive impacts on the economy, society, and the environment of a country (see Figure 1). The IEA analysis concluded that improving energy efficiency has the potential to support economic growth while reducing energy demand, as large energy imports are substituted by domestically produced investment goods and services. The induced economic growth enhances social development, speeds up environmental and climate protection, supports sustainability tendencies, and improves the energy system security of a country.

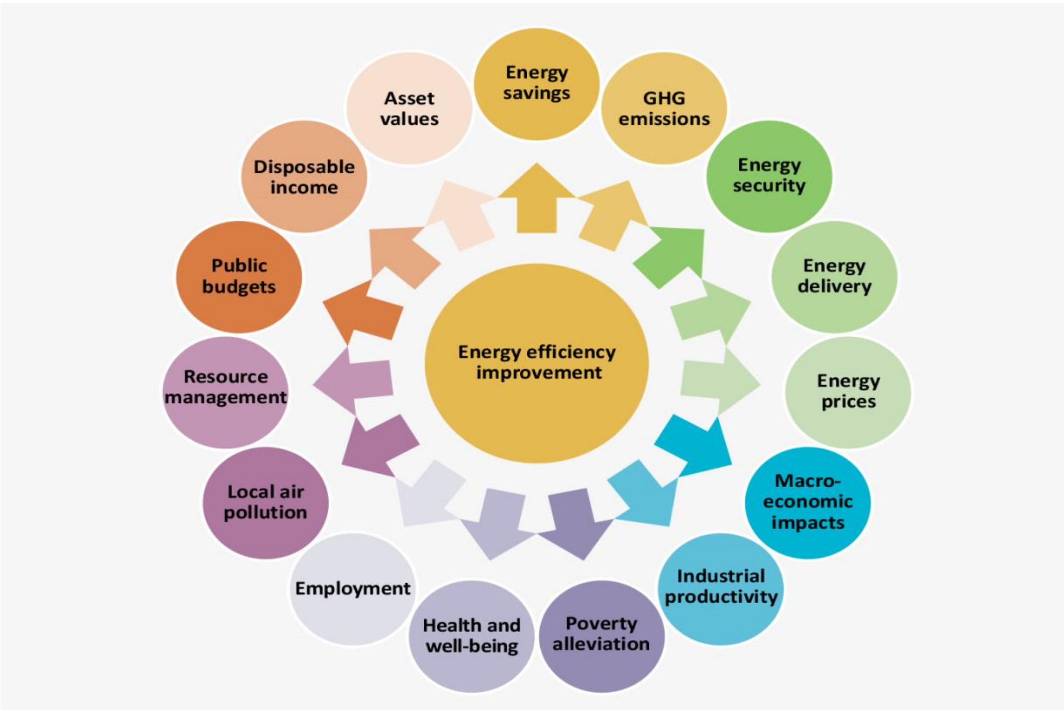

Figure 1: The multiple benefits of improving energy efficiency

Source: [11]

1.1 Obstacles and unfavourable boundary conditions

The limited realization of profitable energy efficiency potentials in industry and the service sector has been the subject of many discussions about obstacles and market imperfections for more than two decades [12][13], more specifically for electric motor systems [14] and the heterogeneity of these obstacles and potentials has been tackled by several sets of policy measures and instruments [15][5].

Surveys and interviews show that often the amount of attention paid to energy efficiency investments in companies is very limited and is heavily influenced by the priorities of those responsible for the company or the production site [16][17][18][19][20]. There are many reasons for this limited attention that depend on factors such as the size of the company, its energy intensity, ownership, and the awareness and leadership of its management, and also its financial strength and easy access to capital. Classical obstacles include [21]:

- lack of knowledge and market surveys of energy managers, particularly in SMEs [22], but also of consulting engineers, architects, system installers, or bankers;
- high transaction costs of the energy manager (to search for solutions, for tendering, decision making, installation [23]; and high cost for professional training of the other groups of actors are perceived in order to overcome the lack of knowledge;
- lack of equity, fear of borrowing more capital for investments in off-sites or relying on the competence of a contracting company; energy efficiency investments are generally not considered a strategic investment [19];
- technology producers or wholesalers often pursue their own interests and may be opposed to the innovations of more efficient solutions;
- 80 % of companies use only risk measures (payback periods), not profitability indicators (e.g. internal interest rate, present net value) for their decisions [24].

Given the existence of several obstacles (and often several unused supporting factors) within the supply chain of an energy-efficient solution, policy analysts ask for a bundle of policy measures to address them simultaneously (e.g. [22].

One way of addressing the dilemma of large profitable energy efficiency potentials and the various obstacles and unused supporting factors preventing their exploitation is the instrument of energy management systems such as ISO 50 001 or national energy management standards such as the DIN EN 16247-1 for performing energy audits. These instruments raise the awareness for energy efficiency in companies, help to re-think and re-structure the priorities of investment plans and set a minimum standard for how energy audits should be performed and how companies should organise the process to implement energy cost savings and sustainable energy use at their production sites.

However, these energy management systems work on an individual basis and lack quality checks. The consulting engineer or the auditor may not be well informed about all the possible fields of energy efficiency. They may have little knowledge of thermodynamics, electrical systems, or electronic control and communication systems. The board of the company may have an interest in formally imple-menting the Energy Management System (EMS) in order to receive a subsidy or reimbursement of an energy tax or a CO_2 surcharge or to formally fulfil a government ordinance.

1.2 Unused supporting factors

Besides the business economics related reasons for the priority setting of companies, there are also psycho-social, motivational, and behavioural aspects that have rarely been analysed except by some sociologists and psychologists in the 1990s (e. g. [25][26][27]. The authors call these aspects “scarcely used supporting factors”:

- Traditional investment priorities steer staff motivation and behaviour and determine the career of young engineers and their activities; energy engineers often have difficulties to “make a convincing case” to the management about efficiency improvements [18].
- The co-benefits of energy-efficient new technologies are rarely identified and in most cases not included in the profitability calculations by the energy or process engineers

due to the lack of a systemic view of the whole production site and possible changes related to the efficiency investments [28].

- Management is often not aware that the workforce may suffer from criticisms made by friends or relatives that they work in a "polluting" or wasteful industrial site.

Social relations such as competitive behaviour, mutual esteem and acceptance not only play a role between enterprises, but also internally within a company. Efforts to improve energy efficiency are influenced by the intrinsic motivation of companies' actors and decision makers, the interaction between those responsible for energy and the management, the internal stimuli of key actors and their prestige and persuasive power [29][18].

2 Learning Energy Efficiency Networks – operating more successfully in a group context and supporting the adaptation of efficient motor systems

This section describes energy efficiency networks (called "Learning Energy Efficiency Networks", LEEN) with a particular focus on how they are operated in Switzerland, Germany and Austria. After a long period of pilot networks (2002 to 2012) first networks have also been established in Belgium, Sweden, Mexico, and China since 2014. These networks can be considered a learning "Group Energy Management System" as they benefit from 10 to 15 energy managers sharing experiences and know-how in a very structured and well organised manner. A four-year long evaluation of 30 learning energy efficiency networks in Germany with 366 participating companies or production sites concluded that the efficiency progress of the participants was twice as high as that of non-participating companies on average [21]. The LEEN concept was developed in Germany between 2002 and 2015 in the basis of the Swiss experience and now represents a premium standard applied in the mentioned European countries, in Mexico and China.

The complex obstacles and the scarcely used supporting factors of energy-efficient solutions in companies mentioned in section 1 require a bundle of policy instruments – something that is rarely known or considered by policy makers in administration or the management in industrial associations or companies. However, in 1987, a Swiss consulting engineer, Thomas Bürki, had the idea for an action involving eight companies in Zürich: the Zurich Energy Model [30][31]: After an initial energy audit of each participant, the energy managers of the companies met four times a year to exchange the experiences gained with energy efficiency investments and organizational measures in a structured manner. At these meetings, the participants discussed a specific topic in more detail, possibly with a presentation by an external expert, and moderated by the consulting engineer. The performance of each company was monitored at least once a year.

The results of this first energy efficiency network were so convincing that the Swiss government's Federal Office of Energy funded several pilot networks as the Swiss Energy Model for industry and the service sector. The average annual energy cost savings were 165,000 CHF per participating company or production site. It was confirmed that the participants in such networks made much faster progress in improving their energy efficiency [32][33] including electric motor systems [34].

Since Switzerland's CO_2 law came into force in 2006, companies which reduce energy-related CO_2 emissions by a negotiated target, accept a yearly evaluation on its efficiency progress, and participate in an efficiency network can be exempted from paying the surcharge on fossil fuels. This was first introduced at a level of 12 CHF per tonne of CO_2 in 2008. The surcharge most recently approved by the Swiss Parliament in line with the Swiss CO_2 law in 2016 is 84 CFH per tonne. The Swiss Energy Agency for Industry, EnAW, acts as an intermediary to negotiate target agreements on CO_2 reduction for 10 years between companies and the Swiss federal government [10]. The target agreements are based on energy efficiency improvements or substitution options for fossil fuels.

Until 2007, most of the existing energy efficiency networks were regional networks. However, over the last 10 years, networks of branches (e.g. hotels, non-ferrous metals, electric steel) or of company groups (e.g. producers of consumer products, retail companies) have also been developed as well as networks for SMEs (small and medium-sized enterprises).

The Swiss Energy Model was transferred to Germany in 2002 by modifying two elements from the very beginning:

- A professional moderator was introduced in addition to the consulting engineer as a second neutral person. He prepares and moderates the regular meetings and writes the minutes; the idea behind this change is that such a moderator is not as technically biased as a consulting engineer might be, but is specialized in dealing with extroverted participants and getting more introverted ones to report their experiences. The moderator may also chair the annual meeting when the participant's monitoring report is discussed with the company board or management.
- The original ten-year target of the Swiss concept was reduced to three to four years. Two network targets (on energy efficiency and CO_2 mitigation) were introduced for internal use to generate a team spirit and an atmosphere of playful competition among the energy managers and for external use for the public image of the participating companies and the network, to demonstrate their engagement in climate protection and resource efficiency.

Between 2002 and 2008, the concept was tested in some 10 energy efficiency networks; five of them were evaluated in a pilot project between 2005 and 2008 with very positive results [25][26]. The German version of these networks was finally called "Learning Energy Efficiency Networks" (LEEN) and was widely tested in 30 pilot networks between 2008 and 2014, funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

2.1 The LEEN concept - a suggested standard operating energy efficiency networks

The establishment and operation of an energy efficiency network is usually considered in three major phases of activity [37], see also Figure 1).

1. *Initiation of the network*: the initiator who may be the president of the regional chamber of commerce or industrial association, the mayor of a larger city, or the CEO of a utility motivates companies in the region to join the planned network. The network operator supports this and considers suitable candidates for the role of consulting engineer and moderator in the planned network. This phase of getting 10 to 15 companies to participate is the crucial challenge. If a network is established, experience and evaluations show that almost all the participants are quite satisfied with how they benefit from the exchange and the network's services [38].
2. *Energy audit and targets*: In Phase 1, every participant undergoes an energy audit by an experienced engineer, who also suggests a (confidential) medium-term efficiency target for each participant as well as a joint network target, which is publicly communicated. The energy audit has to be performed in line with detailed standards for identifying energy efficiency potentials and their economic evaluation in all areas of cross-cutting technologies and organizational measures. The entire process including the report complies with ISO 50,001.
3. *Regular meetings and yearly monitoring*: In Phase 2, the essential cornerstone of a network's success is built upon the regular meetings held over the three to four years at different companies participating in the network. These not only encourage the

exchange of experiences at the four meetings per year, but also bi-laterally when an energy manager consults his network colleagues in specific cases of investments and planning. The meetings, which are well prepared by the moderator, generally cover one topic of an energy-efficient solution. This topic may also be covered by the presentation of an invited external expert, followed by a detailed discussion. Each meeting also includes an on-site inspection at the participant hosting the event. Continuous monitoring of the measures that have been implemented permits the yearly tracking of reduced energy costs and their contribution to higher profits. The monitoring (including the report) complies with ISO 50001. At the level of the network, the consulting engineer can also report on the network's progress in energy efficiency or CO_2 mitigation on a yearly basis, keeping track of the medium-term target adopted by the network in phase 1.

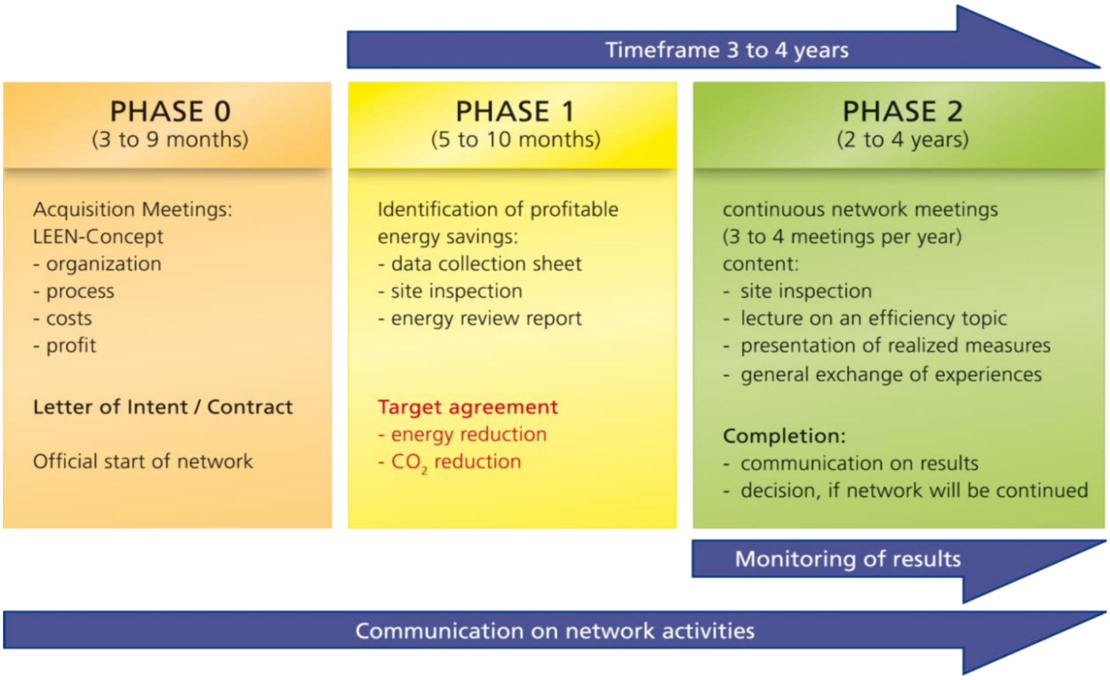

Figure 2: Three phases of establishing and operating an energy efficiency network

The network initiator is also the network operator in many cases. He organizes the contract with the participating companies, the consulting engineer, and the moderator. The cost for operating a network depends on whether the participating company has already had an energy audit, the frequency of the network meetings and the hourly rate of the network operator, the engineer and the moderator. A cost calculator is available on the internet (www.energie-effizienz-netzwerke.de). In general, the network costs are financed by the participating companies; in some cases, financial support may be provided by the federal or local government.

The major components of the underlying theoretical concepts for local learning networks can be summarized as follows:

- The heuristic approach of *innovation systems* is used to explain the network of actors who are involved in bringing about an innovation [39]. An investment in new energy-efficient technology does not come about due to an isolated decision of the management of a company, but is the result of complex interplay among many actors with influence upon a decision in a particular case: consultants, equipment suppliers, installers, architects, outside maintenance staff, key accountant of the energy supplier or cooperating bank, investment decisions of competitors or management colleagues in the region.

- One element follows the *dynamics of a product or investment cycle,* applying them in two dimensions: *(1)* the consulting engineer can take the initiative to present new and reliable efficiency technologies just being introduced to the market and *(2)* changes to the production and product quality at the production site caused by the efficiency investment are analysed in order to identify risks and co-benefits which are often neglected in energy efficiency investment considerations. Examples include absorption technologies substituting the compressor technology for cooling or substituting compressed air driven actors by electric actors. An example of a co-benefit is constant product quality after introducing improved control technology to avoid overheating in ovens at high temperatures.
- Aspects of innovation research, i. e. the concept of *first movers*, followers, and late applicants are considered along with the competences and motivations of these types of companies and their management, company size and whether they can employ specialists from the field of efficient energy use as internal staff or as external consultants. There are examples where participating companies asked their technology providers to improve existing machinery or plants; there are also cases where participating companies started thinking about improving the efficiency of their own products (e.g. high efficient ventilators) or developing new energy management equipment for small and medium-sized companies. The participating companies seem to be "potential first movers" in many cases. The authors therefore suggest offering those innovative participants specific incentives to contact technology providers, applied research institutes, and energy agencies.
- Finally, the concept also integrates *approaches of social and individual psychology*. These include social dynamics such as mutual affirmation and acknowledgement within a company and among the energy managers of several companies or administrations. Social cohesion is another example as well as responsibility and sanctions once a common target has been agreed. In addition, behavioural elements play a role such as the low competitive behaviour in acquainted groups and individual behaviour. This latter also includes several aspects to do with motivation - of individual professional careers, of experts sharing their knowledge with colleagues, or of management with regard to a positive public image and acceptance of the company at its production location [18][27].

One good example here is the generation of so called "energy scouts": apprentices at a production site are given specific measurement appliances to identify energy losses (losses of compressed air, cooling; idling machines, etc.) and the specific training to use them und evaluate their results [40]. These young people are highly motivated to conduct this task as they get very positive feedback from the energy manager for each relevant energy loss they detect. The concept was so convincing that 33 chambers of commerce in Germany now offer specific training courses for energy scouts. More than 1,000 energy scouts of many companies have been trained during the last two years [41].

The LEEN management system, developed with financial support from the German Federal Ministry for the Environment, now features more than 100 elements to support the network operator, the consulting engineer, and the moderator, but also initiators or multiplicators such as trade associations, chambers of commerce, or business developers. These elements comprise recommendations on how to approach and acquire potential participants. They also cover the description and division of tasks for the network operator, the consulting engineer, or the moderator, master contracts for all actors, including the participating companies and how to report the energy audits and conduct the yearly monitoring. Training material as well as training courses are offered for consulting engineers and moderators, and other assistance including 17 calculation tools to evaluate the energy efficiency options of cross-cutting technologies in technical and economic terms such as boilers, compressors, electrical motors, and pumps [42].[53]

A well structured report on the obligatory energy audit or a related, electronically calculated list of measures with their energy and cost savings, risk and profitability measures, and the avoided CO_2 emissions are essential for the LEEN MS. This list forms the basis for the monitoring process, which complies with the energy review outlined in ISO 50001.[54]

2.2 The achievements of LEEN-Networks in Germany

The 366 companies participating in 30 pilot energy efficiency networks between 2009 and 2014 have been evaluated by several analyses including the results of their energy audits, the yearly monitoring as well as questionnaires at the beginning and end of the four years' first operating phase (see Figure 2). The participating companies were asked about their past energy efficiency activities, their expectations at the beginning of the network and their judgment of the network's performance and what they gained from it at the end of the four-year period.

The systemic nature of the energy efficiency networks contributes to reducing many of the obstacles to energy efficiency mentioned in section 1 (e.g. lack of information and knowledge, low awareness of the topic, high transaction costs, decision routines solely oriented to investment risk). The network approach also means that often unused supporting factors (such as motivation, acknowledgement, or self-responsibility) are applied during the meetings and site visits, or in the meetings with the board or management to discuss the results of the annual monitoring.

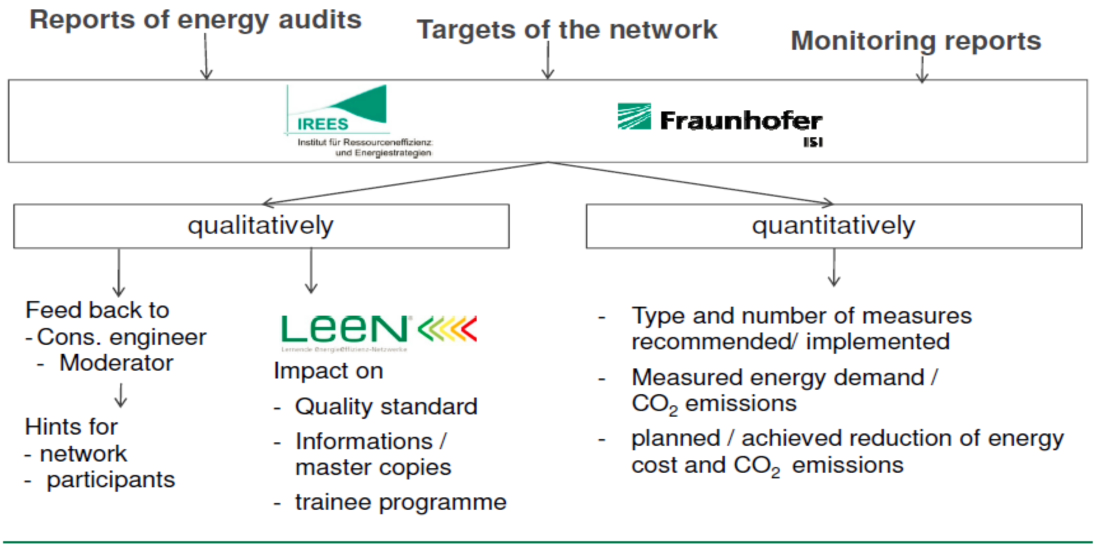

Figure 3: Evaluations of the performance of 30 pilot energy efficiency networks with 366 companies

On average, network participants doubled their energy efficiency progress compared to non-participants of the branch, resulting in an efficiency increase of 2.1 % per year [42]. The average annual savings were € 180,000 per participant (with annual energy costs of around € 2 mill.), inducing investments of almost € 600,000 over the four-year period. Of

[53] Most of the elements of the LEEN management system can be downloaded on the project's homepage in German (https://www.energie-effizienz-netzwerke.de/een-de/info-pakete/downloads.php). An English version is also available for most elements. A 3-day training course is required to be able to use the investment calculation tools properly. A licence is required to use the LEEN MS outside Germany (licence holder: Fraunhofer Gesellschaft, Munich).

[54] Compliance has been certified for the following steps (Rohde et al. 2015): energy review, energy baseline, energy performance indicators, energy objectives and targets, monitoring and measurement, and input to management review.

course, these average figures do not reflect the specific situations of companies, branches, the status of efficiency at the beginning of a network or the engagement of the participating company during the network's four-year operation. Two networks improved their efficiency by less than one percent per year, but two others by more than four percent; 14 networks were between 1 and 2 %, and 10 between 2 and 3 % annually.

Investments in additional energy efficiency also varied substantially by type (e.g. economizer of a boiler, heat exchanger added to an air compressor, high efficiency motors instead of a normal motor, pumps or ventilators) and size depending on the energy services or energy demand at the production site, building or factory (see Table 1). About 80 % of all net investments were below € 50,000. However, the basic re-investment also has to be considered that usually accompanies have to undertake, for instance a new air compressor, a new normal pump, ventilator or efficient electrical motor. The value of this basic re-investment is several times higher than the net energy efficiency investment, but not reported here. This is important when considering financing these investments by third parties like contractors or banks.

Table 1: Distribution of net energy efficiency investments according to their monetary size

Range of net investments in Euros	Number of net investments	Share of total net investments in %
< 5,000	1,387	39.8
5,000 to 50,000	1,511	40.4
50,000 to 250,000	474	13.6
250,000 to 1 mill.	96	2.8
> 1 mill.	17	0.5

Source: [44]

Some further results have been reported by [42][37][38]. They all report convincing results regarding overcoming several obstacles on energy efficiency and speeding up new ideas on energy efficiency improvements of technologies and organisational measures.

3 Results on electric motor systems

Before the results on electric motor systems are reported, it is important to get the complete picture of the evaluation of the 30 pilot energy efficiency networks: more than 7,000 measures were identified in the initial audits of the 366 participants; 3,600 of these were profitable measures (with an internal rate of return of more than 12 %); on average, nine profitable measures were identified for each participating company, energy saving potential of about 2,700 MWh/a and a CO_2 emission reduction potential of approx. 940 tonnes/ a. The joint efforts in the network resulted on average in annual energy efficiency progress that was twice as high as the observed average of German industry [43]. The evaluation of the submitted monitoring reports of 30 pilot networks shows an average increase in energy efficiency of 2.1 % per year and a reduction of CO_2 emissions of 2.4 % per year [38].

The profitable efficiency potentials of electric motor systems were about half of the number of investments (1,770) and about 36 % of the total yearly expected savings. The average internal rate of return varied between the low end at 22.5 % (for efficiency investments in cold) and at the high end at 45 % (for investments in compressed air systems; see Table 2). The differences of average profitability between the different options in energy efficient motor systems are even more pro-nounced, if more detailed technical subcategories of the motor systems are chosen (see Table 3).

Table 2: Number of profitable investments, average yearly savings per investment, average rate of return of energy efficient investments in electric motor systems of 366 network companies

Energy Efficiency Potentials	**Ventilati on**	**Compressed Air Systems**	**Electric Motors**	**Cold**	**Process Cooling**
Number of profitable investments[1)]	390	532	570	136	232
Yearly energy savings per investment (MWh/a)	359	146	179	110	183
Internal rate of returm	35 %	45 %	41 %	22,5 %	23,5 %
[1)] more than 12 % is defines as being profitable					

Source: [44]

The average data on electricity/ energy savings in Euros per year in Table 3 do not directly correspond to the yearly physical electricity/ energy savings, as (1) heat may be saved in some cases with lower monetary values or (2) the varying electricity prices of the participants are also included. A similar reason applies for the values on average CO_2 emission reductions, as saved fuels for saved heat have lower specific CO_2 emissions or the participants may different sources of electricity supply with different specific CO_2 emissions. The figures of internal rate of return in Table 3 also consider changes in maintenance cost.

The more detailed analysis technical subcategories of the electric motor systems refers to further details and more specified activities energy managers, the management or consulting engineers could consider:

- Some subcategories have obviously high or low relevance from the perspective of the probability to be a relevant investment option: waste heat recovery from ventilation or air conditioning equipment occurs only at a percentage of 11 % within the category of ventilation and air conditioning, while optimisation of interior air condition/ rate of fresh air supply/ air quantity via adjustment control/ maintenance has a 58 % probability that it represents a profitable investment.
- However, the occurrence of an energy efficient solution may be misleading, as the average savings in MWh or in reduced energy cost may be promising in this category, e.g. high energy savings for waste heat recovery in ventilation or air conditioning systems or free cooling in process cooling.
- Average investments in most subcategories vary between 10,000 and 45,000 €, which is not attractive for loans from the firm's bank. The transaction costs are generally considered to be too high. A similar attitude may be observed from contractors. The conclusion of the management is quite often to finance the investment from the cash flow. However, investments in the "core competence" may also limit this financing option in many cases [19].
- Average internal rates of return could be considered as candidates for public funding to accelerate the realization of these energy efficient motor solutions. It could be via direct investment grants or a competitive bidding [45].

Table 3: Evaluation of measures in subcategories of electric motor systems (selected results)

Technology area and corresponding measures	Num-ber of Mea-sures	Ø Energy saving, MWh/a	Ø CO_2 Red., [t/a]	Ø Red. of energy costs, €/ a	Ø IRR, %	Ø Invest-ment estimated €
Ventilation and air conditioning						
Optimisation of interior air condition/ rate of fresh air supply/ air quantity via adjustment control/ maintenance	272	171.3	65.6	13,594	61 %	24,521
Optimisation of interior air condition/ rate of fresh air supply/air quantity via modernisation/ supplement/ maintenance of components	143	208.4	65.1	13,370	30 %	45,813
Waste heat recovery in ventilation and air conditioning equipment	53	334.4	66.8	12,373	20 %	44,301
Compressed air						
Adjusting and controlling optimisation	351	61.4	32.0	6,326	103 %	9,322
Optimisation of compressor and its periphery via modernisation/supplement/ maintenance of components	277	74.5	37.9	7,168	57 %	10,275
Optimisation of the distributing system via demand minimisation	133	73.7	42.3	7,310	53 %	9,339
Electric motors and pumps						
Supplement/ replacement of motors	446	69.9	37.5	7,577	27 %	25,393
Controlling/ adjusting of pumps	127	62.1	32.3	7,314	41 %	15,655
Supplement/ replacement of pumps	80	34.2	18.6	3,500	24 %	12,456
Process cooling						
Optimisation of operation via modernisation/ supplement/ maintenance of components	220	111.7	63.0	12,509	41 %	35,200
Free cooling	65	137.1	73.1	15,736	34 %	42,395
Other (mostly due to measures involving ground and well water	57	71.4	29.5	5,670	28 %	22,650

Technology area and corresponding measures	Num-ber of Mea-sures	Ø Energy saving, MWh/a	Ø CO_2 Red., [t/a]	Ø Red. of energy costs, €/ a	Ø IRR, %	Ø Invest-ment estimated €
cooling)						

Source:[38]

The new instrument of competitive bidding may be an interesting element for operators or consulting engineers of energy efficiency networks, particularly for efficient electric motor systems as almost any network participant has investment opportunities in new efficient electric motor systems. The network operator or the consulting engineer could act as a bundler of investments and reduce the transaction cost of the competitive bidding.

4 Conclusions

Energy efficiency networks do respond simultaneously on several obstacles and unused supporting factors. The impact of the networks' collective knowledge and ever increasing experience is the major factor why participants of the networks have above average success by implementing energy-efficient solutions. This observation particularly holds for electrical motor systems.

Energy efficiency networks do not only respond to obstacles and unused supporting factors, but are extremely innovative regarding efficiency improvements they ask for their technology suppliers and regarding their own products in many cases. By sharing their knowledge and experiences by mutual motivation (joint network targets for energy efficiency and CO_2 emission reduction) the participants of the learning energy efficiency networks take up the role of "first movers" as applicants or as producers of highly efficient products (including electrical motor systems which has been observed by the authors several times). On the basis of more than 100 energy efficiency networks observed (covering more than 1,000 companies) the authors are convinced that a broad diffusion of learning energy efficiency networks in industrialised and emerging countries would be one of the most effective instrument to accelerate the diffusion of high efficient electrical motor systems.

The costs of operating an energy efficiency network can be covered by the participants as the participation fee (around 2,000 € to 7,000 € per participant and year) represent only a small share of the total yearly energy cost savings (on average 180,000 €). This observation gives governments the option to negotiate a voluntary agreement with the associations of industry and commerce (e.g. Germany) or to set rules where participating in those networks induces a financial incentive (e.g. Switzerland, Austria, Sweden; see [46]. In both cases, operating energy efficiency networks offers the opportunity to make it a business case. However, the crucial challenge of the business is the initiation of a network, the acquisition of the participants in particular. The Fraunhofer Society, a large German research institution, and the Institute of Resource Efficiency and Energy Strategies (IREES) have founded a company, called LEEN GmbH, in 2012, in order to further develop the concept and the tools used in learning energy efficiency networks and to market them world wide.

The often used term of "low hanging fruits" seems to be misleading in most cases as new ideas are generated by the energy managers, new energy efficient solutions come to the market and/ or undergo cost reductions due to economies of scale. These effects on growing profitable energy efficiency potentials can be observed in many applications of electrical motor systems. More intelligent and less expensive control, information and communication techniques are one reason of this “regeneration” of profitable energy efficient solutions. Increasing mass production and standardisation may be another reason. Finally, a high level of motivation of the energy managers and of the workers at the production lines is an important element for success and improving the energy efficiency of a plant including electric motor systems.

References

[1] Eichhammer, W., Fleiter, T.; Schlomann, B.; Faberi, S.; Fioretto, M.; Piccioni, N.; Lechtenböhmer, S.; Schüring, A.; Resch, G. *Study on the energy savings potentials in EU member states, candidate countries and EEA countries*. Final Report for the European Commission Directorate-General Energy and Transport. Fraunhofer ISI, Karlsruhe: 2009

[2] Fleiter, T., Eichhammer, W., Schleich, J.: *Energy efficiency in electric motor systems: Technical potentials and policy approaches for developing countries*. Unido Wien: 2011

[3] Fleiter, T., Plötz, P. *Diffusion of energy-efficient technologies.* in Encyclopedia of Energy, Natural Resource, and Environmental Economics. Vol.1: Energy. Shogren, J. F. (Ed.) p.63-73. Elsevier: Amsterdam: 2013. ISBN: 978-0-12-375067

[4] Brandmeier, M.; Franke, J. *Ontology-Based User Guidance for Energy Efficiency Optimization Measures.* International Conference on Industrial Engineering and Operations Management, Kuala Lumpur, Malaysia, March 8-10, 2016. Proceed. p.1649-1657

[5] Waide, P., Brunner, C.U. *Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems*. Working Paper. Energy Efficiency Series. OECD/IEA, Paris: 2011

[6] Levine, M. et al. (1995): *Energy efficiency policies and market failures.* Annual Review of Energy and the Environment 20; 1995. p.535ff

[7] Romm, J. *Cool Companies*. Earthscan, London: 1999

[8] COM European Commission COM 2011 (0109) final. 2011. Brussels.

[9] Köwener, D., Nabitz, L., Mielicke, U., Idrissova, F. *Learning energy efficiency networks for companies – saving potentials, realization, and dissemination.* ECEEE Proceed. 2014. p.91-100.

[10] EnAW – EnergieAgentur der Wirtschaft. *Der Partner für Klimaschutz und Energieeffizienz. Tätigkeitsbericht 2014*. Zürich: 2015

[11] IEA, International Energy Agency*. Capturing the Multiple benefits of energy efficiency. Energy efficiency: a key tool for boosting economic and social development*. 2014. Paris.

[12] IPCC Working Group III. *Working Group III contribution to the Intergovernmental Panel on Climate Change.* Fourth Assessment Report. Climate Change 2007: Mitigation of Climate Change. Technical Report. p.50-56. Cambridge Univ. Press. Cambridge.

[13] Blesl, M.; Kessler, A. *Energieeffizienz in der Industrie*. Springer. Berlin-Heidelberg: 2013. ISBN: 978-3-642-36513-3

[14] Cagno E, Trianni A. *Evaluating the barriers to specific industrial EEMs: an exploratory study in small and medium-sized enterprises.* Journal of Cleaner Production 2014; 82: p.70–93.

[15] DeCanio, S. J. *The efficiency products: bureaucratic and organisational barriers to profitable energy saving investments.* Energy Policy 1998; 26: p. 441ff

[16] Ramesohl, St. *Social interactions and conditions for change in energy-related decision making in CMCs*. in: Jochem, E. et al. (eds.): Society, behaviour, and Climate Change Mitigation. Advances in Global Change research. Kluwer Acad. Publishers, Dordrecht: 2000. p. 207 ff,

[17] DeGroot, H. L. F. et al. *Energy savings by firms: decision-making, barriers and policies.* Energy Economics 2002; 23; p. 717ff

[18] Schmid, Ch. *Energieeffizienz in Unternehmen: eine handlungstheoretische und wissensbasierte Analyse von Einflussfaktoren und Instrumenten*. Dissertation. Vbf Zürich: 2004

[19] Coremans, C. *Make it strategic! Financial investment logic is not enough*. Energy Efficiency. 2011; 4: p. 473 ff. DOI 10.1007/s12053-011-9125-7

[20] Wohlfarth, K., Eichhammer, W., Schlomann, B., Worrell, E. *Chances for changes – tailoring energy-efficiency measures to target groups.* Proc. of the ECEEE 2016 industrial energy efficiency conference. Berlin September 12 to 14, 2016. ISBN 978-91-980482-8-5

[21] Jochem, E., Lösch, O., Mai, M., Mielicke, U., Reitze, F. *Energieeffizienz in der deutschen Industrie – brachliegende Chancen.* Energiewirtschaftliche Tagesfragen. 2014: 64;1/2, p. 81-85

[22] Trianni, A., Cogno, E., Farné, S. *Barriers, drivers and decision-making process for industrial energy efficiency: A broad study among manufacturing small and medium-sized enterprises.* Applied Energy 2016;162: p. 1537-1551.

[23] Ostertag, K. *No-regret Potentials in Energy Conservation. An Analysis of Their Relevance, Size and Determinants.* In: Technology, Innovation and Policy, Series of the Fraunhofer Institute for System and Innovation Research, Physica Verlag Heidelberg: 2003

[24] Schröter, M.; Weißfloch, U.; Buschak, D. *Energieeffizienz in der Produktion – Wunsch oder Wirklichkeit? Energieeinsparpotenziale und Verbreitungsgrad energieeffizienter Techniken*. Mitteilungen aus der ISI-Erhebung. No. 51, Karlsruhe: 2009

[25] Stern, P.C. *What psychology knows about energy conservation*. American Psychologist, 1992: 47; p.1224-1232

[26] Jochem, E., Sathaye, J.; Bouille, D. (edrs) *Society, Behaviour, and Climate Change. Advances in Global Change Research.* Kluwer Academic Publ. Dordrecht/Boston/London: 2000

[27] Flury-Kleubler, P., Gutscher, H. *Psychological principles of inducing behaviour change. In R. Kaufmann, H. Gutscher (Eds.), Changing things – moving people: Strategies for promoting sustainable development at the local level*. p.109ff. Birkhäuser Basel: 2001

[28] Madlener, R., Jochem, E. *The Forgotten Benefits of Climate Change Mitigation: Innovation, Technological Leapfrogging, Employment, and Sustainable Development.* OECD Working Paper ENV/EPOC/GSP(2003)16/FINAL, OECD, Paris: 2004

[29] InterSEE *Interdisciplinary Analysis of Successful Implementation of Energy Efficiency in Industry, Commerce and Service*. Wuppertal, Kopenhagen, Wien, Karlsruhe, Kiel: 1998

[30] Bürki, T. *Das Energie-Modell Schweiz als Erfahrungsfaktor für Schweizer Unternehmen*. Bundesamt für Energie: Energie 2000, Ressort Industrie. Benglen: 1999

[31] Graf, E. *Evaluation of the Energy Model Switzerland* (in German) Fed. Office for Energy, Bern: 1996

[32] Kristof, K. u. a. *Evaluation der Wirkung des Energie-Modells Schweiz auf die Umsetzung von Maßnahmen zur Steigerung der Energieeffizienz in der Industrie und seiner strategischen energiepolitischen Bedeutung*. Bundesamt für Energie, Bern: 1999

[33] Konersmann, L. *Energy efficiency in the economy – Evaluation of the Energy Model Switzerland and Conception of a multi-agent model*. Master Thesis (in German). ETH Zurich: 2002

[34] Jakob, M., Häberli, A. *Stromeffizienz der Schweizer Wirtschaft - Auswertung und Szenarien aus der Erfahrung der EnAW.* TEP Energy. Zurich: 2012

[35] Jochem, E., Gruber, E. *Local learning networks on energy efficiency in industry – Successful initiative in Germany.* Applied energy 84(2007) p. 806-816

[36] Bauer, J., Bradke, H., Held, St., Jochem, E., Köwener, D., Lohmann, L., Ott, V., Wagner, Th., Weissenbach, K. *Umweltkommunikation und Energieeffizienz in KMU: Moderierte EnergieEffizienz-Tische in Unternehmensnetzwerken reduzieren CO_2.* Abschlussbericht für die Deutsche Bundesumwelt-Stiftung. Waldenburg, Karlsruhe, Hannover und Berlin: 2008

[37] Köwener, D., Mielicke, U., Nablitz, L, Idrissova, F. Learning Energy Efficiency Networks for Companies – Saving Potentials, Realisation, and Dissemination. Proc. of the ECEEE 2016 industrial energy efficiency conference. Berlin September 12 to 14, 2016, p.91-100. ISBN 978-91-980482-8-5.

[38] Dütschke, E., Idrissova, F., Hirzel, S., Nabitz, L., Mielicke, U., Mai, M. *Regional energy efficiency networks – what factors make them successful?* Article 5-082-16, Proc. of the ECEEE 2016 industrial energy efficiency conference. Berlin September 12 to 14, 2016. ISBN 978-91-980482-8-5

[39] Kuhlmann, St. *Governance of Innovation Policy in Europe – Three Scenarios. In: Research Policy.* Special Issue „Innovation Policy in Europe and the US: New Policies in New Institutions", edited by Klein, H.K., Kuhlmann, St. and Shapira, P. vol. 30,6/2001, p. 953-976 ISSN: 0048-7333.

[40] ebmpapst *The ebm-papst energy scouts project for apprentices*. Mulfingen. 2016

http://www.greentech.info/en/greentech/philosophy_1/energiescouts/energiescouts.html

[41] DIHK *Energie-Scouts - Qualifizierung für Azubis*. 2016 http://www.mittelstand-energiewende.de/mie-vor-ort/energie-scouts-qualifizierung-fuer-azubis/

[42] Rohde, C., Mielicke, U., Nabitz, L., Köwener, D. *Learning Energy Efficiency Networks –Evidence based experiences from Germany*. ACEE Summer Study on Energy Efficiency in Industry, Arnheim: 2015

[43] Bradke, H., Jochem, E., Mielicke, U., Ott, V., Mai, M., Köwener D., Idrissova, F., Weissenbach, K., Bauer, J., Meier, N., Hack, M., Diemer, R., Feihl, M., Bergmann, K., Berger, R., Ernst, C., Kubin., K. *Lernende Energieeffizienz- und Klimaschutz-Netzwerke. 30 Pilot-Netzwerke und Entwicklung von Investitionsberechnungshilfen*. ISI-Research Report. Karlsruhe: 2015.

[44] Mai. M., Gerspacher, A., Jochem, E., Mielicke, U., Eberle, A. *Energy efficiency networks – A group energy management system as a business model?* Proc. of the ECEEE 2016 industrial energy efficiency conference. Berlin September 12 to 14, 2016. p. 641-650. ISBN 978-91-980482-8-5.

[45] ProKilowatt *Dritte Wettbewerbliche Ausschreibungen für Stromeffizienz 2012 – Kurzbeschreibungen bewilligte Programme 2012*. Geschäftsstelle für Wettbewerbliche Ausschreibungen im Stromeffizienzbereich. Sitten, Switzerland: 2012

[46] IPEEC (International Partnership for Energy Efficiency Cooperation) *Energy Efficiency Networks – Towards good practices and guidelines for effective policies to stimulate energy efficiency.* Working Paper. IEA Paris: 2017

Swiss training for Industrial Energy Optimization

Rolf Tieben, Rita Werle, Conrad U. Brunner

Impact Energy

Abstract

Audits in 25 Swiss factories analyzing 4142 motor systems have shown that many motor systems are old, inefficient, oversized and need to be optimized systematically. This has been hampered by different barriers, including a lack of know-how, competence and capacities of in-house technical staff. A new Swiss training program for industrial energy optimization (IEO) aims to close this gap through building a pool of skilled professionals to implement motor systems optimization projects.

IEO is supported by the Swiss Federal Office of Energy, local governments, utilitites and other organizations and is managed by Impact Energy.

The primary target group of the training is factory engineers working in industrial plants, the secondary target group is energy consultants, representatives of utilities and government authorities, etc. IEO is the first unique training program combining both technical knowledge and management skills.

IEO is six days long and consists of the following main parts:

1. Introduction
2. General energy management
3. Specific technology focus including laboratory or facility demonstration for the following modules: motors and converters, pumps, fans, compressors. Examples of realized optimizations and group work also play an important element within the program.
4. Final exam, including presentation of individual optimization assignments.

The goal of IEO is on the one hand, to teach the technical fundamentals of electric motors, applications (pumps, fans, compressors, etc.) and system optimization including the audit methodology Motor-Systems-Check (www.topmotors.ch). On the other hand, to train technical staff how to sell an investment project to company management.

A feasibility study was conducted in 2014 including all relevant educational institutions preceding the choice of training sites, supporting national organizations and teachers in 2015. Courses are held both in the German and French part of Switzerland, in both languages. The first German course was held in 2016. The feedback of the first participants was collected and carefully evaluated, based on which an update of the program was elaborated. The first French and second German courses were held in 2017, the next course dates for 2018 are already published. After the first trainings, possibilities for a longer training duration and introduction in other countries will also be investigated.

Introduction

Electric motor systems are responsible for more than 50% of Swiss electric energy consumption. The analysis in 25 Swiss industrial and infrastructure plants has shown that motor systems are responsible for more than 80% of electric energy consumption in these companies, with savings potentials between 20% to 30%.

Switzerland has a long tradition of over two decades with target agreements. Companies commit to reducing their CO_2-relevant energy consumption and in turn get the tax they pay on their CO_2 emissions reimbursed. As in Switzerland electric energy is generated almost CO_2-neutral, there has been little incentive in the past for companies to improve their electric energy efficiency. Although new policy instruments (e.g. public tenders with financial incentives [6], financial benefits for energy-intensive users, etc.) gave a new impetus in this field during the past few years, motor systems so far have been a neglected area of action for many companies in the industrial and services sectors. [3] [7]

In order to tackle this issue, the Topmotors program (www.topmotors.ch), managed by Impact Energy and supported by the Swiss Federal Office of Energy, has been running in Switzerland since 2007. The goal of the program is to raise awareness of industrial end-users, manufacturers of motors and machines and other relevant stakeholders on the potential of efficient electric motor systems used in industrial and infrastructure facilities and large buildings and to show ways to exploit these.

Topmotors has since 2007:

- Developed the four-step Motor-Systems-Check methodology with software tools for each step, designed to find the 20% of motors within a factory which bring 80% of the potential savings of electric motors;
- Developed a number of fact sheets on the efficient design of motor systems, i.e. pumps, fans, the use of Variable Frequency Drives (VFD), compressors for air and cold, etc.;
- Organized a number of workshops on specific topics related to motor systems, such as pumps, fans, compressors, measurements on site, specific applications (escalators, elevators, hydraulic machines, machine tools), the use of VFDs, etc.
- Organized the international Motor Summit conference (www.motorsummit.ch) in Zurich six times, bringing together policy and technology experts across the globe to debate the latest developments on efficient electric motor systems.

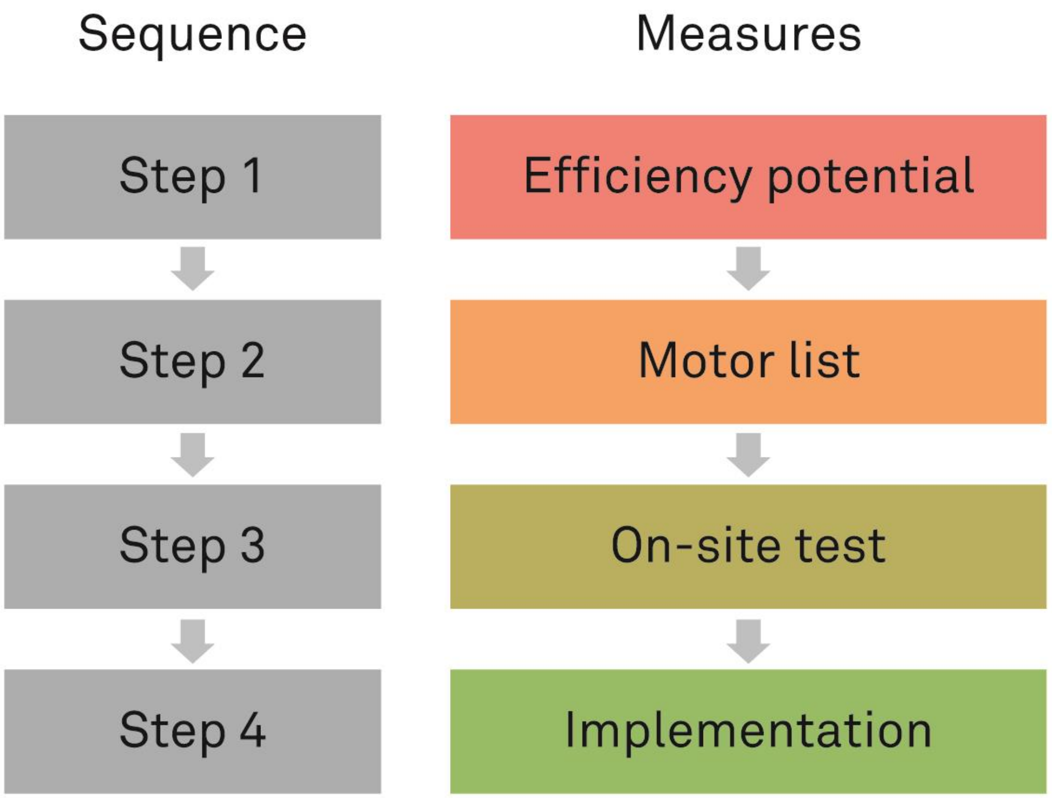

Figure 1 - The four steps of the Motor-Systems-Check

Between 2010 and 2014, Topmotors ran the financial incentive program EASY (Efficiency for motor systems, www.topmotors.ch/easy) [3][4]. The goal of EASY was to help factories with financial incentives and know-how to improve their existing motor systems. The program aimed at overcoming the barriers preventing companies from efficiency improvements in terms of necessary resources (time, know-how, financial resources). Within four years, 25 companies started the four-step Motor-Systems-Check audit, a method to make a systematic approach to check and optimize the electric energy consumption of the motor systems. During this period, 4142 motor systems have been analyzed in detail. Results have shown that many motor systems are old, inefficient, oversized and need to be optimized systematically. Within the framework of the EASY program, measures with an overall saving of 74 GWh (over the lifetime[55] of the improved motors) have been implemented.

Almost all companies participating in EASY have one thing in common. They are specialists in producing high-quality products but they all have a lack of knowledge concerning electric energy efficiency and in particular, motor systems efficiency. Technical staff is well trained in maintenance work and their main goal is to keep the system running. Saving energy has a much lower or even no priority, also due to the fact that for most companies, energy costs represent only a minor fraction within total costs (except for energy-intensive companies).

During the course of the program, the need for a dedicated training of technical factory staff became evident.

Feasibility (2014)

In 2014, Topmotors made a feasibility study for the training program "Industrial Energy Optimization" (IEO) dedicated to motor systems in Switzerland [2]. In the framework of this feasibility study, a survey was conducted with 34 participants, including 17 potential training sites and a number of other stakeholders: utilities, industry associations, manufacturers, planning engineers, representatives of cantons (public authorities) and industrial end-users. The results of the feasibility study can be summarized as follow:

- There is no training program available in Switzerland specifically focusing on motor systems only. Some trainings briefly treat this topic, while the majority of trainings focuses on buildings, renewable energy and a few trainings dealing with the industrial sector on thermal energy. Despite some earlier training programs that focused on some specific technologies (compressed air, cooling, etc.) there has never been a universal efficiency training program for all important types of motor driven systems. In conclusion: the topic is relevant and not sufficiently present within the continuous education landscape.
- The training is fitting into continued education, i.e. it will be addressing professionals in a working environment with some years of work experience, not students within their tertiary education programs (bachelor, master).
- The primary target group of the training should be technical staff working in industrial factories. The secondary target group: energy consultants, people working for utilities, industry associations, energy agencies, public authorities, etc. Addressing (non-technical) managers was investigated but decided against.
- The training duration was fixed for 6 days, always two consecutive days (Friday and Saturday) on three different occasions. A longer training duration was investigated but decided against. The reason for this was to accommodate for the limited availability of the target group. It also seemed important to split the training time between work time (three Fridays) and free time (three Saturdays) equally.

[55] The assumed lifetime of newly installed equipment is between 10 to 20 years, depending on the size of the motors (for motors below 1 kW 10 years, for motors above 100 kW 20 years).

- The unique selling proposition of the training program is that it combines technical knowledge and management skills. Technical knowledge is being built up in the part of the program with the specific technology focus and management skills in the part concerning general energy management.

The feasibility study gave a good opportunity to engage with relevant stakeholders in the field, as a first step towards building up a national organization behind the training program.

Build-up (2015)

In 2015 work began to elaborate the content of the IEO training program, to choose the training sites, the teachers and to build up the organization.

Training sites

Topmotors established a collaboration with two universities of applied sciences as training sites:

- Lucerne University of Applied Sciences and Arts (Hochschule Luzern HSLU) at Horw in the German-speaking part of Switzerland
- Haute École d'Ingénierie et de Gestion du Canton de Vaud (HEIG-VD) at Yverdon-les-Bains in the French-speaking part of Switzerland.

Both universities have a very-well equipped laboratory for motor systems. At HEIG-VD a pump demonstrator machine is available to showcase the difference in the electric input power of pumps when used with or without a VFD. A similar machine is currently being built for fans at the HSLU.

Figure 2 - Pump demonstrator at HEIG-VD

Organization

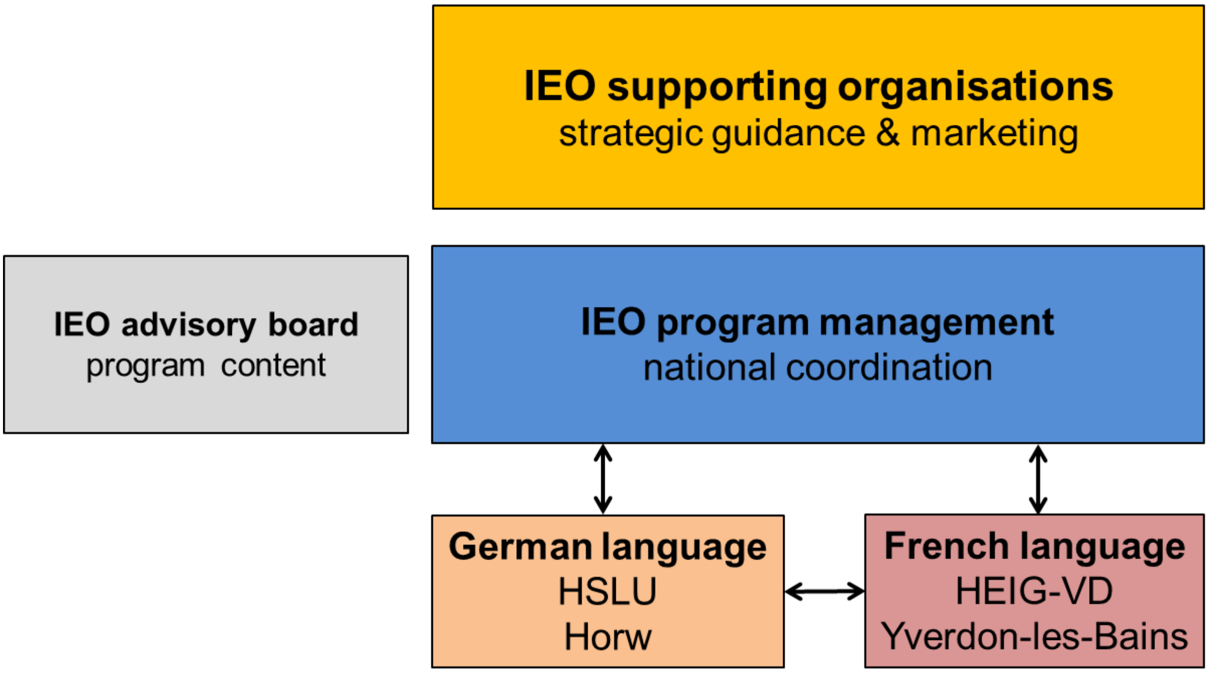

Figure 3 - Organizational structure of IEO

Topmotors entered into partnership agreements with a number of organizations supporting the program with financial contributions and/or their marketing channels in an attempt to inform potential participants on IEO. The supporting organizations include energy agencies, an industrial association with a wide network of technical professionals, utilities with industrial customers as well as public authorities, acknowledging the importance of the topic (see **Figure**). Public authorities also gave financial support in the form of a reduced training fee to participants, to encourage greater participation.

Figure 4 - IEO supporting organizations

The IEO advisory board played an important role in the elaboration of the training content.

Goal

The goal of IEO is to empower technical staff in industrial factories to:

- establish a long-term, continuous improvement process for motor systems within the factory,
- lead and implement efficiency optimization projects for motor systems involving external specialists, manufacturers and service providers and
- present the optimization projects and convince upper management to invest into them on a regular basis.

Content

The training consists of the following main parts:

1. Introduction to the Swiss energy efficiency policy background and legal requirements,
2. general energy management, communication, profitability calculations, and suggestions to convince upper management,
3. specific technology focus including laboratory or facility demonstration for motors systems, and
4. a final exam, including a presentation of individual optimization assignments.

There are three crucial aspects of the IEO training: its practical orientation, a systems approach and the combination of technology and energy management topics.

The IEO program recognizes that it is not enough to have a sound technical proposal for optimizing a system, but technical personnel also needs to be able to convince the people within management who have authority over investment decisions. This is the reason for addressing profitability calculations (including life cycle costs) and communication aspects within IEO. Studies have shown that the assessment of life cycle cost or total cost of ownership is not very widespread yet in companies although it clearly increases the implementation of efficiency improvements. [8]

Practical assignment

For a successful completion of IEO, participants have to make an individual practical assignment which means they have to:

- identify a suitable motor system (i.e. a pumping or fan system) within their factory, or any other suitable object,
- describe the system, gather parameters for peak and average load, annual operation characteristics,
- investigate variants for optimizing the energy efficiency of the complete system and quantify the expected savings, and
- present the motor system optimization recommendations to the class.

Pilot course (2016)

During June/July 2016, the first pilot course was held at the Lucerne University of Applied Sciences and Arts in German. Seven participants were trained in energy efficient motors in industry. Although the primary target group of the program is technical staff in industrial factories, all seven participants were energy consultants belonging to the secondary target group.

All participants were asked for a detailed feedback on the first course, consisting of written feedback to a comprehensive questionnaire and oral feedback within the group in form of a discussion. Their feedback can be summarized as follow:

1. The topic of IEO is good, important and not sufficiently covered in the running continued education programs in Switzerland.
2. The structure, timing and duration of IEO is optimal.
3. Participants wished to include even more practical work and examples in the training course and less theoretical background.
4. They especially valued the exchange among one another which was intensive during the last day of IEO when participants presented their individual practical assignments.
5. While they acknowledged the importance of energy management, they urged to reduce the time spent on it (originally one training day) and make it more focused.
6. As there are many small and middle sized enterprises (SME) in Switzerland there was a wish to dedicate more attention to an SME-approach within IEO.

The program management assessed this feedback, taking into account that the participants were from the secondary target group of the program, and changed the structure of the program for the regular courses accordingly (see **Figure**).

The practical orientation was reinforced through more group work and the fact that Modules 1 to 5 take place in the university laboratory or on site within a factory. The theoretical background for explaining how efficient motor, pump, fan and compressor systems work was reduced, assuming that participants are already familiar with basic concepts. For each participant, detailed information is required on their educational and professional background (work experience) upon their registration for the training. This enables the program management to assess in advance the profile of participants and make adjustments to the program content if deemed necessary.

Day 1	**Day 2**
Welcome, Introduction	**Module 1: Motors** -typology, -losses, -measurement
Swiss Energy Industry	
Pre-post comparison	
Practical assignment	Motor-Systems-Check: methodology and tools
Questions & Answers	Questions & Answers

On site practical assignment

Day 3	**Day 4**
Module 2: Variable Frequency Drive (VFD) -typology, -losses, -measurement	Energy management and internal communication
Module 3: Pumps -typology, -losses, -measurement	Practical assignment -current status of the motor system -definition of improvements
	Questions & Answers

On site practical assignment

Day 5	**Day 6**
Modul 4: Fans -typology, -losses, -measurement	Written exam
	Presentation practical assignment
Modul 5: Compressors -typology -losses, -measurement	Presentation practical assignment
	Feedback
	End

Figure 5 - Updated IEO training content. Training participants are required to work on their practical assignments in between the training days, namely after days 1&2 and days 3&4.

Regular courses (2017)

The first French course with 13 participants took place between March and April 2017 and the second German course with 8 participants took place between May and June 2017.

In the French course, around half of the participants came from the primary target group (technical persons working in industrial facilities) and the other half of the participants was made up from persons within the secondary target group, i.e. persons working for utilities, public authorities, universities, or as energy consultants. In the German course the audience was mixed as well, with participants from the primary and secondary target groups, i.e. technical persons working in industrial facilities, for utilities and energy consultants.

The feedback of training participants was very positive for both courses, especially for the French edition. Here the training site offered the advantage of using the pump demonstrator plus the factory visit on site was also appreciated. Participants of the

German course suggested a more extensive use of the infrastructure provided by the German training site, where currently a fan demonstrator is being built up and to be used in the next training editions.

Other forms of training

Topmotors is launching regular webinars from 2017. These are online seminars that last between 30 and 60 minutes. There is usually a presentation of a topic related to efficient electric motor systems, followed by questions from the audience (questions are usually raised in writing, i.e. chat). The main characteristics of these webinars are:

- Online streaming which makes live participation possible,
- no need to travel and being physically present to attend the webinar and
- recording and publishing the webinar online makes looking at it later possible.

While nowadays webinars are getting more and more widespread, this form of training is currently not being considered for IEO as not found suitable. Within IEO, the practical hands-on training is a key element, as well as an intensive exchange between teachers and training participants, requiring physical presence throughout the six training days. This is well demonstrated by the fact that throughout the three trainings held so far, only one participant was missing during one training day because of an accident..

www.hslu.ch/w103

www.entrainements-electriques.ch

Figure 6 - Flyer images and website links of the German and French IEO courses

Program costs and financing

The IEO program is designed to run for at least five years. The program costs consist of the following three key elements:

1. Basic research:
   feasibility of topic, prerequisites and level of training, identification of target group, training program concept, training sites, etc.
2. Preparation of the training courses:
   preparation of coordinated training material, selection and training of the trainers, coordination of lessons (terminology, no overlap, few contradictions, same methodology for both German and French courses, etc.), selection and cooperation with training sites, building of an association with industry and utilities to carry the program nationally for the next decade, publicity for students and sponsors.
3. Implementation of the training:
   Classrooms, schedule, laboratory and field studies, monitoring of results, evaluation of participants' feedback.

For the basic research and preparation of the training external funding was needed, to a large extent provided by the Swiss Federal Office of Energy. During the implementation of the training, it is assumed that a minimum number of 12 participants paying the training fee of USD 3 000 should be sufficient to cover the costs.

Financial support by other further sponsors was twofold:

a. Support for the preparation of the training courses
b. Reduction of training fee by 50% for participants.

While the financial support for the basic research and preparation of the training courses was absolutely crucial, the incentive reducing the training fee proved to be very helpful in attracting participants for the training.

The program management continues its efforts for attracting further financial support from local governments, utilities, industry associations and other interested stakeholders.

Conclusions and next steps

After the pilot course and during the preparation and launch of the regular courses the program management faced a number of challenges and learned important lessons which can be summarized as follow.

1. The branding of the program with renowned host universities, the Topmotors program, the Swiss Federal Office of Energy and several well-known national supporting organizations was a key to success. It helps in the program positioning and strengthens credibility.
2. Marketing remains a big challenge. With the Swiss continued education landscape offering roughly 300 different courses it is crucial to get the right information to the right target audience and show the unique selling proposition of the program. The program management puts great effort into an information and marketing campaign through print and online media as well as through the network of the IEO supporting organizations to reach the target groups of the training. As long as the training is not well-known, it is more difficult to attract participants. Participants have a long planning horizon, they need to know several months in advance the training dates to be able to plan their absence from their workplace.
3. The teachers of the training were both university professors (rather strong theoretical knowledge) and external technical practitioners (rather strong practical knowledge). The program management put great emphasis on securing the most knowledgeable experts within their respective fields and on the coordination of the program contents, the use of one common terminology, key messages to be conveyed and reinforced, avoiding overlaps, repetitions or contradictions among multiple teachers. This combination of university professors and external

practitioners was seen as valuable, while at the same time it was a challenge to make sure that the whole training material suits the level of the target group and is close enough to their practical field of work.

The availability of laboratories was important while at the same time a stronger focus with the use of demonstrators (see

4. **Training sites**) or work at a factory was desirable. A stronger focus is also given to work in groups, to enhance the exchange among participants. The courses so far have shown that an access to objects suitable for the individual practical assignments did not constitute a hurdle (as originally expected by the program management).
5. The whole IEO project was supported from its outset in 2014 by the Swiss Federal Office of Energy. The program management analyzed the costs of the training program for a period of five years based on a business plan. It was clear from the outset that the operational phase of the training could be covered through the course fees paid by the participants (USD 3 000 for six days), but the build-up of the program needed additional financial support. This was secured through support from the national and local governments as well as other parties.

IEO is planned to continue in the coming years with at least one German and one French course per year. From 2018 two German courses are planned per year and in 2020 two French courses per year. The program management is investigating potentials for exporting the program to other countries. German and French-speaking countries are in favor due to ease of implementation, translation into English and Chinese is also being considered.

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References

[1] Paul Waide, Conrad U. Brunner, et al.: Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems, International Energy Agency Working Paper, 2011.

[2] Swiss Agency for Efficient Energy Use, University of Geneva, Feasibility study: energy technology and management in industry (ET&M), internal report (unpublished), 2014.

[3] Rolf Tieben, Rita Werle, Conrad U. Brunner: EASY- Lessons learned from four years of the Swiss EASY audit and incentive program. In: proceedings of the International Conference on Energy Efficiency in Motor Driven Systems, 15 - 17 September 2015, Helsinki.

[4] Rita Werle, Conrad U. Brunner, Rolf Tieben: Swiss motor efficiency program EASY: results 2010 - 2014. In: proceedings of the ACEEE Summer Study on Energy Efficiency in Industry, 4 - 6 August 2015, Buffalo, NY, USA.

[5] Rita Werle, Conrad U. Brunner, Rolf Tieben, Training for Energy Management and Technology in Industry: ET&M. In: proceedings of the 9th International Conference on Energy Efficiency in Motor Driven Systems, 15 - -17 September 2015, Helsinki, Finland.

[6] Richard Phillips: Swiss competitive tenders for promoting efficient motor systems, In: proceedings of the 9th International Conference on Energy Efficiency in Motor Driven Systems, 15 - -17 September 2015, Helsinki, Finland.

[7] Rita Werle, Conrad U. Brunner: Is management a key driver of energy performance? In: proceedings of the 10th International Conference on Energy Efficiency in Motor Driven Systems, 6 - 8 September 2017, Rome, Italy.

[8] Schröter, M.; Weißfloch, U.; Buschak, D. (2009): Energieeffizienz in der Produktion –Wunsch oder Wirklichkeit? Energieeinsparpotenziale und Verbreitungsgrad energieeffizienter Techniken. Mitteilungen aus der ISI-Erhebung. No. 51, Karlsruhe.

[9] Cooremans, C. (2012): Investment in energy efficiency: do the characteristics of investments matter? Energy Efficiency (2012) 5:497–518 DOI 10.1007/s12053-012-9154-x

[10] https://www.energieschweiz.ch/page/de-ch/effiziente-druckluft

GMEE "Global Motor Energy Efficiency" Program Update

Daniel E. Delaney

Regal Beloit

Introduction

Over the past twenty years, the motor industry has made significant progress to provide more energy efficient motor products to improve electric motor energy performance. Arguably the most effective stimulus to increase the demand for these energy efficient motors has been MEPS (Minimum Energy Performance Standards) [1, 2, 3] and national energy efficiency regulations. The MEPS programs are focused on reducing the electric motor driven system power consumption since electric motor driven systems account for approximately 45% of all global electricity consumption [4]. There are many national and/or regional global motor energy efficiency regulations currently in place [5] with many more in development. This paper presents an update to the GMEE globally recognized motor efficiency registration program that is designed to decrease some of the burdens of complying with the multitude of motor efficiency regulations. Table 1 below provides a brief overview of a few of the national and regional Motor MEPS programs operating around the world today.

Country/Region	IE Level	Power	Max Voltage	Poles
United States	IE3	0.75-375kW	600V	2-8
China	IE2	0.75-375kW	1000V	2-6
Japan	IE3	0.75-375kW	1000V	2-8
Korea	IE2/IE3	0.75-37kW 37-375kW	600V	2-8
Australia / New Zealand	IE2	0.75-185kW	1100V	2-8
Brazil	IE2	0.75-185kW	1000V	2-8
Columbia	IE2	0.75-185kW	600V	2-8
Chile	IE2	0.75-375kW	600V	2-8
Canada	IE2/IE3	0.75-150kW 151-	600V	2-8

		375kW		
Mexico	IE3	0.75-375kW	600V	2-8
Saudi Arabia	IE3	0.75-375kW	600V	2-6
India	IE2	0.75-375kW	600V	2-8
Turkey	IE2	0.75-375kW	600V	2-8
EU	IE3	0.75-375kW	1000V	2-8
Argentina	IE2	0.75-185kW	600V	2-8

Table 1 - Global MEPS National Regulatory Programs

Many of these global MEPS programs have common requirements. One of these requirements is known as the registration or CCE (Certification, Compliance and Enforcement) rules and regulations at the national and regional levels. While many of these regulations have similar requirements, full compliance with each national regulation differs. Below are common requirements found in most motor energy efficiency regulations.

- Motor Efficiency Test Standard
- Product Definition (Scope of Regulated Motors)
- Test Laboratory Qualification
- Registration and Certification
    - Testing of minimum number of test samples
    - Labeling or Product Marking
    - Initial registration of compliant motor models
    - Annual compliance reporting of compliant motor models

With motor regulations increasing throughout the world, it is important that there be an effective enforcement process to identify non-compliant motors sold in commerce and shipped embedded in equipment. National regulation goals cannot be achieved without an effective enforcement policy. It is the goal of the GMEE program to ensure common enforcement policies are clearly written and can be understood and implemented by the electric motor industry.

In 2010 NEMA attempted to address this lack of enforcement issue with the development and subsequent release of the NEMA Premium License program [5]. This voluntary motor efficiency program provides a certification program based upon the US Department of Energy (US DOE) motor energy efficiency regulation codified in the Code of Federal Regulations (CFR) at 10 CFR Part 431. The major deficiency that NEMA attempted to address with the NEMA Premium License program was the installment of the verification testing process. Each year NEMA randomly selects a motor rating and then instructs the participating members to provide this motor sample from their distribution network to an independent third party motor test laboratory for verification testing. If the motor sample is found to be non-compliant as marked, the manufacturer faces the penalties of the program which can result in fines and revocation of the NEMA Premium license as a participating member. One additional feature of the NEMA Premium License program is the ability for each member to challenge another participating member or other motor manufacturer not participating in the program. If the challenged motor manufacturer is validated as compliant then the challenger must pay the administrative and testing costs for the challenge. This program has been a global success with 17 global motor manufacturers participating [4].

Global Motor Energy Efficiency (GMEE) Program

In the effort to extend the benefits of the NEMA Premium License, NEMA began looking for ways to expand the global reach of the NEMA Premium License. Following the 2011 EEMODS conference in Washington, DC NEMA, CLASP (Collaborative Labeling and Standards Program) and IECEE members informally met to discuss efforts to develop a global motor efficiency labeling program. The discussion focused on the following key issues that need to be addressed for a successful program.

- Lack of common certification process (registration, sample selection, test laboratory requirements, test standards, efficiency levels and efficiency marking)
- Lack of globally recognized label or mark for motor efficiency
- Lack of enforcement policy (verification testing and border enforcement)
- Global certification program that can be adopted by developing nations and regions
- Benefits to existing national and regional regulations to alternatively accept a globally recognized efficiency program

After a series of informative discussions between NEMA and IECEE it was agreed these issues could be best addressed by an IECEE conformity assessment scheme by combining the NEMA Premium License and the IECEE globally recognized CB (Certification Body) Scheme [8]. The IECEE 50 plus global member countries, per Figure 1 below, was a key factor in this decision.

Figure 1 - IECEE Member Countries

The IECEE is a multilateral certification system based on International Standards prepared by the International Electrotechnical Commission(IEC) per Figure 2 below. Its Members use the principle of mutual recognition (reciprocal acceptance) of test results to obtain certification or approval at national levels around the world. The IECEE's multilateral Conformity Assessment Schemes, based on IEC International Standards reduce trade barriers caused by different certification criteria in different countries and help industry to access new markets. Removing the significant delays and costs of multiple testing and approval allows industry to market its products faster, while reducing financial costs. Reassurance is needed for such users and consumers that their product is reliable and will meet their expectations in terms of performance, safety, durability and other criteria in compliance with International Standards that align with local regulations.

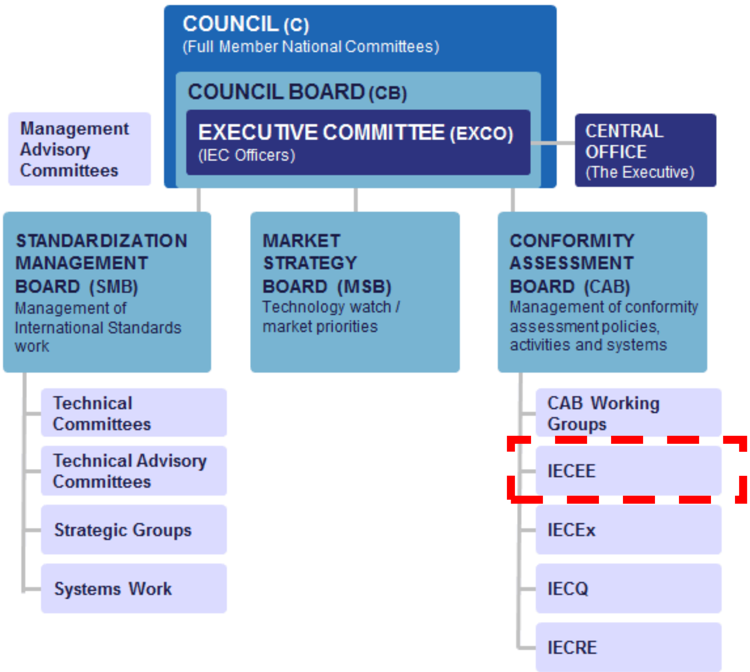

Figure 2 – IEC Organization

IECEE Policy and Strategy Committee (PSC) Working Group 5 (Strategy-GMEE) and 6 (Technical-GMEE) were formed under the IECEE to develop the GMEE program. WG5 focused on the planning and marketing of the program while WG6 was concentrated on the technical and certification details of the program. Over the next few years these two working groups would develop and release the first IECEE energy efficiency certificate called GMEE.

In 2016 the IECEE officially launched the GMEE program and as of early 2017 has issued the first GMEE certificate. It is expected to have multiple certified motor manufacturers and certifying NCB's in this program in the next year.

Additional challenges still lie ahead for the GMEE program. National regulatory bodies do not directly participate in the IECEE so these contacts need to be identified and educated on the value of the IECEE programs. During the last GMEE PSC WG5 meeting the following action items were developed.

- Interest from manufacturers to develop a direct to regulator approach for GMEE. WG5 members are in agreement that the advantage of this program would be greatly improved if the program could be accepted as an alternate regulatory approval in all of the IECEE member countries. WG5 is prepared to engage these countries to determine necessary steps to gain this approval.

- WG5 members with test laboratory expertise are interested and willing to join the appropriate CTL ETF (Committee of Test Laboratories Expert Task Force) as necessary.
- US WG5 members have petition the US NIST to accept the IEC test standards as equivalent to the US accredited standards. This approval should clear the way for approval of the IECEE GMEE program in the US and Canada.
- WG5 members are concerned with proposed sampling process for motors. A working draft revision of OD-2041 has been circulated and looking for additional comments. It is proposed that this new revision will address any concerns on ambiguity on number of samples and testing that a motor manufacturer can expect for this program.

Useful IECEE Acronyms[5]

IECEE - IEC System of Conformity Assessment Schemes for Electrotechnical Equipment and Components

NCB - National Certification Body (Examples: SGS, DEMKO, NEMKO, VDE, Underwriters Laboratory (UL), CSA, TUV Rheinland, Intertek, Bureau Veritas, etc.)

CBTL - Certification Body Test Laboratory

CBTC - Certification Body Test Certificate

CB Scheme - "Certification Body" Scheme is a globally recognized conformity assessment procedure

Regulatory Requirements: The restrictions, licenses, and laws applicable to a product or business, imposed by the government or the national authority.

Q: What is Conformity Assessment?

A: The fundamental principle of conformity assessment is to determine whether a product adheres to specified requirements, such as in the IEC International Standards. There are three types of assessment:

First party: the manufacturers evaluate their own products. This may include product construction evaluation and testing in their in-house test laboratories and may provide a supplier's declaration of conformity.

Second party: the companies buying the product perform their own product evaluations, which may include product assessment and testing by use of their own laboratory.

Third party: independent parties carry out product evaluation and testing. IECEE Conformity Assessment offers third party services as the best means of providing independency and impartiality.

Q: What IEC Standards are covered by the GMEE program?

A: The GMEE program includes the following standards

IEC 60034-1 Rotating electrical machines – Part 1: Rating and performance

IEC 60034-2-1, Rotating electrical machines – Part 2-1:Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)

IEC 60034-30-1 Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code)

Q: How does the GMEE program work?

A: A manufacturer applies to a participating National Certification Body (NCB) operating in the IECEE CB Scheme for a CB Test Certificate. The NCB works with one of their associated CB Testing Laboratories (CBTLs) to conduct complete testing and evaluation of the manufacturer's product to determine conformity with the IEC standards 60034-2-1 (Efficiency test standard) and 60034-30-1 (IE Efficiency level ratings).

If the product is found to be in compliance with the manufacturer's declared IE level, the CBTL issues a CB Test Report, which is the basis for the NCB issuing a CB Test Certificate.

In many cases, per a manufacturer's request, the NCB will also issue its own national approval or certification for the product. The manufacturer can then present the CB Test Report and CB Test Certificate directly to the Regulatory authority, their customer or to other participating NCBs in order to obtain additional certifications.

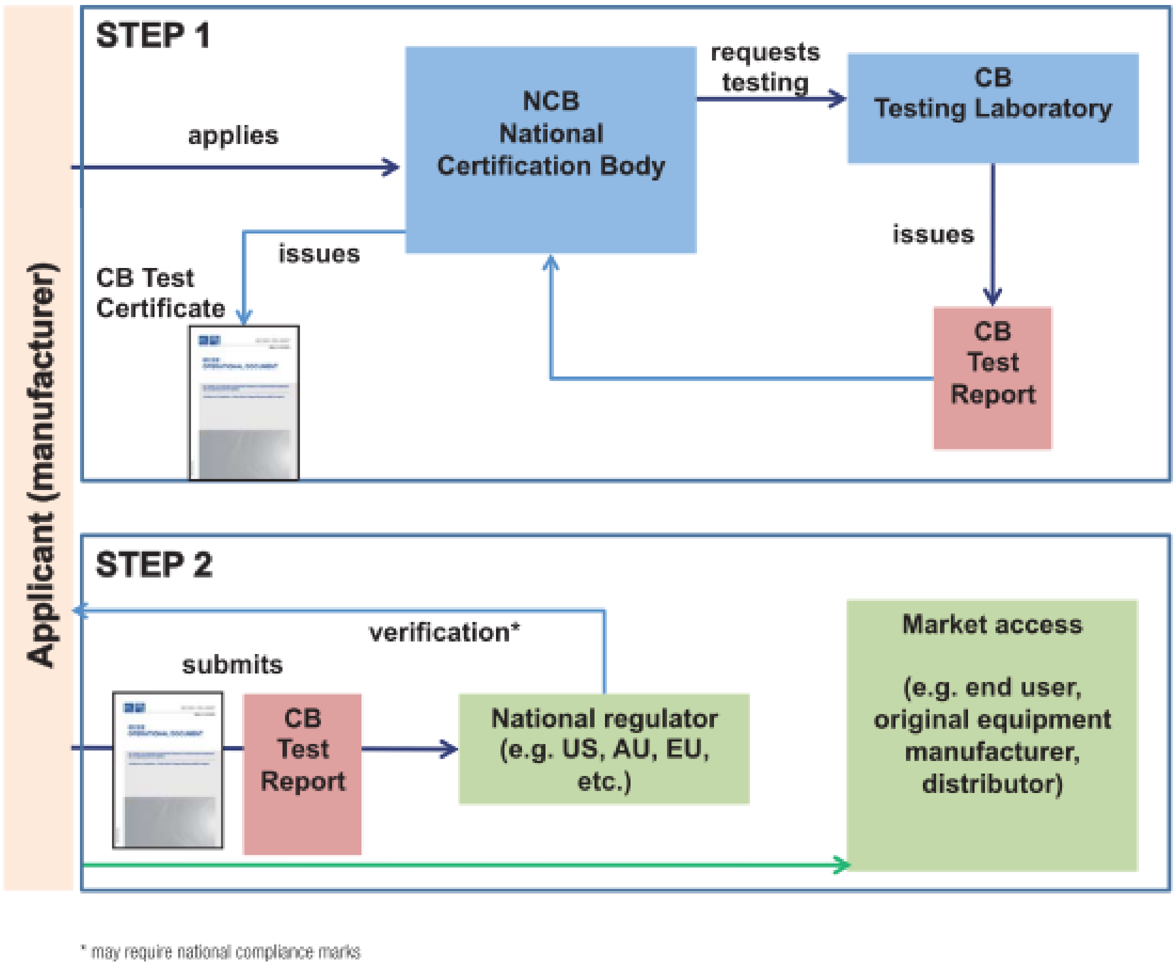

Figure 3 - GMEE Process Flow

Q: Where can I test and evaluate my products?

A: The manufacturer can choose to conduct their testing at the NCB's CBTL facilities or at their own test facilities. Testing at the manufacturer's facility may require the NCB to witness the test if the manufacturer does not have an NCB approved test facility. Before conducting testing outside of a NCB/CBTL site, the manufacturer must ensure that all IEC 60034-2-1 requirements (power supply stability, instrumentation accuracy, etc.) at your selected testing site is qualified. Additionally, IECEE registration must be completed by the NCB prior to the start of your testing outside of the NCB or CBTL site. Testing can also be split between the manufacturer and NCB/CBTL sites.

Q: Are there guidelines to ensure compliant equipment is used for testing?

A: Equipment used to perform GMEE testing must meet the IEC 60034-2-1 test requirements to ensure accurate results. Test equipment owned by the manufacturer may be used, but it must be calibrated and must meet accuracy requirements. The calibration provider must be accredited by an Accreditation Body that is recognized as a full member and signatory of the International Mutual Recognition Arrangements (MRAs) for IAAC, ILAC, APLAC, and EA, from National Metrology Institutes' (NMI's) recognized through the International Committee for Weights and Measures (CIPM) MRA.

Q: How can I apply for the GMEE Program?

A: A manufacturer begins this process by applying to any NCB for the GMEE program which can be found on the IECEE website [5].

Q: What are the benefits of the GMEE to the Manufacturer?

A: The GMEE program provides significant benefits to those manufacturers who wish to export their

products to countries that participate in the Scheme. These benefits include:

- GMEE program is VOLUNTARY and developed to encourage global market access of energy efficient electric motors in established and emerging countries.

- Manufacturers can select their NCB of choice

- Manufacturers can test their products at the NCB CBTL or their own test facility

- Manufacturers can declare their own efficiency level (i.e. IE level)

- Manufacturers can have their products evaluated once and accepted globally (50 plus member countries)

- Manufacturers can use the CB Test Report and Certificate obtained from one NCB to obtain national approvals in many other member countries through their participating NCBs.

References

[1] John Malinowski/ Jani Korkeakoski, ABB Motor Summit 2016, NEMA /CEMEP White Paper: market surveillance, compliance and enforcement

[2] Conrad U. Brunner, Impact Energy, Global overview

[3] Zheng Tan, Renergy Technology Consulting Beijing, Update on Chinese policy and programs for energy efficient motor systems

[4] Kulterer K., Werle R., *EMSA--Analysis of Motor Policies around the World.* 2011 EEMODS Conference

[5] Brunner, C. IEA 4E EMSA. *Efficient Electric Motor Systems.* 2012 Motor Summit Conference

[6] Boteler, R. Nidec, NEMA Member, *XXXX*

[7] Hoyt, W., NEMA Industry Director, NEMA 1MG 2013 Annual Meeting Minutes, (New Orleans, LA March 18-19, 2013)

[8] IECEE Website, http://www.iecee.org/

Industrial Motors and Drives: Global Market Update

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Abstract

List of topics: 1,2,3,4,5,6

This update offers a guided discussion about the global low-voltage (LV) motor and variable speed drive (VSD) markets, with a discussion of systems efficiency in the motor-driven system at both the component as well as the kWh input level. The discussion will define the market in terms of revenues and units with supporting qualitative analysis regarding changes in manufacturing, distribution, and other technological advancements. Much of the focus is on how governmental legislation for motors will affect the markets at global and regional levels. Industrial low-voltage motors are globally recognized as operating on 690 volts or less and are considered to be the primary workhorse in the automated factory and field. Shipping in the tens of millions of units every year to an industrial market fed by several global suppliers and thousands of regional suppliers, it has historically been the only industrial machinery market to be governed by energy-efficiency legislation in all three major world regions. New amendments to existing MEPS in both the EU and North America have now had a significant influence on the market's sales of higher-efficiency, low-voltage motors and VSDs. The discussion will also cover growing motor technologies such as IE4 Super Premium designs, other major trends influencing the global motor market, and a market share profile of the leading suppliers. The state of the VSD market's penetration at an industry level will also be discussed, with the adoption of other energy-saving components in applications, such as pumps, fans and compressors, also being reviewed. This presentation will also consider emerging trends such as the Industrial Internet of Things (IIoT) and the continuance of motor and drive suppliers embracing a "full system" approach to energy efficiency, reduction of downtime, and optimizing productivity.

Introduction

This update includes an overview of the worldwide low-voltage motor and drive markets in 2016, with projections from 2017 to 2021. The global market for low-voltage motors and drives, with a combined value of almost USD$20.7 billion in 2016 according to the latest data from IHS Markit, experienced poor growth for the year. Total market revenues grew by less than -5.0% for the LV motor market and a very poor -10% for the LV drive market in 2016, but revenue growth is expected to stabilize by 2018 after another rough 2017. IHS Markit predicts that total revenues for LV motors and drives will decline by 1.0% in 2017, but unit shipments will grow by a little more than 1.0% this year. This poor performance has been apparent since late 2014, and is directly correlated with a dependence on the energy-intensive industry sectors. Oversupply is still rampant, especially in Southeast Asia, and input costs have remained depressed over the past three years. The decline of the oil and gas industry had a sharp negative impact on the motor and drive markets in 2014 and has hindered these markets' growth in recent years as well. Furthermore, global machinery production is forecast to increase by only 1.2% in 2017[56], which does not bode well for suppliers to these markets. Of course, slow growth in China's economy, coupled with political unrest in many areas around the world, now including highly industrialized nations, lessened the markets' growth potential in 2016, so 2017 has received mixed signals regarding investor confidence. Generally, manufacturers

[56] IHS Markit Economics and Country Risk publishes quarterly GDP, Industrial Production and Machinery Production data by country.

have reported that they have moved away from their previously adopted "wait-and-see" attitude regarding investments and manufacturing decisions, and are now reaping the benefits of the past several years of intense research & development (R&D) investment. The thinking behind many manufacturers' decisions today is to pursue a new market identity and maintain market share amid pressing difficulties to remain profitable. As government agencies around the world have tightened their requirements for Minimum Energy Performance Standards (MEPS) of motors and drives, it has been reported that motor end-users are asking for higher-efficient equipment regardless of any governmental mandates, but this largely depends on the specific verticals in which that equipment will be utilized. This represents a pressing shift in the way that suppliers and customers view their products, and the more technologically sound suppliers are the ones best positioned to succeed during the next five years. Furthermore, with the advent of the Industrial Internet of Things (IIoT) the main focus for end-users and original equipment manufacturers (OEMs) is not always merely energy efficiency. Saving clients' money is the real driver, and that can now take many innovative forms.

Low-voltage Motor Market Update

In the case of low-voltage motors, a market that was valued at $11.3 billion in 2016, unit shipments grew more rapidly than revenues due to severe price reductions resulting from a weak commodities market and desire to maintain customer bases. The focus has shifted from maintaining market share to attaining profitability, as suppliers are still struggling to pass on input costs from the inherent 15-20% price increase associated with higher-efficient motors. Various motor efficiency legislations being enacted around the world (Figure 1) were not enough over the past couple of years to boost motor supplier revenues. Since 2014, both the Eurozone and North America has broadened the scope of its motor efficiency regulations, which should theoretically accelerate the average selling prices (ASPs) of motors in those regions, serving as a boon to the manufacturers. However, the lack of concrete enforcement has historically been a problem, and remains one to this day. If there is no market surveillance, despite the significant reduction of loopholes, then doubts will remain about these programs' efficacy.

While the various legislative initiatives are a major focus currently, most key suppliers are ahead of schedule or working on portfolio expansion of their efficient motors. This is a significant market development, but it's not the biggest trend facing the industrial automation sector, especially with regards to electric motors. Over time, we have seen motors become a couple of percentage points more efficient, last longer, and increase in some other subtle ways. These have been notable changes, but not enough to alter the majority of consumers' cost-consciousness when making purchasing decisions. With the burgeoning development of the factory of the future and IIoT, functionality and connectivity are going to play a larger role in the development of the LV motor market's competitive environment. Over the next five years, the fastest growth of motor class will come from those that are not going to be mandated, specifically permanent magnet IE4 and even IE5 motors. Without regard to efficiency class, the real growth areas in the motor market are connected devices, and motors with sensors are becoming more and more common. While stricter efficiency regulations will make the developed world more homogenous, motor suppliers are broadening their product portfolios in order to offer what customers need. As the end-users have adapted and digested the concept of full system efficiency, it has become the case that purchasing the properly sized and fitted equipment is more important than simply buying the most efficient products. It is with this process that system efficiencies can be optimized. Due to the increase in higher-efficient motor sales forecast during the next five years and the inevitable bounce back from the downturn of motor sales over the past couple of years, IHS Markit estimates the worldwide LV motor market to experience revenue growth with a CAGR of 3.4% in 2016-21. With multiple political uncertainties, recent environmental disasters, and a continued slowdown in the heavy industries, growth expectations have been tempered during the early part of this forecast period, and 2017 is still expected to be a year of negative growth for motor suppliers.

In terms of unit shipment growth, Figure 1 highlights the expected impact of efficiency regulations on the motor market. With the advent of the IIoT, however, it remains to be seen whether the true impetus for change will be the governments' actions or just the nature of the new customer demand.

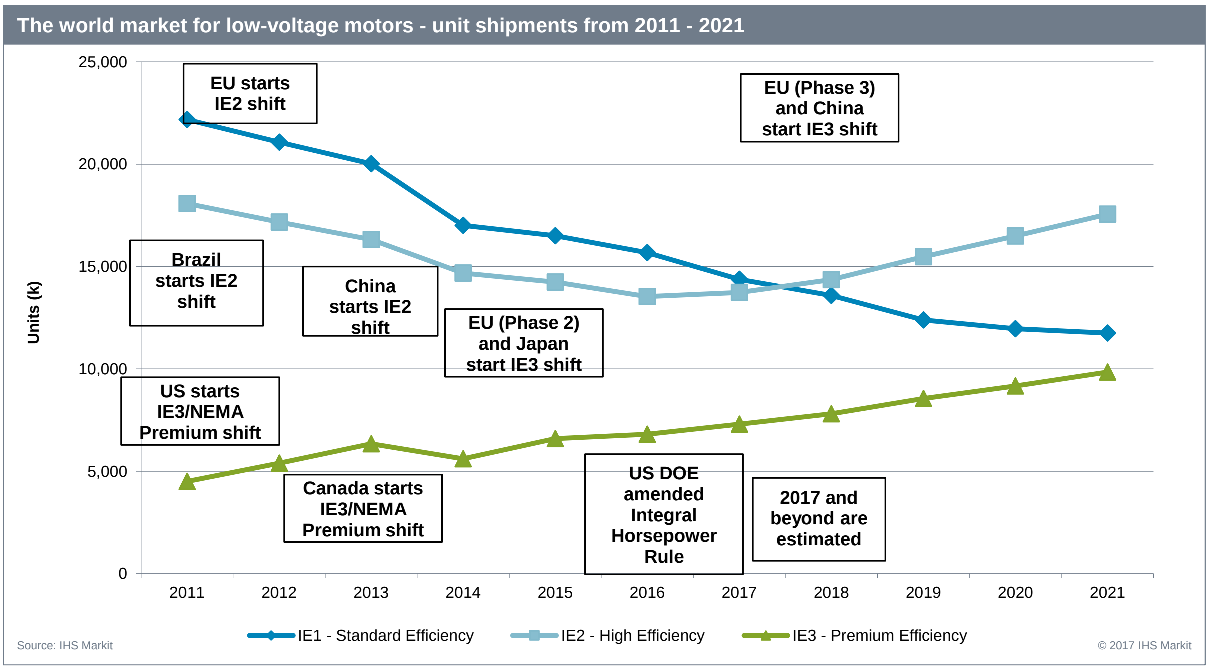

Figure 1

After accounting for 40% of the market's unit shipments in 2015, IE1 (Standard Efficiency) motors made up an estimated 37.7% of the market in 2016 and are expected to comprise less than 27% of market shipments by 2020 (Figure 2). These products are sold mainly in the emerging markets that have yet to adopt any type of efficiency regulations; however, many leading suppliers are still successfully selling these motors in developed countries because of stockpiled inventory, product specs outside of the existing regulatory scope, and vague sales channels in which motors are already integrated into a full system. This is expected to decline dramatically in the near future in North America now that the DOE has tightened its efficiency standards over the last two years and reduced the amount of motors that are exempt from regulation. As deregulation ramps up in the United States, however, a lot of uncertainty remains. IE2 (High Efficiency) motors represented an estimated 34% of global shipments in 2015, but are expected to account for more than 41% of total units sold by 2020. The main market for these motors through 2012 was that of North America, but since then both Europe and China's transitions have significantly increased demand for these motors. IE3 (Premium Efficiency) motors accounted for a very small minority of motors sold in 2010, but made up almost 15% of the market in 2014, after which IE3 motors saw another uptick in demand thanks to the European Union's (EU) move to implement the second phase of its motor efficiency legislation. The total effect that this could have on the overall market was limited due to the nature of the scope of this phase[57]. The third phase of the EU MEPS for electric motors is more encompassing, but still allows for IE2 motors to be sold with a VSD. For this reason, suppliers, are keeping their product offerings fairly wide, and are very much in need of more feedback from end users in order to make the best recommendations as to which product and systems are best suited for their needs.

[57] The second phase of the EU LV motor efficiency transition mandates the use of LV motors operating above 7.5kW, which accounted for only 11% of LV motor shipments in 2015.

The world market for industrial IE4 low-voltage motors is estimated to have been worth $133 million in 2016, with roughly 283,000 units shipped. This represents massive growth from 2009, the year widely considered to be the first year that IE4 motors were marketed to the industrial machinery markets as IE4 Super Premium Efficiency motors. Market revenues are forecast to grow by 7.1% in 2017 to $143 million with more than 9.0% growth in units shipped as well.

The IE4 category, which consists mainly of squirrel-cage permanent magnet, synchronous and switched reluctance motors accounted for much less than nearly 0.1% of market revenues in 2009. However, this segment accounted for more than 1.0% of global revenues in 2016, preceding a year of decline in 2015 and a flat year in 2014. Despite the slow growth during the last few years, IE4 LV motors are expected to nearly double in terms of global revenue share, and will account for about 2.0% of global motor shipments. IIoT could, however, prove to be disruptive to advanced motor technologies like higher-efficient IE4 and IE5 motors. Because end-users are realizing that more efficiency gains occur from system efficiency initiatives that incorporate communication and predictive maintenance, it could be the case that investments go into system optimization rather than buying high-end components. While this could be a limiting factor in the long-term, IE4 and the emerging IE5 motors are forecast to experience strong and rapid growth as customers expand their awareness of the importance of energy efficiency and energy prices likely increase during the forecast period.

EFFICIENCY CLASS TRANSITIONS (UNITS)

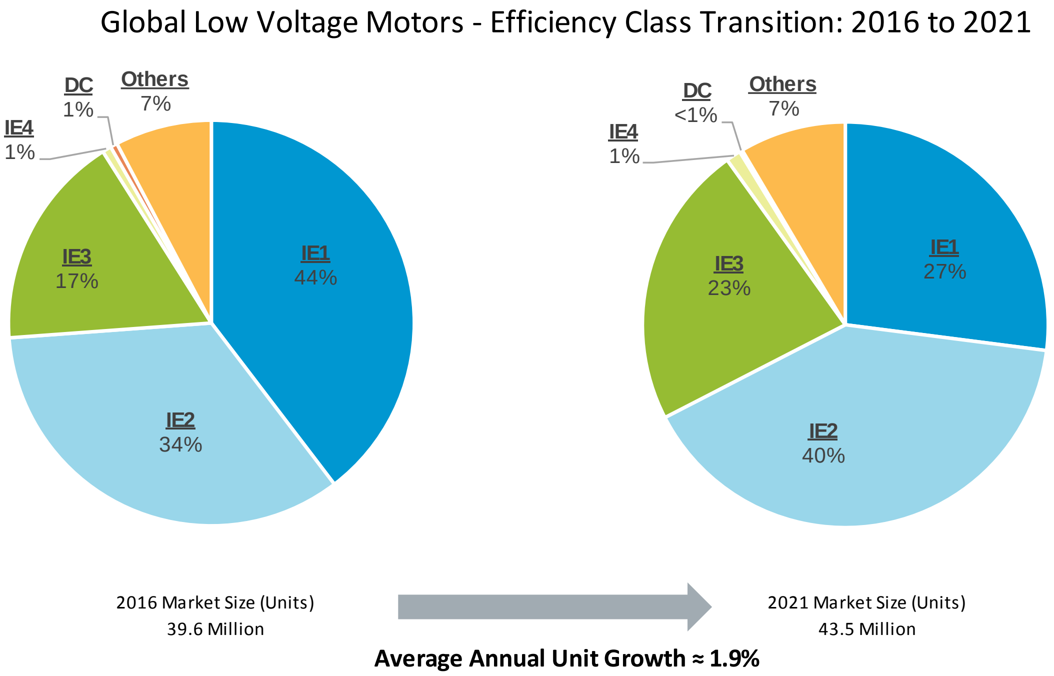

Figure 2

Efficiency in the Americas:

In the Americas, there is a stronger push for component-focused efficiency than in other developed areas like the Eurozone. This means that the United States, Mexico, and Canada have been quicker to implement Premium Efficient motor requirements through their respective governments, whereas the Eurozone has historically been more focused on implementing full system efficiency metrics that account for all parts of a machine, such as a motor, drive, and end equipment (such as a pump, fan, or compressors). The debate on how to properly reconcile both techniques into an effective regulatory endeavour are still quite prevalent, but the key takeaway is that end users in developed nations are more keen to reduce their carbon footprint and, more importantly (for corporate purposes, at least), reduce lifetime costs.

Because North America and Brazil have been pushing for higher-efficient motor sales since 2010, the motor product breakdown is different than the global allocations. Figure 2b highlights the differences between global figures (Figure 2a) and the Americas (including South America).

EFFICIENCY CLASS TRANSITIONS (UNITS)

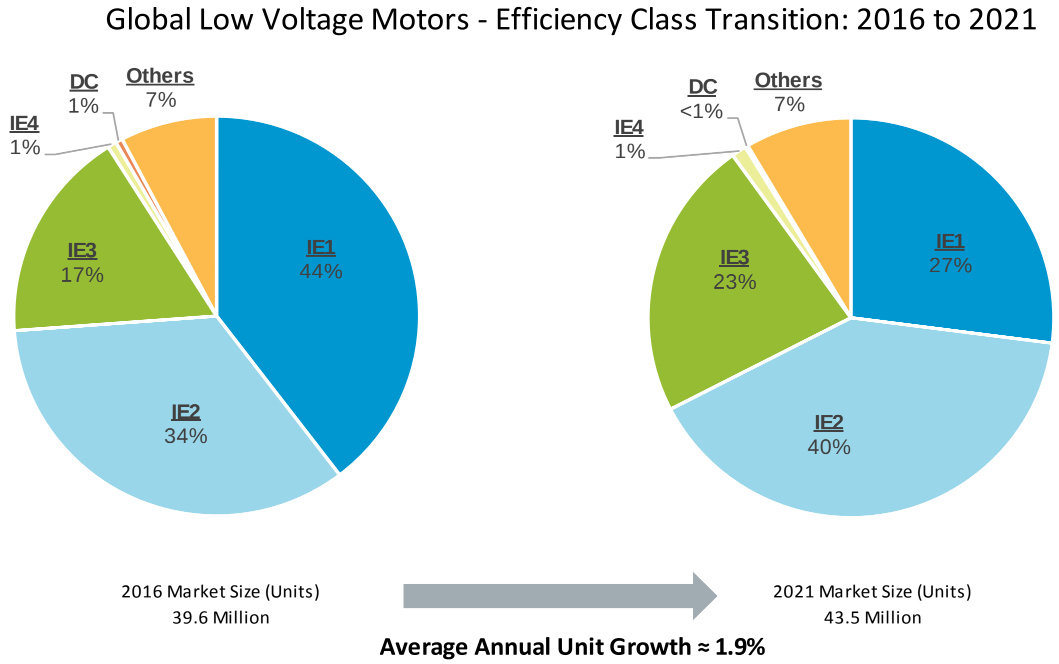

Figure 2b

The low-voltage motor markets in North and South America accounted for almost 27% of global revenues in 2016 (Figure 3). China was the largest individual country market for low-voltage motors in 2016, with revenues accounting for 23% of the worldwide total. The European, Middle Eastern and African (EMEA) region comprised approximately 30% of global revenues during 2016. The Chinese market experienced a very difficult year in 2016, contracting by roughly 12%, and it is quite clear now that the Chinese LV motor market will again decline in 2017, though by only about 3.0% in terms of revenues. The Chinese and Indian markets will drive motor market growth in the Asia-Pacific (APAC) region throughout the forecast period as the energy and construction sectors rebound in late 2017 or early 2018. China currently has a large share of the IE2 LV motor market, and IHS Markit expects that a transition to IE3 class motors in 2017 will lead to an eventually large share of the global shipments of premium efficiency motors. With China, APAC comprised more than 43% of global revenues in 2016, a share that will remain fairly constant through 2021.

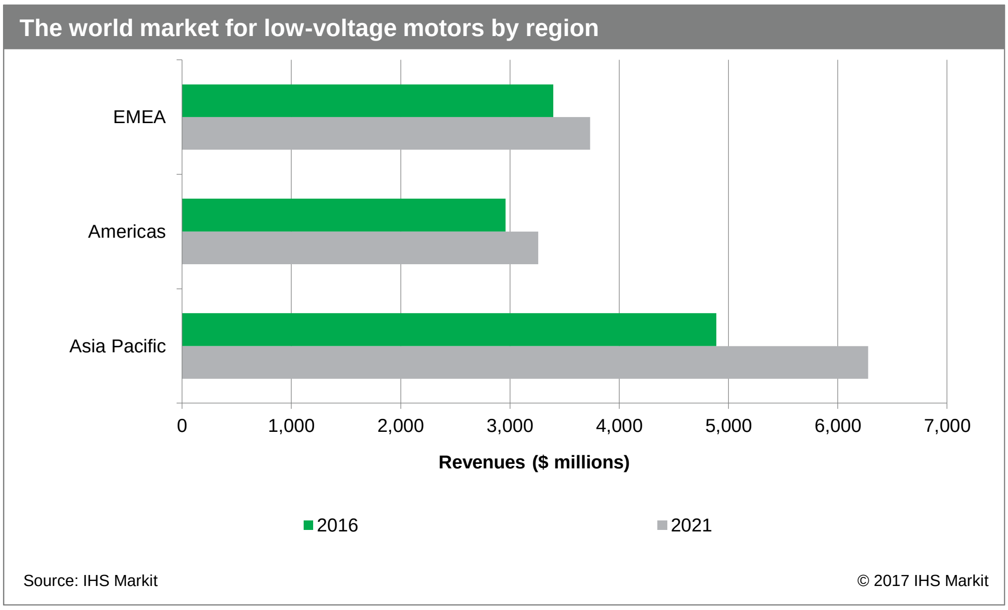

Figure 3

The top industry sectors for LV motors in 2016 included commercial HVAC, food and beverage, mining, utilities, paper, material handling, plastics and oil and gas. The leading suppliers of LV motors on a global level included ABB, Siemens, Regal Beloit, WEG, TECO, Toshiba, Hyosung and Nidec. Leroy Somer is also a major supplier to the LV motor market for highly efficient motors, and is now part of Nidec Motor Corporation.

Low-voltage Drives Market Update

Total 2016 LV motor drive revenues are estimated to have been more than $9.4 billion, reflecting a decline of over 10% from 2015 revenues. 2016 was a very difficult year for the same reasons that hindered the LV motor market. Although low-voltage motor drive revenues do not directly benefit from the positive effects of the minimum motor efficiency legislation as with low-voltage motor revenues, the overall drives market benefits from the greater focus on system efficiency. This is the bright spot in the expected future performance of the LV drive market for the period 2017-21, in which stable revenue growth with even faster unit shipment growth forecast. This indicates that average sales prices will remain generally lower and suppliers will be hard pressed to offer the most competitive features with little price flexibility. Thus far in 2017, all indications are that the third phase of the EU MEPS for LV motors, which requires that motors that do not achieve an efficiency grade of IE3 premium efficiency be equipped with a VSD, has had a positive, though mitigated, effect on drive sales. The determining factors for whether a customer opts for a more efficient motor or a less expensive motor with a VSD largely depends on customer and application at this point. In variable speed applications, motor drives have the potential to save massive amounts of energy. In the future, as energy costs increase, the economic benefit from installing such a motor drive will also continue increasing exponentially. The greatest return on investment with regards to drives is mostly seen in pump, fan, and compressor applications, which are forecast to outperform the market average for drive applications. These applications combined account for about 80% of global unit shipments.

This past decade has seen vast improvements in terms of motor lifespan, efficiency, and design, and the drive market is poised to be the center of attention going forward in this regard. The extended product approach continues to grow in acceptance, and with that comes an inherent need to focus on the whole drive system. Drives have come a long way: they can now be controlled by mobile devices; can identify problems; and can work more efficiently at various speeds and loads. In addition, they are much easier to purchase and install. IHS Markit has been tracking the penetration of connectivity, specifically related to drives. Corroborating the belief that connected devices are on the rise, an IHS Markit survey found that 69% of VSDs sold in 2016 were network-enabled, as opposed to 68% in 2015. IHS Markit predicts that this figure will expand to 76% in 2021.

Conclusion

2016 featured weak performances by the low-voltage motor and drive markets, but 2017 is poised to be a year with slightly better, but ultimately negative, growth results before a slight rebound is forecast in 2018. Machinery production is expected to remain at healthy levels, while projects in many industries, particularly HVAC and water and wastewater, are also expected to do very well as construction and infrastructure projects in emerging and developed countries take form. More importantly, it is now apparent that more than just components with high efficiency are required from successful partners. Things, services, and people are all equally important with regards to what equipment suppliers need to focus on. When those are all considered, suppliers are having great success in securing and maintaining a loyal customer base. This can be seen in a recent survey by IHS Markit to industrial automation end users, in which they were asked about their plans to incorporate IIoT (Figure 4). While industry players who understand and utilize IIoT are more likely to incorporate such a new and advanced technology, the trend is still quite clear that a large number of end users are becoming more aware of the inevitable technology that is very likely to reshape the whole competitive landscape. Predicting the future amid the eve of new technological developments can be quite difficult for motor and drive suppliers. Based on IHS Markit survey data, suppliers have more to consider than merely energy efficiency, and the determining factor of a successful company will certainly be its ability to help customers purchase the properly sized system (not just components), reduce downtime, and simplify the manufacturing process, among other key areas of focus. Motors and drives can no longer operate as separate islands, and the manufacturers that can best combine all of these factors will be the best poised to succeed in this new age of factory automation.

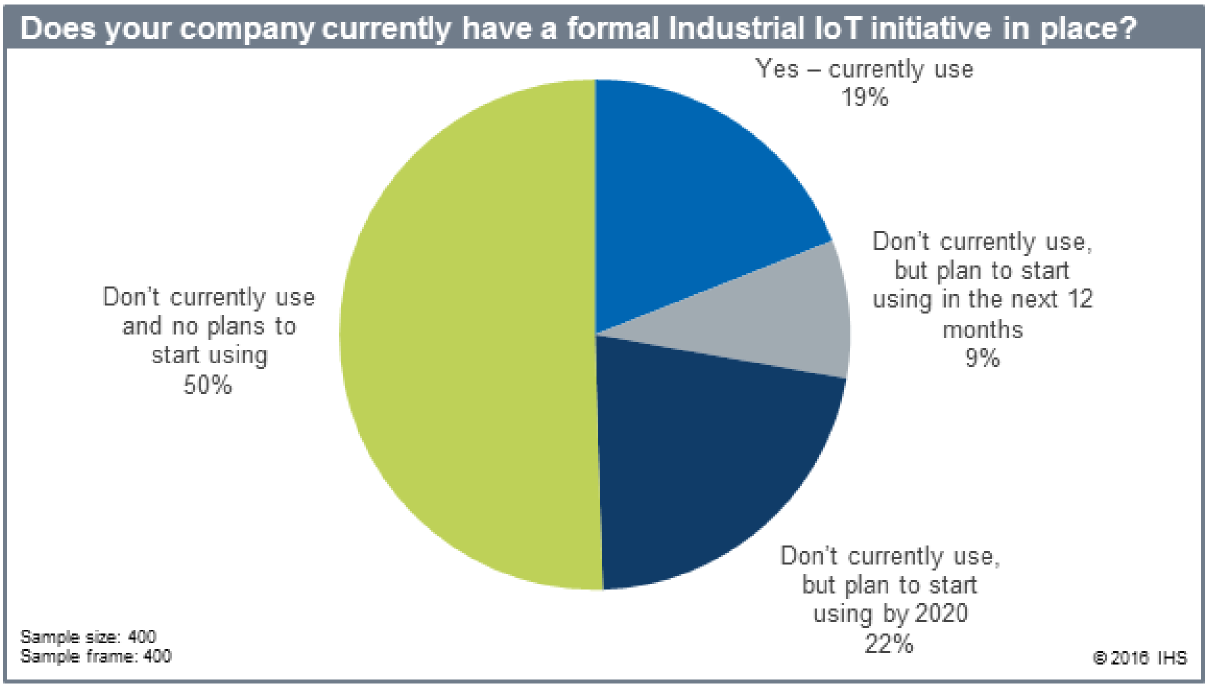

Figure 4

Barriers to the application of energy efficient motors in Latin America

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Abstract

The increase in application of energy efficient motors (EEM) in Latin America is an opportunity that has not been sufficiently exploited, due to numerous barriers that prevent it. In this work, the main barriers are analyzed, and measures to eliminate some of them are suggested, a good many related to educational actions. Eliminating barriers usually requires a package of measures, because, if the major part of barriers are not eliminated or reduced, there will be the risk that the expected objectives are not reached. This paper presents an analysis of the most important barriers that are impeding the increase in the application of EEM in Latin America.

Keywords:

Barriers; energy efficient motors; electric motor; energy policies; Latin America; university.

Introduction

The world is currently facing an unprecedented energy and environmental problem, which makes it necessary to take immediate action to reduce the consumption of fossil fuels and pollutant emissions. Electric motor driven systems (EMDS) are estimated to be responsible for 46% of global electricity use and, in the industrial sector, they are estimated to account for approximately 70% of electricity consumption [1]. If we consider that approximately 68% of the world's electricity is produced by fossil fuels [2], increased operating efficiency of electric motors is one of the most important actions to reduce greenhouse gas emissions, improve industry energy efficiency and reduce electricity consumption. The increase of energy efficiency in EMDS is an indispensable element to improve the energy performance of the industrial processes. This can be achieved by the application of energy efficient motors (EEM) [3] or the application of energy management system to industrial processes [4], or both at the same time.

In this context, a major effort is being made in the world to increase the application of EEM, mainly in Europe and North America through the harmonization of international standards and implementing national regulatory policies. However, the application of EEM is an option that has not been fully utilized in Latin America due to many barriers that have prevented its diffusion and adoption.

There are many barriers to the adoption and rapid dissemination of EEM in the world, which include international trade problems, economic aspects, traditional investment decisions and high transaction costs for investors, among others. Other barriers are related to the fact that electricity prices do not fully reflect the overall costs due to government policies. Many barriers limit the market response to EEM solutions, even if they are economically effective: lack of knowledge; short-term thinking about investments and operations; excessively risk-averse practices; high initial costs; lack of production benchmark analysis; and barriers of international trade. Some of these barriers are common to other energy end-use products, and they are subject to similar energy policy and solution analysis [5] - [7]; but other barriers are specific to EEM [1] [8] [9]. Investors usually favor low-cost solutions, regardless of the benefits EEM will report throughout its life cycle. A well-educated investor is very important, who is fully informed of the investment-related markets, the behavior of the seller, and the quality of the EEM [9].

In this work, the main barriers that are impeding the increase in the application of EEM in Latin America are analyzed. Eliminating barriers usually requires, a package of measures, because, if the major part of barriers are not eliminated or reduced, there will be the risk that the expected objectives are not reached.

International status of the application of Energy Efficient Motors

At least five different stakeholders need to interact to transform the market for motor systems:

- Governments that can set mandatory energy performance standards (MEPS),

- International standards makers that can focus on development of international standards of EEM, and standardization of testing.

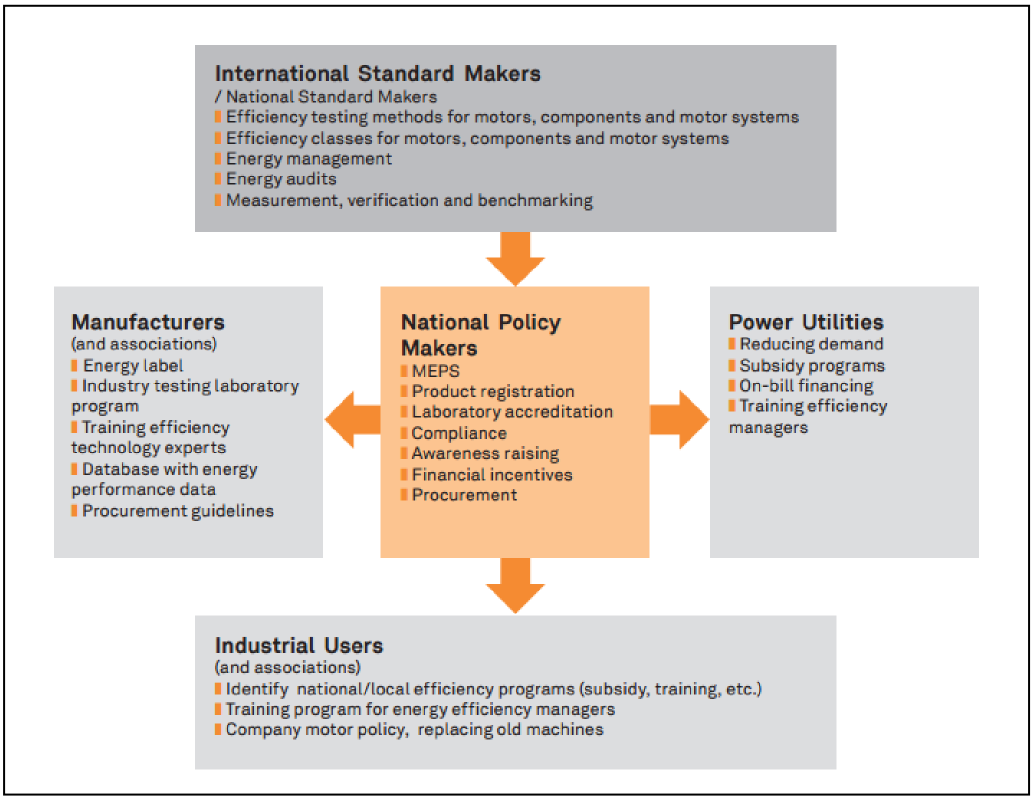
- Manufacturers and industrial associations can develop and support energy label programs,

- Industrial users that should set energy saving targets

- Electric power utilities that can design and run procurements for end-users to benefit from energy savings.

The efficacious government policies are those that encourage action amongst these stakeholders and influence the national and international standard makers, industry associations, industrial users and power utilities. Figure 1 illustrates the potential for policy interaction among these groups [10].

Figure 1. Influence of National Policy Markers. Source: Kulterer et al. (2014)



International standards

Standards makers play a fundamental role in defining test methods and energy efficiency classifications. International standards provide a mechanism to improve global harmonization and reduce trade barriers; therefore, international standards can be adopted for local use. The principal International Electrotechnical Commission (IEC) standards for efficiency of low voltage electric motors are:

- IEC 60034-2-1 edition 2.0, 2014, Rotating electrical machines - Part 2-1: Standard methods for determining losses and efficiency from tests [11].
- IEC 60034-30-1 edition 1.0, 2014, Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors [12].

The other important international market of electric motors is the USA, in this market the main standards that guide the efficiency of low voltage electric motors are:

- IEEE Std 112 - 2004, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators [13].
- NEMA MG1-2014 Motors and Generators [14].

There is currently an equivalence between IEC 60034-2-1 [11] and IEEE Std 112 [13] in the methodology applied to evaluate the electric motor efficiency. This means that efficiency results are valid for both USA and European markets. This is an important achievement in the harmonization of standards and in the elimination of barriers that prevent the spread of EEM.

USA was the first country to propose the standardization of EEM in 1992 through the Energy Policy Act of 1992 (EPAct 92) which declared them mandatory from 1997 onwards. The proposed new motor was called "High Efficient Motor". The minimum nominal efficiency values for high efficiency motors appeared in Table 12-10 of standard NEMA MG1.1997 [15].

Europe started this race in 1997 when the Directive of Eco-design, Energy Using Products (EuP 2009) was adopted, which declared mandatory use of a new motor equivalent to high efficiency EPAct 92 from 2011 onwards. In 1998 the European Committee of Manufacturers Electrical Machines and Power Systems (CEMEP) proposed the EFF1 motor, in order to have a motor with an equivalent NEMA EPACT 92 efficiency [16]. Later in 2008 the IEC 60034-30 enact three levels of efficiency IE1, IE2 and IE3, where the IE2 motor have an equivalent efficient as high efficient motor EPAct-92.

Currently, there is equivalence in the designation of the efficiency level of the electric motors between NEMA MG1.2014 (which proposes the levels, EPAct efficiency, Premium efficiency, Super Premium efficiency and Utra Premium efficiency) and IEC 60034-30-1 (which proposes levels IE1, IE2, IE3, IE4 and IE5). The equivalence between the efficiency levels given by standards NEMA and IECs of electric motors is shown in Table 1.

Table 1. Equivalence between the efficiency levels established by the NEMA and IEC standards

Efficiency Levels	**Efficiency Class**	
	NEMA MG1. 2014 (USA)	**IEC 60034-30-1 (International)**
Standard	Not Apply	IE1
High	NEMA EPAct Efficiency	IE2
Premium	NEMA Premium	IE3

Super Premium	NEMA Super Premium	IE4
Ultra Premium	NEMA Ultra Premium	IE5

Source: IEC 60034-30-1, MG1. 2014 and Rosero et al. (2015).

Minimum Energy Performance Standards (MEPS) regulations worldwide

One of the most important mechanisms to increase the application of EEM was the establishment of MEPS. The clear evidence from earlier developments in the USA is that markets for high efficient motors are only moved with the EPAct 92. Indeed this was the first MEPS decree on electric motors [9], [16].

Initially, standards were defined to obtain the MEPS. These standards were the NEMA MG1 and IEC 60034-30-1. Then some efficiency levels given in the standards were adopted as minimum requirements of permitted efficiency. The term used throughout the world for these minimum efficiencies is MEPS: minimum energy performance standards [16], [17].

At present, the countries that have established MEPS have increased the use of EEM, among them we have USA, Canada and the countries belonging to European Communities (EC). In this context, the EC through the Regulatory Commission EU No. 4 of 2014 amending Regulation EC No. 640/2009, that implements Directive 2005/ 32/ EC, declared mandatory the use of IE3 motor in the range of 0.75 kW to 375 kW since January 2017. USA, through Energy Conservations Standards for Commercial and Industrial Electric Motor given by the DOE (which implements the EISA 2007), stated mandatory the use of NEMA Premium Efficiency motor in the range of 0.75 kW to 375 kW since June 2016. Canada, with its CSA regulation C390-10 established the same mandatory as USA. China, with its MEPS GB 18613 of 2012 fixed the application of IE3 motor since September 2017 [17]. The application of MEPS at the international level has resulted in an increase in the application of EEM.

Manufacturers and associations that support the application of EEM in the world

One of the peculiarities of the countries of European Community, the United States, Canada and other developed countries is that there is a great interaction between electric motor manufacturers, professional associations and universities, which have led to increased application of EEM. For example, large electric motors suppliers such as Siemens, ABB, WEG, General Electric, Toshiba, Emerson, TECO-Westinghouse Motor Company, NIDEC - US Motors, etc., have been manufacturing EEM and its research and develop departments are coordinating with universities or research centers to continue developing new types of EEM. Additionally, these important companies along with others such as Underwriters Laboratories UL, Lawrence Berkeley National Laboratory LBNL, Georgia Tech, etc. have accredited laboratories in order to perform the motor efficiency tests.

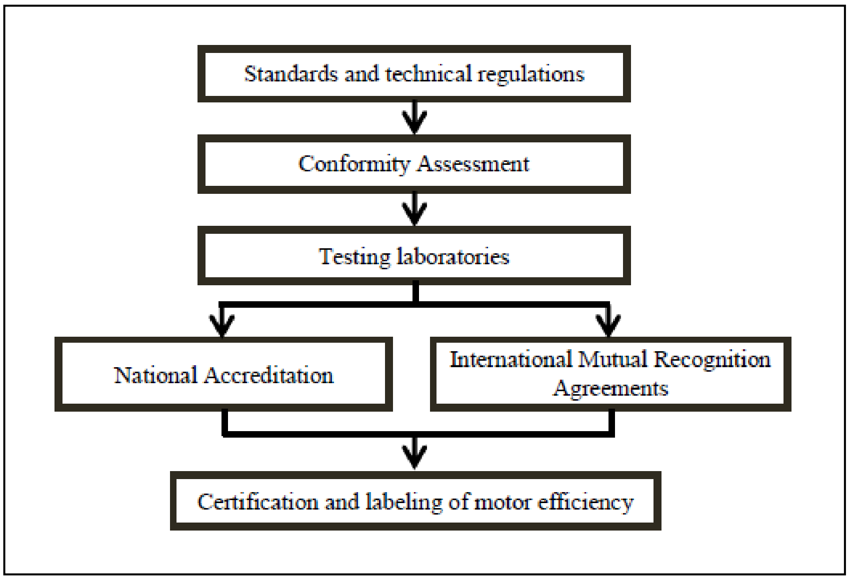
On the other hand, there is a strong cooperation activity between industrial, professional and governmental associations that are contributing to the increase in the use of EEM. Among them we have: IEEE, NEMA, Joint Research Center - European Commission, IEC, Natural Resources Canada, EASA etc. Therefore, in these large countries there is an interaction between manufacturers, industrial associations, professional and governmental associations, which is strongly driving the increase in the application of EEM.

Labeling Programs for Electric Motors

Labeling programs are another important element for increasing the use of EEM, especially in the country that has a framework of technical standards for EEM, MEPS and there are accredited laboratories to perform the efficiency test. In this way accredited laboratories can check if the values given on the motor nameplate are correct or incorrect and if they satisfy with the efficiency values specified in the MEPS.

Therefore, the process of certification of the electric motor efficiency has two important elements. First is the test procedure to calculate energy performance of the electric motor, developed in an accredited test laboratory; in this case the test procedures must be according to standard 60034-2-1 or IEEE 112. The second element is the MEPS that set limits over energy consumption, as has been said previously. The MEPS are different in each country and in some countries do not exist. Fig. 2 shows a simplified procedure to certificate electric motor efficiency; the application of this scheme allows ensuring both that the procedure for determining the motor efficiency complies with the standard and the labeling is correct. Moreover, following the procedure presented in Fig. 2, it is possible to satisfy and/or achieve Mutual Recognition Agreements (MRAs) or Multilateral Agreements (MLAs) approved by accreditation organizations. Notice that MRAs and MLAs required the acceptance of the technical competence of the laboratory responsible for emitting the certificate. In any case, the tests to determine motor efficiency should be done by an accredited test laboratory.

Figure 2. Electric motors efficiency certification process. Source: Londoño et al.



(2013)

Barriers to the application of EEM in Latin America

Latin America started its road to energy efficiency approximately in year 2000, with the enactment of laws and government programs. Some of these laws are: Law 7447 URE in Costa Rica (1994), Law 697 URE in Colombia (2000), Law 10.295 Energy Efficiency in Brazil (2001), Law 27345 Promotion UEE in Peru (2001) and Law UREE in Venezuela (2011). Likewise, several programs have been begun to promote the efficient use of energy, some of these programs are: PUREE and PAyEE in Argentina, PROCEL in Brazil, PROURE and CONOCE in Colombia, PRONACE in Costa Rica, CUREN in Chile, PAE in Ecuador, CONAE and FIDE in Mexico, PREE in Peru, PAEC in Cuba, PESIC in Honduras, and PEE in Uruguay. These politics and programs have been principally focused in the increase of energy efficiency of seven sectors, these sectors are: illumination, buildings, cogeneration, transport, electrical appliances, pumping systems, and electric motors [17], [18]. In the first six sectors, most countries of the Latin America present important advances. But in the sector of electric motors, except for Argentina, Brazil, Mexico, Chile and Colombia, the rest of countries do not have shown enough interest to improve electric motors efficiency [15], [18].

The international experience shows that to obtain the increase of the application of EEM in a country it is necessary that at least four elements exist: technical standards, MEPS, accredited laboratories and an electric motor labeling program. The standards classify the EEM and define the methodology for evaluating the motor efficiency in the laboratory. The MEPS determine the mandatory efficiency level. Finally, the accredited laboratories allow the evaluation of the motor efficiency and determine if the data of the motor nameplate is correct or not. Labeling programs complement the process. Only in this context can the electric motor labeling programs work effectively. In Latin America, there is a deficiency in the first three elements, which means that in some countries the labeling programs are not effective.

These four elements that constitute a barrier to increasing the application of the EEM in Latin America are analyzed below.

Delay in the harmonization of standards about Energy Efficient Motors (EEM)

Latin America is lagging behind the international context in the harmonization of standards over EEM. For example only few countries have a standard equivalent of IEC 60034-2-1 or IEEE 112 that specify the methodology for evaluating the efficiency of electric motors. The same applies to the standards that define the efficiency levels of electric motors. However, it is important to point out that there is a significant initiative in these fields, and it is the *Comisión Panamericana de Normas Técnicas* (COPANT), which brings together most of the countries of Latin America and has a Technical Committee CT 152 of Energy Efficiency and Renewable Energy that is working on this topic.

Countries that have standards equivalent to IEC 60034-2-1.2014 or IEEE 112, are few in the region. Among them we have Mexico with the Norm NOM-016-ENER-2016 equivalent to IEEE 112, Brazil with standard NBR 5383-1.2002, Colombia with standard NTC 3477-2015 and Chile with standard NCh 3086 that adopt the standard IEC 34-2-1. Still, the majority of countries in Latin America do not have a standard equivalent to the international standard to evaluate the motor efficiency, and this is one of the causes for the delay in the application of EEM.

Regarding the efficiency levels of electric motors, the majority of countries recognize the standard IEC 60034-30-1, and this is because most Latin American countries are associated with COPANT and its technical committee CT 152 issued the standard COPANT 1720-2016 *Energy Efficiency. Three-Phase Induction Electric Motors - Efficiency Class (EI) and Labeling*, which is equivalent to the international standard IEC 60034-30-1. In addition there are three countries that have equivalent standards and these are Mexico with the standard NOM-016-ENER-2016, Colombia with the standard NTC 5105-2015 and Argentina with IRAM 62405 [16], [19].

Among the causes of the delay in the standards harmonization in Latin America are: there are few specialists in the electric motors field, there are few national manufacturers of electric motors and therefore most electric motor are imported. Industrial users, companies that sell imported electric motors and the academic sector have limited interest in the development of national standards. So the standardization technical committees do not function effectively, generally only university lecturers, national motor manufacturers and industrial consulters attend [19], [20].

Obstacles in the establishment of Minimum Energy Performance Standards (MEPS).

The MEPS are one of the most decisive mechanisms to increase the application of EEM, however in Latin America there is a delay in the establishment of MEPS on EEM and this is one of the major barriers that currently exist.

Among the few countries that have established MEPS in Latin America are Mexico, Brazil, Chile and Colombia. Mexico through the Standard NOM-016-ENER-2016 declared mandatory the use of IE3 induction motor in the range of 0.75 kW to 375 kW since January 2017. Brazil as a result of the Interministerial Decree No. 553 (Dec. 2005) INMETRO NBR 17094-1 stated obligatory the motor equivalent to IE2 from 0.75 kW to 185 kW since January 2010. Chile with standard NCh 3086 Of. 2008 (PE No. 7/01/2, Ley No. 18.410 DS No. 298 of 2008), declared mandatory the use of IE1 induction motor in the range of 0.75 kW to 7.5 kW since January 2011. Finally Colombia, through Resolution 41012 of 2015, issued the RETIQ (Labeling Technical Regulation), for induction motors

0.75 kW to 373 kW. RETIQ stated obligatory IE1 motor from September 2017, IE2 motor from September 2018, IE3 motor in the range 7.5-373 kW from September 2020 and lastly IE3 motor from 0.75 to 373 kW from September 2021 [16]. Table 2 summarize the established MEPS and accredited laboratories to certify the motor efficiency in Mexico, Brazil, Argentina, Colombia and Chile.

If we consider as reference the year 2017, it can be observed that only two Latin American countries have made mandatory the application of EEM; Mexico with IE3 motor and Brazil with IE2 motor. And Mexico and Brazil are the countries with the largest economies in Latin America. This underscores a hurdle to the establishment of Minimum Energy Performance Standards (MEPS) in this region of the world.

Among the causes of the delay of the establishment of MEPS in Latin America can be considered that the majority of countries have a low developed industry and therefore the energy consumption of the industry does not have the greatest weight in the country consumption. Perhaps this makes that the energy policy makers consider that the electric motors MEPS is not a determining factor for the increase of energy efficiency in the country. On the other hand few countries of Latin America accept as official the standard IEC 60034-2-1 to evaluate the motor efficiency, then, there are few staff prepared to perform these tests. And finally there are few accredited laboratories to determinate the motor efficiency and this also delays the fixed of the MEPS.

Table 2. MEPS and accredited laboratories in motor efficiency test in Latin America.

Country	**MEPS**	**Accredited laboratories to certify the motor efficiency.** **IEC 60034-2-1**
Mexico	Std. NOM-016-ENER-2016. IE3 Mandatory since January 2017. 0.75 – 375kW	Five (5) Laboratories: ANCE, Nuevo León. GEIMM Mexico. Siemens. USE Mexico, WEG Mexico.
Brazil	Interministrerial Decrete Nº 553. INMETRO NBR 17094-1. IE2 Mandatory since January 2010. 0.75 – 185kW	Two (2) Laboratories: CEPEL Río de Janeiro. LABELO-PUCRJ, Rio Grande do Sul.
Argentina	Does not have yet. (Labeling mandatory)	Two (2) Laboratories: IADEV, Buenos Aires. LENOR SRL, Buenos Aires.
Colombia	Resolution 41012 of 2015. RETIQ. IE1 Mandatory since September 2017. IE2 Mandatory since January 2018. 0.75 – 373kW	Does not have yet
Chile	Std. NCh 3086 of 2008. CPE. Nº 7/01/2, Ley Nº 18410. DS Nº 298 of 2008. IE1 Mandatory since January 2011. 0.75 -7.5 kW	Does not have yet

Source: Londoño C. M. *et al*. (2013), Rosero J. A. *et al*. (2016), Gerrero H. (2016)

Few accredited laboratories to carry out the motor efficiency test.

In Latin America there are few accredited laboratories to perform the efficiency test in electric motors. Laboratories that can certify the motor efficiency must meet both IEC 60034-2-1 and ISO/IEC 17025. In other words, they must meet the methodology of the IEC 60034-2-1 and also must comply with the requirements of ISO/IEC 17025, which means having all their equipment calibrated, with adequate facilities and a minimum organizational structure.

Studies show that there are only nine accredited laboratories in Latin America [16], [19]. Mexico has 5, Brazil 2 and Argentina 2. We consider that three factors influence this fact. One is that most countries do not have a national standard on evaluation of motor efficiency (equivalent to IEC 60034-2-1). The second factor is that most countries also do not have MEPS, which implies the third factor: there is no demand for tests that encourages an investment and can comply with ISO / IEC 17025.

In Colombia, for example, according to the National Laboratory Network database, ONAC and SIC, currently (2017) there does not exist any laboratories accredited for efficiency tests of electric motors [19]. However, a study by the GEF / UNDP / UPME [16], [21] identified that there are thirteen laboratories that can measure motor efficiency, and are potentially accredited laboratories; but, for accreditation requires an investment and a market that ensures the return of the investment.

Other technological and cultural barriers.

Barriers by Different feeding systems

In Latin America, the electric supply networks use both frequencies of 50 and 60 Hz, this indicates the influence that Europe (50 Hz) and USA (60 Hz) have had in this part of the world. Largely because of its geographic proximity Latin America has been more influenced technically and economically by the USA. One consequence of this influence is that most countries operate their electricity network at 60 Hz (Brazil, Mexico, Colombia, Venezuela, Peru, Ecuador, Costa Rica, Panama, Cuba, etc.), while the minority countries do so at 50 Hz (Argentina, Chile, Bolivia, Uruguay, Paraguay, etc.). Regarding the nominal supply voltages for three-phase low voltage electric motors, they have a range from 380 to 480 V depending on national voltage standards.

The motors are usually designed and optimized for a given nominal frequency and voltage, and can not normally be exchanged without affecting their performance and reducing their efficiency. There are designs for two frequencies and multiple voltages, available for special markets, but usually have a lower efficiency than electric motors for a frequency and a voltage [7]. On the other hand, it is interesting to note that while electric motors manufactured with the NEMA Standard of USA allow a voltage variation of ± 10% of the nominal voltage, motors manufactured with IEC Standard only allow a variation of ± 5% of the rated voltage. This fact has drawbacks for IEC electric motors when operating in locations with voltage variations greater than ± 5% of rated voltage [1].

Different measurement systems

In the manufacture of electric motors, two different types of units are used, according to whether the manufacturer adopts the IEC Standard or NEMA Standard. The electric motors manufactured with NEMA Standards use the output power dimensioned in HP and the frame dimensioned in inches, while the electric motors manufactured with IEC Standard specify their output power in kW and the dimensions of the frame in metric units (millimeters). Therefore, the motors cannot be easily interchanged and manufacturers must supply electric motors under these two technical standards.

In the countries of Latin America a peculiar situation arises with the use of electric motors manufactured with both NEMA Standards and IEC. For example, in countries like Colombia and Perú, although the feeding system frequency is 60 Hz, in the industry both motors manufactured with NEMA standard and IEC standard are used. In recent years the use of IEC motors has increased in Latin America since several countries recognized the IEC Standard and in those countries the national technical committees of electric motors are the mirror of the IEC technical committees of electric motors.

Decisions of purchase usually based on the lowest capital cost.

In Latin America, the purchasing departments have the habit of making purchase decisions, considering only the motor purchase cost; and this has been transformed into a routine. That is, the life cycle cost of the motor is not considered. If it were known that the motor purchase cost represents approximately only 3% of the life cycle cost, it would increase the purchase of EEM.

Fortunately, this is starting to change, because companies are beginning to implement energy management system (SGE) according to ISO 50001 standard, and the SGE require that in the purchasing committees this is a representative of energy management. Therefore the advance of the energy management in the companies, will also become a driver of the use of the EEM.

Decisions based on short periods of return on investment.

The use of short periods of return on investment is another of the habits rooted in Latin America. The desired time of return on the investment is a maximum of three years usually; this is often not fulfilled in energy efficiency projects. However, it should be borne in mind that energy efficiency projects, such as the EEM application, may have a return time greater than three years but having a low investment risk, this is a great advantage when doing financial analysis and should also be taken into consideration for decision making when investing in EEM [23].

Conclusions

Reducing all barriers, obstacles and market imperfections to implement EEM is a complicated issue that requires multiple approaches. Policy decisions should be based not only on investor profitability considerations but also on the total cost to society in a way that reflects the indirect benefits in reduction of electricity demand through more efficient EEM. This also provides a rational basis for subsidizing information campaigns, professional training or other policies to promote the dissemination of motors and motors systems of high efficient.

Among the most important barriers that is impeding the increase in the application of EEM in Latin America are:

- The delay in most countries to issue national standards equivalent to IEC 60034-30-1, 60034-2-1, MG1.2014, IEEE Std 112 or to accept these standards.
- Labeling programs in each country only work effectively if they present standards, MEPS and accredited laboratories. The backwardness of Latin American countries in these matters has led to motor labeling programs not yielding satisfactory results.
- Latin America has a delay in the establishment of MEPS on electric motors and accredited laboratories. Only four countries have MEPS: Brazil, Mexico, Chile and Colombia. Furthermore there are few accredited laboratories to determinate motor efficiency; Mexico has five, Brazil has two and Argentina has two.
- It is very important propose projects to help the government to issued MEPS on electric motors and give financial support to establish accredited laboratories.
- There are few specialists in electric motors; therefore the work of the technical committees that produce the national standards is difficult. This means that higher education institutions must train more professional in this field of knowledge to disseminate the advantages of efficient motors.
- One way to increase the use of EEMs is the association of National Police Makers with US or EU groups such as IEA-4E, 4E-EMSA, IEEE, IEA, attend key conferences such

as EEMODS, Motor Summit, ACEEE, ICEM, IEMDC, and create joint projects for training industrialists and professors in this region.

References

[1] Wade P. and Bruner C.U. *Energy-efficiency police opportunities for electric motor-driven system.* Energy Efficient Series. Working Paper. International Energy Agency. Paris France 2011. Can be downloaded at www.iea.org

[2] IEA, International Energy Agency. *Key World Energy STATISTICS 2015*, France. Can be downloaded at: http://www.iea.org/publications/freepublications/publication/KeyWorld_Statistics_2015.pdf

[3] Quispe E.C. *Una visión integral para el uso racional de la energía en la aplicación de motores eléctricos de inducción*, El hombre y la máquina, vol. 20–21, pp. 52–59, Colombia, 2003. Can be downloaded at www.redalyc.org

[4] Castrillón R., Quispe E.C., González A.J., UrhanM. y Fandiño D. *Metodología para la implementación del Sistema de Gestión Integral de la Energía. Fundamentos y casos prácticos*. Editorial Universidad Autónoma de Occidente, 2014, pp 280. Colombia. ISBN 9789588713540. Can be ordered from www.libreriadelau.com

[5] Sorrel S., Mallet A. and Nye S. *Barriers to industrial energy efficiency: a literature review*. Working Paper 10/2011. United Nations Development Organization UNIDO. Viena, Austria, 2011. Can be downloaded at www.unido.org

[6] Baruah P., Eyre N., Norman J., Griffin P., and Hammond G. *Firm-level perspective on energy efficiency barriers and drivers in UK industry – indications from an online survey*. Proceedings of European Conference on Behavior and Energy Efficiency. Oxford. UK. 2014.

[7] Borroto A.E., Montesino M., Viego P.R., Odobez N. y Soldatii M. *Barreras y factores claves para promover la eficiencia energética en la industria. Revista Universidad y Sociedad, Vol. 6, No 2, pp. 30-35, Cienfuegos, Cuba, 2014.*

[8] Fleiter T. and Eichhammer W. *Energy efficiency in electric motor systems: Technology, saving potentials and policy options for developing countries.* Working Paper 11/2011. United Nations Industrial Development Organization UNIDO. Vienna, Austria 2012. Can be downloaded at www.unido.org

[9] Viego P.R., Borroto A.E., Gomez J.R., Quispe E.C. y Sousa V. *Barriers against increasing efficiency of electric motor driven system*. Proceedings of Congreso de Eficiencia y Gestión Energética, CIUREE 2016 (Cartagena, Colombia, 3-5 Feb. 2016). Can be downloaded at www.reciee.com

[10] Kulterer K., Werle R., Lackner P., Brunner C.U. and Ellis M. *Policy Guidelines for Electric Motor Systems. Part 2: Toolkit for Policy Makers*. October 2014. 4E Electric Motor Systems EMSA, 4E Energy Efficient End-use Equipment, International Energy Agency, 2014. Can be downloaded at www.motorsystems.org

[11] IEC, International Electrotechnical Commission. *IEC 60034-2-1. Rotating electrical machines - Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)*. Edition 2.0, 2014. Publishing by IEC, Geneva, Switzerland, 2014. Can be ordered from www.webstore.iec.ch

[12] IEC, International Electrotechnical Commission. *IEC 60034-30-1, Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors*. Edition 1.0, 2014. Publishing by IEC, Geneva, Switzerland, 2014. Can be ordered from www.webstore.iec.ch

[13] NEMA, National Electrical Manufacturers Associations. *NEMA MG1-2014 Motors and Generators*. Publishing by NEMA, Rosslyn, Virginia, USA, 2014. Can be ordered from www.nema.org

[14] IEEE, IEEE Std 112 - 2004, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators. IEEE Power Engineering Society. Publishing by IEEE, New York, USA, 2004. Can be ordered from www.ieee.org

[15] Quispe E.C. y Mantilla L.F. *Motores eléctricos de alta eficiencia: características electromecánicas, ventajas y aplicabilidad.* Revista Energía y Computación, 12 (1), Colombia, pp.11-19, 2005. Can be downloaded at www.bibliotecadigital.univalle.edu.co

[16] Rosero J.A., Quispe E.C. y Castrillón R. *Trends in standardization, technology development and applications of energy efficient motors*. Proceedings of Congreso de Eficiencia y Gestión Energética, CIUREE 2016 (Cartagena, Colombia, 3-5 Feb. 2016). Can be downloaded at www.reciee.com

[17] SIEMENS. *Minimum Energy Performance Standards. MEPS regulations worldwide*. Edited by Siemens A G., Deutschland, November, 2015. Can be downloaded at www.siemens.de/international-efficiency

[18] SENER. *Reporte del Foro sobre Eficiencia Energetica y Acceso en América Latina y el Caribe.* Secretaría de Energía de México, BID, Banco Mundial, Ciudad de México, 2010. Can be load at www.ecpamericas.org

[19] Londoño C.M., Lopera E.H., Valencia F. *Standards of Energy Efficiency of Induction Motors: Latin American Context*. Proceedings of VII Simposio Internacional sobre Calidad de la Energía Eléctrica, SICEL 2013 (Medellin, Colombia, 27-29 Nov. 2013). Can be load at www.revistas.unal.edu.co

[20] Bruner C.U. *Standard Format for IEC Standards - Learning from motor standards for other electric equipment*. Proceedings of the 8th International Conference EEMODS´2013 Energy Efficiency in Motor Driven System. Edited by European Commission. Joint Research Centre, Institute for Energy and Transport, 2014. Print in Italy. ISBN 978-92-79-39137-8. Can be downloaded at //_eqno_jrc90351_proceedings_eemods2013.pdf

[21] Guerrero H. *Fortalecimiento metrólogico de laboratorios de calibración y ensayo orientados a la medición del consumo de energía para equipos objeto del Reglamento Técnico de Etiquetado RETIQ*. Informe Final Proyecto de Etiquetado de Eficiencia Energética en Colombia-GEF/PNUD/COL/76979. UPME MINMINAS, Noviembre 2016. Can be downloaded at www.etiquetaenergetica.gov.co

[22] ISO, International Organization for Standardization *ISO 50001:2011 Energy management systems. Requirements with guidance for use*. Geneva, 2011. Can be ordered from www.iso.org

[23] Salazar C., De Oliveira E. Vidal J. *ISO La eficiencia energética como herramienta de gestión de costos: una aplicación para la identificación de inversiones en eficiencia energética, su evaluación económica y de riesgo*. Revista del Instituto Internacional de Costos, Edición Especial XII Congreso, abril 2012. Can be downloaded from www.revistaiic.org

3 MOTORS

On the Reliability of Electrical Drives for Safety-Critical Applications

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Abstract

The aim of this work is to present some issues related to fault tolerant electric drives, which are able to overcome different types of faults occurring in the sensors, in the power converter and in the electrical machine, without compromising the overall functionality of the system. These features are of utmost importance in safety-critical applications. In this paper, the reliability of both commercial and innovative drive configurations, which use redundant hardware and suitable control algorithms, will be investigated for the most common types of fault: besides standard three phase motor drives, also multiphase topologies, open-end winding solutions, multi-machine configurations will be analyzed, applied to various electric motor technologies. The complexity of hardware and control strategies will also be compared in this paper, since this has a tremendous impact on the investment costs.

Reliability

The use of electrical drives as a means to achieve efficient electromechanical energy conversion is a key element in the global vision of sustainable development that is compatible with the safeguard of the environment and of the future generations. For example, in automotive applications, electrical drives are able to guarantee low emissions, high efficiency in the energy conversion process, compact size and reduced weight. Furthermore, in automotive and more in general in safety critical applications, it is also necessary to guarantee high levels of reliability.

Reliability can be defined as the attitude of the drive or of one of its parts to perform its intended function for a specified time interval, under specific operating conditions. Conversely, the lifetime T_{part} of the part is the amount of time during which it performs its intended function. By nature, T_{part} is a continuous random variable with a probability density function $f_{part}(t)$, known as the time to failure distribution, [1]. The probability that a part will survive beyond a specified time t, $P(T_{part} > t)$, is its reliability function, $R_{part}(t)$. This is formally defined in probability theory as a complementary cumulative distribution function:

$$R_{part}(t) = P(T_{part} > t) = \int_{t}^{+\infty} f_{part}(x)dx \qquad (1)$$

Assuming the part to be non-repairable, the mean time to failure (MTTF) of a single part, $MTTF_{part}$, is defined as the mean value of T_{part}:

$$MTTF_{part} = \int_{0}^{+\infty} t f_{part}(t)dt = \int_{0}^{+\infty} R_{part}(t)dt \qquad (2)$$

Moreover, the failure rate of the part, $h_{part}(t)$, is defined as the conditional probability that a fault may occur in a time interval dt, given that the part has not failed before time t. It is formally defined as:

$$h_{part}(t) = \frac{f_{part}(t)}{R_{part}(t)} = -\frac{d[\log(R_{part}(x))]}{dx} \quad (3)$$

Based on this, it is also possible to express $R_{part}(t)$ as:

$$R_{part}(t) = e^{\left(-\int_0^t h_{part}(x)dx\right)} \quad (4)$$

Figure 1 shows a typical life cycle curve for which the faiure rate is plotted as function of time; many components fail very soon after they are put into service. Failures within this period are caused by defects and poor design that cause a component to be retained damaged. These are called infant mortality failures and the failure rate in this period is relatively high. After a component reaches a certain age, it enters the period where it begins to wear out, and failures start to increase. The period where failures start to increase is called the wear out phase of component life. When faults due to infant mortality and to ageing are not taken into account, it is quite common to assign a constant failure rate to many electronic components: $h_{part}(t) = \lambda$. Thus, the reliability function of a single component of the drive becomes an exponential distribution:

$$R_{part}(t) = e^{-(\lambda t)} \quad (5)$$

For this distribution, it can easily be calculated that:

$$MTTF_{part} = \frac{1}{\lambda} \quad (6)$$

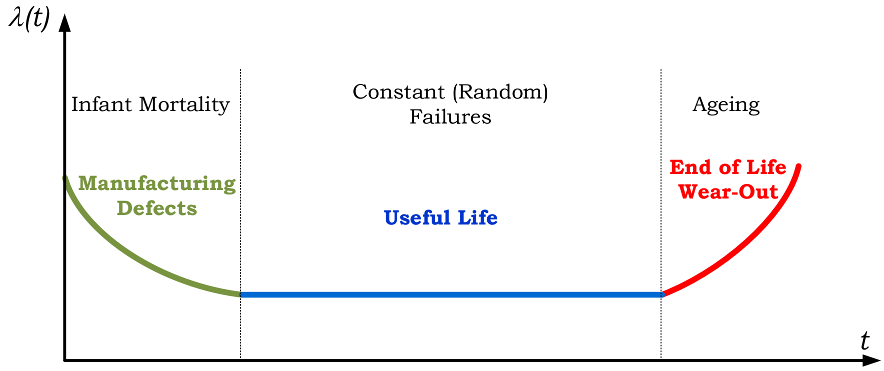


Figure 1 Bathtub curve of Failure Rate □(t)□

Reliability in Electrical Drives

The above definitions can be applied to each component of an electrical drive, leading to the results shown in Tab.I. It can be noted that the highest failure rates are associated with the position sensor, with the bearings and with the winding of the electrical machine, strongly affecting the useful life of the drive. This is one of the reasons to try to remove these components from the electrical drive system through solutions technically named as sensorless drives and bearingless drives, for instance, [2]-[7].

Table I: Failure Rates and MTTF of some electrical drive components.

Components	Failure Rate λ (h^{-1})	Failure in Time FIT ($10^{-9}h$)	**MTTF** (h)
Encoder	$11.2x10^{-7}$	1120	892857
Current Sensors	$2x10^{-7}$	200	5000000
IGBT+Gate Drive	$2x10^{-7}$	200	5000000
Capacitors	$2.5x10^{-7}$	250	4000000
Windings	$3.2x10^{-6}$	320	277778
Bearings	$6.4x10^{-6}$	640	156250

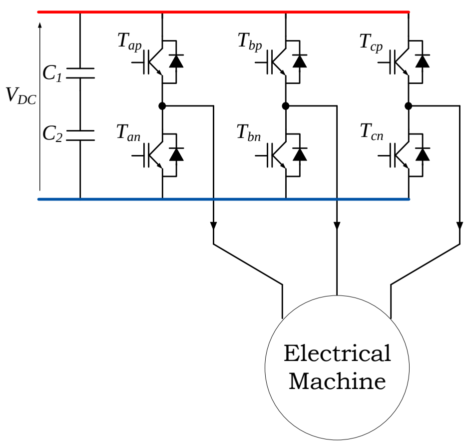
Combining the failure rates of the single components, it is possible to determine the failure rate of a drive; for example, it is well known that in a standard three-phase inverter, Fig. 2, the failure of one component compromises the functionality of the entire drive. From a reliability-engineering point of view, this is a series reliability architecture, in which the reliability of the system is equal to the product of the reliability of the single components:

$$R_s(t)=R_1(t)\cdot R_1(t)\cdot \ldots \cdot R_n(t)=\prod_{i=1}^{n} R_i(t) \qquad (1)$$

If we assume that the reliability functions are of the type indicated in (5), equation (7) then can be expressed as a simple relationship between MTTF and □:□

$$R_i(t)=e^{-(\lambda_i t)} \Rightarrow \lambda_s=\sum_{i=1}^{n}\lambda_i \quad R_s(t)=e^{-(\lambda_s t)} \Rightarrow MTTF_s=\frac{1}{\lambda_s}=\frac{1}{\sum_{i=1}^{n}\lambda_i} \qquad (2)$$

From (8) it can be seen that the reliability of the inverter is less than the reliability of the weakest among its components. A practical example of the calculation of the failure rate and MTTF for the three-phase inverter shown in Fig.2 is reported in (9) and (10), considering the failure rates of Table I.



$$\lambda_s=\sum_{i=1}^{6}\lambda_{i\_IGBT}+\sum_{i=1}^{2}\lambda_{i\_Cap}= =6\times 200+2\times 250=1700FIT \qquad (9)$$

$$MTTF_s=\frac{1}{\lambda_s}10^9=588235h \qquad (10)$$

Figure 2 Standard Three-Phase Inverter Topology.

Tab.II shows the MTTF reported in the datasheets of two commercial electrical drives and the respective reliabilities after one and five years of 24h operation. It can be seen that the probability of failure in both time intervals is still quite low, although it progressively increases with time. The MTTF is less than the one calculated in (10) because, for a commercial product, it is necessary to take into account additional components, such as the control unit, the current and position sensors and the rectifier.

Table II: MTTFs of commercial variable speed drives.

	***Schneider:*** ATV312H018M2 variable speed drive 0.18kW- 200..240 V	MTTF 400000h $R_s(8760)=e^{-\left(\frac{8760}{400000}\right)}\cong 98\%$ $R_s(5\cdot 8760)=e^{-\left(\frac{5\cdot 8760}{400000}\right)}\cong 89.6\%$
	***Yaskawa:*** SIGMA II SGDH SGDH-30DE - S2 AMP 400V 3PH 3KW	

Fault Tolerant Electrical Drives

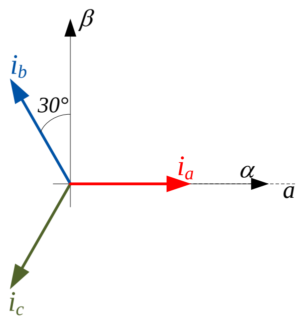
Although electrical drives have high values of MTTF and thus of reliability, in some cases, such as in aerospace or automotive applications, it is imperative to ensure the safety of human beings, machines and environment, while guaranteeing maximum efficiency and flexibility. These results are obtained by further increasing the reliability of the drives, making them able to guarantee correct operations even in the event of faults. This category of electrical drives is known as “fault tolerant”. Many topologies of fault tolerant drives exist and have different abilities in mitigating the effects of specific faults; nonetheless, the general characteristics of a fault tolerant drive are:

- the detection and identification of faults;
- the isolation of faults;
- the reconfiguration of the drive, either by using reserve components or by redistributing the process to working components;
- the restoration of a fault-free operating condition

Drives tolerant to Current Sensor Failures

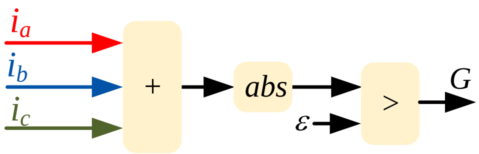
Some of the many ways to make a drive tolerant to current sensor faults are described in [8]-[15]. A simple technique is the one described in [8], where three fault indicators are obtained, C_{ri}, i=1,2,3, starting from the stator three phase currents, transformed in an orthogonal stationary reference frame □□, (11), (12). These three fault indicators give the projections of the rotating stator current vector on the □□ axes, by using different combinations of the measured currents and using the condition *ia+ib+ic=0* which is valid during normal operation of the drive. In this condition, the three indicators coincide at each instant with the amplitude of the reference current I_{ref}.

$$\begin{cases} i_{\alpha 1}=i_a \\ i_{\alpha 2}=-(i_b+i_c) \end{cases} \quad (11) \qquad \begin{cases} i_{\beta 1}=\frac{1}{\sqrt{3}}(i_b-i_c) \\ i_{\beta 2}=\frac{1}{\sqrt{3}}(i_a+2i_b) \\ i_{\beta 3}=-\frac{1}{\sqrt{3}}(i_a+2i_c) \end{cases} \qquad \begin{cases} C_{r1}=i_{\alpha 2}^2+i_{\beta 1}^2 \\ C_{r2}=i_{\alpha 1}^2+i_{\beta 3}^2 \\ C_{r3}=i_{\alpha 1}^2+i_{\beta 2}^2 \end{cases} \quad (12)$$



The fault is detected simply by monitoring the condition *ia+ib+ic=0*; when the sum of the three currents exceeds a specified threshold □, a flag G which indicates a fault changes state. The identification of a faulty sensor is obtained by comparing each fault indicator C_{ri} with I_{ref}. The Cri that has been obtained with healthy sensors shows no difference with respect to normal operating conditions. The remaining two indicators will have amplitudes that exceed that of I_{ref}, beyond a threshold □, and active flags F_i. A unique combination for each faulty sensor is obtained, as shown in table III. After having detected the fault and identified the broken sensor, it is necessary to reconfigure the system to guarantee continuity of service. A simple solution consists in combining the current projections on the □□ reference frame so as to select the two current measurements that don't include the faulty sensor measurement.

$$i_\alpha = K_1 i_{\alpha_2} + K_2 i_{\alpha_1} + K_3 i_{\alpha 1} + K_4 i_{\alpha_1}$$
$$i_\beta = K_1 i_{\beta_1} + K_2 i_{\beta_3} + K_3 i_{\beta 2} + K_4 i_{\beta_2} \qquad (13)$$



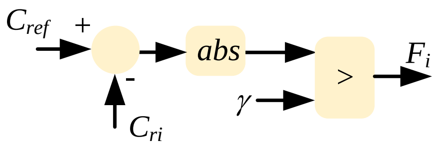
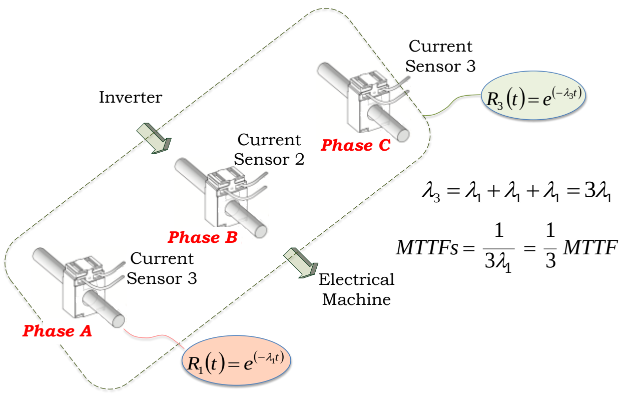


Figure 3 Fault detection

Figure 4 Broken sensor identification

Table III:

Faulty Sensor	G	F_1	F_2	F_3	K_1	K_2	K_3	K_4
Phase a	1	0	1	1	1	0	0	0
Phase b	1	1	0	1	0	1	0	0
Phase c	1	1	1	0	0	0	1	0
No Fault	0	0/1	0/1	0/1	0	0	0	1



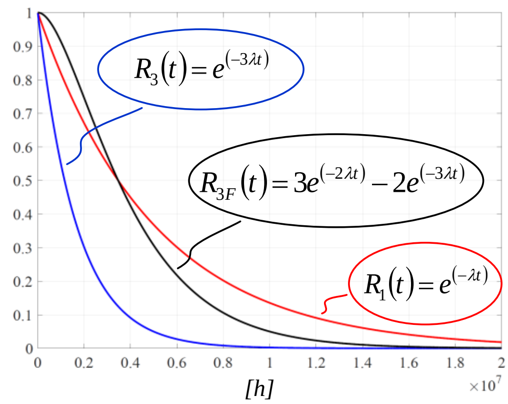


Figure 5 Structure of the current sensing system.

Figure 6 Comparison between the reliability of a single sensor R_1, of the traditional sensing system R_3 and of the fault tolerant system R_{3F}.

The above described fault tolerant solution allows a significant increase in the reliability of the current sensing system, as visible in (14), obtained by applying the functional rules for "k-out-of-n" Systems, [1]; the MTTF of the above described method $MTTF_{3F}$ has been compared with that of the standard acquisition current sensing system $MTTF_{3F}$, obtaining a more than double increase in the current sensing system reliability.

$$MTTF_{3F} = \frac{5}{6} MTTF_1 , \qquad MTTF_3 = \frac{1}{3} MTTF_1 , \qquad \frac{MTTF_{3F}}{MTTF_3} = \frac{15}{6} = 2.5 \qquad (14)$$

Drives Tolerant to Position Sensors Faults

Recently, it has been shown that position-sensing systems based on discrete low-resolution sensors, such as binary Hall-effect sensors, may become fault-tolerant, [16], [17].

A well-known layout uses three sensors, H_1, H_2, H_3, displaced 120 electrical degrees apart. Each sensor has a binary output equal to 0 or 1 depending on the rotor flux position. This layout provides a 60 electrical degree resolution, i.e. 3 bits per pole pair. Fig.7 shows the locus of the $\boldsymbol{H}_{\alpha\beta}$ vector, obtained by applying the following transformations to the Hall-effect sensor signals:

$$\begin{pmatrix} H_a \\ H_b \\ H_c \end{pmatrix} = 2 \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} - 1 \qquad (15)$$

$$\begin{pmatrix} H_\alpha \\ H_\beta \end{pmatrix} = \frac{\pi}{4} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{pmatrix} H_a \\ H_b \\ H_c \end{pmatrix} \qquad (16)$$

As the rotor revolves, $\boldsymbol{H}_{\alpha\beta}$ moves in a quantized fashion jumping from one direction to the next, every 60° electrical, forming the hexagonal locus shown in Fig.7. When one of the Hall-effect sensors fails, its output goes to logical 0 or 1 indefinitely. A total of six different single faults are possible. For example, Fig.8 shows the $\boldsymbol{H}_{\alpha\beta}$ locus in the event of a H_1=1 fault: the locus becomes rhomboidal, splitting the reference frame into four sectors. Two sectors are 60° wide, while the other two are 120° wide. A zero vector, $H_{\alpha\beta 7}$, appears when the sensors' states are (111); this is not present during normal operation.

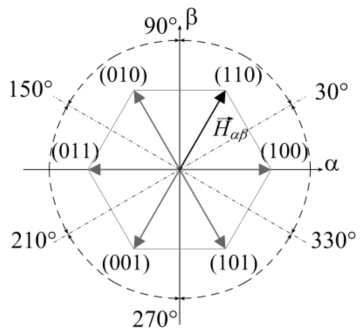


Figure 7 Quantized rotating position vector $H_{\alpha\beta}$ loci for a 3 BPP low-resolution position-sensing system, [16].

A similar zero vector is also present for faults in which one sensor output goes to 0, i.e. for a (000) combination. The shapes of the $\boldsymbol{H}_{\alpha\beta}$ loci are the same for all six single faults. However, the position of the loci within the reference frame is unique for each fault. If a fault detection, identification and compensation algorithm is not used, a failure of any one of the three Hall-effect sensors will compromise the entire sensing system. In this case, the reliability function of the sensing system, $R_{3\Sigma Hall}(t)$, is equal to the product of the reliability functions of each sensor:

$$R_{3\sum Hall}(t)=R_{Hall,1}(t)\cdot R_{Hall,2}(t)\cdot R_{Hall,3}(t)=R_{Hall}^{3}(t) \tag{17}$$

and the MTTF for such an arrangement is:

$$MTTF_{3\sum Hall}=\frac{1}{\sum_{k=1}^{3}\lambda_k}=\frac{1}{3\lambda_{Hall}}=\frac{1}{3}MTTF_{Hall} \tag{18}$$

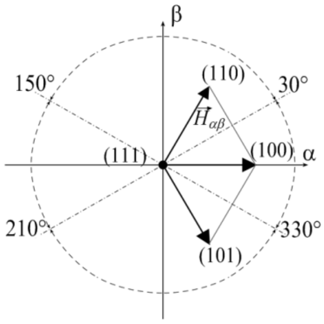


Figure 8 Quantized locus *H*□□ in the stationary reference frame for a *H₁* = 1 single fault. [16].

A sensor fault can be detected when a zero vector appears in the $H_{\alpha\beta}$ locus. Since the locus associated to each fault is unique, the broken sensor and fault type are identified unambiguously by the phase of $H_{\alpha\beta}$ in the sector following the zero vector. Following fault detection and identification, the fault can always be compensated by appropriately modifying the position and speed algorithm that is implemented in the motor control system, [16]. By providing the appropriate fault compensation, the sensing system possesses a triple modular redundancy and constitutes a parallel reliability architecture. In this case, it can be shown that the reliability function, $R_{3//Hall}(t)$, is equal to:

$$R_{3/Hall}(t)=1-[1-R_{Hall}]^{3} \tag{19}$$

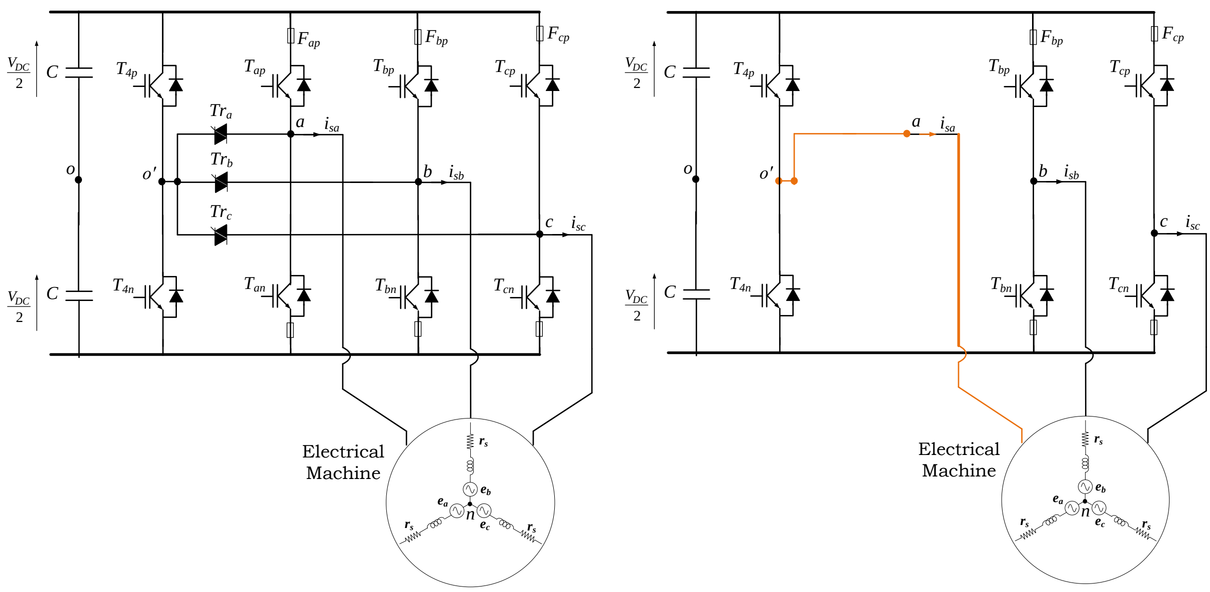
This implies that the reliability of the system will be larger than that of each sensor. It can be calculated that the MTTF for such an arrangement is equal to:

$$MTTF_{3//Hall}=\frac{1}{\lambda_{Hall}}\sum_{k=1}^{3}\left(\frac{1}{k}\right)=\frac{11}{6\lambda_{Hall}}=\frac{11}{6}MTTF_{Hall} \tag{20}$$

By comparing (8) and (10), it can be seen that the MTTF improves by a factor of 5.5 when a fault detection, identification and compensation algorithm is used. According to the limited literature available, estimates of Hall-effect sensor MTTFs are in the range of 10^6-10^8 hours, with the former value suggested for use in extreme environmental conditions. For example, for an $MTTF_{Hall}$ = 1.8 10^7 hours, $MTTF_{3\Sigma Hall}$ = 6 10^6 hours and $MTTF_{3//Hall}$ = 3.3 10^7 hours.

Fault Tolerant Drive Topologies

In order to mitigate the effect of faults that arise in the switches, the traditional structure of the inverter may be modified by adding circuit elements that are required to identify and isolate the fault [18]-[45]. Immediately after a fault, the converter is reconfigured so as to restore, partially or fully, the performances of the drive. A low cost solution which allows to survive a fault is shown in Fig.9, [27], [28]. This topology includes six ultra-rapid fuses, three triacs and an additional leg. When one of the switches fails due to a short circuit or and open circuit, the related fuse opens the leg and activates the triac connected between the faulty leg and the additional leg. The additional leg is commanded with the same switching commands sent to the gate drives of the damaged leg. In this way, normal operation is restored and the same modulation strategy and control structure is maintained. Unfortunately, this fault tolerant topology cannot handle an open phase.



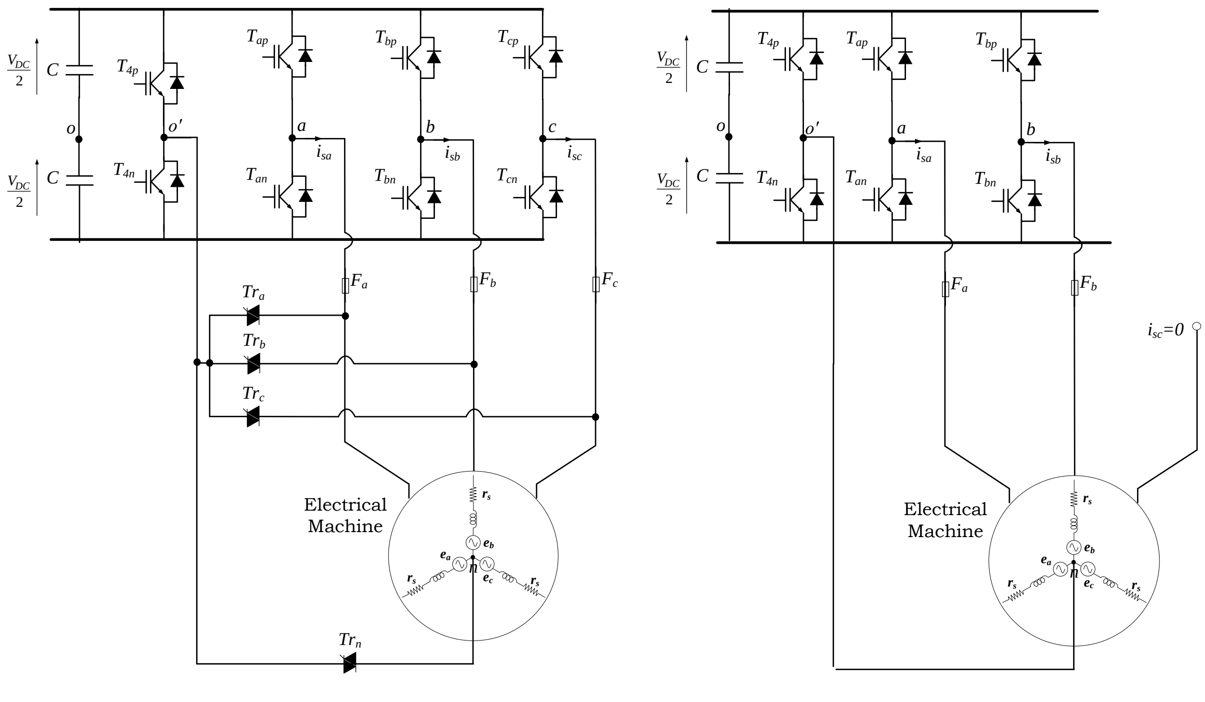
(a) (b)

Figure 9 Fault Tolerant Three Phase Inverter Topology (1).

In order to mitigate the effect of an open phase fault, the topology shown in Fig.10 can be used, [27], [28]. Such a fault can be handled by exploiting the connection between the center of the star of the stator winding and the mid-point of the additional leg. In this case, after the onset of the fault, the same rotating magnetic field is obtained in the airgap by modifying the currents that flow in the two healthy phases, as indicated in (21).

$$\begin{cases} i_i(t) = \sqrt{3}I\cos(\omega_e t + \phi + \gamma_1) \\ i_j(t) = \sqrt{3}I\cos(\omega_e t + \phi + \gamma_2) \end{cases} \qquad (i,j) = \begin{cases} \left(-\frac{5}{6}\pi, \frac{5}{6}\pi\right) \text{ open phase 'a'} \\ \left(\frac{\pi}{6}, \frac{\pi}{2}\right) \text{ open phase 'b'} \\ \left(-\frac{\pi}{6}, -\frac{\pi}{2}\right) \text{ open phase 'c'} \end{cases} \tag{21}$$

From an operational point of view, the control structure may remain similar to that of a healthy drive, as shown in the example reported in Fig.11. The current vector control loop is modified in the reference frame transformations with new matrices ***A***, ***B***, $\boldsymbol{R_I}$ and $\boldsymbol{R_V}$, in which the terms depend on the faulty phase, [19],[20].



(a) (b)

Figure 10 Fault Tolerant Topology (2).

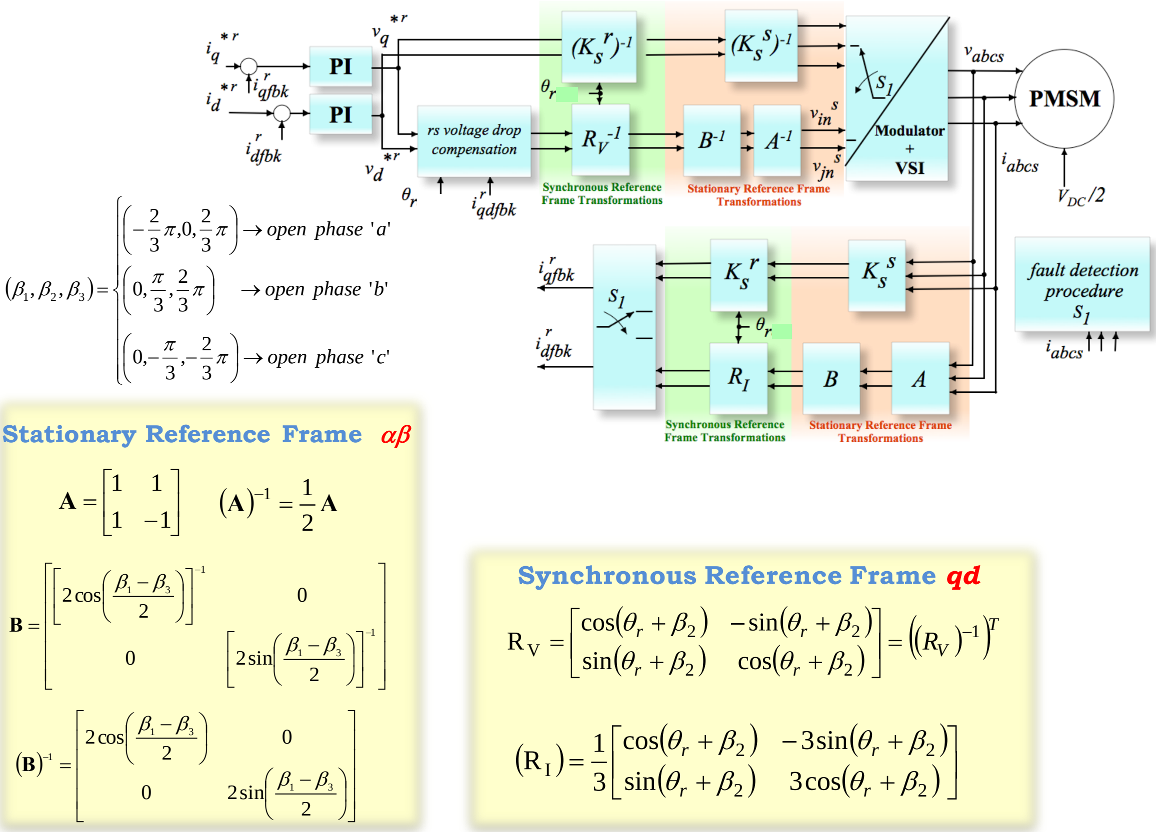


Figure 11 Fault Tolerant Current Vector Control Strategy.

Fault Tolerant Multi-Phase Motor Drives

In order to increase the ability to operate in the presence of multiple faults, some topologies have been developed which include electrical machines with a number of phases greater than three, as shown in Fig.12, [31]-[45]. In this way, the drive is able to manage more than one fault and maintain satisfactory dynamic and engergetic performances (i.e. limited torqe ripple and limited increase of losses); on the other hand, specific control logic is required in the selection of the current references.

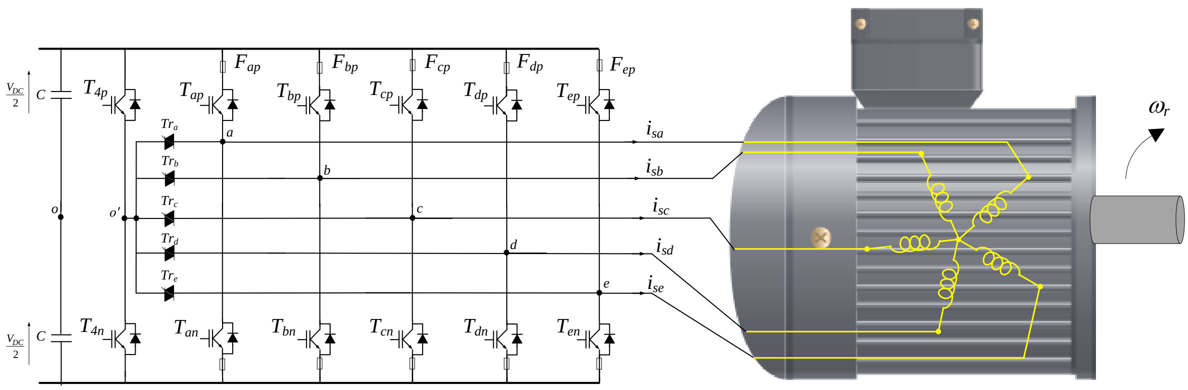


Figure 12 Fault Tolerant Multi-Phase Motor Drive Topology

Fault Tolerant Multi-Motor Drives

In the case of multi-motor drives, the reliability of the system is increased by allowing the single constituent modules to operate in parallel or sequentially, [1], [15]. If one of the modules is damaged it is de-energized and the remaining modules operate and guarantee service even for long periods of operation. This modular configuration is tolerant to various types of machine faults (inter-turn, phase to phase and phase to ground short circuits) and of sensor faults (current and voltage sensors). On the other hand, this flexibility entails an increase in costs and in the complexity of the system.

In the case of active redundancy, the modules are operated permanently in parallel and each drive is capable of controlling the torque and speed profiles that are required by the application. The continuity of operation of the system is ensured as long as a single drive is operating correctly; moreover, it is demonstrated that the MTTF is increased by 50% with respect to the case of a single drive.

$$MTTF_{\mathrm{Redundancy}(1)} = \frac{3}{2}\frac{1}{\lambda_{Module}} = \frac{3}{2}MTTF_{Module} \tag{22}$$

If the same topology is managed by using a passive or sequential redundancy strategy, module 2 becomes operational only if module 1 undergoes a fault. Specifically, when module 1 is faulty, an ideal commutation system having negligible failure rate and operating instantaneously will de-activate module 1 and activate module 2. This functional configuration in which the two modules operate in parallel and sequentially guarantees that the MTTF is doubled (23).

$$MTTF_{\mathrm{Redundancy}(2)} = \frac{2}{\lambda_{Module}} = 2MTTF_{Module} \tag{23}$$

This last solution requires periodic inspections of the stand-by module; furthermore, the overall reliability is strongly dependent on that of the commutation system and the commutation transient might compromise the continuity of service.

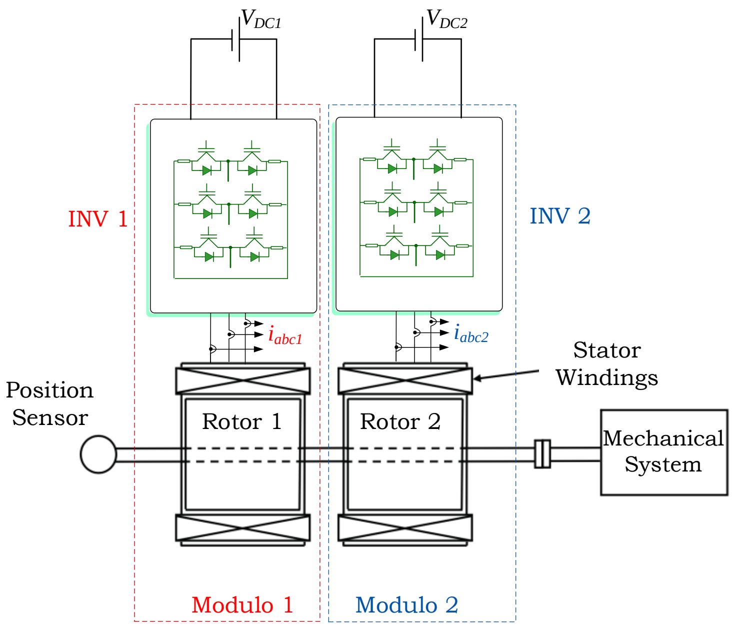


Figure 13 Modular configuration of Fault Tolerant Drives

Increase in Reliability via Sensorless Control Strategies

In order to further increase the reliability of the system it is possible to implement control techniques in which the position sensor is eliminated replaced by machine self-sensing

[2]-[7]. These technical solutions, known as sensorless controls reduce the complexity of the drive, increase the reliability of the system and reduce the maintenance and wiring; they are able to guarantee performances that are similar to "sensored" control in terms of accuracy and dynamics. Furthermore, they must be able to guarantee the continuity of service in the even of faults, if they are integrated into sensorless-fault tolerant drives. Sensorless controls use a fundamental excitation machine model in the medium to high speed range, while they use high frequency signal injection at zero and low speeds.

Model based sensorless techniques use estimation algorithms or observers to obtain an estimate of the rotor flux position and of the speed of rotation. Signal injection based techniques instead are useful only if the machine has a structural or magnetic saliency which ii detectable by injecting additional high frequency fields.

Conclusions

This paper has given a brief overview of how reliability analysis can be applied to electrical drives, operating in safety-critical applications. It has been shown how standard drives may be inadequate and how using hardware or software modifications or a combination of both may increase the reliability considerably. Some state of the art solutions have been described, indicating the pros and cons.

References

[1]. Patrick D. T. O'Connor, Andre Kleyner, *Practical Reliability Engineering*, Fifth Edition, A John Wiley & Sons, Ltd., Publication, 2012.

[2]. A. Consoli, G. Scarcella, G. Scelba, A. Testa, D. A. Triolo, *Sensorless Rotor Position Estimation in Synchronous Reluctance Motors Exploiting a Flux Deviation Approach*, IEEE Transaction on Industry Applications, September/October 2007, vol. 43, no. 5, pp. 1266-1273.

[3]. Y.D. Yoon, S.-K. Sul, S. Morimoto and K. Ide, *High-Bandwidth Sensorless Algorithm for AC Machines Based on Square-Wave-Type Voltage Injection*, IEEE Transactions on Industry Applications, May/June 2011, vol.47, no.3, pp. 1361-1370.

[4]. S. Sato, H, Iura, K. Ide, S.-K. Sul, *Three years of industrial experience with sensorless IPMSM drive based on high frequency injection method*, 2011 Symposium on Sensorless Control for Electrical Drives (SLED 2011), pp. 74-79.

[5]. S.-C. Yang, R. D. Lorenz, *Comparison of Resistance-Based and Inductance-Based Self-Sensing Controls for Surface Permanent- Magnet Machines Using High-Frequency Signal Injection*, IEEE Transactions on Industry Applications, May/June 2012, vol. 48, no. 3, pp. 977-986.

[6]. J. Holtz, *Sensorless control of induction motor drives*, Proceedings of the IEEE, August 2002, vol. 90, n. 8, pp. 1359-1394.

[7]. S. Alireza Davari, Davood Arab Khaburi, Fengxiang Wang, Ralph M. Kennel, *Using Full Order and Reduced Order Observers for Robust Sensorless Predictive Torque Control of Induction Motors*, July 2012, IEEE Transactions on Power Electronics, vol. 27, n. 7, pp. 3424-3433.

[8]. Imen Bahri, Ilhem Slama-Belkhodja, Eric Monmasson, *FPGA-based real-time simulation of fault tolerant current controllers for power electronics*, 2009 IEEE International Symposium on Industrial Electronics, pp. 378-383.

[9]. Ali Mohamad Bazzi, *designing better induction motor drive systems from efficiency, reliability, and power electronics perspectives*, PhD Thesis, University of Illinois (USA), 2010.

[10]. Chia-Chou Yeh, *fault tolerant operations of induction motor-drive systems*, PhD Thesis, Marquette University (USA), 2008.

[11]. A. Gaeta *Fault Tolerant Sensorless Permanent Magnet Synchronous Motor Drives*, PhD Thesis, University of Catania, Italy, 2011.

[12]. Michele Dai Prè, *Analysis and design of Fault-Tolerant drives*, PhD Thesis, University of Padova, Italy, 2008.

[13]. Jingwei Zhu, Modelling, *Simulation and Implementation of a Fault Tolerant Permanent Magnet AC Motor Drive with Redundancy*, PhD Thesis, University of Adelaide, 2008.

[14]. James Alexander Haylock, *Fault Tolerant Drives for Safety Critical Applications*, PhD Thesis, University of Newcastle upon Tyne, 1998.

[15]. Rammohan Rao Errabelli, *Inverter and Controller for Highly Available Permanent Magnet Synchronous Drives*, PhD Thesis, University of Darmstadt, 2012.

[16]. Giacomo Scelba, Giulio De Donato, Giuseppe Scarcella, Fabio Giulii Capponi, Filippo Bonaccorso, *Fault-Tolerant Rotor Position and Velocity Estimation Using Binary Hall-Effect Sensors for Low-Cost Vector Control Drives*, IEEE Transactions on Industry Applications, vol. 50, n.5, September/October 2014, pp. 3403-3413.

[17]. Giacomo Scelba, Giulio De Donato, Mario Pulvirenti, Fabio Giulii Capponi, Giuseppe Scarcella, *Hall-Effect Sensor Fault Detection, Identification, and Compensation in Brushless DC Drives*, IEEE Transactions on Industry Applications, March/April 2016, vol. 52, n.2, pp. 1542-1554.

[18]. Juan Colmenares, Diane-Perle Sadik, Patrik Hilber, Hans-Peter Nee, *Reliability Analysis of a High-Efficiency SiC Three-Phase Inverter*, IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, n.3, September 2016, pp. 996-1006.

[19]. Alberto Gaeta, Giacomo Scelba, Alfio Consoli, *Modeling and Control of Three-Phase PMSMs Under Open-Phase Fault*, IEEE Transactions on Industry Applications, January/February 2013, vol. 49, n.1, pp. 74-83.

[20]. Mario Pulvirenti, Giuseppe Scarcella, Giacomo Scelba, Mario Cacciato, Antonio Testa, *Fault-Tolerant AC Multidrive System*, IEEE Journal of Emerging and Selected Topics in Power Electronics, June 2014, vol. 2, n.2, pp.224-235.

[21]. K. Rothenhagen, F. W. Fuchs, *Performance of diagnosis methods for IGBT open circuit faults in three phase voltage source inverters for AC variable speed drives*, 2005 European Conference on Power Electronics and Applications, 2005, pp. 1-10.

[22]. R. Peuget, S. Courtine, J. -P. Rognon, *Fault detection and isolation on a PWM inverter by knowledge-based model*, IEEE Transactions on Industry Applications, November/December 1998, vol. 34, n.6, pp. 1318-1326.

[23]. Jorge O. Estima, Nuno M. A. Freire, A. J. Marques Cardoso, *Recent advances in fault diagnosis by Park's vector approach*, 2013 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), pp. 279-288.

[24]. Behrooz Mirafzal, *Survey of Fault-Tolerance Techniques for Three-Phase Voltage Source Inverters*, IEEE Transactions on Industrial Electronics, October 2014, vol. 61, n. 10, pp. 5192-5202.

[25]. R. R. Schoen, T. G. Habetler, F. Kamran, R. G. Bartfield, *Motor bearing damage detection using stator current monitoring*, IEEE Transactions on Industry Applications, November/December 1995, vol. 31, n. 6, pp. 1274-1279.

[26]. Ke Ma, Huai Wang, Frede Blaabjerg, *New Approaches to Reliability Assessment: Using physics-of-failure for prediction and design in power electronics systems*, IEEE Power Electronics Magazine, December 2016, vol. 3, n. 4, pp. 28-41.

[27]. B. A. Welchko, T. A. Lipo, T. M. Jahns, S. E. Schulz, *Fault tolerant three-phase AC motor drive topologies: a comparison of features, cost, and limitations*, IEEE Transactions on Power Electronics, July 2004, vol. 19, n.4, pp. 1108-1116.

[28]. R. L. de Araujo Ribeiro, C. B. Jacobina, E. R. C. da Silva, A. M. N. Lima, *Fault-tolerant voltage-fed PWM inverter AC motor drive systems*, IEEE Transactions on Industrial Electronics, April 2004, vol. 51, n. 2, pp. 439-446.

[29]. Andr M. S. Mendes, A. J. Marques Cardoso, *Fault-Tolerant Operating Strategies Applied to Three-Phase Induction-Motor Drives*, IEEE Transactions on Industrial Electronics, December 2006, vol. 53, n. 6, pp. 1807-1817.

[30]. Oskar Wallmark, Lennart Harnefors, Ola Carlson, *Control Algorithms for a Fault-Tolerant PMSM Drive*, IEEE Transactions on Industrial Electronics, August 2007, vol. 54, n. 4, pp. 1973-1980.

[31]. Ahmed Sayed-Ahmed, Nabeel A. O. Demerdash, *Fault-Tolerant Operation of Delta-Connected Scalar- and Vector-Controlled AC Motor Drives*, IEEE Transactions on Power Electronics, June 2011, vol. 27, n. 6, pp. 3041-3049.

[32]. Behrooz Mirafzal, *Survey of Fault-Tolerance Techniques for Three-Phase Voltage Source Inverters*, IEEE Transactions on Industrial Electronics, October 2014, vol. 61, n. 10, pp. 5192-5202.

[33]. Nicola Bianchi, Silverio Bolognani, Michele Dai Pre, *Strategies for the Fault-Tolerant Current Control of a Five-Phase Permanent-Magnet Motor*, IEEE Transactions on Industry Applications, July/August 2007, vol. 43, n. 4, pp. 960-970.

[34]. Suman Dwari, Leila Parsa, *An Optimal Control Technique for Multiphase PM Machines Under Open-Circuit Faults*, IEEE Transactions on Industrial Electronics, May 2008, vol. 55, n. 5, pp. 1988-1995.

[35]. Malakondaiah Naidu, Suresh Gopalakrishnan, Thomas W. Nehl, *Fault-Tolerant Permanent Magnet Motor Drive Topologies for Automotive X-By-Wire Systems*, IEEE Transactions on Industry Applications, March/April 2010, vol. 46, n. 2, pp. 841-848.

[36]. Angelo Tani, Michele Mengoni, Luca Zarri, Giovanni Serra, Domenico Casadei, *Control of Multiphase Induction Motors With an Odd Number of Phases Under Open-Circuit Phase Faults*, IEEE Transactions on Power Electronics, February 2012, vol. 27, n. 2, pp. 565-577.

[37]. Luigi Alberti, Nicola Bianchi, *Experimental Tests of Dual Three-Phase Induction Motor Under Faulty Operating Condition*, IEEE Transactions on Industrial Electronics, May 2012, vol. 59, n. 5, pp. 2041-2048.

[38]. John W. Bennett, Glynn J. Atkinson, Barrie C. Mecrow, David J. Atkinson, *Fault-Tolerant Design Considerations and Control Strategies for Aerospace Drives*, IEEE Transactions on Industrial Electronics, May 2012, vol. 59, n. 5, pp. 2049-2058.

[39]. Ali Mohammadpour, Siavash Sadeghi, Leila Parsa, *A Generalized Fault-Tolerant Control Strategy for Five-Phase PM Motor Drives Considering Star, Pentagon, and Pentacle Connections of Stator Windings*, IEEE Transactions on Industrial Electronics, January 2014, vol. 61, n. 1, pp. 63-75.

[40]. Rammohan Rao Errabelli, Peter Mutschler, *Fault-Tolerant Voltage Source Inverter for Permanent Magnet Drives*, IEEE Transactions on Power Electronics, February 2012, vol. 27, n. 2, pp. 500-508.

[41]. Yantao Song, Bingsen Wang, *Analysis and Experimental Verification of a Fault-Tolerant HEV Powertrain*, IEEE Transactions on Power Electronics, December 2013, vol. 28, n.12, pp. 5854-5864.

[42]. Chee-Shen Lim, Emil Levi, Martin Jones, Nasrudin Abd Rahim, Wooi-Ping Hew, *A Fault-Tolerant Two-Motor Drive With FCS-MP-Based Flux and Torque Control*, IEEE Transactions on Industrial Electronics, December 2014, vol. 61, n.12, pp. 6603-6614.

[43]. Ayman M. EL-Refaie, Manoj R. Shah, Kum-Kang Huh, *High-Power-Density Fault-Tolerant PM Generator for Safety-Critical Applications*, IEEE Transactions on Industry Applications, May/June 2014, vol. 50, n.3, pp. 1717-1728.

[44]. Guillermo R. Catuogno, Guillermo O. Garcia, Roberto Leidhold, *Fault-Tolerant Inverter for Power Flow Control in Variable-Speed Four-Wire Permanent-Magnet Generators*, IEEE Transactions on Industrial Electronics, November 2015, vol. 62, n. 11, pp. 6727-6736.

[45]. Hugo Guzman, Mario J. Duran, Federico Barrero, Luca Zarri, Blas Bogado, Ignacio Gonzalez Prieto, Manuel R. Arahal, *Comparative Study of Predictive and Resonant Controllers in Fault-Tolerant Five-Phase Induction Motor Drives*, IEEE Transactions on Industrial Electronics, January 2016, vol. 63, n. 1, pp. 606-617.

SRM Flux Linkage Profile Measurement and Estimation Methods

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Abstract

Due to the growing interest of the industry for PM-less machines, switched reluctance machine (SRM) became more and more attractive for variable speed-variable torque drive systems or for servo drives for position, speed or torque control. For proper control and high performances achievement, the magnetic characteristics of the machine are of great importance.

There are several theoretical models and experimental methods for determining the magnetic characteristics, each of them with its advantages and limitations. The present paper presents, in a comparative manner, three experimental methods vs a theoretical approach for raising the flux linkage profile of a commercial 8/6 4-phase SRM. An experimental platform is developed in order to implement the measuring methods and to enhance the accuracy and reduce the interval for data acquisition and postprocessing.

1. Introduction

In the quest for PM-less drives, switched reluctance machines (SRMs) are drawing important attention due to several advantages like simple and robust construction, low inertia and high torque to volume ratio. Nevertheless, due to its double salient topology the machine is predisposed to saturation. Therefore, for SRM optimal design and control the determination of magnetic characteristics is an important step.

There are several methods to raise these characteristics using either theoretical calculations or experimental measurements, direct or indirect methods, each with its limitations or drawbacks. Choosing the suitable one for a particular application needs first of all an overview of the approaches reported and discussed in the literature.

The paper presents, in a comparative manner, four methods for obtaining the flux linkage characteristics of SRM and analyzes their results and accuracy. A brief review of the flux linkage profile measurement methods for SRM is presented in Section II, followed in Section III by a detailed description of the theory behind each method principle. Section IV analyzes the results and the conclusions are summarized in Section V.

2. Flux linkage profile measurement methods for SRM

Many articles have been published during the last decades on the SRM magnetic characteristics models and experimental approaches. The magnetization curves of SRM can be obtained using either numerical modeling and analysis methods or analytical. approaches. The Finite Element Method (FEM) is the most used numerical method as it takes into account the magnetic saturation [1-3]. Its main disadvantage is connected to the high time computation and several attempts were done for reducing it and enhancing the accuracy.

Analytical approaches seemed to be a solution, but with an important penalty on the accuracy of the results. Moreover, all these approaches are based either on complex models of magnetic circuit or on curve fitting functions, therefore measured data or data obtained by FEM-calculation are needed [4]. The SRM magnetization curves measurement methods are presented in detail in the literature. Different articles either present or compare a number of experimental methods, emphasizing the advantages and disadvantages and proposing solution in order to overcome the latter ones. The experimental investigation of the flux linkage profile can be carried out using different methods. The most used are briefly presented below.

A. Static torque measurement

The SRM rotor is blocked at different rotor positions (from the unaligned to the fully aligned one) and one phase is fed with direct current between 0 and the maximum value. The flux characteristics can then be developed from the coenergy, as:

$$\Psi(\theta_0, i_0) = \frac{\partial W'(\theta_0, i_0)}{\partial i} \quad (1)$$

where $\Psi(\theta_0, i_0)$ is the flux linkage at θ_0 rotor position and a phase current equal to i_0, and $W'(\theta_0, i_0)$ is the magnetic coenergy derived from the measured torque T as:

$$W'(\theta_0, i_0) = \int_0^{\theta_0} T(\theta_0, i_0) d\theta + L_0 \frac{i_0^2}{2} \quad (2)$$

L_0 corresponds to the slope of the flux characteristic for unaligned position and can be determined by measuring the flux with a static method [2-4]. The main advantage of this method is that the phase is fed with DC current, without any specific requirement for the DC power supply and with no extra losses that could affect the measurement.

The main disadvantage is connected with the fact that beside the torque profile additional information on the inductance at unaligned position is required. This makes the method not suitable for small torque SRM.

B. Direct measurement of flux linkage

The method asks for a magnetic sensor (search coil) installed in the motor, during the assembling. Due to the complexity of the construction and to the low accuracy, this method is rarely used.

C. Indirect measurement of flux linkage

Several indirect flux linkage measuring methods were developed and discussed. These indirect methods are based on the fact that the flux is given as the integral of the electromotive force induced in the phase:

$$\Psi = \int_0^t [u(t) - R \cdot i(t)] dt + \Psi(0) \quad (3)$$

with $\Psi(0)$ representing the value of the flux linkage at $t=0$ and R representing the phase resistance. The terminal voltage, $u(t)$, and the line current, $i(t)$, are measured. The measurements can be done using either DC or AC voltage power supply.

If a DC power supply is used, the transient current response of the phase is measured during the energizing, saturation and de-energizing periods. For the AC power supply measurements the voltage and the current are measured at steady-state, either the instantaneous waveforms or the rms values.

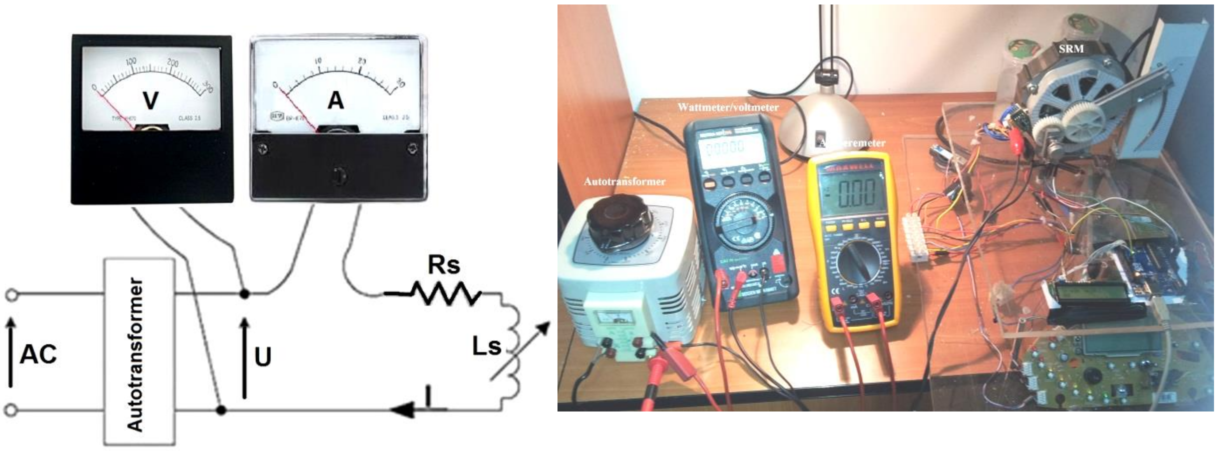

Figure 1. Classical circuit for flux linkage AC measurement.

DC method has several problems due to specific requirements for the DC power supply and the extra equipment necessary for synchronization and control of the collected data, as well as for additional switching electronic circuits [5].

3. Flux linkage profile using different measurement/estimation methods

Three methods were applied and compared for a commercial 4-phase 8/6 SRM. An experimental platform was developed for automate the measurement procedure and increase the accuracy.

A. AC measurement method

The classical circuit for carrying out the AC measurement is presented in Figure 1. The motor shaft is mechanically locked at different angles of rotation, and the phase is fed from an AC power supply. In the absence of mechanical locks the rotor at different angles, it would rotate to get into position aligned, stable equilibrium position in which torque is zero and where the flux-linkage respectively are the maximum phase inductance. By computing the inductance of the phase the flux linkage can be calculated.

$$\Psi = L \cdot i \tag{4}$$

The steps of measurement procedure using an AC power supply are as follows:

- The rotor is blocked in one position (as it can be seen in Figure 2);
- One phase of the machine is fed with AC voltage from an autotransformer;
- The voltage and phase current are measured.

The measurement is repeated for different current values and for different rotor. During the tests, the current I was kept constant at values: 0.2A, 0.4A, 0.6A, 0.8A, 1.0A, 1.2A, 1.4A, 1.6A, 1.8A, 2.0A, 2.2A şi 2.4A for the rotor positions at: 0°, 5°, 10°, 15°, 20°, 25° and 30° by changing the phase voltage from the autotransformer.

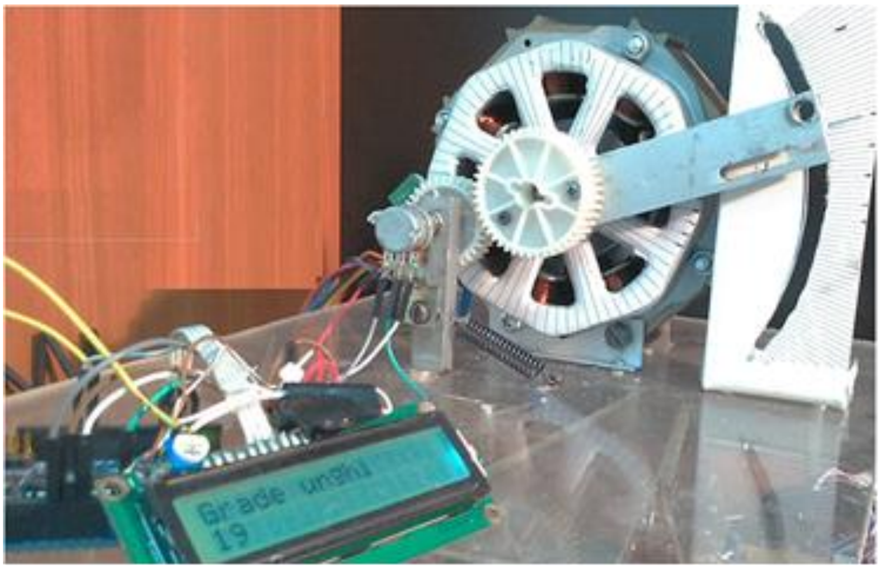

Figure 2. Experimental set-up.

Using the measured voltage, current and power factor (computed by the experimental platform) the phase impedance and resistance are calculated using:

$$Z = \frac{U}{I} \quad (5)$$

$$R = \frac{UI \cos \varphi}{I^2}$$

The phase reactance results as:

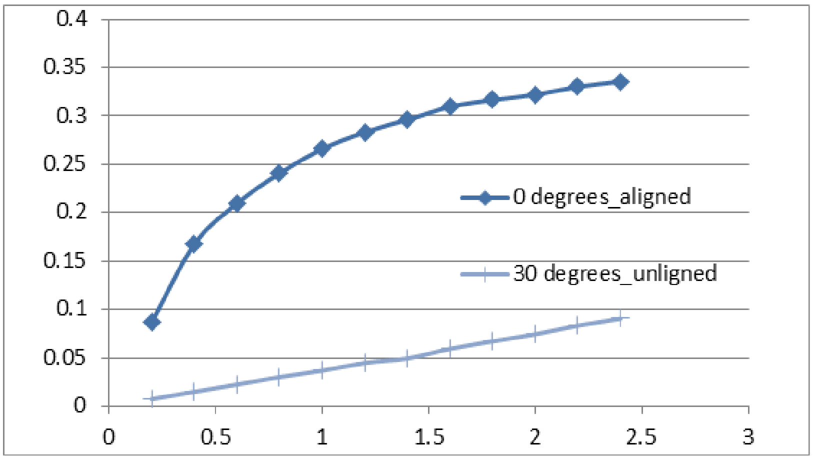

Figure 3. Flux linkage at unaligned and aligned position measured using the AC measurement method.

$$X = \sqrt{Z^2 - R^2} \quad (6)$$

So the inductance is given by:

$$L = \frac{X}{\omega} = \frac{X}{2\pi f} \tag{7}$$

with the frequency of the power supply, *f*, equal to 50 Hz.[1]

The flux linkage at unaligned and aligned position as a function of phase current and rotor position is given in Figure 3.

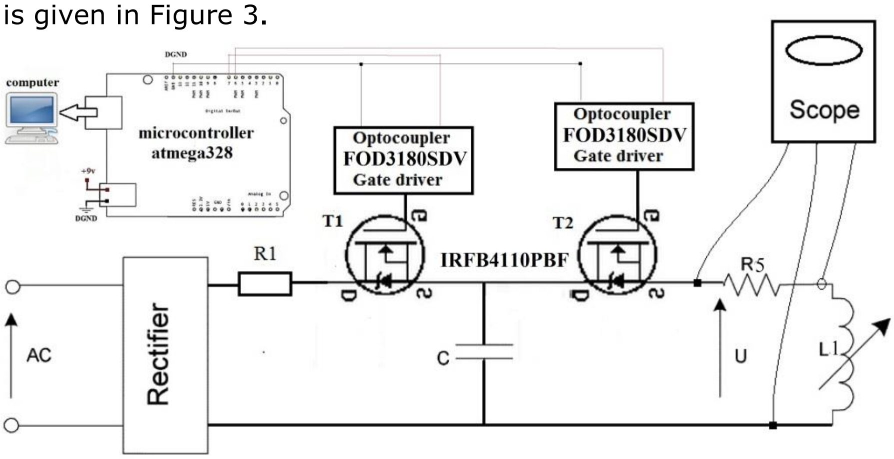

Figure 4. Experimental set-up for DC measurements.

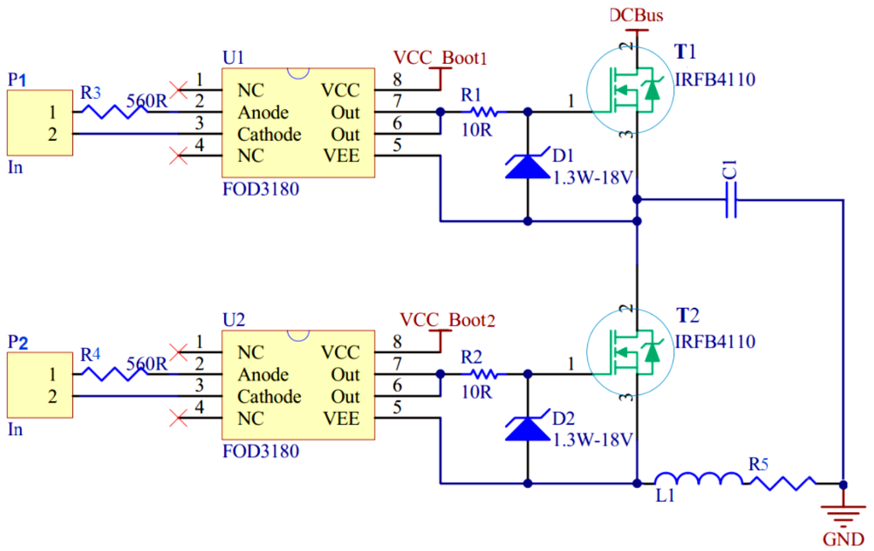

Figure 4.a Details of IRF connections for DC measurements.

B. DC measurement method

The DC proposed method, named also one-pulse test method was applied to the same SRM. The circuit in Figure 4 is used for the measurement of the instantaneous value of the phase inductance that corresponds to an instantaneous value of the phase current.

The measurements are performed in the following way:

Step 1) T1 turn on, T2 turn off. The external capacitor is charged to the desired level of the dc voltage.

Step 2) T1 turn off, T2 turn on. The external capacitor is discharged through the phase winding.

The experimental data of phase voltage and current are recorded by a digital oscilloscope and transferred to a computer. The process of discharging the external capacitor takes about a fraction of a second. The SRM is not heated at all. As a result, the SRM phase resistance does not change during the measurements. [2-5]

The magnetic flux linkage in the SRM phase could be estimated from the experimental data using Equation (3). The graphs were obtained while only the rising part of the current wave is considered. The waveforms of the phase voltage and current (Fig. 5) should be first processed to reject the DC bias of the oscilloscope. The waveform of the phase voltage is used only in (3), while the waveform of the stator current is used also for the computation of the SRM phase inductance. The current waveform should be further processed to reject the noise it contains. The processing could be performed into two ways: the waveform could be smoothed by using a moving average filter or square estimation by a high degree polynomial could be applied.

C. Dynamic measurement of the induced voltage.

The SRM under study is driven at a constant speed, and one of the machine phases is fed by a direct current (Figure. 6). The induced voltage, e(t), in one of the other phases is then measured. The flux linkage of this specific phase results as the integral of the induced voltage:

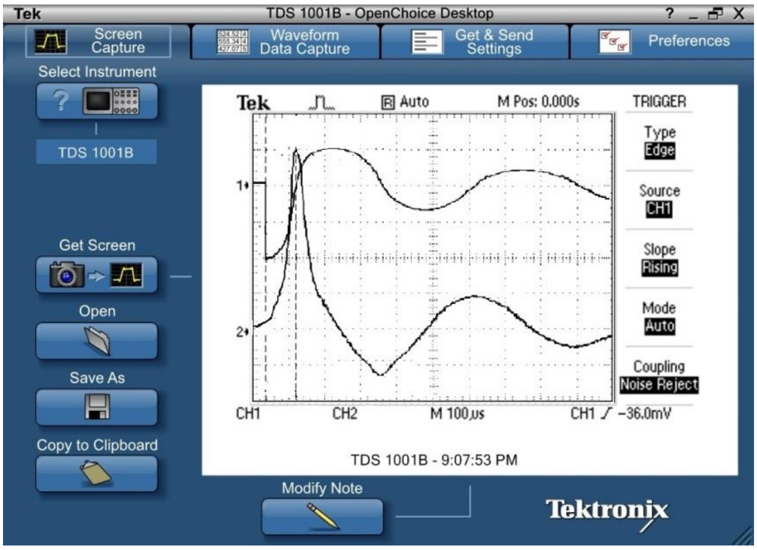

Figure 5. Phase current and voltage across the stator phase. Channel 1 is the phase voltage, Channel 2 is the phase current.

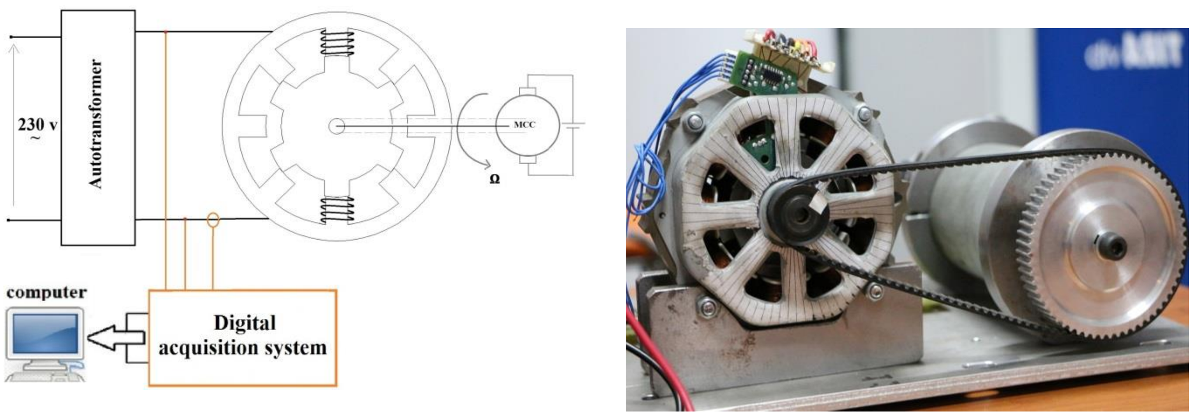

Figure 6. Dynamic measurement of the induced voltage experimental set-up.

$$\Psi = \int_0^t e(t)dt + \Psi(0)$$

(8)

The results of the applied method to the SRM under study are plotted in Fig. 7. The variation of the phase flux linkage between the maximum and minimum value corresponds to the aligned and unaligned position reached by the rotor during the rotation.

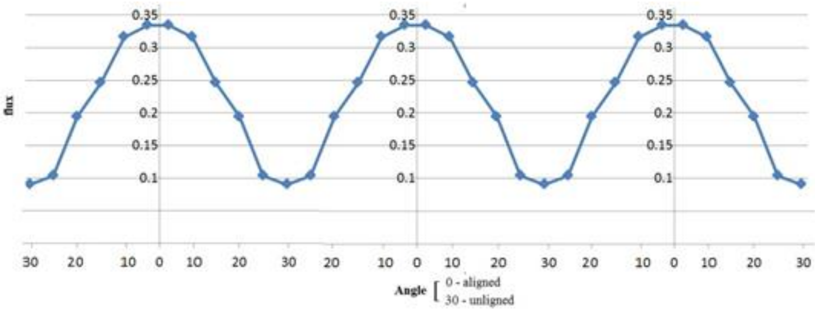

Figure 7. Flux linkage vs rotor position for dynamic measurement of the induced voltage method.

D. FEM analysis

Using the geometrical dimensions of the SRM under study, a model was developed, and analyzed for different phase current values and different rotor positions, using a FEM-based software. The simulations were done for the same rotor positions and phase currents as in the experimental measurement. Fig. 8 presents the map of the magnetic field density, the flux lines and its distribution along a pole pitch.

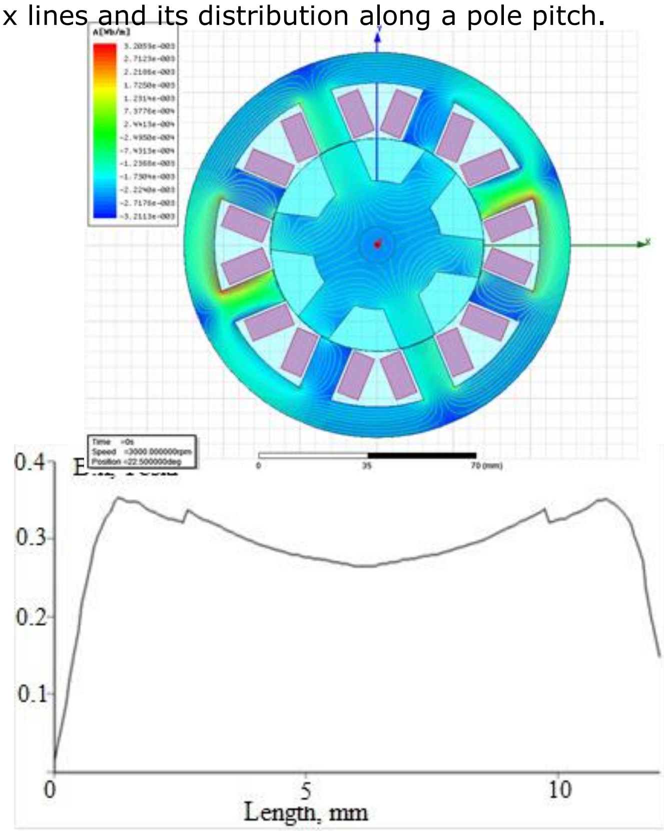

Figure 8. Magnetic field map in the cross-section of the machine and its distribution along the pole pitch

The FEM estimated magnetic characteristics of the SRM under study are presented in Figure 9.

4. Results

The results of the flux linkage measurement methods are presented, together with the FEM analysis results, in Fig. 9. As it can be noted the differences between the results of the above mentioned methods are quite small, but a deeper analysis will provide more information on additional effects (iron losses influence, mutual coupling between phases, temperature dependence, etc.) to be taken into account for future work.

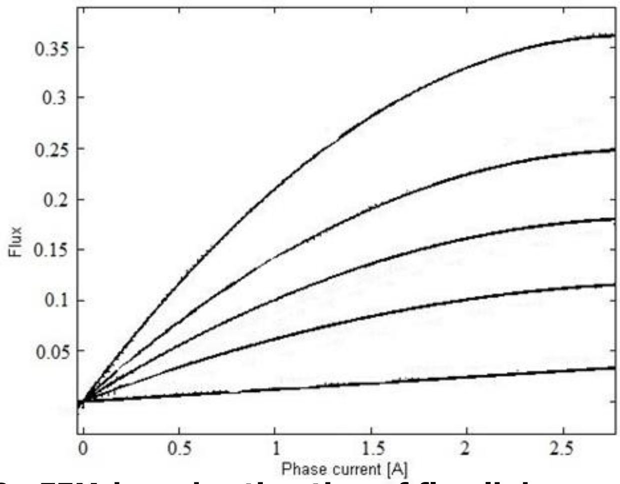

Figure 9. FEM-based estimation of flux linkage profile.

5. Conclusions

Four flux linkage profile measurement and estimation methods were presented in the paper. A commercial 4-phase 8/6 SRM was considered for AC and DC static indirect flux linkage measurement, DC dynamic indirect flux linkage measurement and FEM-based flux linkage estimation. The developed experimental platform, based on an ARDUINO UNO microcontroller is simple and it is easily automated.

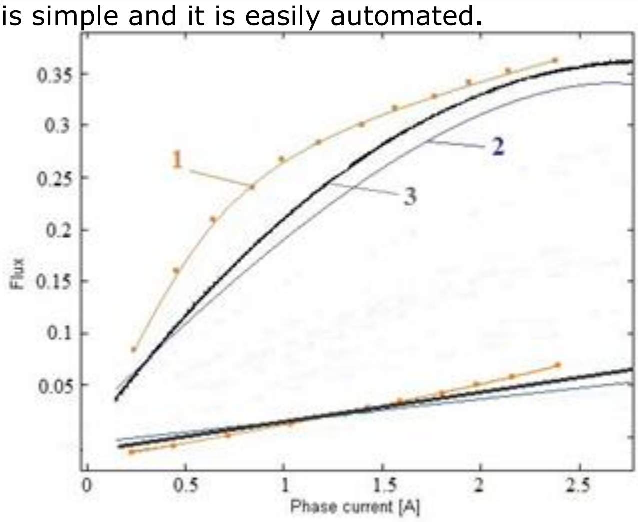

Figure 10. Results of estimating of the stator flux in aligned and unaligned positions of the rotor; 1 - Measured values with voltage versus current test, 2 – One-pulse test 3 - FEMM 4.2, 4

The proposed test system is flexible, allowing different types of methods to be implemented and also machines with different power ratings can be accommodated.

Moreover, with little extra work the set-up can be used for the flux linkage measurement of other types of machines (PMSM, SyRM).

6. Acknowledgment

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References

[1] Maşini electrice speciale – Aplicaţii, Ed. Mediamira, 2007 Ioan-Adrian VIOREL, Daniel FODOREAN, Florin Nicolae JURCĂ

[2] Inductance Measurements in Switched Reluctance Machines, Nikolay Radimov, Natan Ben-Hail and Raul Rabinovici

[3] A new Measuring Method of Flux Linkage of SRM, Chuntang Zhang, hui kong

[4] COMPARISON OF MEASUREMENT METHODS TO DETERMINE THE ELECTROMAGNETIC CHARACTERISTICS

OF SWITCHED RELUCTANCE MOTORS, H. Cailleux, J-C. Mouchoux, B. Multon, E. Hoang, J-Y. Le Chenadec

[5] A New Method to Measure the Switched Reluctance Motor's Flux, Jinhui Zhang and Arthur V. Radun

Design and Implementation of a Line Start PM Synchronous Motor and Synchronous Reluctance Motor and Performance Comparison with Induction Motor

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Abstract

Due to the on-coming regulations and increasing demand on energy efficient motors, alternative motor designs have been implemented and applied in the industry. Considering the high efficiency motors, line start permanent magnet synchronous motor (LSPMSM) and synchronous reluctance motor (SynRM) are drawn attention for the industrial applications. In this paper, 1,5 kW, 4-pole LSPMSM and SynRM with IE4 efficiency level are designed and manufactured. The design is made on the rotor side.

The main parameters for the comparison of experimental results are efficiency, stator current and losses of the IM, the LSPMSM and the SynRM. As an application case study, the experimental results on a dynamometer test are given for LPMSM, SynRM and advantages of LPMSM and SynRM over the IM are highlighted as well.

Introduction

Approximately 35-40% of the generated electric energy is consumed by electric motors which are used in industrial applications [1]. Pump applications account for 10 % of the world's total energy consumption [2]. Based on the market report in [3], compressor, fan and pump applications account for 76 % of the low voltage electric motor applications. For this type of applications, induction motors (IM) are the most preferred type of electric motors due to their low cost, high reliability and easy maintenance

New regulations have introduced about consuming energy for electric machines nowadays. Super-Premium Efficiency Level (IE4 Class) is defined in the IEC 60034-30-1 standard. Besides, IEC 60034-30-2 is released newly so IE5 efficiency level for variable speed AC motors is defined. Due to the new regulations, high efficiency motors are drawn attention by industrial motor users. Because IM has low efficiency and power factor especially for small rated power, in order to provide higher efficiency level, copper cage needs to be replaced by aluminum one. However, due to copper material, price of motor will be more expensive. Especially for the small rated power, line start permanent magnet synchronous motors (LSPMSM) and synchronous reluctance motors (SynRM) are two candidates of high efficiency motors instead of IM [2]. As the permanent magnets become more available and, cost of the motor drives goes down compared to the past, the LSPMSM and the SynRM have started to stand out again although both of them have aged literatures. SynRMs can be used for variable speed applications while LSPMSMs and IMs are proposed for line-start fixed speed applications. The IE4 LSPMSM is proposed up to 7.5 kW powers and IE4 IM is proposed for 5.5 – 355 kW power range. If considering long term usage, although the price of IE4 LSPMSM is higher due to the magnets buried on the rotor, it is more advantageous than IE1, IE2 and IE3 IM in terms of economic aspects [4] – [5].

Both the LSPMSM and the SynRM have high efficiency while the LSPMSM has high power factor as well. The other advantage of the LSPMSM according to the SynRM, it starts across the line without any motor drive unit thanks to the squirrel cage on its rotor. LSPMSM also eliminates any faults due to the motor drive unit. In the global market, there are a few motor manufacturers which produce LSPMSM and SynRM.

Basic Principles of Line Start Permanent Magnet Synchronous Motors

Line start permanent magnet synchronous motor is a hybrid type of electric motor. Its stator similar to that of an asynchronous motor while rotor topologies are different. It has both rotor conductor bars and magnets. The magnets are buried on the below of the rotor bars. Thanks to squirrel cage, the LSPMSM can start direct on line without any inverter.

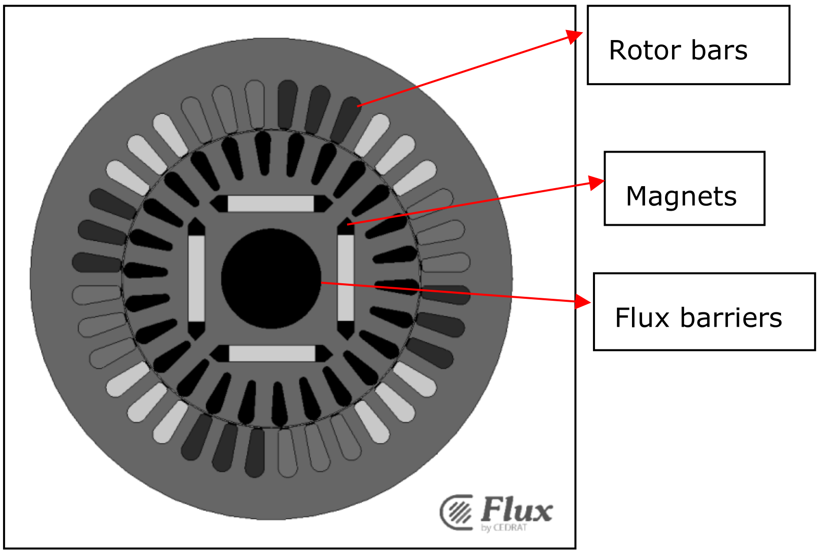

Figure 1. Geometry of LSPMSM

Due to the hybrid rotor topology of LSPMSM, it starts asynchronously and operates synchronously at steady state. If at any fault condition, the motor passes to asynchronous mode from the synchronous mode, squirrel cage behaves like damping windings. It prevents the oscillations and tries making the motor work synchronously.

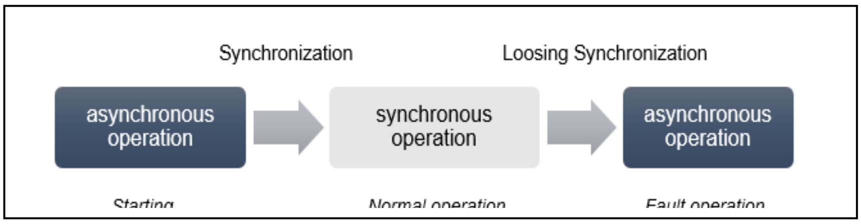

Figure 2. Operation modes of LSPMSM

The design of LSPMSM is tricky. When the motor starts, braking torque is produced by the magnets. The braking torque affects the asynchronous (cage) torque negatively. The asynchronous torque depends on the cage material and conductor bar design mainly. To successfully starting and synchronizing process for the LSPMSM, the squirrel cage design is important. If the magnet braking torque is greater than cage torque, the motor cannot start or not synchronize. Figure 3 shows that torque components of the LSPMSM.

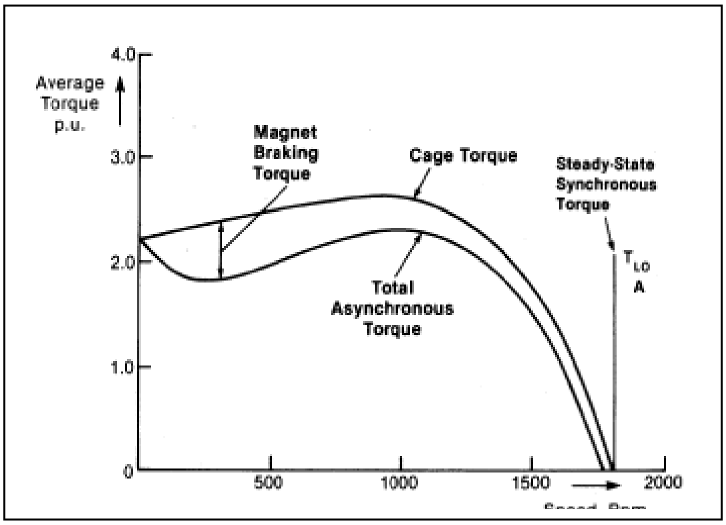

Figure 3. The LSPMSM torque components

Total torque of the LSPMSM has three components and the synchronization process depends on the balance of these components. This process can be expressed with the mechanical equilibrium equation which is given below

$$J\frac{d\omega}{dt} = T_{synch} - T_{load} + T_{asynch}$$

where J is the total moment of inertia and ω is the angular velocity of the rotor.

The total average asynchronous torque is expressed summation of the cage torque and magnet brake torque.

Mathematical Model

The LSPMSM mathematical model is written in d-q reference frame. Electrical circuit belong to the LSPMSM is shown in Figure 4.

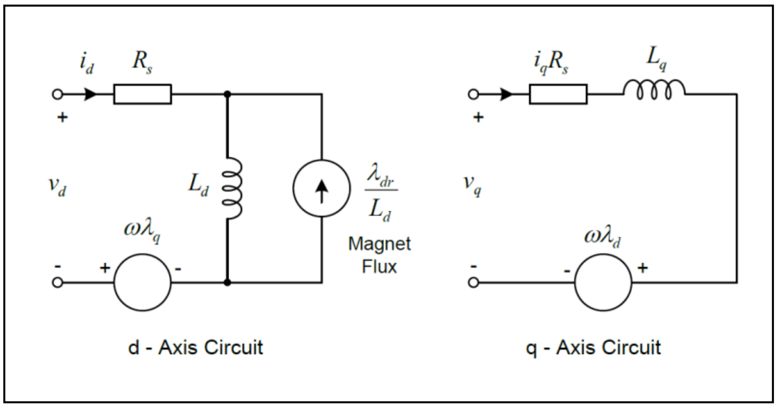

Figure 4. Equivalent circuit of PMSM in d-q reference frame

Voltage equations of PMSM in d-q reference frame are given below:

$$v_q = i_q R_s + L_q \frac{di_q}{dt} + (\omega i_d L_d + \omega \lambda_{dr})$$
$$v_d = i_d R_s + L_d \frac{di_d}{dt} - (\omega i_q L_q)$$
$$\lambda_q = i_q L_q$$
$$\lambda_d = i_d L_d + \lambda_{dr}$$

where v_q and v_d are the stator d and q axis voltages; i_q and i_d are the stator d and q axis currents; R_s is the stator resistance, $L_q$and L_d are the q and d axis inductances, λ_{dr} is PM flux linkage and ω is angular velocity respectively.

At steady state operation,

$$v_q = i_q R_s + (\omega i_d L_d + \omega \lambda_{dr})$$
$$v_d = i_d R_s - (\omega i_q L_q)$$

The synchronous torque equation at steady state operation,

$$T_s = \frac{3pE_0 V}{2\omega_s X_{sd}} \sin\delta + \frac{3pV^2(X_{sd} - X_{sq})}{4\omega_s X_{sq} X_{sd}} \sin 2\delta$$

where the first term is PM torque and the second term is reluctance torque. In equation V is supply voltage, E_0 is no-load back-emf, X_{sd} and X_{sq} d and q axis reactance, p is the number of pole pairs, ω_s electrical angular speed and $\delta$is electrical load angle.

Braking torque produced by magnets influences cage torque negatively when the motor starts up. Magnet braking torque and cage torque equations are given below respectively:

$$T_b = -\frac{3p}{2\omega_s}\left[\frac{r_s^2 + (1-s)^2 X_{sq}^2}{r_s^2 + (1-s)^2 X_{sd} X_{sq}}\right]\left[\frac{r_s E_0^2 (1-s)}{r_s^2 + (1-s)^2 X_{sd} X_{sq}}\right]$$
$$T_C = \frac{3}{\omega_s} \frac{V_{th}^2 \left(\frac{r_r'}{s}\right)}{(r_{th} + {r_r'}/{s})^2 + (X_{th} + X_{lr}')^2}$$

where V_{th}, X_{th} are therein equivalent voltage and reactance, r_r', X_{lr}' are rotor resistance and rotor leakage reactance.

Basic Principles of Synchronous Reluctance Motors

Synchronous reluctance motor is the simplest synchronous motor. Rotor losses of SynRM do not exist because its rotor has no any active material. Therefore, this type of motors are very cost-effective. The main disadvantage of SynRM is low power factor.

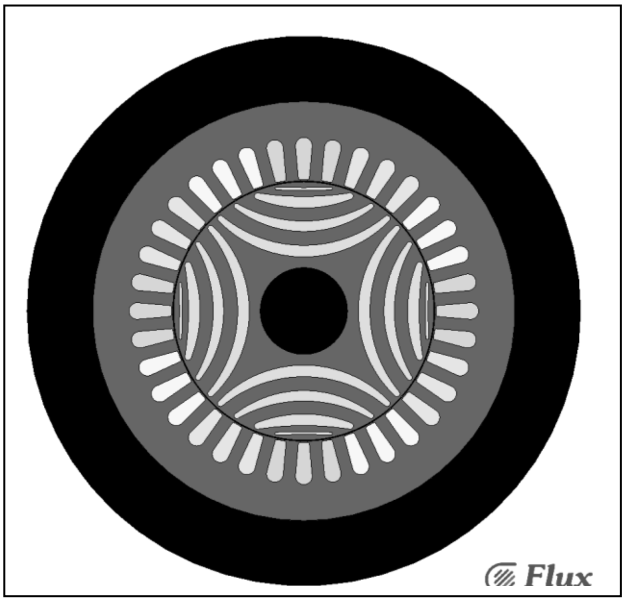

Figure 5. Geometry of SynRM

To achieve good performance for the SynRM, flux paths should be designed to have minimum d-axis reluctance and maximum q-axis reluctance. High anisotropy ratio namely high saliency ratio is the key of a great performance. The power factor depends on this saliency ratio (L_d/L_q) while the output torque is proportional to the difference between d-axis inductance and q-axis inductance. If the difference between d and q axis inductance is greater, than reluctance torque is greater.

The reluctance torque and power factor equations are given below:

$$T_e = \frac{3}{2}\frac{p}{2}\left(L_d - L_q\right)i_d i_q$$

$$\cos\varphi = \frac{\xi - 1}{\sqrt{\xi^2 \frac{1}{(\sin\gamma)^2} + \frac{1}{(\cos\gamma)^2}}}$$

$$\xi = {L_d}/{L_q}$$

where L_d and L_q are the inductances of d and q axis, i_d and i_q are the stator d and q axis currents, p is the number of poles and γ is current angle.

Design Process

In this section, design of LSPMSM and SynRM with IE4 efficiency level are described. Both LSPMSM and SynRM are 90 fr, 1,5 kW 4 poles motors. Stator is kept with the same as IM and just a new rotor has been designed for LSPMSM and SynRM.

Friction and ventilation losses are neglected for efficiency calculation. Motor efficiency values has been calculated with this formula given below:

$$\eta = \frac{P_{out}}{P_{out} + P_{cu} + P_{iron}} x100$$

Design of the Line Start Permanent Magnet Synchronous Motor

Line start permanent magnet synchronous motor design is tricky. Because of having both magnets and conductor bars on the rotor brings about critical design process and detailed optimization. During the design process, stator is kept same with IM; only rotor is redesigned.

At LSPMSM rotor design, starting and synchronization process are critical. Not only rotor conductor bar size and resistance but also magnet size and position are related with these processes directly. If the resistance of conductor bar is too high, motor may not be synchronized. Namely, it starts but does not reach synchronize speed. Determining magnet volume is also critical due to the braking torque. If the volume is too high, then the motor cannot start [6].

90 frame 1.5 kW 4p are the nameplate values of the prototype motor. NdFeB type of magnet has been used on the rotor. Efficiency, stator current and losses are the main design parameters. FLUX 2D has been used for analysis of motor. Simulation results of the motor are given in Table 1.

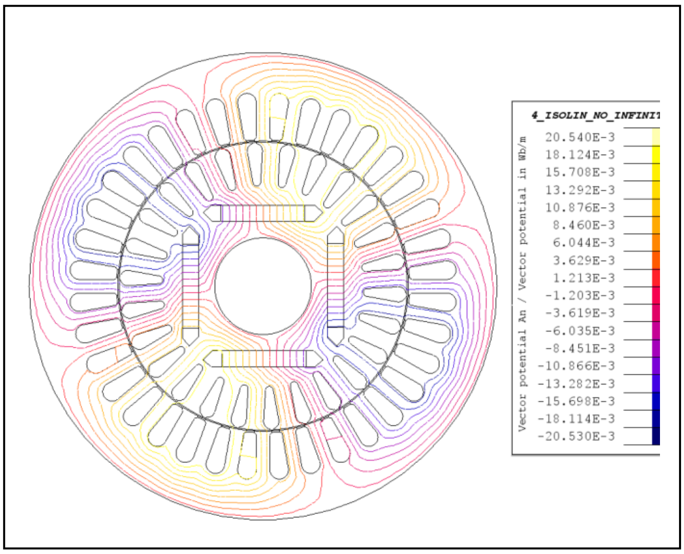

Figure 6. Isolines of LSPMSM

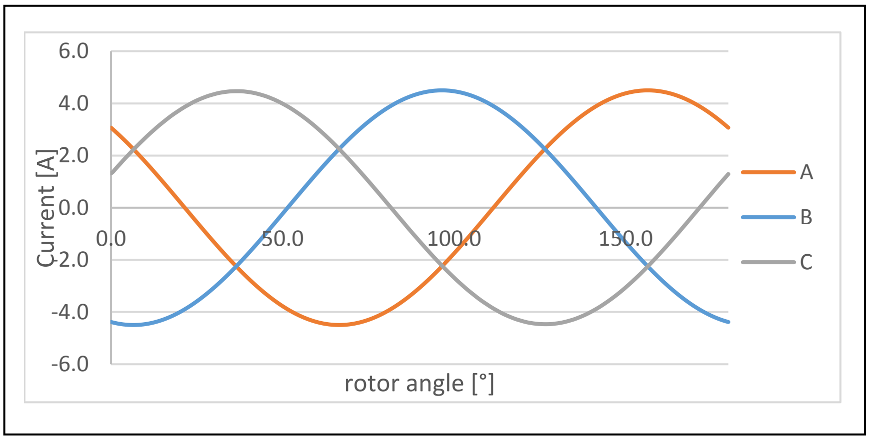

Figure 7. Phase currents curve of LSPMSM

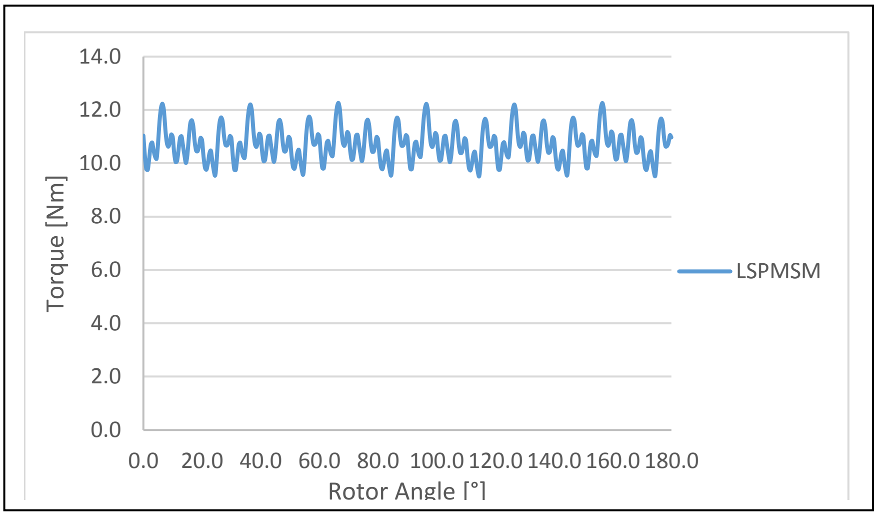

Figure 8. Torque curve of LSPMSM

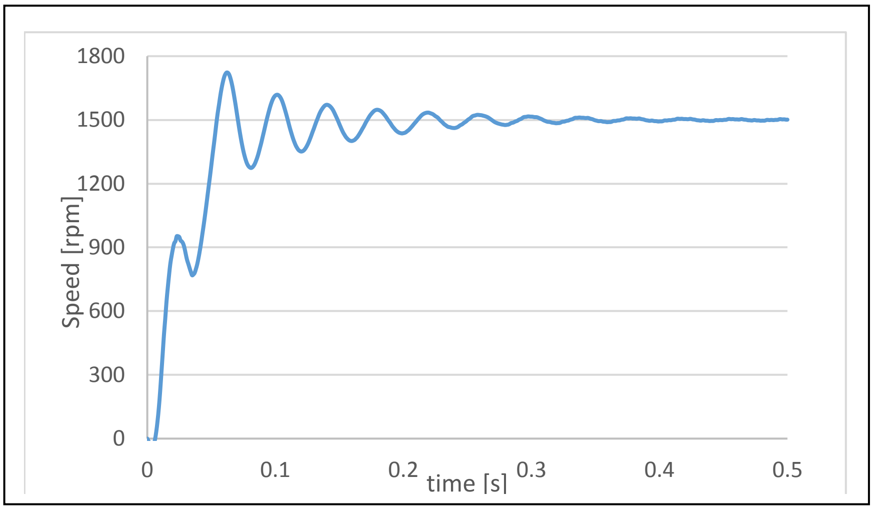

Figure 9. Synchronization curve of LSPMSM

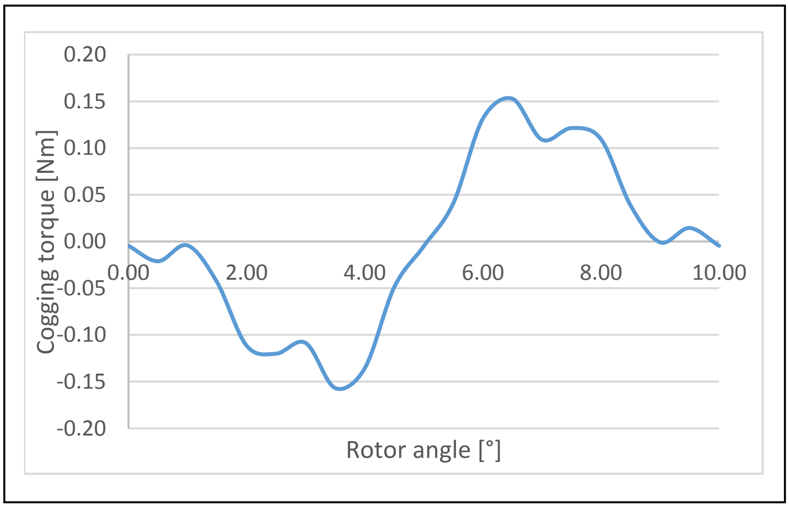

Figure 10. Cogging torque curve of LSPMSM

It can be seen in Figure 9, the LSPMSM has synchronized on between 0,4-0,5 s.

Design of the Synchronous Reluctance Motor

Operating principle of the SynRM is based on difference between d-axis and q-axis inductances. Saliency ratio (L_d/L_q) is the key point that should be considered during the design process. Similar to the LSPMSM design, just rotor is redesigned.

Synchronous reluctance motors have low power factor even though having high efficiency level. Number of rotor barriers and rotor pole pitch influence on reluctance moment, power factor and efficiency. For lower rotor pole pitch value power factor is higher while efficiency is lower. Number of rotor barriers also effects torque ripple of the motor. Magnetic ribs which are replaced middle of the rotor magnetic barriers, decrease reluctance torque because magnetic conductivity of q-axis increases [7].

90 frame 1.5 kW 4p are the nameplate values of the prototype motor. Efficiency, stator current and losses are the main design parameters. FLUX 2D has been used for analysis of motor. Simulation results of the motor are given in Table 1.

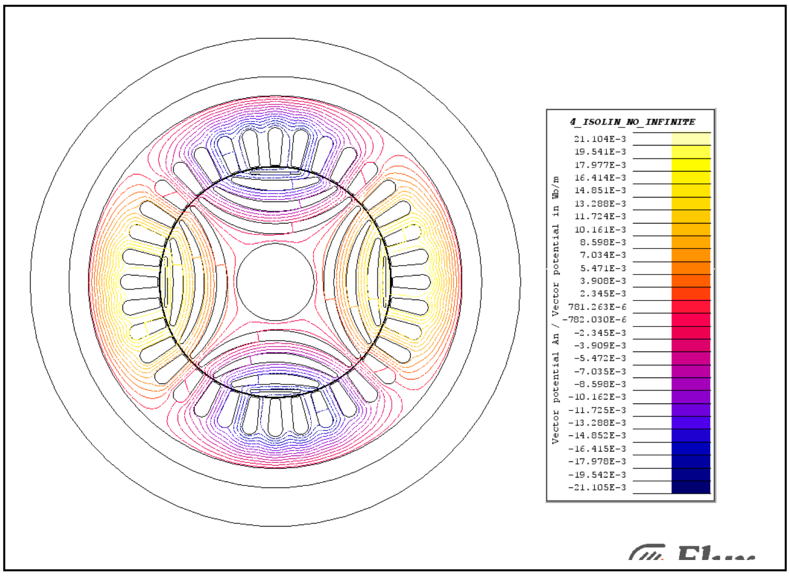

Figure 11. Isolines of SynRM

Table 1. Simulation results of prototype motors

Motor Type	**Moment [Nm]**	**Current [A]**	**Output Power [W]**	**Stator losses [W]**	**Iron losses [W]**	**Efficiency* (%)**	**cosϕ**
LSPMSM	10,7	3,18	1682,2	101,6	62,1	90,6	0,85
SynRM	9,56	3,54	1502,4	126,9	68,1	88,7	0,60

*Friction and ventilation losses are neglected for efficiency calculation.

Experimental Evaluation of the Design Results

The proposed LSPMSM and SynRM are prototyped. For LSPMSM, the magnets had been inserted to the rotor after the aluminum injection process. Prototypes of LSPMSM and SynRM were compared with 1.5 kW 4-pole IE3 efficiency level IM. Comparative test results and separated losses of the LSPMSM, SynRM and IM given in Table 2 and Table 3 respectively.

Table 2. Comparative test results of LSPMSM, SynRM and IM

Motor Type	**Current [A]**	**Shaft Moment [Nm]**	**Output Power [W]**	**Input Power [W]**	**Eff. (%)**	**Speed [rpm]**	**cosϕ**
LSPMSM	3,18	10,3	1616	1831	88,3	1500	0,83
SynRM	4,18	10,3	1602	1721	88,0	1500	0,63
IM	3,32	9,9	1503	1776	84,6	1448	0,77

Table 3. Separated losses of LSPMSM, SynRM and IM

Motor Type	**Stator losses [W]**	**Rotor losses [W]**	**Iron losses [W]**	**Fric.&Vent. Losses [W]**	**Stray load losses [W]**
LSPMSM	101	0	60	24,5	29,5
SynRM	107	0	52	20,5	39,5
IM	112	55	79	14	12,5

A commercial drive unit is used for the operation of the SynRM.

Conclusion

In this paper, design of 1,5 kW 4-p line start permanent magnet synchronous motor and synchronous reluctance motor are described. Stator is kept with the same as IM while new rotors has been designed for the LSPMSM and SynRM. Each of motor has been analyzed with Flux 2D. According to analysis results, the best models which have low stator current and losses and high efficiency were prototyped. 1,5 kW 4-p IE3 efficiency level IM has used for comparing with SynRM and LSPMSM. The LSPMSM and SynRM prototype motors have been tested and both of two have reached IE4 efficiency level according to IEC 60034-30-1 standards.

References

[1] http://energy.grundfos.com/en/facts-on-pumps-energy/the-surprising-truth-about-pumps

[2] Marchi, A., Simpson, A.R., Ertugrul, N., "Assessing variable speed pump efficiency in water distrbiutions systems", *Drinking Water Engineering and Science*, Jul, 2012, pp. 15-21.

[3] www.edriveonline.com (Current and Future World Markets for Motor and Motor Control, 2016 IHS Report)

[4] Marcic, T., "A short review of energy-efficient line start motor design", TECES, Res. Development Centre for Elec. Mach. (1), 2011, ISSN 0033-2097,87, (3), pp.119-122.

[5] De Almeida, A., Ferreira, F., Baoming, G., "Beyond induction motors – technology trends to move up efficiency," in *Proc. IEEE/IAS I&CPS Tech. Conf.,* Stone Mountain, GA, USA, Apr 30–May 3, 2013, pp.1-13.

[6] De Almeida, A.T., Ferreira, F.J.T.E., Duarte, A.Q., "Technical and Economical Considerations on Super High-Efficiency Three-Phase Motors", IEEE Transactions on Industry Applications, Vol. 50, No. 2, pp. 1274-1285, Mar/Apr. 2014.

[7] Libert, F., Soulard, J., Engström, J., "Design of a 4-pole line start permanent magnet synchronous motor," in *Proc. ICEM 2002*, pp.1-6, Brugge, Belgium, Aug.25-28,2002.

[8] Hudak, P., Hrabovcova, V., Rafajdus, P., "Geometrical dimension influence of multi-barrier rotor on reluctance synchronous motor performances", Inter. Symp. On Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM'06), Taormina, Italy, May 2006.

[9] IEC60034-30-1, 1st Ed: Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code), Jun. 2014.

[10] IEC60034-30-2, 1st Ed: Rotating electrical machines – Part 30-2: Efficiency classes of variable speed AC motors (IE-code), Dec. 2016.

[11] Dorrell, D. G., Knight, A. M., Popescu, M., Evans, L., Staton, D. A., "Comparison of different motor design drives for hybrid electric vehicles", *IEEE Energy Conversion Congress and Exposition (ECCE'10)*, Atlanta, GA, USA, Sept 12-16, 2010.

[12] Jedryczka, C., Wojciechowski, M. R., Demenko, A., "The influence of squirrel cage geometry on synchronization of line start permanent magnet synchronous motor", 9th IET International Conference on Computation in Electromagnetics (CEM 2014), pp.1-2, 2014.

[13] Pyrhönen, J., Jokinen, T., Hrabovcova, V. "Design of Rotating Electrical Machines", John Wiley&Sons Ltd.,2008.

[14] Debruyne, C., Polikarpova, M., Deremmelaere, S., Sergeant, P., Pyrhönen, J., Desmet, J.J.M., Vandevelde, L., "Evaluation of the efficiency of line-start permanent-magnet machines as a function of the operating temperature," *IEEE Trans. Ins. Electron*., vol.61, no.8, pp. 4443-4454, Aug. 2014.

High performance PM-assisted Synchronous Reluctance Motor for Electric Truck: a case study

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Abstract

A PM-assisted Synchronous Reluctance motor for 4x4 electric truck has been designed for the agricultural sector. Particularly, this vehicle has one motor per wheel that is connected by a mechanical gearbox. For this specific application, a duty cycle has been imposed and the machine is water cooled with a water jacket around the stator core. A solution with 6 pole 54 slots has been chosen with distributed hairpin winding. The rotor structure presents 4 flux-barriers per pole in order to increase the saliency ratio.

Introduction

The reduction of carbon dioxide emission represents one of the main goals and more and more efforts are being made to replace the internal combustion engine of vehicles by an electric traction drive. Especially, in case of agricultural machines where the emission reduction is an urgent problem, and easy controllable and environment friendly electric vehicles can be a valid alternatives.

The aim is to design efficient and compact electric drives with specific and hard specifications that are different from conventional ones used in other industries. The most challenging requirements for traction motors are high power density, high efficiency, reasonable costs and small size as well as good overload capability.

The research in this field has been intense in the past few years and new motor concepts have been studied and their performances have been compared.

The permanent magnet (PM) synchronous motors are becoming more attractive and the main advantages are their inherently high efficiency, high power density, and high reliability. The key problem is their relatively high cost due to PM materials and this has stimulated designers to investigate other high efficiency solutions.

The Synchronous Reluctance motor (SRM) and PM-assisted Synchronous Reluctance motor with low cost PM Ferrite magnets are efficient alternatives and are well-suited to be employed in electric vehicles.

In this paper, a low-cost ferrite PM-assisted SRM motor for 4x4 electric truck for agricultural sector has been designed for sprayer applications. This vehicle has one motor per wheel that is connected by a mechanical gearbox. For this specific application, a duty cycle has been imposed and the machine is water cooled with a water jacket around the stator core. The rotor has required an accurate design due to the remarkable saturation phenomena in certain parts of the rotor: moreover, a bar wound stator has been chosen.

A solution with 6 pole 54 slots has been designed and the performance in different operating conditions have been analysed and discussed.

The PM-assisted Synchronous Reluctance Motor

The basic characteristics of an electric motor for electric vehicles are the following:

- high torque density and power density;
- very wide speed range;
- high efficiency over wide torque and speed ranges;
- wide constant-power operating capability;
- high reliability and robustness for vehicular environment;
- reasonable cost.

The recent increase of rare-earth PMs cost and the uncertain supply has led the manufacturers to investigate the use of "lower-cost" motors, stimulating the designers to develop others high efficiency, high performance solutions.

The Synchronous Reluctance Motor with "flux-barriers" (SRM) represents a good alternative [1,2,3] with a rugged rotor without PMs and windings and negligible rotor losses. A typical rotor cross section is shown in Fig. 1: laminated rotors with flux barriers can be manufactured with normal punching tools at very low cost. The number of barriers can vary from 2 to 5 and depends on the number of pole pairs, stator slots and outer rotor diameter.

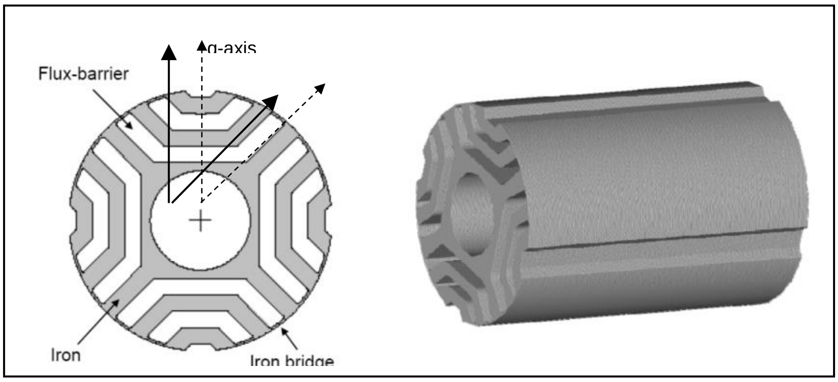

Fig.1 Rotor with flux-barriers for synchronous reluctance motor

The torque produced by the SRM is due to the anisotropy (different *d* and *q*-axis inductances L_d and L_q) of the rotor that causes an angular displacement between the space vectors of stator linkage flux and current. In the SRM, both L_d and L_q vary with saturation, and the *d*-axis inductance is more sensitive to saturation than the *q*-axis inductance due to the low reluctance path of *d*-axis flux.

The number of rotor flux barriers affects the anisotropy, so as this number increases the reluctance torque component increases.

Since the stator winding of the synchronous reluctance motor is sinusoidally distributed, flux harmonics in the air gap contribute only an additional term to the stator leakage inductance. Hence, the equations that describe the behavior of the synchronous reluctance machine can be derived from the conventional Park's equations for a wound field synchronous machine. In terms of the variables, the electromagnetic torque is identical to that of a synchronous machine:

$$T = \frac{3}{2} p \left(L_d - L_q \right) I_d \, I_q \qquad (1)$$

where p is the number of pole pairs, I_d and I_q the direct and quadrature axis currents.

The power factor of a synchronous reluctance motor can be expressed as the ratio of the projection of the voltage vector on the current vector divided by the amplitude of the voltage vector. It is convenient to neglect the stator resistance. Clearly, this is a pessimistic assumption because any resistive component will clearly raise the power factor. Hence, the result to be obtained is a minimum limit. It is shown that the maximum power factor can be expressed as:

$$pf = \frac{k_s - 1}{\sqrt{\left(k_s^2 \frac{1}{\sin^2 \varepsilon} \right) + \left(\frac{1}{\cos^2 \varepsilon} \right)}} \qquad (2)$$

where, k_s is the saliency ratio (L_d/L_q) and ε the current angle between the space vector of the stator current (I_s) and the d-axis current.

SRMs with multi-barriers rotor structures have been widely used in brushless AC drives and their main advantages are:

- no winding or PM in the rotor ("cold" rotor);
- low inertia;
- good acceleration performance;
- good flux weakening operation;
- low manufacturing cost.

On the other hand, SRMs exhibit some drawbacks such as low power factor and high torque ripple that is mainly due to the discontinuity reluctance change between stator and rotor: it can be drastically reduced by an accurate design of the rotor and stator shape or by means of the rotor skewing.

Adding the proper quantity of permanent magnets into the flux barriers of the rotor core, the operating performance of the SRM (torque density, power factor) improve. In this case cheaper PMs such as Ferrite [4] are used. The motor is similar to an Interior PM motor and it can be called PM-assisted SRM (Fig.2).

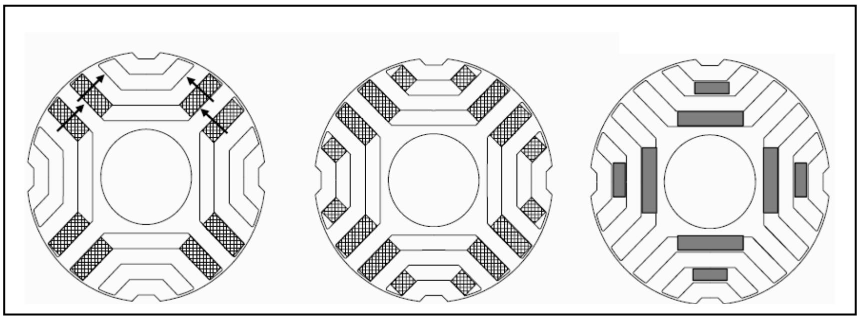

Fig.2 Rotors for PM-assisted Synchronous Reluctance Motors

With the presence of the magnets in the rotor, the torque expression (1) changes. So, adding magnets to the rotor will increase the produced torque if the same amount of current is applied.

$$T = \frac{3}{2} p \left[\left(L_d - L_q \right) I_d \, I_q + \Phi_{PM} I_d \right] \qquad (3)$$

Magnets, weakening the *q* axis stator flux without effecting the *d* axis one, increase the angular displacement between the space vectors of stator linkage flux and current. This gives rise a torque improvement of about 20÷30 % respect to the SRM without PM and a significant increase on power factor.

The amount of the Ferrite placed in the rotor core is limited by the geometry of the rotor and by the manufacturing cost which is considered as one of the design constraints.

The PM-assisted SRM could become attractive for the following advantages:

- low cost of Ferrite;
- easy to handle;
- high efficiency;
- high power density;
- good power factor (reduction of the inverter rating).

The low cost Ferrite PM could have irreversible demagnetization at cold temperature; the knee point appears at very low temperature (about -30°C). When the EV operates in cold weather, a deterioration of motor performance would occur and this requires an accurate motor design.

The stator winding

The stator winding for this high torque density motor is often realized with "flat wires" (hairpins) as shown in Fig.3. This solution shows significant advantages over stranded conventional design. The use of rectangular slots allows to increase the slot fill factor up to 0.7 to 0.85 (higher with respect to stranded winding and trapezoidal slot). Moreover, the fully automated manufacturing process allows the winding overhead to be reduced. High slot-fill and shorter end-turns reduce the resistance, the Joule losses, the thermal resistance and the temperature rise.

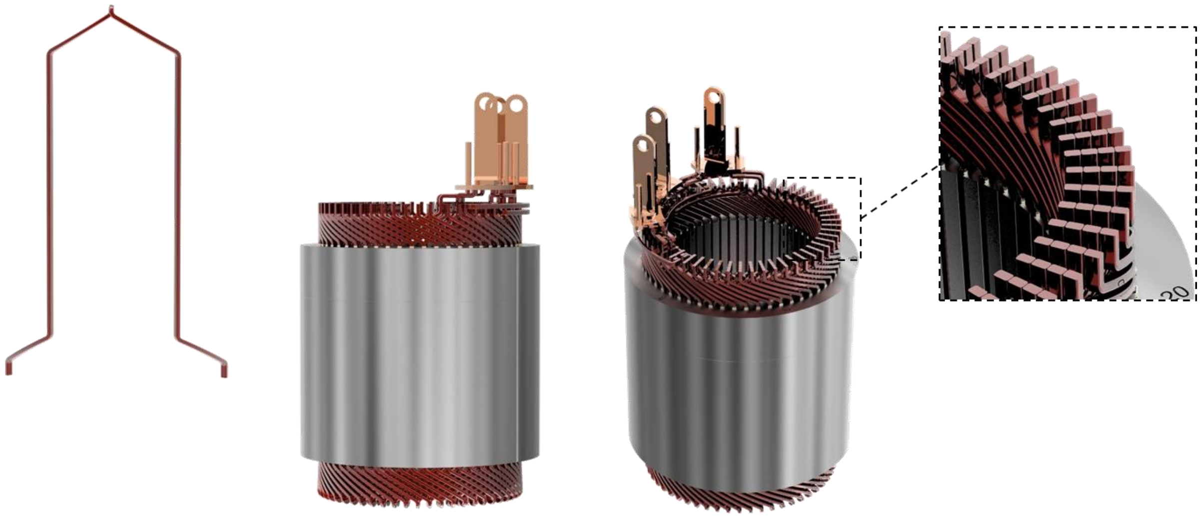

Fig.3 Bar wound stators

The winding bars with a huge cross section area generate additional losses by eddy effects and current displacement. For massive conductors – arranged in stator slots and supplied by an alternating current of higher frequency – three effects superimpose. The *skin effect* describes the current displacement to the conductor edges, caused by an AC current through the conductor itself. If the current displacement results from the alternating field of a second conductor, the effect then is called *proximity effect*. The third cause for current displacement, which is the dominating effect in slotted machines, is the varying *slot stray field*. This magnetic field mostly has a transverse orientation to the current conduction, which is why eddy effects occur in axial and radial direction. Thus, the current inside the conductor is being displaced towards the air gap.

These effects gives rise to significant increase of the phase resistance [5] that, for a separate slot bar with rectangular cross section, can be calculated by the following expressions:

$$R_{AC} = K_R R_{DC} \qquad (4)$$

where R_{DC} is the DC resistance.

$$K_R = \xi \frac{\sinh 2\xi + \sin 2\xi}{\cosh 2\xi - \cos 2\xi} \qquad (5)$$

$$\xi = h_b \sqrt{\frac{\pi \mu f w_b}{\rho w_s}} \qquad (6)$$

where ξ is the "reduced conductor height", h_b the height of massive bar, w_b and w_s are the widths of conductor and slot, f the frequency, μ the permeability and ρ the electrical resistivity of the conductor material.

The AC resistance and with it the displacement losses decrease by:

- a reduced height of the conductor bar in radial direction;
- a lower frequency of the alternating stray field;
- a conductor material with lower permeability;
- a higher resistivity or a lower electrical conductivity of the conductor;
- greater dimensions of the stator slots in tangential direction.

Furthermore, the AC resistance rising can be limited by a proper winding scheme implementation: electromagnetically symmetrical winding leads to a reduction of the displacement currents passing through eventual parallel paths.

The hairpins' extremities are managed and positioned on the basis of our patented technology (Fig. 4 and Fig. 5) in order to reduce the use of jumper conductors to achieve the coils continuity. Whether they are needed, special formed patented jumpers are placed through the overhead and not over it, in order to keep the total winding overhead as short as possible.

US008922078B2

(12) **United States Patent**
Guercioni

(10) **Patent No.: US 8,922,078 B2**
(45) **Date of Patent: Dec. 30, 2014**

(54) **STATOR FOR AN ELECTRIC MACHINE**

(75) Inventor: **Sante Guercioni**, Martinsicuro (IT)

(73) Assignee: **Tecnomatic S.p.A.**, Teramo, Corropoli (IT)

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USPC **310/71**

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CPC H02K 5/225; H02K 3/50; H02K 3/12; H02K 3/28
USPC 310/71
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,039,875 A * 8/1977 Morreale 310/194
5,231,324 A * 7/1993 Kawamura et al. 310/198
6,049,154 A * 4/2000 Asao et al. 310/201
6,285,105 B1 * 9/2001 Asao et al. 310/208
6,459,187 B1 10/2002 Oohashi et al.
6,624,544 B2 * 9/2003 Higashino et al. 310/201
6,661,146 B2 * 12/2003 Oohashi et al. 310/180
6,717,317 B2 * 4/2004 Akita et al. 310/184
6,862,797 B2 * 3/2005 Neet 29/596
6,894,417 B2 * 5/2005 Cai et al. 310/198
7,170,211 B2 * 1/2007 Chen et al. 310/207
(Continued)

FOREIGN PATENT DOCUMENTS

FR 2 841 701 1/2004

OTHER PUBLICATIONS

International Search Report and Written Opinion of the International Searching Authority of Application No. PCT/IT2011/000231, mailed May 25, 2012.

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(57) **ABSTRACT**

A stator for an electric machine includes a stator core having a first and a second face and a circular row of stator slots extended between said faces and which are distributed around a stator axis; and, a winding bar comprising a plurality of basic conductors and a plurality of special conductors interconnected with one another to form the bar winding. The basic conductors each comprise two basic conductor legs and a connecting portion of basic conductor between said legs. The basic conductors are inserted into the stator slots with the free end portions protruding from said second face. The special conductors comprise a jumper of a first type having a first and a second leg of jumpers connected respectively to two of said free end portions, and one jumper connection portion between said legs of jumpers.

8 Claims, 5 Drawing Sheets

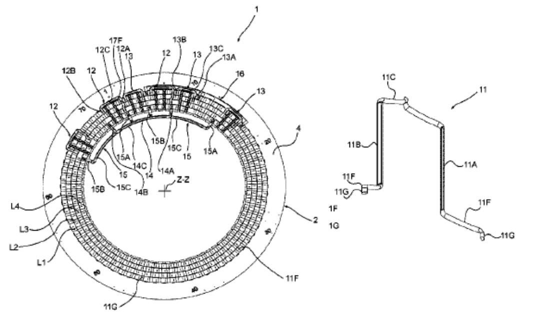

Fig.4 First page of the Tecnomatc's patent

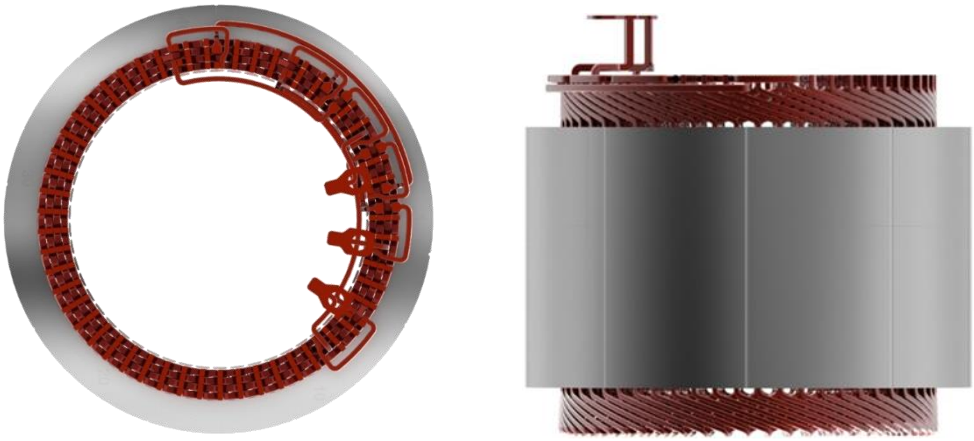

Fig.5 Stator of the PM-assisted Synchronous Reluctance motor

Finally, all the other parts which the wounded stator is composed by (slot liner, epoxy, varnish, etc.) is automatically managed.

Further studies and developments are being carried on regarding a new technology which aim is to achieve a stator winding with reduced or any welding points. This will represent a big step forward by which it will be possible to furtherly reduce the DC resistance (and consequently the AC resistance) and increase the number of flat wires per slot. This new technology will be a fit for many fields in which electric motors are involved in: agricultural, aerospace, maritime and so on.

Design of PM-assisted Synchronous Reluctance Motor

The analysis of the SRMs requires the use of numerical techniques like Finite Element (FE) method to take into account the remarkable saturation phenomena in certain parts of the rotor. The motor is modelled using FE "parametric model" that allows the geometric dimension of motor, the current distribution and rotor position to be varied.

The input data of the FE model are the motor geometry and the *d*-*q* axis currents. By means of an out-of-line procedure, the phase currents can be automatically calculated and assigned to each slot. Then, the motor torque is calculated by Virtual Work principle.

The rotor shape and dimensions of the flux-barriers affect heavily the motor performance and the PM-assisted SRM requires an accurate design in order to fully satisfy the specifications and the constraints on the encumbrance. For this reason a suitable optimization procedure has been used and linked with the Finite Element model [6, 7].

A three-phase PM-assisted SRM is proposed for a 4x4 electric truck for agricultural sector. Particularly, this vehicle has one motor per wheel that is connected by a mechanical gearbox.

For this specific application, a duty cycle has been imposed and in Table 1 are listed the required performance in different operating points and the imposed encumbrances for the installation of the motor. P1 is a hard operating condition of short duration (less than 1 min) while the others points correspond to a continuous duty S1. Moreover, the battery voltage level and the maximum current of the inverter have been fixed. The machine is water cooled with a water jacket around the stator core.

Table 1 – Requirements of the electric motor

P1 short duration	Speed_1 Torque @ speed_1	rpm Nm	1200 300
P2	Speed_2 Torque @ speed_2	rpm Nm	3500 130
P3	Speed_3 Torque @ speed_3	rpm Nm	5000 80
P4	Speed_4 Torque @ speed_4	rpm Nm	7500 50
DC Voltage		V	700
Stack length mm			150
Outer stator diameter mm			240
Cooling			liquid

Fig. 6 presents the cross section of the designed motor with 6 pole, 54 slots and 4 flux barriers per pole with low cost PM in Ferrite (Br=0.40 T, Hc=300 kA/m @ 20°C): the stator presents a distributed flat-wire winding with 4 conductors per slot and the filling factor of about 0.8. The inner stator diameter is 165 mm and the airgap 0.5 mm.

The iron bridges in the rotor core have been carefully sized since they have impact on the motor performance and rotor robustness. Moreover, resin can be inserted in the flux barriers in order to improve the robustness of the rotor structure against the centrifugal forces at high speed.

The performance of the PM-assisted SRM are listed in Table 2 and refer to the motor operation at "maximum torque-ampere ratio". A temperature of 120°C has been imposed for the stator winding and 70°C for the PMs.

The results point out how the proposed design fully satisfies the requirements. The operating points P2, P3 and P4 present an efficiency higher than 94% and a good power factor: in P1 the torque and phase current are higher with respect to the other points but in this case the operating time is very short: however, the efficiency is satisfactory and it is about 88%.

The demagnetization effect has been investigated and verified by means of the FE software, within the whole working range to validate the reliability of the proposed design.

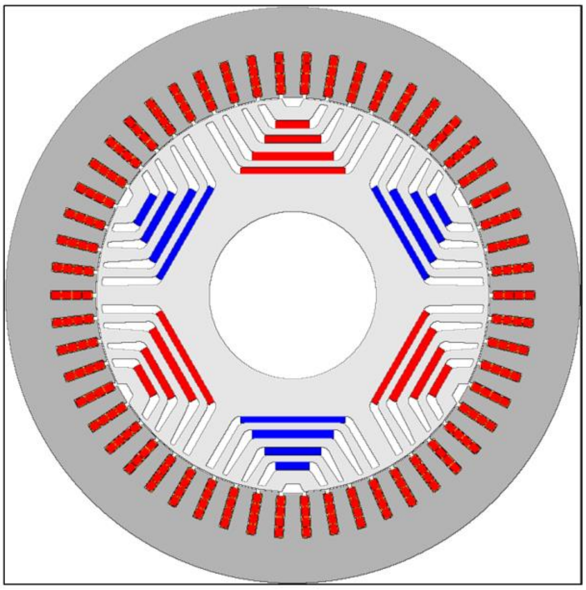

Fig.6 Cross-section of 6 pole-54 slots PM-assisted SRM

Table 2 – Performance of PM-assisted SRM – 6 pole-54 slots

	P1 (*)	**P2**	**P3**	**P4**
Torque Nm	300	136	87	54
Speed rpm	1261	3596	5028	7500
Phase current Arms	207	99.0	81.3	74.2
Output Power kW	39.6	51.2	45.9	42.4
Phase resistance AC mΩ	3.76	4.53	5.35	7.34
Joule losses W	4849	1331	1062	1213
Power factor	0.75	0.81	0.88	0.90
Efficiency %	87.9	95.0	95.1	94.4

(*) short duration

Fig. 7 shows the torque behaviour for the operating point P2 where the ripple (defined like as the ratio between the difference of the maximum and minimum values of the torque and the average one) is about 15% without skewing. Moreover, the efficiency map has been calculated for different speed and Fig.8 points out satisfactory efficiency values.

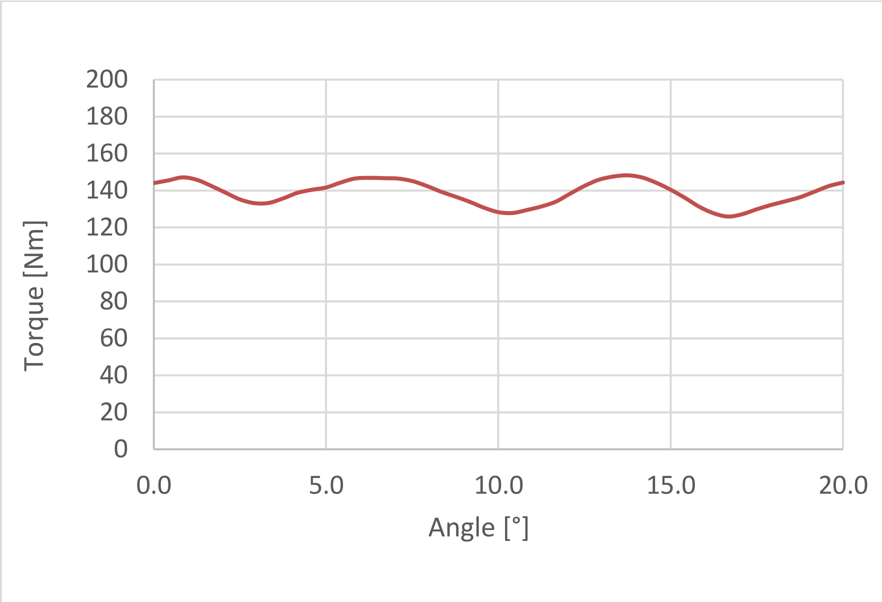

Fig.7 PM-assisted SRM: Torque ripple (point P2)

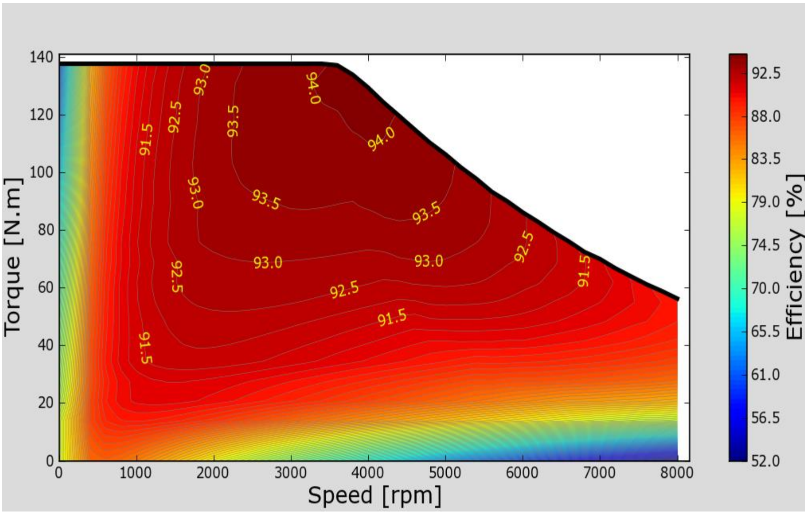

Fig.8 Efficiency map

Conclusions

In the agricultural sector the emission reduction represents an urgent problem. Easy controllable and environment friendly electric vehicles can provide an alternative.

A motor for 4x4 electric truck has been designed: this vehicle has one motor per wheel that is connected by a mechanical gearbox. For this specific application a PM-assisted SRM solution has been proposed that improves the operating performance of the conventional SRM (torque density, power factor) by adding the proper quantity of low cost permanent magnets into the flux barriers of the rotor core.

A duty cycle has been imposed and the motor has been designed by a sizing procedure and optimization algorithm. The proposed design fully satisfies the requirements and the encumbrance: at rated operating conditions, the motor has good efficiency and power factor.

This study points out that the low-cost ferrite PM-assisted SRM can be considered a strong potential for powertrains and an efficient alternative to interior high cost rare earth PM motors and induction motors.

References

[1] I. Boldea, Reluctance Synchronous Machines and Drives, Oxford: Clarendon Press, 1996.

[2] F. Parasiliti, M. Villani, "Magnetic analysis of flux barriers Synchronous Reluctance Motors", XVIII International Conference on Electrical Machines, ICEM 2008, Vilamoura (Portugal), September 2008, DOI: 10.1109/ICELMACH.2008.4800151, E-ISBN: 9781424417360.

[3] F. Parasiliti, M. Villani, S. Tassi, "Dynamic Analysis of Synchronous Reluctance Motor Drive based on Simulink and Finite Element Model", IECON'06, Paris, November 2006, pp.1516-1520. DOI: 10.1109/IECON.2006.347814.

[4] P. Niazi, H. A. Toliyat, Dal-Ho Cheong, Jung-Chul Kim, "A Low-Cost and Efficient Permanent-Magnet-Assisted Synchronous Reluctance Motor Drive", IEEE Transactions on Industry Applications, vol. 43, no. 2, March/April 2007, pp.542-550.

[5] J. Pyrhonen, T.Jokinen and V.Hrabovcova, *Design of Rotating Electrical Machines*, Wiley, ISBN 978-0-470-69516-6.

[6] L. Cirio, S. Lucidi, F. Parasiliti, M. Villani, "A global optimization approach for the synchronous motors design by finite element analysis", International Journal of Applied Electromagnetics and Mechanics, IOS Press, n. 16 (2002), ISSN 1383-5416, pp. 13-27.

[7] S. Lucidi, F. Parasiliti, F. Rinaldi, M. Villani, "Finite Element Based Multi-Objective Design Optimization Procedure of Interior Permanent Magnet Synchronous Motors for Wide Constant-Power Region Operation", IEEE Trans. on Industrial Electronics, vol. 59, p. 2503-2514, ISSN: 0278-0046.

Synchronous Reluctance Motor vs. Permanent Magnet Synchronous Motor Comparative Study for Automotive Applications

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Abstract

The paper presents a comparison between two types of synchronous motors for a low power automotive application (cooling fan drive system). Based on the same requirements and geometrical constraints, a Synchronous Reluctance and a Surface Permanent Magnet Machine are proposed, analyzed and assessed. Due to technological constraints concentrated stator winding configuration is considered. Electromagnetic behavior, torque production and cost are considered for the final comparative assessment.

Introduction

When addressing low power automotive applications which require actuation, there is a tendency to reduce the cost of electric motors. This is the reason why synchronous reluctance motors (SynRM) have been a subject of study and are considered more and more as a viable option when compared to the more traditional permanent magnet synchronous motors (PMSM) [1]. The lack of expensive rare earth elements, inexistent cogging torque and no demagnetization occurring at high temperatures, are the main advantages of SynRM over traditional alternatives. On another hand, they generally have lower power to weight ratio, lower starting torque and a lower power factor [2], which will inevitably lead to an oversizing of the power inverter.

The study proposed in this paper focuses on the comparative analysis and design of SynRM and PMSM. The aim is to highlight the differences, concerning power to weight ratio, overall weight and cost of active materials, as well as their electromagnetic compatibility / electromagnetic interference (EMC/EMI) capabilities, while considering similar output characteristics (300 W) and keeping the outer diameter fixed (installation space constraint). Moreover, key quantities for evaluating the performance of a motor (i.e. average torque and torque ripple) are considered as well.

In the paper also the design and analysis of electric motors for low power automotive applications will be discussed. Even though distributed windings have better performance for both machine topologies [3], concentrated windings is a key requirement when taking the manufacturing costs into account.

After designing and analyzing multiple topologies of SynRM, based on a parametric finite element analysis (FEA), it can be stated that the 4-pole design exhibits the highest torque density due to a rather good saliency ratio [4]. Despite the fact that the PMSM shows better performances with a higher number of poles, the same slot/pole combination will be used (12 slot 4 poles), in order to achieve a fair comparison.

The work also addresses the common and normal mode stray capacitances of the two motor topologies which can have an influence on the whole system EMC/EMI behavior

[5], when implementing a field oriented control (FOC) strategy. Considering the fact that the PMSM has higher power to weight ratio, it is safe to assume that the stator structure, such as tooth width, number of turns, area of the coil, will be different and also the high frequency circuit parameters of each stator will also be different, having higher or smaller impact on the system as a whole.

SynRM and PMSM under study

As stated previously, two machine topologies will be analyzed based on an electromagnetic FEA. Their cross sections are shown in

Figure 1. The same slot/pole combination was used, the only difference being in their working principle. Unlike the SynRM motors, PM motors use high-performance rotor magnets to create a magnetic field which is always present, resulting in higher efficiency and power factor.

SynRM is a motor configuration which uses the variable reluctance concept and rotating sinusoidal magneto motive force (MMF) for torque production. SyRMs have a cost advantage as they do not need rare earth permanent magnets. It tolerates both overheating and overcurrents, because there are no magnets to overheat and demagnetize.

The paper presents a direct comparison between PMSM and SynRM, that only uses concentrated windings in order to investigate the performances of the machines, for low power automotive applications (i.e. up 300 W). Most studies illustrate that the distributed windings exhibit higher performances than the same range of concentrated winding. However, from the manufacturing point of view, a distributed winding topology is more expensive and complicated when compare to a concentrated one. There are various advantages to use concentrated winding in electrical machines, due to the non-overlapping single tooth coils, which reduces the end windings, and in turn, the quantity of needed copper.

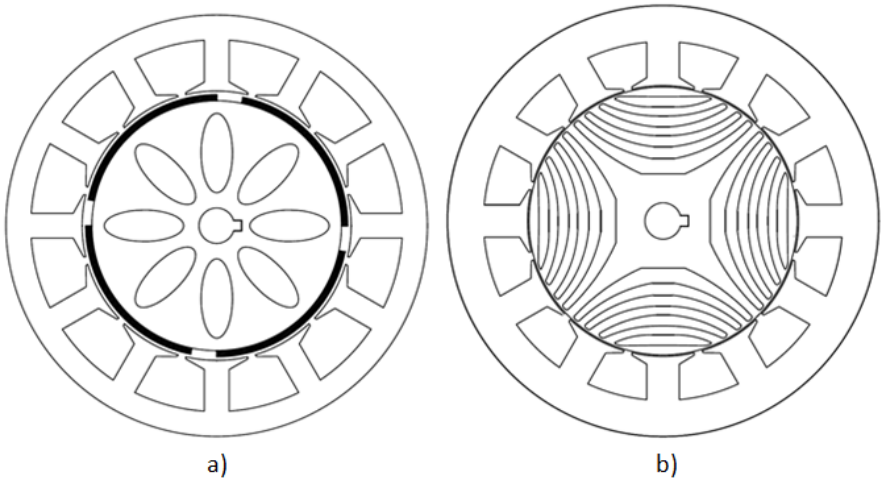


Figure 1 Cross section of the a) PMSM b) SynRM

The stator and rotor parameters of each machine have been optimized to obtain the maximum average torque and the lower torque ripple according to the machine specifications summarized in Table 1.

Table 1 Proposed Machines Specifications

Symbol	Parameter	SPMSM	SynRM
D_{out} [mm]	stator outer diameter	*	*
L [mm]	stack length	13	26
g [mm]	air-gap	1	0.5
V_0 [V]	I. DC bus voltage	13	13
I_{ph} [A]	peak current	25	37
n [rpm]	rated speed	2700	2700
T [N·m]	rated torque	0.845	0.850
PWr [W/kg]	power density	298	177

*Data removed due to privacy/confidentiality requirements

The torque resulting from the FEA analysis is depicted in Figure 2.

Table 2 shows the average as well as the torque ripple percentage generated by both machines.

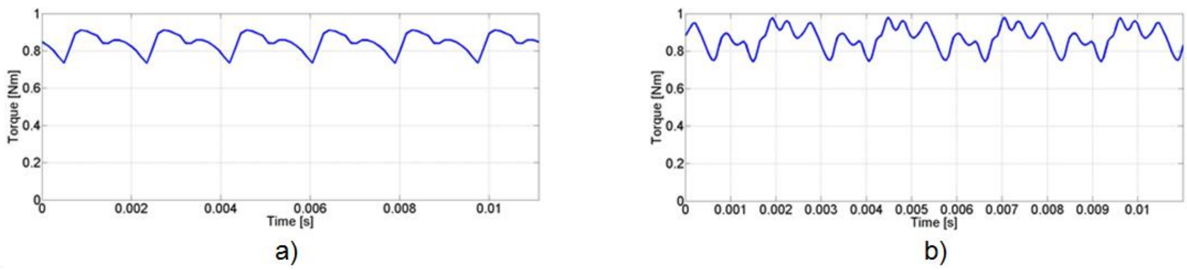


Figure 2 Electromagnetic Torque for a) PMSM b) VRSM

Table 3 Torque value for PMSM and SynRM

	PMSM	SynRM
Avg. torque [N·m]	0.845	0.850
Torque ripple [%]	20	27

Table 4 Weight comparison

	PMSM	**SynRM**
Copper mass [g]	249	400
Stator mass [g]	433	797
Rotor mass [g]	323	492
Magnet mass [g]	31	0
Motor mass [g]	1006	1690

Table 5 Cost comparison

	PMSM	**SynRM**
Copper material cost [€]	1.61	2.86
Stator material cost [€]	0.43	0.79
Rotor material cost [€]	0.32	0.49
Magnet material cost [€]	2.48	0
Motor material cost [€]	4.84	4.14

Table 6 Material price references

Material	**Cost [€/kg]**
Copper material cost [€/kg]	6.5
Steel material cost [€/kg]	1
Magnet material cost [€/kg]	80

EMI/EMC study

In this chapter, the two electric motors designed (PMSM and SynRM) will be evaluated from the transient point of view. In order to achieve this, modeling and simulation of a speed sensored field oriented control (FOC) of the both motors drives was developed by using MATLAB/Simulink. The high frequency circuit of each machine will be attached to this model, to observe the high frequency currents, which flow through the normal and common paths.

Nowadays, vector control and driving strategies gain more and more attention in the way of reduction the harmonics, vibration and energy management. The space vectors of FOC (magnetic flux, current and voltage) are controlled in such a manner that they can handle the rotor mechanical speed, to perform real-time control of torque variations demand and to regulate phase currents in order to avoid current spikes during transient phases [6, 7]. For better performance of the cooling fan, vector control is widely used. The imposed speed of the motors is set by the user or by a higher-level controller, which controls the whole process for reducing the control algorithm and removing the time-varying quantities.

The mathematical equations which describe the mechanical torque are very similar for both machines, the only difference being the lack of magnet flux, φ_a the case of the SynRM. The voltage equation of a PMSM on *d-q* axis components is represented as following:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -\omega L_q \\ \omega L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\varphi_a \end{bmatrix} \quad (1)$$

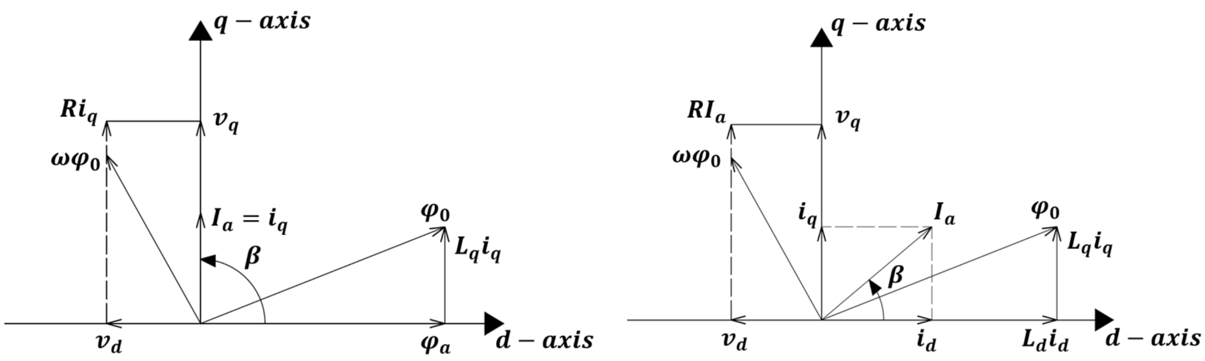
where, $\omega\varphi_a$ is the armature flux linkages generated form the magnets along the *d-q* axis, i_d, i_q the *d* and *q*-axis components of armature current, V_d, V_q are *d* and *q*-axis component of the armature voltage, *R* the armature winding resistance, ω the angular velocity and $p=d/dt$.

The output torque T_e depends on the interlinkage flux φ_a and the difference between *d* and *q*-axis inductances L_d and L_q. The torque produced by a PMSM (2) and the reluctance torque generated by the SynRM (3) can be expressed by:

$$T_e = \frac{3}{2}\frac{p}{2}\left[\left(L_{ds} - L_{qs}\right)i_{qs}\, i_{ds} + i_{qs} + \varphi_a i_{qs}\right] \quad (2)$$

$$T_e = \frac{3}{2}\frac{p}{2}\left[\varphi_a I_a \cos\beta + \frac{1}{2}\left(L_q - L_d\right)I_a^2 sin2\beta\right] \quad (3)$$

where, *p* is the number of pole pair, I_a, the armature current amplitude and β the armature current lead angle from the *q*-axis. It can be notice that the output torque is a function of the electric current phase angle β in (3). The vector diagrams of PMSM and SynRM are shown in Figure 3 Vector diagrams of synchronous motors a) PMSM b) SynRM. In order to achieve the maximum torque per ampere β has an important role for both structures.



a) b)

Figure 3 Vector diagrams of synchronous motors a) PMSM b) SynRM

In Figure 4 the FOC used for determining the voltages is given, which is used for feeding the high frequency circuit, in order to obtain the normal and common mode currents. We can observe the incoming reference speed command profile which goes in the Speed PI Regulator and the q–axis reference current output. The d–axis current reference is set to zero. The $Id*$ and $Iq*$ current references and their corresponding feedbacks are connected to PI regulators. Current PI Regulator generate stator dq–axes voltage references which are then connected to the dq to $\alpha\beta$ block to perform the transformation from a dq rotating reference frame to a $\alpha\beta$ stationary reference frame. The stationary voltage references are imputed in the space vector PWM generator where the signals are converted to the abc frame based duty cycle equivalences.

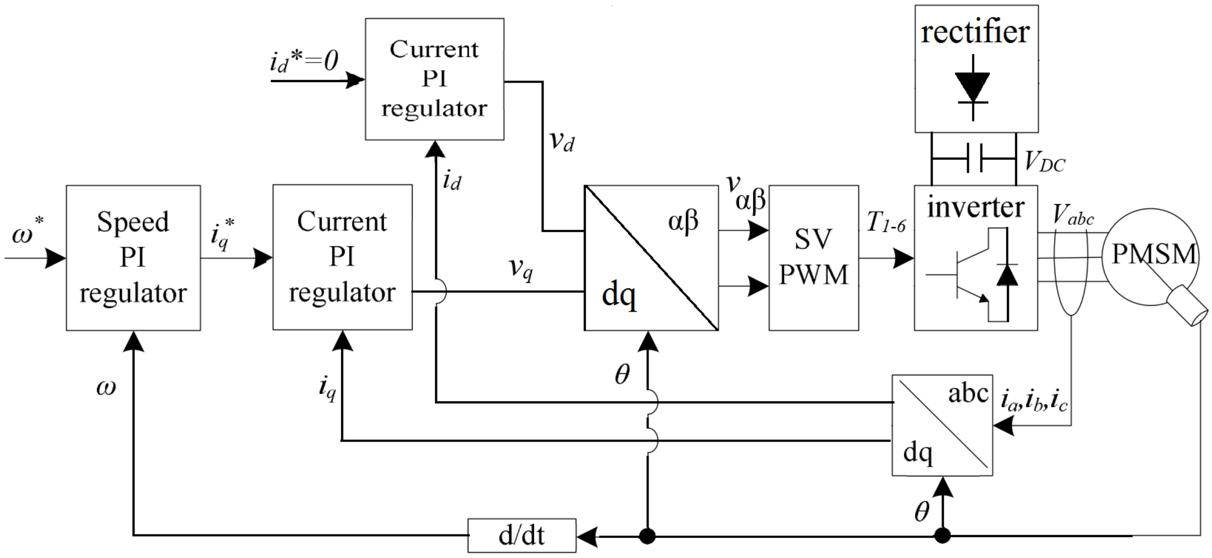


Figure 4 Structure diagram of the PMSM based FOC

The vd, vq, id, iq are the stator d and q–axes voltages and currents in the rotor reference frame, ω is the rotor angular electrical velocity, I_{abc} are the three sinusoidal current phase, V_{DC} is the DC bus continues voltage and θ is the angular position of the rotating frame [8].

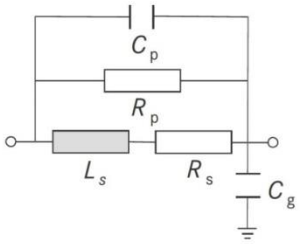


Figure 5 High frequency circuit for electric motor

Both FOC algorithms were developed starting from the same theory. The models were developed using MATLAB/Simulink and the influences of magnetic field saturation and magnetic hysteresis was omitted. The SynRM FOC refers to controlling the stator currents vector [9, 10]. In this case, two machine constants are needed as input references: the torque and flux components.

$$T_e = \frac{3}{2} p(\lambda_d i_q - \lambda_q i_d) \tag{4}$$

By using FOC strategy, the rated flux will align in phase with the d axis, so $\lambda_q = 0$, leading to simplification of the equation 5.

$$T_e = \frac{3}{2} p \lambda_d i_q \tag{5}$$

When talking about the EMI capabilities of the motors in question, the normal and common mode currents need to be taken into account. These currents, are generated due to parasitic capacitances which in turn create disturbing currents flowing through both common-mode and normal mode paths. There are two capacitances which need to be identified: ground capacitance and coil to coil capacitance. Figure 5 shows the high frequency circuit used for calculating the currents mentioned earlier, where R_s represents the phase resistance, R_p, the resistance modeling the eddy current losses, L_s, the phase inductance, C_p, the coil own capacitance and C_g the motor to ground capacitance [11, 12]. This high frequency circuit was implemented in MATLAB-Simulink and uses the voltage coming from the power inverter used for the speed control (FOC) as input. In order to identify these parameters, a 3D model of the motor was created (Figure 55).

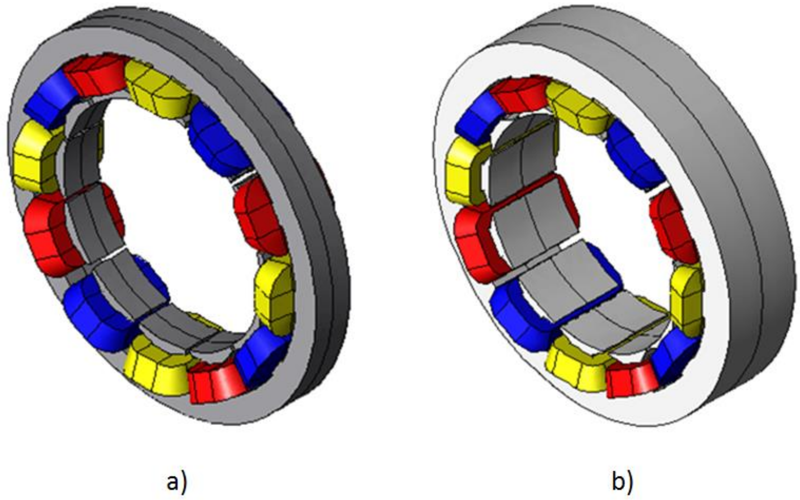


Figure 6 3D model of a) PMSM b) SynRM

Figure 7 show the speed characteristic of both motors and we can see a small delay in reaching the rated speed, because of the added weight of the rotor in the case of the SynRM. The current profile for both machines can be seen in **Figure 8**.

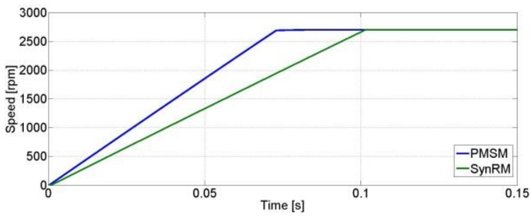


Figure 7 Speed characteristic

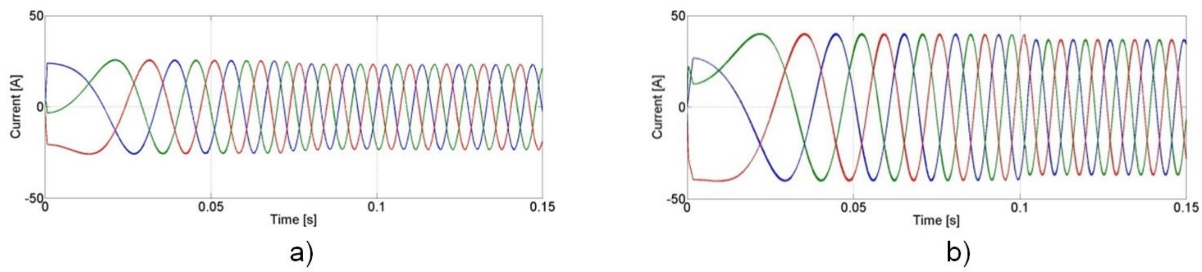


Figure 8 Starting current profile for a) PMSM b) SynRM

The normal (**Figure 9**) and common (**Figure 10**) mode currents have lower values in the case on the PMSM, because of the smaller area where the coils from different phases come into contact, due to the reduced length of the motor. We can also observe, that, the use of concentrated windings has a great impact on the capacitance between coils, for both motor topologies (**Table 7**), reducing the value 10 fold, when comparing it to the stator to ground capacitance. This reduces the current flowing through the normal path, by a factor of 10.

Table 7 Capacitance Values

	PMSM	**VRSM**
Normal mode capacitance C_p	$1.07 \cdot 10^{-13}$ F	$5.85 \cdot 10^{-13}$ F
Common mode capacitance C_g	$7.27 \cdot 10^{-12}$ F	$8.16 \cdot 10^{-12}$ F

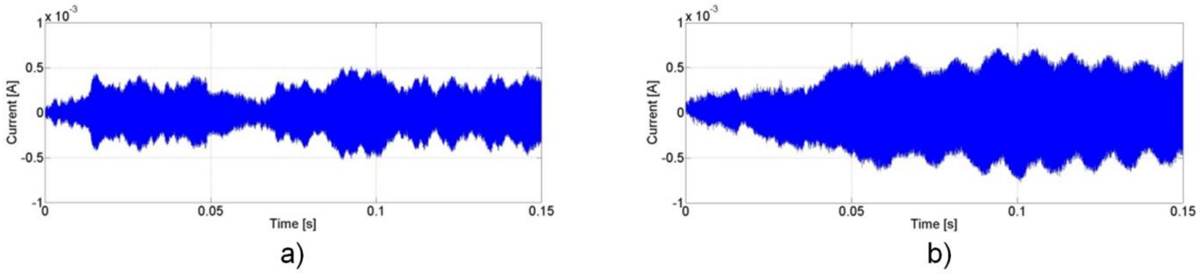


Figure 9 Normal mode current profile for a) PMSM b) SynRM

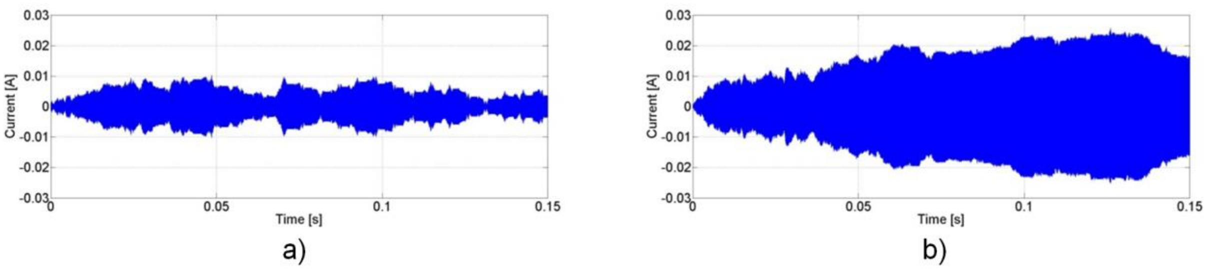


Figure 10 Common mode current profile for a) PMSM b) SynRM

The normal and common mode currents given in percentage of the peak value, can be seen in Table 8.

Table 8 Normal and Common mode current percentage

	PMSM	**VRSM**
Normal mode current (%)	0.002	0.0018
Common mode current (%)	0.04	0.06

Conclusions

The aim of this paper was to design two motor topologies, a PMSM and a SynRM, with similar output power (300 W), torque (0.84 N·m) and rated speed (2700 rpm) and using the same slot/pole combination in order to achieve a fair comparison. The active material cost, was obviously lower in the case of the SynRM because no permanent magnet material was needed for the rotor, even though, in order to achieve the rated parameters, the stack length is doubled and the peak current is 33% higher in comparison with the PMSM. The added weight of the rotor for the SynRM causes the rated speed to be reached with a delay of 0.0285 s, at rated torque load. The use of concentrated windings presents an advantage from the EMI/EMC point of view which allows limited overlapping of windings, producing very low currents in the normal and common mode paths.

When talking about low power automotive applications, the SynRM is a powerful candidate to replace the more commonly used PMSM. Even though it presents similar characteristics to, the stack length will always need to be higher, in order to produce the same torque. This limits its applicability because of space constraint requirements of such applications. The PMSM remains the strongest candidate, even though the cost of active materials in higher, having the manufacturing tools and procedures already in place.

Acknowledgment

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References

[1] Murakami, Hiroshi, et al. "The performance comparison of SPMSM, IPMSM and SynRM in use as air-conditioning compressor." *Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE*. Vol. 2. IEEE, 1999.

[2] Bianchi, Nicola. "Synchronous Reluctance and PM Assisted Reluctance Motors." *The Rediscovery of Synchronous Reluctance and Ferrite Permanent Magnet Motors*. Springer International Publishing, 2016. 27-57.

[3] Spargo, C. M., B. C. Mecrow, and J. D. Widmer. "Application of fractional slot concentrated windings to synchronous reluctance machines." *Electric Machines & Drives Conference (IEMDC), 2013 IEEE International*. IEEE, 2013.

[4] Pop, F. P., et al. "Design and analysis of slot-pole combination for synchronous reluctance machine with concentrated windings for automotive applications." *Electrical and Power Engineering (EPE), 2016 International Conference and Exposition on*. IEEE, 2016.

[5] K. Gulez, et al. "High-frequency common-mode modeling of permanent magnet synchronous motors," IEEE Transactions on Electromagnetic Compatibility, vol. 50, no. 2, pp. 423-426, 2008.

[6] Harib, Khalifa H., Emad Abu Khousa, and Abdulla Ismail. "Field oriented motion control of a 3-phase permanent magnet synchronous motor." *Electric Power and Energy Conversion Systems (EPECS), 2011 2nd International Conference on*. IEEE, 2011.

[7] Brejl, Milan, and Michal Princ. "Using the PMSM vector control ETPU function." *Application Note, Rev. 1* (2006).

[8] Pillay, Pragasen, and Ramu Krishnan. "Modeling, simulation, and analysis of permanent-magnet motor drives. I. The permanent-magnet synchronous motor drive." *IEEE Transactions on industry applications* 25.2 (1989): 265-273.

[9] Toliyat, Hamid A., Ruhe Shi, and Huangsheng Xu. "A DSP-based vector control of five-phase synchronous reluctance motor." *Industry Applications Conference, 2000. Conference Record of the 2000 IEEE*. Vol. 3. IEEE, 2000.

[10] Matsuo, Takayoshi, and T. A. Lipo. "Current sensorless field oriented control of synchronous reluctance motor." *Industry Applications Society Annual Meeting, 1993., Conference Record of the 1993 IEEE*. IEEE, 1993.

[11] Marţiş R., Siecoban R., Marţiş C., Szabó L.: *Common and Normal Mode Currents in PMSM PWM Drives*, Proceedings of the 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM '2016), Capri (Italy), pp. 500-504, 2016.

[12] Marţiş R., Siecoban R., Marţiş C., Szabó L.: *Vibro-Acoustic Behavior vs. Conductive Interferences in PMSM drives*, Proceedings of the 2016 International Conference and Exposition on Electrical and Power Engineering (EPE '2016), Iaşi (Romania), 2016.

Software Tool for Fast and Optimized Design of Three-Phase Stator Windings of Induction Motors

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Abstract

In this paper, an overview of the electric motor market and repair/rewinding services is presented, and the latest version of an innovative user-friendly software tool for (re)design of motor stator windings is described in detail. Its main advantages are pointed out and some application examples are presented. It can be used in technical courses on industrial motor maintenance/rewinding/repair (didactic purposes) and by the technicians and engineers dealing with motor rewinding/repair/design activities (professional purposes), being an excellent tool to, in a fast and accurate way, improve/optimize the original design of the motors. In the optimization process, it can be taking into account that, in general, handmade rewinding task has less design limitations/restrictions than those associated with automatic large-scale motor winding processes used by manufacturers. The unique automatic tool for simultaneous optimization of the coil pitch and number of turns provides the user with the best combined solution, which may allow improving the original winding design of motors of all efficiency classes, including IE4 class. If the automatic design features are used, this software tool reduces significantly the time associated with the required calculations to evaluate the impact of different design options. Moreover, it facilitates the stator winding technical information/data exchange and organization/standardization, promoting an easier and error-free data exchange between the professionals dealing with motor repair/rewinding tasks.

Introduction

World industrial electric motor market is moving toward IE4 and IE5 efficiency classes, and the European Union is strongly contributing to that trend (Fig. 1) [1-5]. New three-phase motor technologies are being developed and introduced in the market, such as line-start synchronous motors (Fig. 2) [2]. Nevertheless, the three-phase squirrel-cage induction motor (SCIM) still dominates the line-operated motor market for fixed-speed applications, being available from IE1 to IE4 classes.

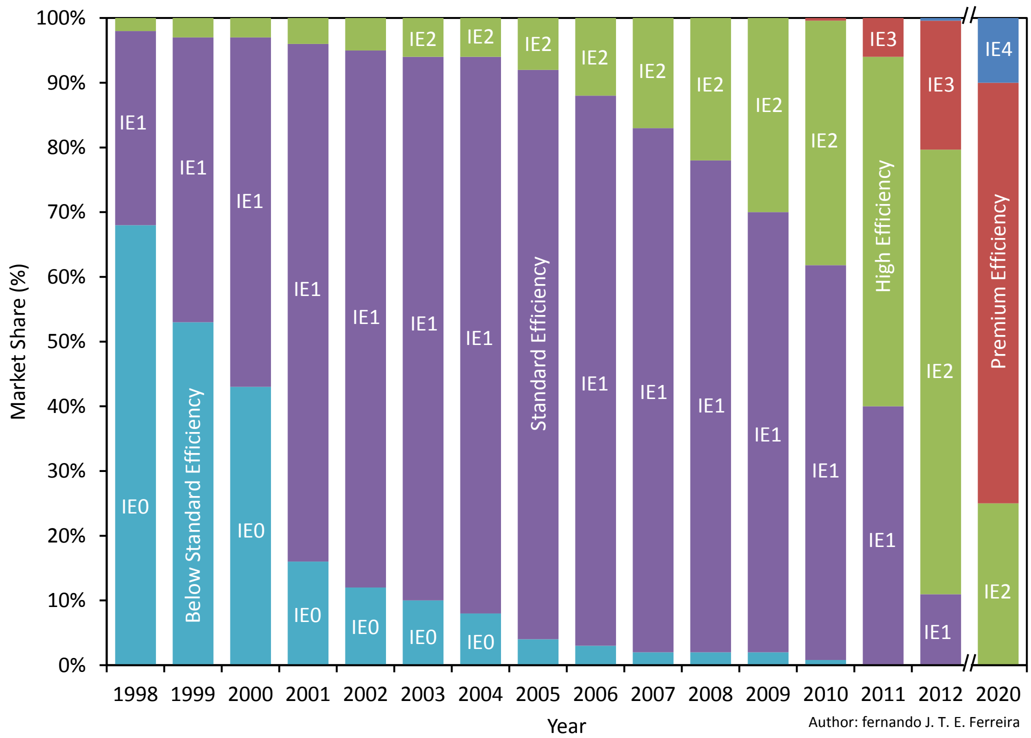


Fig. 1. Low-voltage motor market share evolution and 2020 forecast for E.U., 0.75-375 kW power range [1-5].

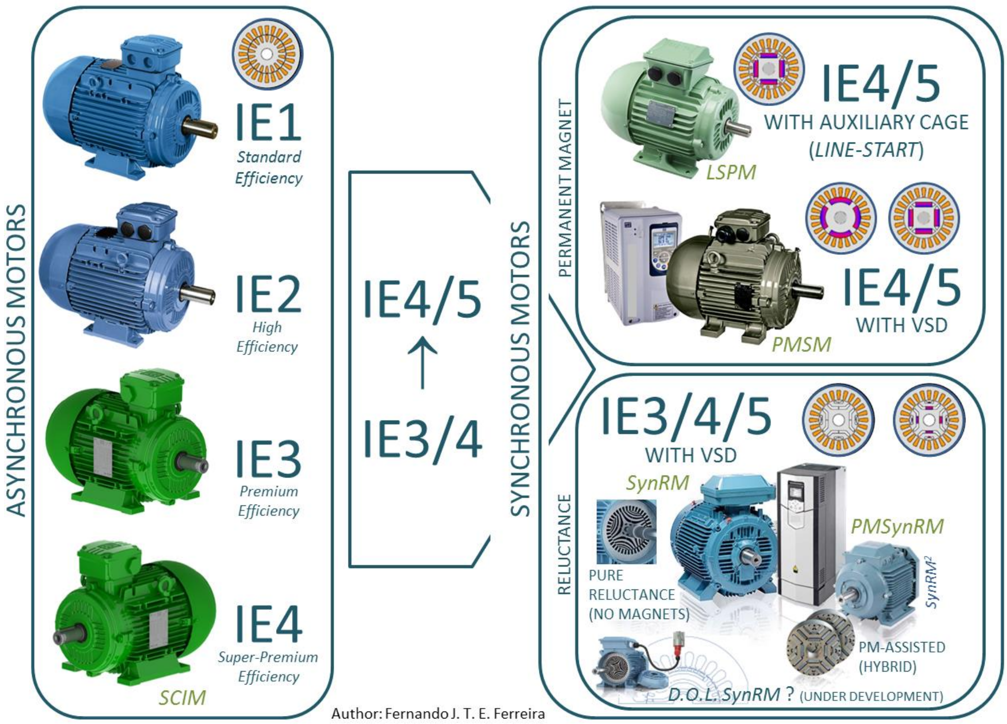


Fig. 2. Overview of the three-phase motor technologies available in the market and/or under development [6].

In Fig. 3, the percent nominal efficiency and the nominal efficiency gain in percentage points (p.p.) when moving to the higher efficiency class are shown. The lower the motor rated power is, the higher the efficiency gain will be.

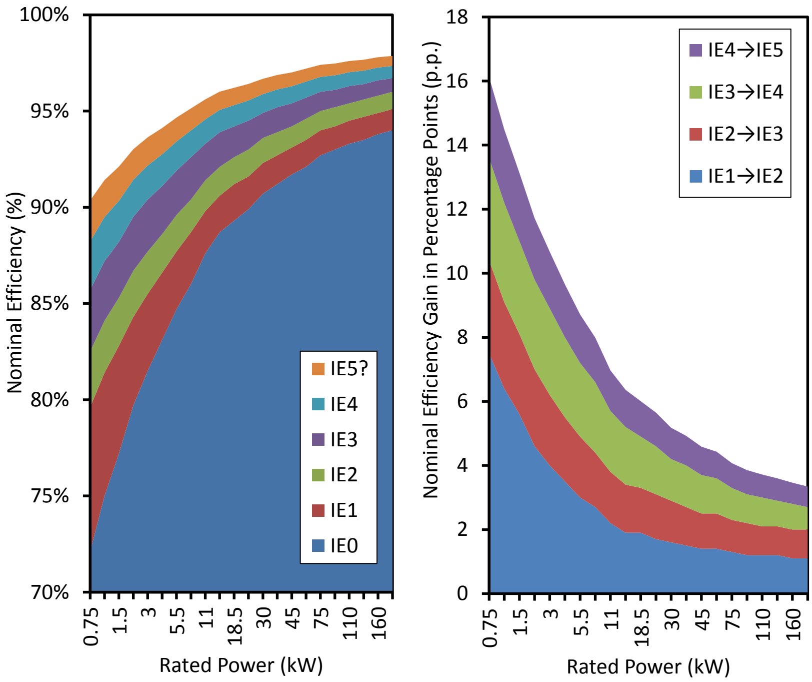


Fig. 3. Motor efficiency classes defined by IEC60034-30-1 standard for 4-pole, 50-Hz, single-speed motors in the 0.75-200 kW power range: (left) nominal efficiency limits; (right) nominal efficiency gain [2, 7, 8].

Typically, it is assumed that SCIMs have a useful lifetime of 12 to 20 years. However, SCIMs older than 40 years can be easily found in the industrial sector (Fig. 4). On average, the motor load factor is 50-60%, but motors with a load factor lower than 20-30% are quite common in the industrial sector (Fig. 5).

Fig. 4. Data on SCIM actual age in the industrial sector, Switzerland, 2013 (4142 data points) [9].

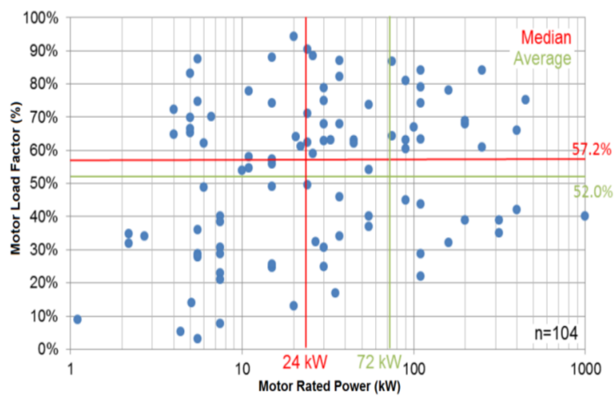


Fig. 5. Data on SCIM actual age and load factor in the industrial sector, 2013 (104 data points) [9].

Typically, SCIMs over 4 kW are rewound 2 to 4 times during their useful lifetime [10]. In most cases, a copy of the original winding configuration is made, which is the recommended option if (i) the motor is well sized to the actual maximum load over the entire operating cycle, (ii) the technical knowledge of the technicians performing the rewinding is limited, and/or (iii) the winding configuration has not been incorrectly changed in previous repair/rewinding services [10].

In Figs. 6 and 7, motor list prices from one of the largest motor manufacturers and the repair prices offered by a typical European repair shop, in EUR/kW, are presented. The most significant motor price jump occurs when changing from induction to permanent magnet motor technology. Typically, the repair price is independent of the motor class but depends on the pole number. Therefore, for 4-pole motors, the percent repair price varies from 20 to 40%, decreasing with the efficiency class due to the price increase (Fig. 8). The motor repair service cost is mainly related to the manpower, energy, cooper, resin and bearings cost. But, regarding the copper, in most cases repair shops attenuate the new cooper cost by selling the old used windings copper. This explains the independency of this cost on the motor efficiency class. For new IE3- or IE4-class motors, there is room for an increase in the repair price without losing the cost-effectiveness of the service. If the repair price is maintained, the repair services become more competitive as the motors move to higher efficiency classes. An interesting fact is that the repair cost as a percentage of the new motor price decreases from 2- to 4-pole SCIM because the repair price is the same for these two different models and the price of the new motor increases from 2- to 4-pole motors.

In Fig. 9, the average nominal efficiency and variation in respect to the immediately lower efficiency class can be seen for the 5.5-160 kW power range, 2- and 4-pole motors, using the datasheet efficiency values from a single motor manufacturer. The average nominal efficiency gain is between 1.3% and 2.0%.

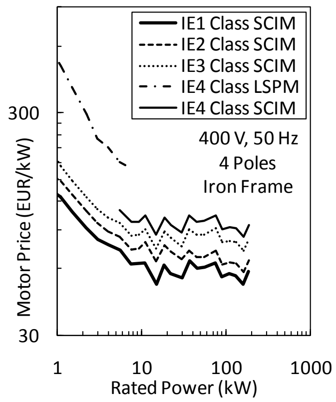


Fig. 6. List prices in EUR and EUR/kW for commercial motors of different efficiency classes (from the same manufacturer).

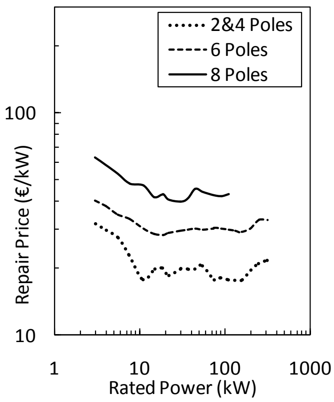


Fig. 7. SCIM repair prices per kW in a typical European repair shop including stator rewinding, standard bearing replacement, rotor dynamic calibration, painting and basic quality control tests.

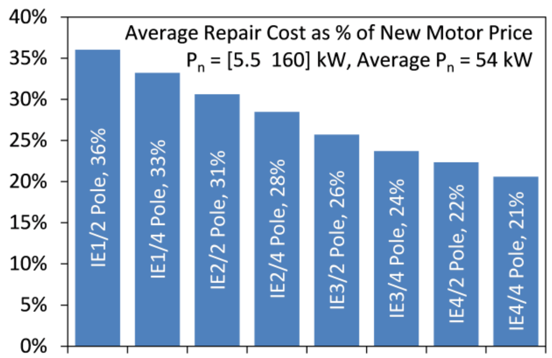


Fig. 8. Average repair cost as a percentage of new motor price.

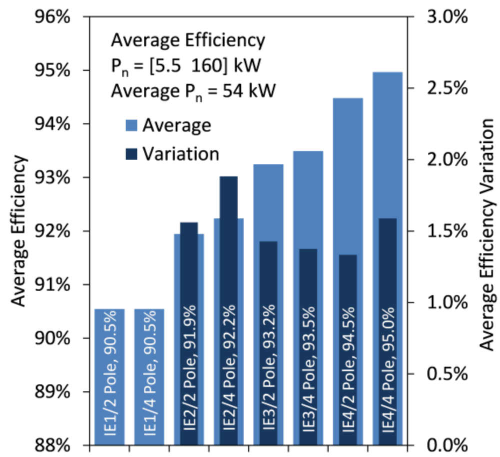


Fig. 9. Average nominal efficiency and the percent efficiency increase in relation to the efficiency class immediately lower, for the 5.5-160 kW power range.

In Fig. 10, the average payback time for different scenarios is shown, for 4-pole IE1/2/3/4-class motors in the 5.5-160 kW power range, neglecting the possible operating point change (or speed change). Since the payback time to recover the extra cost of the new motor is higher than 3 years in most cases, the repair is an interesting low-cost option for all efficiency classes.

It should be referred that motor repair shops have two significant advantages. Firstly, they perform most of the work manually, not having the large-scale production equipment limitations, particularly concerning the stator winding insertion into the stator core slots, allowing the implementation of more complex winding configurations such as the short-pitched double-layer imbricated windings. Secondly, in most cases, they receive the motor with the damaged winding, having the opportunity to sell the copper for recycling. That is why, independently on the motor efficiency class, they can keep the price of the rewinding service more or less constant. Of course, in the case of the bearings, they should follow the manufacturer specifications and these components are typically more expensive in the premium and super-premium motors.

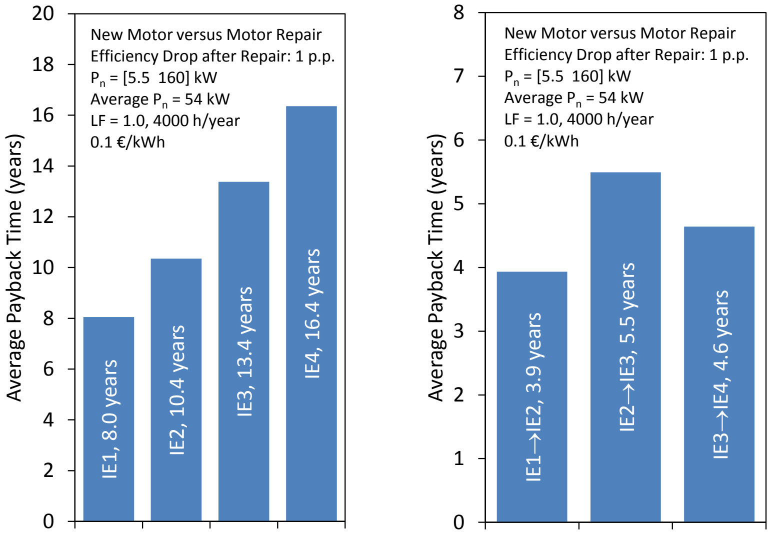


Fig. 10. New motor vs. motor repair average payback time for the 5.5-160 kW power range, considering: (left) the same motor efficiency class; (right) the new motor with a higher efficiency class.

There are several customized aspects that can be specified to the motor manufacturer when potential operating issues can be predicted. However, most of the motor operation problems are identified after buying, during installation, running and after failure. Examples of problems identified after the motor failure are bearing current activity, unbalanced winding overheating or single-phasing, voltage surges/transients and partial-discharge occurrence. During the repair service, the motor can be upgraded and/or equipped with extra components to increase its reliability and efficiency.

For VSD-fed motors, examples of possible improvements during motor repair/rewinding are:

- Installation of a partial faraday shield in the slot openings to reduce the electrostatic coupling between the windings and the rotor;
- Installation of shaft-ground brushes to deviate common-mode currents form the bearings;
- Reinforcement of the winding insulation in the first coil(s) of each phase, including the use of inverter grade magnetic/enameled wire with extra layers and special enamel compounds;
- Upgrade of the insulation system class to accommodate the additional harmonic losses due to the PWM voltage supply;

- Redesign of the stator winding for star connection at rated voltage to avoid homopolar circulating currents in the delta loop.

For line-operated SCIMs, examples of possible improvements during motor repair/rewinding are:

- Reduction of the average length of the end-windings (or coil heads), which does not contribute for the torque production, only contributing the increase of the stator Joule losses, stator winding resistance, leakage reactance and amount of copper used;
- Increase of the slot fill factor, leading to the reduction of the winding resistance and Joule losses, as well as to the improvement of the heat dissipation;
- Potting of the winding heads with thermal conductive polymers/resins to improve heat dissipation. At full-load, a decrease of 22% in the average coil temperature can be obtained or, alternatively, an increase of 16% is possible in the output power at original nominal temperature;
- Replacement of the conventional general purpose bidirectional fans with more efficient unidirectional fans if the motor operates in a single direction (which is typical in fan and pumps);
- Replacement of the existing bearings by low-friction bearings (20 to 30% lower friction losses);
- Upgrade of the insulation system class to extend motor winding lifetime.

Since the largest loss share is associated with the Joule losses in the stator winding (Fig. 11), the improvement of the stator winding by means of an optimized redesign is an excellent opportunity for the motor user to benefit from a significant efficiency gain in the motor when a repair/rewinding service is required, taking advantage from the fact that, in general, handmade rewinding task has less design limitation/restrictions than those associated with automatic large-scale motor winding processes used by manufacturers. The optimizations can involve shortening the winding head length, increasing the slot fill factor, reducing the space harmonic content of the magnetomotive force (MMF), and/or adapting the fundamental flux to the motor actual load. The latter possibility (optimized rewinding [11, 12]), may allow converting a strongly oversized IE1-class SCIM into a well-sized IE5-class SCIM, as shown in Fig. 12, and, at the same time, improving significantly the power factor.

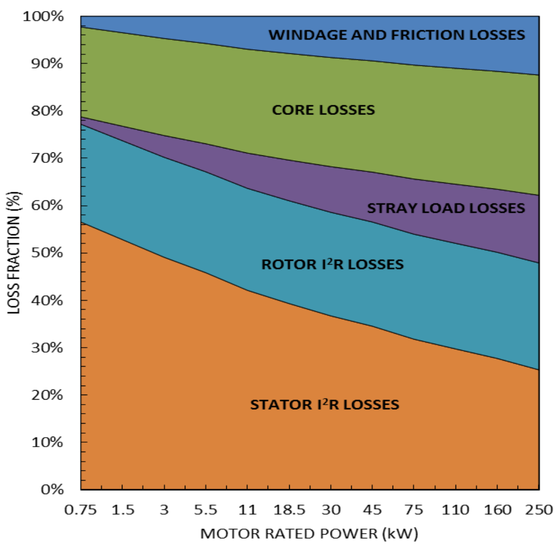


Fig. 11. Typical SCIM loss fraction as a function of the motor rated power [13].

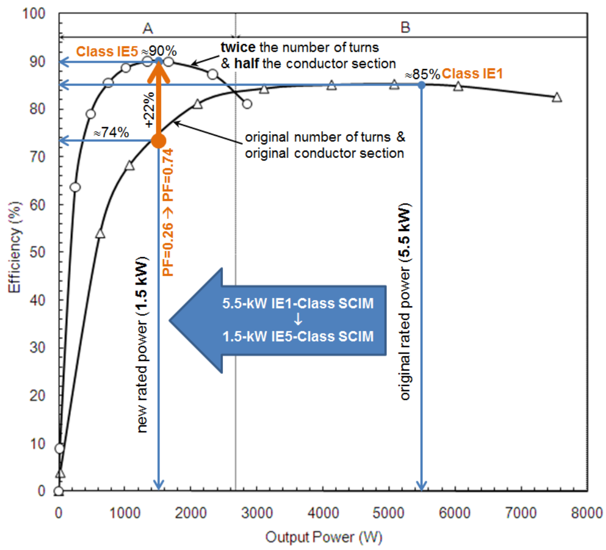


Fig. 12. Converting a strongly oversized IE1-class SCIM into a well-sized IE5-class SCIM, by means of adapting the fundamental magnetizing flux.

Software for Motor Winding Design

In order to facilitate the (re)design process of the motor stator windings and to help repairers/rewinders improving the motor efficiency, a software tool was developed in 2004, named BobiSoft [14]. This software tool is very easy to use and integrates a unique computing algorithm that simplifies the original winding improvement or change process (Fig. 13). It helps the user to quickly, easily and accurately design an optimized motor winding, computing key stator winding parameters such as MMF space harmonics and total distortion, wire length, copper weight, electric resistance, Joule losses, magnetic flux, current density, slot fill factor, etc.

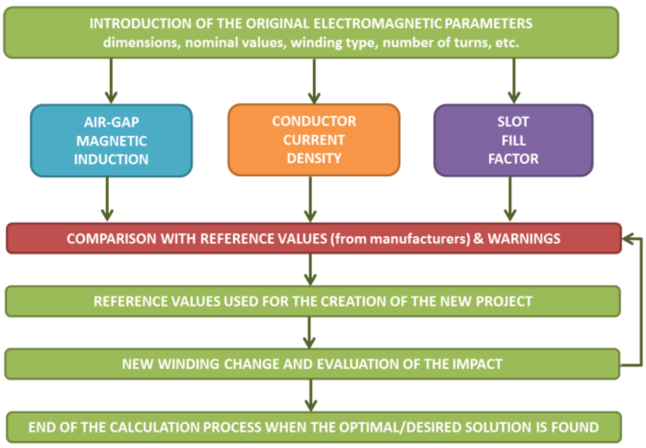


Fig. 13. Computing algorithm to improve or change the original winding design.

Basically, the user has to fill-up the original mechanical and electrical parameters of the motor (Fig. 14 and 15) and, after that, it will be able to change the original winding and check for the improvements in the Joule losses and spatial harmonic distortion of the air-gap MMF. After concluding the new design, the user can print the graphical (circular and planar) or numerical schemes of the coils (Fig. 16 and 17), which can then be printed out and used to help positioning correctly the coils in the stator. Key electrical and magnetic data is computed and presented immediately for both the original and new windings (Fig.

18). A section for additional information on the rewinding/repair service is also offered, in which some quality control information and photos can be saved (Fig. 19).

Design procedures that take hours can be done within a few minutes. Moreover, there is a section for the core loss test that performs all the required calculations. Each project/design can be saved as a separate file (*.bob), which can be attached to e-mails, facilitating the stator winding technical information/data exchange and organization/standardization, promoting an easier and error-free data exchange between the professionals dealing with motor repair/rewinding tasks. The automatic reports are an excellent way to show to the clients of repair shops what was actually done in the service and to demonstrate the quality of the provided service.

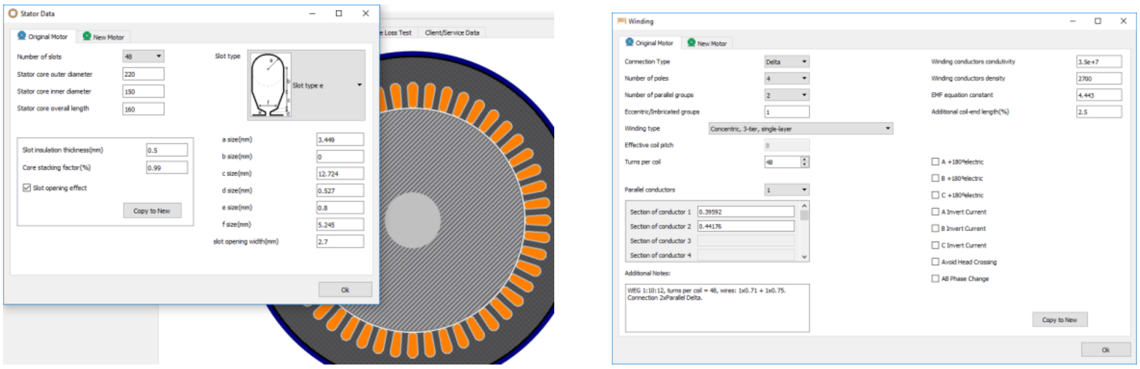


Fig. 14. Section to insert the stator data of the original and new motor/winding.

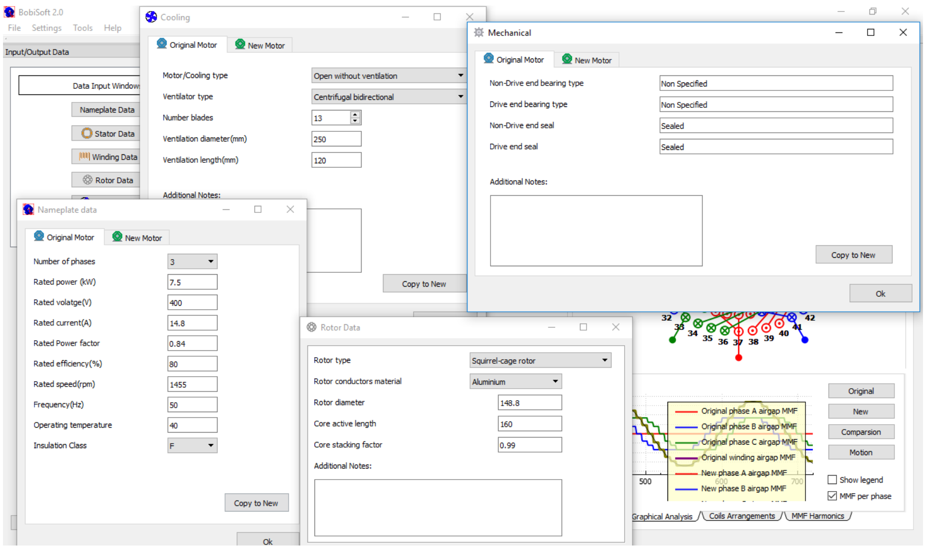


Fig. 15. Section to insert nameplate and mechanical data of the original and new motor.

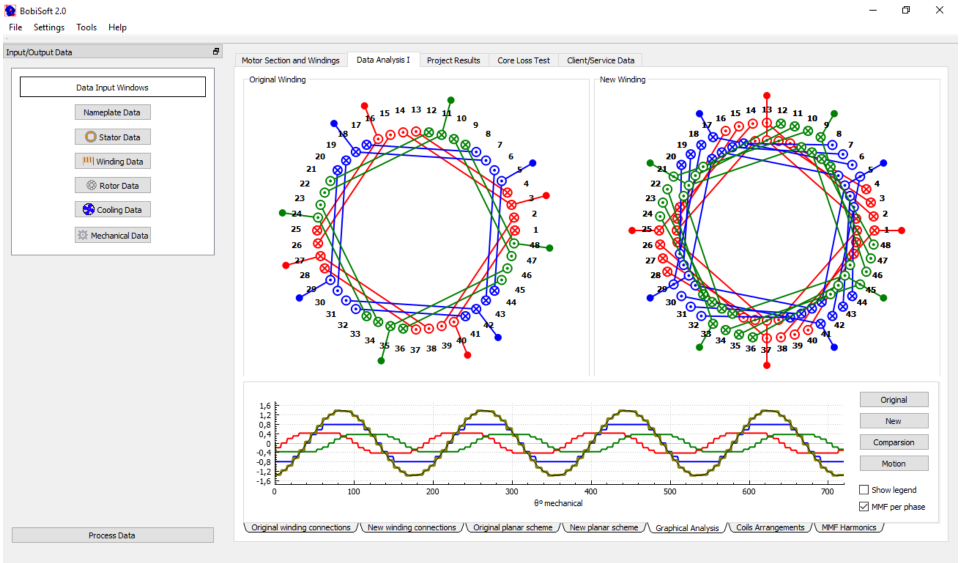


Fig. 16. Circular representation of the windings and of the MMF waveform.

BobiSoft 2.0 can handle windings for stator cores with up to 180 slots and offers 9 different automatically-generated winding types (Fig. 20), 6 single-layer and 3 double-layer windings, as well as fully-editable single- and double-layer windings, where the user is able to define the position and number of turns of each coil in each phase. It also allows designing two-phase windings for single-phase motors, as well as converting three-phase to two-phase windings and vice-versa.

This new version of BobiSoft offers extra and improved functionalities, namely, new and simpler user interface, 2D graphical representation of the stator core section, improved winding schemes/diagrams (circular scheme has the orientation of the coil and planar scheme has the number of winding parallel groups along with their connection to the motor terminals and the heads are fully represented), improved design of the MMF in the airgap and free winding editor (where the user can customize the winding design, with variable number of turns per coil; fractional windings can also be implemented).

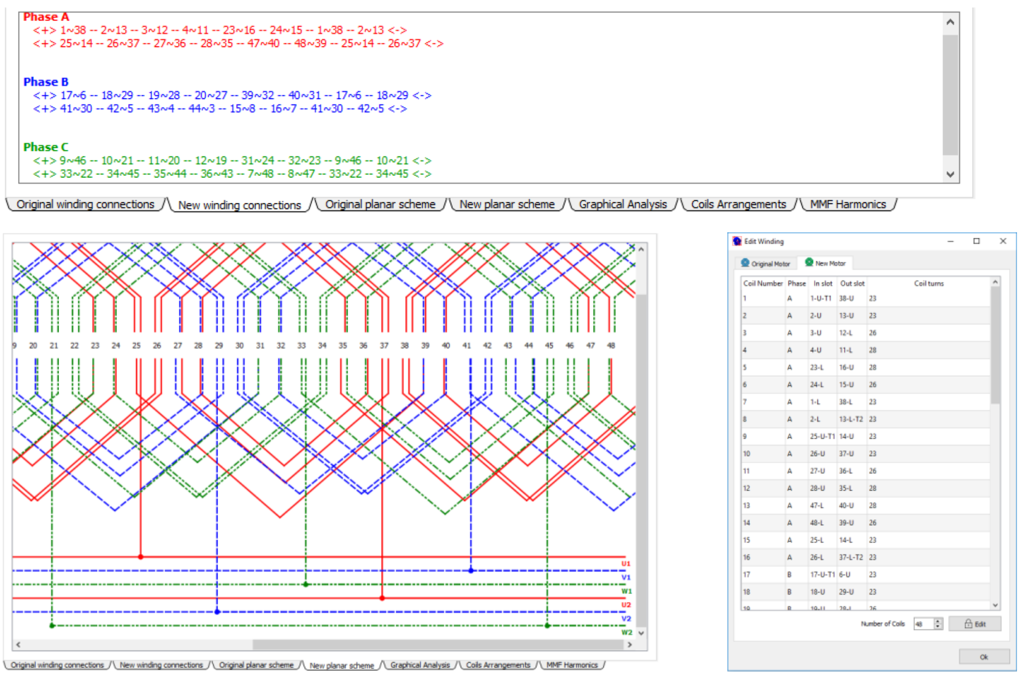


Fig. 17. Numerical and planar representation of the windings and coils.

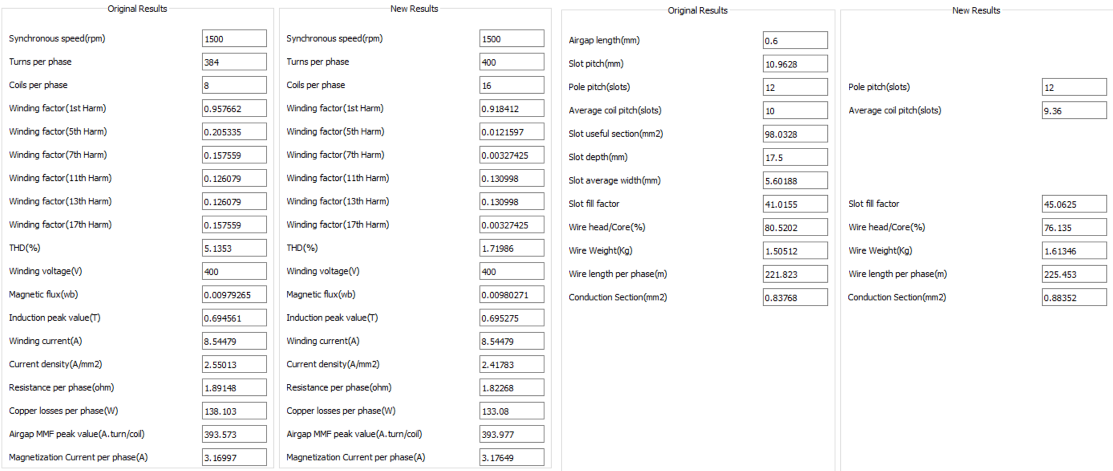


Fig. 18. Display of the computed data associated with the original and new winding.

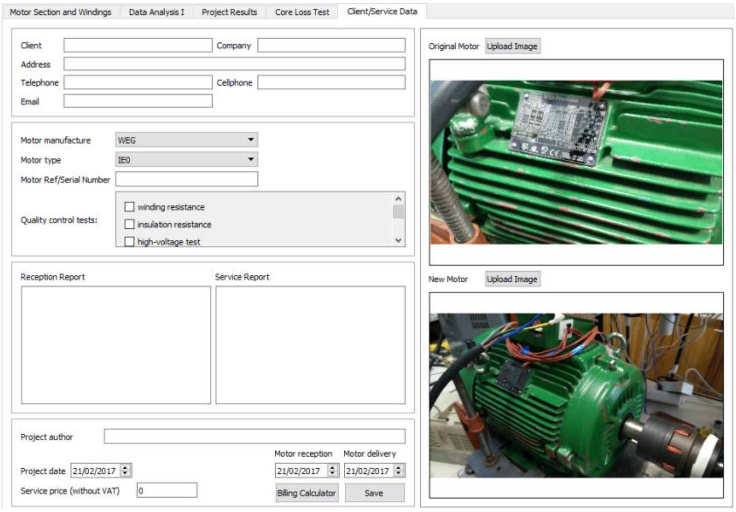


Fig. 19. Section to insert additional information photos associated with the repair/rewinding service.

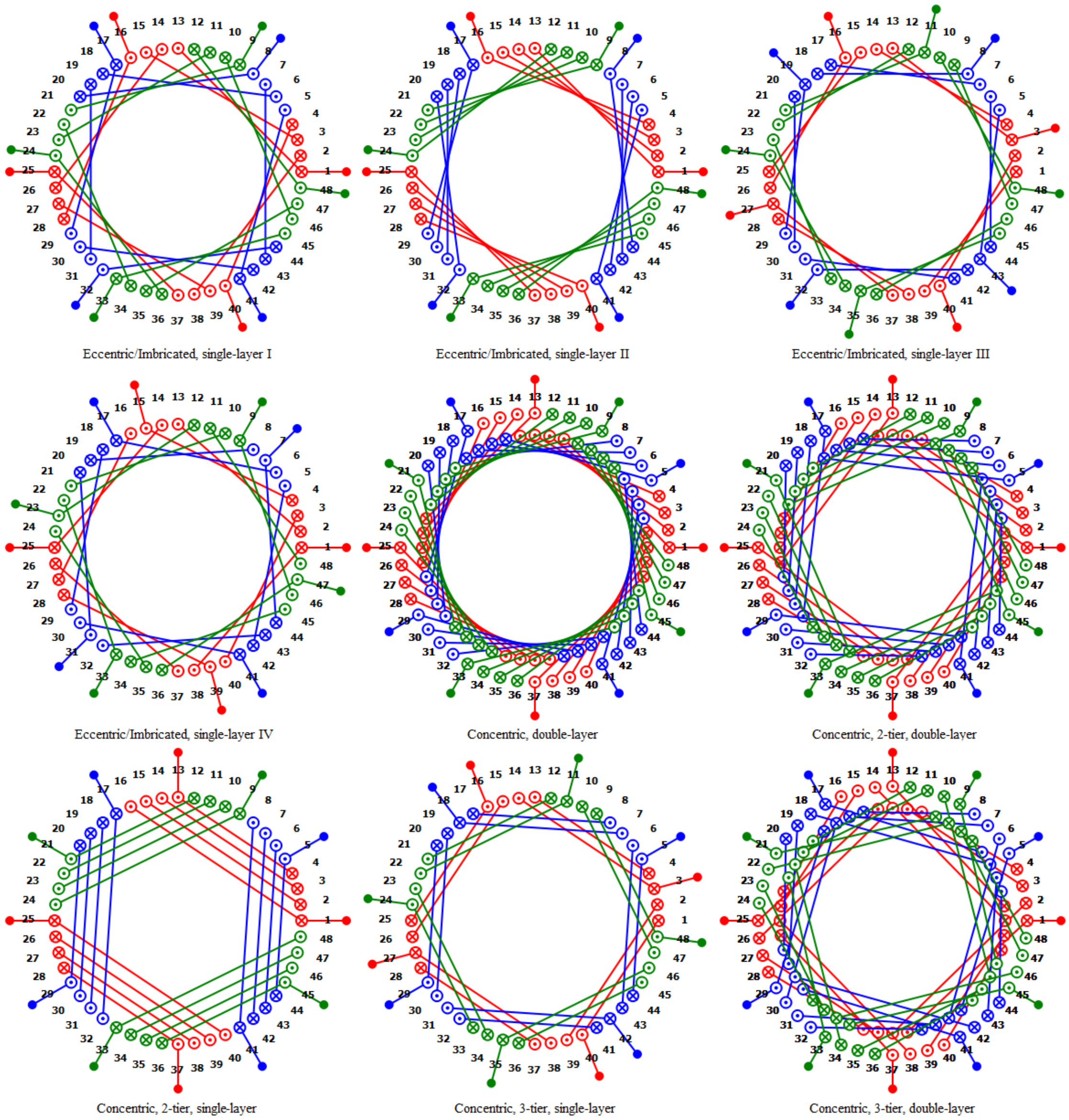


Fig. 20. The nine different automatic winding configurations available in BobiSoft.

An innovative and very useful feature of BobiSoft 2.0 is the automatic winding optimization tool (Fig. 21) to determine separately or simultaneously (combined solution) the best coil pitch in double-layer windings and the best number of turns of each coil in concentric windings, maintaining, if desired, the product of the fundamental winding factor by the total phase turns constant (in order to avoid changing the fundamental flux and, thus, the electromagnetic torque developed by the motor). In the case of double-layer imbricated/eccentric windings, only the coil pitch is optimized (it is assumed the same number of turns for all coils). Basically, the software evaluates all the eligible combinations (using advanced parallel processing techniques) and identifies the one minimizing the total space harmonic distortion of the MMF. As far as the authors know, this is the only software in the market offering this feature/tool.

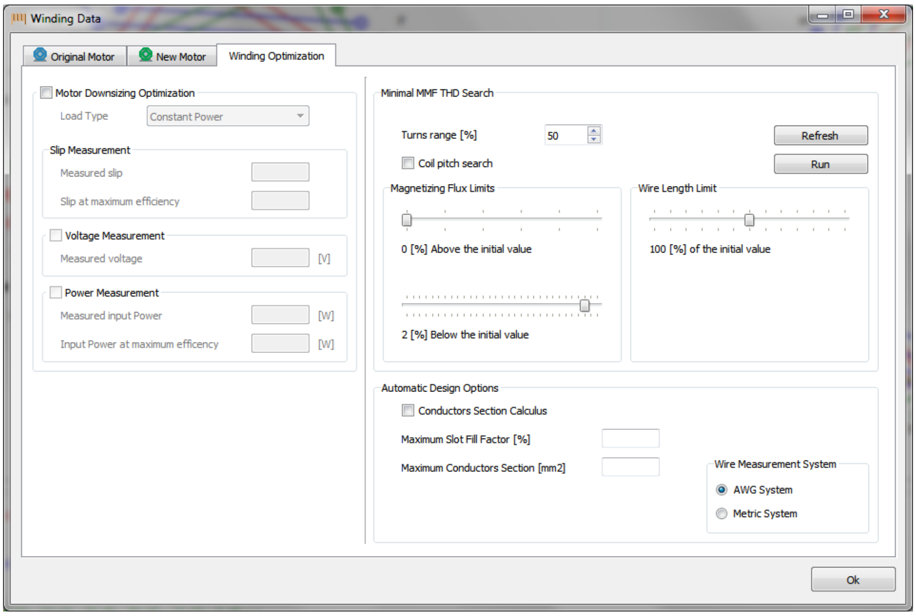
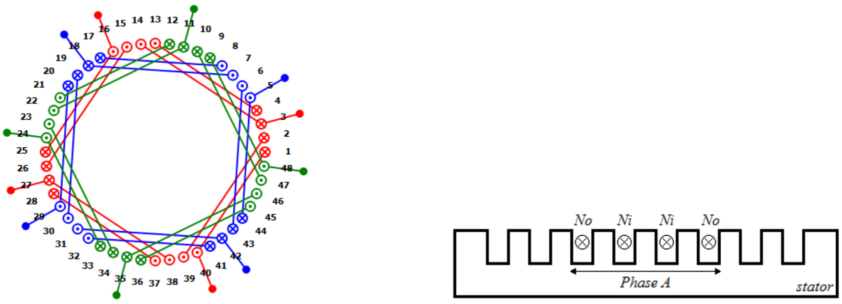


Fig. 21. Winding optimization window of BobiSoft.

Application Examples

In this section, some stator winding optimization examples are presented.

As a base case, the typical stator winding configuration used by one of the largest motor manufacturers in three-phase, 400-V, 7.5-kW, 4-pole SCIMs of classes IE1, IE2, IE3 and IE4, is considered. The 48-slot, concentric, single-layer stator winding of these motors only differs in the phase turns and section of the conductors. The respective winding configuration generated with BobiSoft is shown in Fig. 22a.



(a) (b)

Fig. 22. Concentric, single-layer, 3-tier, stator winding configuration (original): (a) circular scheme; (b) identification of inner and outer coils.

In single-layer windings, the spatial harmonic distortion of the magneto-motive force (MMF) is significantly affected by the number of stator slots per pole. In general, the lower the number of slots per pole is, the higher the MMF harmonic distortion will be. In this type of winding, the coil pitch cannot be shortened. Hence, the only possibility to improve the MMF spatial distribution is by means of changing the number of turns of each coil individually.

Since the original winding has 4 slots or coil sides per pole, there are four degrees of freedom to modify the MMF waveform. However, if the odd symmetry of the MMF waveform is to be maintained, there are only two degrees of freedom. Thus, the two coil sides of a pole can be combined in pairs in respect to their distance from the pole center, as represented in Fig. 22b, namely, two inner coil sides (denoted by N_i) and, two outer coil sides (denoted by N_o). For example, considering one pole of *Phase A*, coils 1-40 and 4-13 are the outer coils and coils 2-39 and 3-14 are be the inner coils.

Considering that the fundamental per-phase magnetic flux is to be kept equal to the one produced by the original winding and the fundamental winding factor does not change significantly, the total number of phase turns has to be equal to that of the original winding. As a result, adding 1 turn in the outer coils implies subtracting 1 turn in the inner coils. Applying this design strategy iteratively, the best coil turn combination can be found. In Fig. 23, the evolution of the MMF space harmonics and total harmonic distortion (THD) as a function of the turn difference is shown. The original winding has 48 turns per coil, which is the base case (turn difference equal to zero). As it can be seen, it is not possible to reduce simultaneously all harmonics with this strategy. The spatial THD is minimized for a turn difference of 3.

The fundamental winding factor slightly decreases with the crescent number of turns in outer coils (for the minimum spatial THD point, it decreases less than 0.5% in relation to the original case). Therefore, when the best combination is found, an adjustment of the total number of turns per phase in order to have the original magnetic flux may be required. This is an example that demonstrates how single-layer concentric windings can be improved just by properly adjusting the number of turns of each coil, following a simple rule, i.e., iterative symmetrical turn number change.

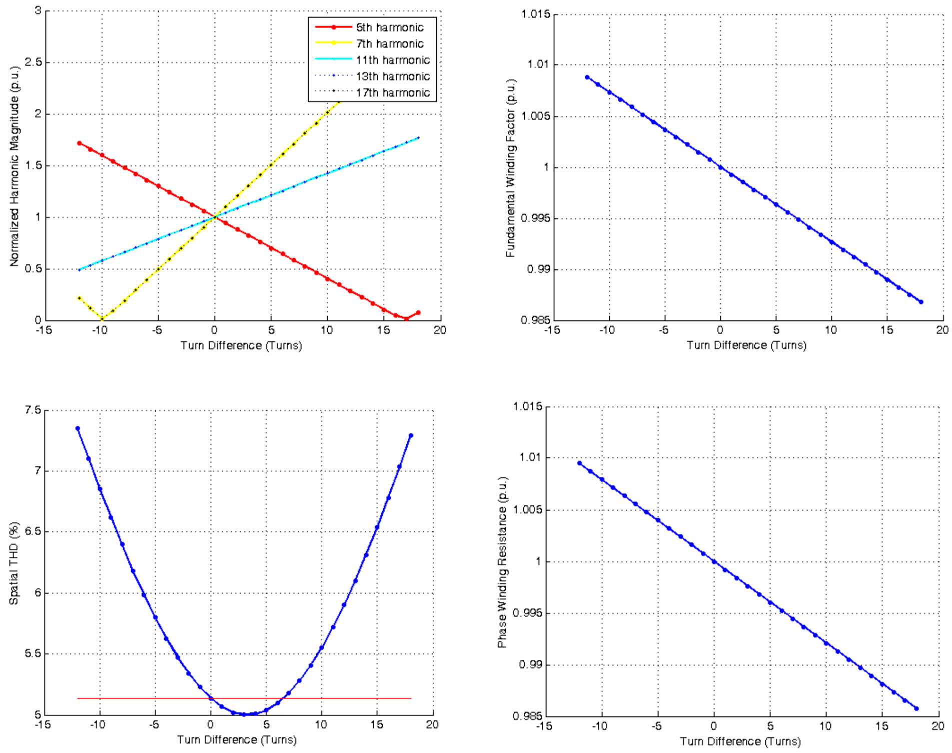
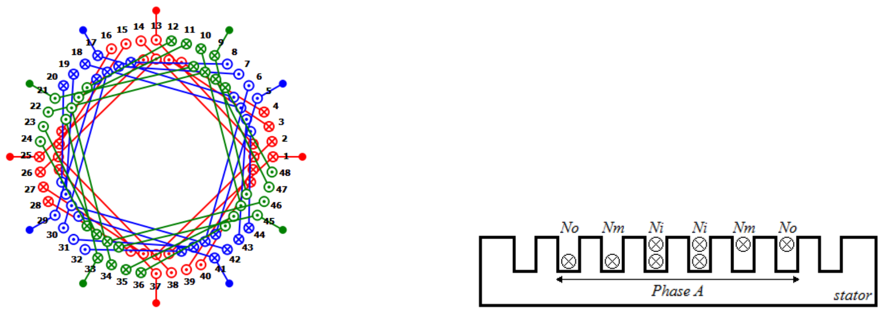


Fig. 23. MMF space harmonics (normalized in relation to the fundamental) and THD as a function of the turn difference, for a 48-slot, 48-turn/coil, concentric, single-layer winding.

It should be noted that the reduction of the 5^{th} spatial harmonic (negative sequence) of the MMF contributes to the reduction of the rotor harmonic losses. The reduction of the 7^{th} spatial harmonic (positive sequence) is important to attenuate the respective perturbation in the accelerating torque for a slip between 1.0 and 0.8.

In the case of double-layer windings, both the coil pitch and the number of turns per coil can be changed (Fig. 24a). In this type of windings, there is an optimal coil pitch which minimizes the spatial THD of the MMF. In Table I, the MMF space harmonic content for different coil pitches is presented. A coil pitch of 10 slots minimizes the MMF space harmonic content, although there is a small decrease of the fundamental winding factor (–3.4%), which can be compensated by adding a few more turns to the winding in order to ensure a fundamental magnetic flux as close as possible to original. From this point, it is possible to reduce even more the spatial THD of the MMF by also properly changing the number of turns of every single coil of this winding, as it was done for the single-layer winding case. In this case, the outer coil sides (with N_o turns) and inner coil sides (with N_i turns) are adapted (Fig. 24b). N_m is kept constant (equal to the original). The effect of these two strategies combined is presented in Fig. 25. Similarly to the result obtained for the single-layer case, the fundamental term of the MMF is slightly reduced when the turn difference increases, so to keep the magnetic flux as much equal as possible to the one of the original winding, the total number of turns may have to be properly adapted.



(a) (b)

Fig. 24. Concentric, double-layer, 3-tier, stator winding configuration: (a) circular scheme; (b) identification of inner and outer coils.

Table I

Fundamental and harmonic winding factors for different coil pitches.

Coil pitch (in slots)	**12**	**11**	**10**	**9**	**8**
k_{w1}	0.95766	0.94947	0.92503	0.88476	0.82936
k_{w5}	0.20534	0.16290	0.05314	0.07858	0.17783
k_{w7}	0.15756	0.09592	0.04078	0.14557	0.13645
k_{w111}	0.12608	0.01646	0.12178	0.04825	0.10914

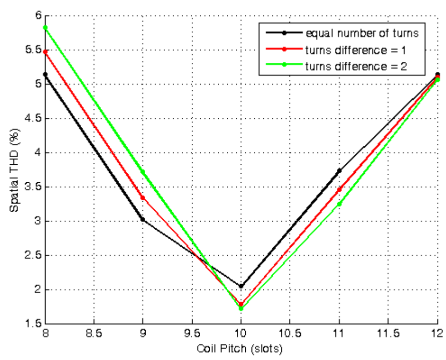


Fig. 25. MMF spatial THD as a function of the coil pitch for a 48-slot, 48-turn/coil, eccentric, double-layer winding.

Two additional winding optimization examples, using two different strategies, are analyzed next.

In first place, the winding of a commercial IE1-class, 4-pole SCIM has been optimized, being the results presented in Table II.

Considering Fig. 26 as reference, the coil distribution for Case 2 is N_0=13 turns, N_1=25 turns, N_2=36 turns and N_3=22 turns. In Fig. 27, the MMF waveforms for the Cases 0 and 2 are presented, evidencing the much better waveform of the MMF spatial distribution of the optimized winding. The spatial THD decreased from 8.046% to 5.909%. The coil position and number of turns of the optimized winding are presented in Fig. 28.

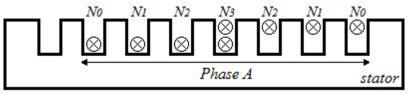


Fig. 26. Coil side distribution in the optimized double-layer winding.

Table II

Optimization of the Original Stator Winding of an IE1-Class SCIM.

Case	0	1	2
	Original Winding	Coil Pitch Optimization	Coil Pitch & Turns Optimization
Winding Type	Concentric, Single-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier
Average Coil Pitch (slots)	10.0	9.50	9.40
Slot Fill Factor (%)	41.02	42.72	41.02 (1)
Head to Slot Wire Ratio (%)	80.52	77.09	76.38
Wire Weight (kg)	1.51	1.54	1.47
Wire Length (m/phase)	221.82	226.68	216.74
Conduction Section (mm²)	0.396+0.442	0.396+0.442	0.396+0.442
Wire Resistance per phase (Ω)	1.891	1.933	1.848
Turns per phase	384	400	384
k_{w1}	0.95766	0.92503	0.91267
k_{w5}	0.20534	0.05315	0.00494
k_{w7}	0.15756	0.04078	0.00234
k_{w11}	0.12608	0.12178	0.00328
k_{w13}	0.12608	0.12178	0.00328
k_{w17}	0.15756	0.04078	0.00234
THD (%)	8.046	6.291	5.909
Magnetic Flux (Wb)	0.00979	0.00973	0.01027
Current Density (A/mm²)	2.55	2.55	2.55
Winding Joule Losses (W/phase) (2)	138.1	141.1	134.9
Airgap MMF Peak Value (A.turn/coil)	393.6	391.2	413.0

(1) Highest fill factor higher than the original. Some slots have lower slot fill factor.

(2) Considering the nominal current.

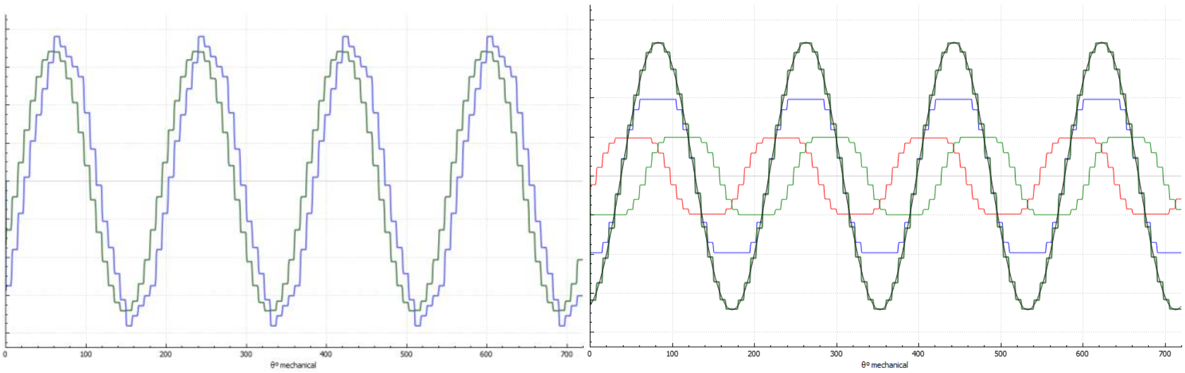


Fig. 27. MMF waveform: (left) comparison between original (in blue color) and new (in green color) winding; (right) new winding pulsating fields.

Coil Number	Phase	In slot	Out slot	Coil turns
1	A	1-U-T1	37-L	22
2	A	2-U	12-L	36
3	A	3-U	11-L	25
4	A	4-U	10-L	13
5	A	22-L	16-U	13
6	A	23-L	15-U	25
7	A	48-L	38-U	36
8	A	1-L	13-L-T2	22
9	A	25-U-T1	37-U	22
10	A	26-U	36-L	36
11	A	27-U	35-L	25
12	A	28-U	34-L	13
13	A	46-L	40-U	13
14	A	47-L	39-U	25
15	A	24-L	14-U	36

Coil Number	Phase	In slot	Out slot	Coil turns
16	A	25-L	13-U-T2	22
17	B	17-U-T1	5-L	22
18	B	18-U	28-L	36
19	B	19-U	27-L	25
20	B	20-U	26-L	13
21	B	38-L	32-U	13
22	B	39-L	31-U	25
23	B	16-L	6-U	36
24	B	17-L	29-L-T2	22
25	B	41-U-T1	5-U	22
26	B	42-U	4-L	36
27	B	43-U	3-L	25
28	B	44-U	2-L	13
29	B	14-L	8-U	13
30	B	15-L	7-U	25

Fig. 28. Position and number of turns of the coils of the new optimized winding.

In second place, the winding of a commercial IE4-class, 4-pole SCIM has been optimized, being the results presented in Table III. It should be referred that the simultaneous optimization of both coil pitch and number of turns is performed automatically by BobiSoft in a few seconds.

Considering Fig. 26 as reference, the coil distribution for Cases 2 and 3 is N_0=7 turns, N_1=13 turns, N_2=18 turns and N_3=11 turns. The only difference between Cases 2 and 3 is the conduction section, which has a direct impact in the slot fill factor and winding resistance.

The optimization strategy used in Cases 2 and 3 leads to a lower head to slot copper ratio, which is an advantage.

In Fig. 29, the MMF waveforms for the Cases 0 and 3 are presented, evidencing the much better waveform of the MMF spatial distribution of the optimized winding. The spatial THD decreased from 8.046% to 5.916%. The coil position and number of turns of the optimized windings (Cases 2 and 3) are presented in Fig. 30.

In Fig. 31, the approximate electromagnetic torque curve for the IE4-class SCIM, considering the effect of 5th- and 7th-order space harmonics of MMF, is presented for Cases 0 and 3.

The obtained results, either for the IE1- or IE4-class motor windings may lead to an increase of the motor efficiency particularly due to the reduction of the space harmonics and its influence on the rotor losses. A further reduction in the stator Joule losses may be obtained if the coil heads are shortened by means of reducing its average distance to the stator core.

Table III

Optimization of the Original Stator Winding of an IE4-Class SCIM.

Case	**0**	**1**	**2**	**3**
	Original Winding	Coil Pitch Optimization	Coil Pitch & Turns Optimization	Coil Pitch & Turns Optimization
Winding Type	Concentric, Single-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier
Average Coil Pitch (slots)	10.0	9.50	9.34	9.34
Slot Fill Factor (%)	47.17	53.33	55.99 (1)	49.18 (1)
Head to Slot Wire Ratio (%)	66.09	63.75	63.03	63.03
Wire Weight (kg)	6.94	7.73	8.08	7.10
Wire Length (m/phase)	128.35	143.05	134.2	134.2
Conduction Section (mm^2)	4x0.5027	4x0.5027	4x0.5027+1x0.2299	3x0.5027+2x0.2299
Wire Resistance per phase (Ω)	1.071	1.194	1.005	1.144
Turns per phase	**184**	**208**	**196**	**196**
k_{w1}	0.95766	0.92503	0.91010	0.91010
k_{w5}	0.20534	0.05315	0.01121	0.01121
k_{w7}	0.15756	0.04078	0.00067	0.00067
k_{w11}	0.12608	0.12178	0.00159	0.00159
k_{w13}	0.12608	0.12178	0.00159	0.00159
k_{w17}	0.15756	0.04078	0.00067	0.00067
THD (%)	8.046	6.291	5.914	5.914
Magnetic Flux (Wb)	**0.0102**	**0.0094**	**0.0101**	**0.0101**
Current Density (A/mm^2)	4.135	4.135	3.711	4.225
Winding Joule Losses (W/phase) (2)	74.0	82.5	69.5	79.1
Airgap MMF Peak Value (A.turn/coil)	336.7	308.4	440.7	332.6

(1) Highest fill factor higher than the original. Some slots have lower slot fill factor.

(2) Considering the nominal current.

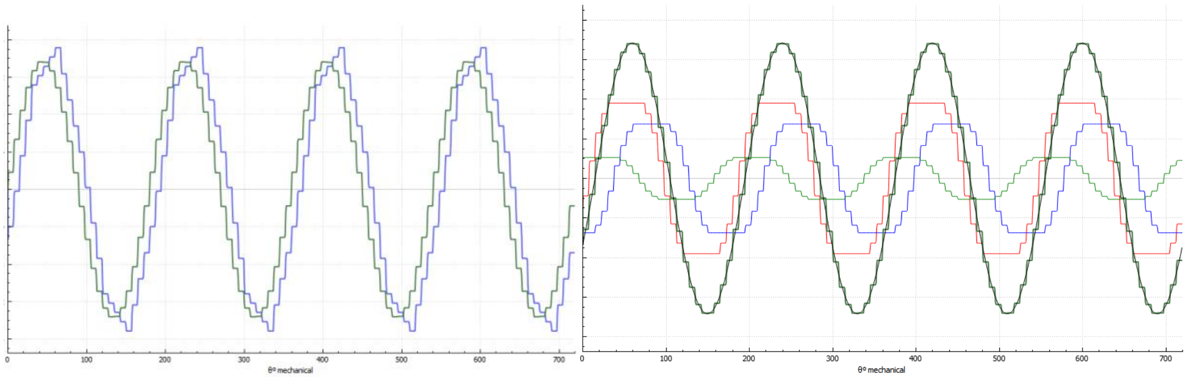
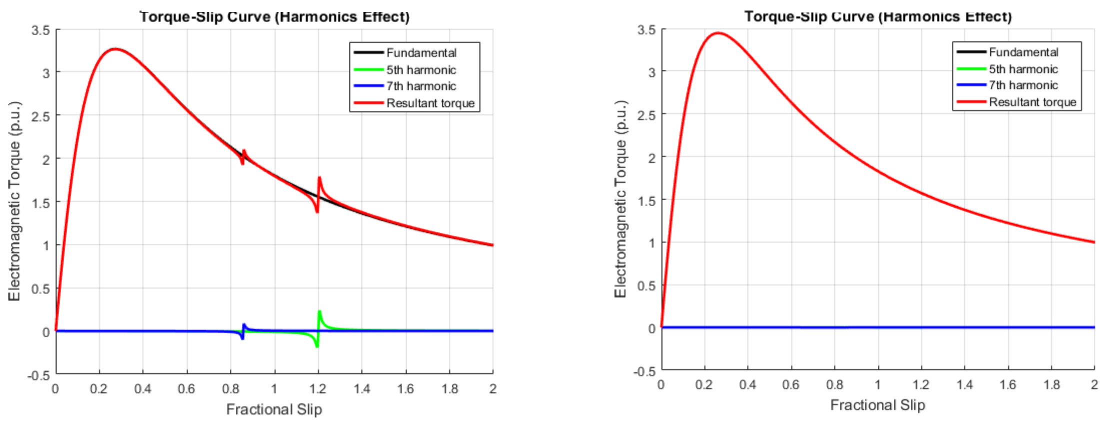


Fig. 29. MMF waveform for the IE4-class motor winding: (left) comparison between original (blue trace) and new optimized winding (green trace; Case 3); (right) new optimized winding (Case 3) pulsating phase MMF.

Coil Number	Phase	In slot	Out slot	Coil turns
1	A	1-U-T1	37-L	11
2	A	2-U	12-L	18
3	A	3-U	11-L	13
4	A	4-U	10-L	7
5	A	22-L	16-U	7
6	A	23-L	15-U	13
7	A	48-L	38-U	18
8	A	1-L	13-L	11
9	A	25-U	37-U	11
10	A	26-U	36-L	18
11	A	27-U	35-L	13
12	A	28-U	34-L	7
13	A	46-L	40-U	7
14	A	47-L	39-U	13
15	A	24-L	14-U	18
16	A	25-L	13-U-T2	11
17	B	17-U-T1	5-L	11
18	B	18-U	28-L	18
19	B	19-U	27-L	13
20	B	20-U	26-L	7
21	B	38-L	32-U	7
22	B	39-L	31-U	13
23	B	16-L	6-U	18
24	B	17-L	29-L	11
25	B	41-U	5-U	11
26	B	42-U	4-L	18

Coil Number	Phase	In slot	Out slot	Coil turns
23	B	16-L	6-U	18
24	B	17-L	29-L	11
25	B	41-U	5-U	11
26	B	42-U	4-L	18
27	B	43-U	3-L	13
28	B	44-U	2-L	7
29	B	14-L	8-U	7
30	B	15-L	7-U	13
31	B	40-L	30-U	18
32	B	41-L	29-U-T2	11
33	C	9-U-T1	45-L	11
34	C	10-U	20-L	18
35	C	11-U	19-L	13
36	C	12-U	18-L	7
37	C	30-L	24-U	7
38	C	31-L	23-U	13
39	C	8-L	46-U	18
40	C	9-L	21-L	11
41	C	33-U	45-U	11
42	C	34-U	44-L	18
43	C	35-U	43-L	13
44	C	36-U	42-L	7
45	C	6-L	48-U	7
46	C	7-L	47-U	13
47	C	32-L	22-U	18
48	C	33-L	21-U-T2	11

Fig. 30. Position and number of turns of the coils of the new optimized winding (Cases 2 and 3).



(a) (b)

Fig. 31. Approximate motor electromagnetic torque curve considering the 5th- and 7th-order space harmonics of MMF: (a) original single-layer winding (Case 0); (b) optimized double-layer winding (Case 3).

Conclusions

The presented software tool allows to (re)design and evaluate the performance of complex stator winding configurations in a fast and accurate way (less than 10 minutes, if an automatic winding configuration is used).

The unique tool for simultaneous optimization of the coil pitch and number of turns provided in the latest version of BobiSoft, can be used to minimize the spatial THD of the air-gap MMF in single- or double-layer concentric windings, for a given fundamental magnetizing flux, offering the opportunity to improve the motor performance during rewinding.

The examples provided with the winding designs of commercial motors of classes IE1 and IE4, clearly demonstrate that even very well designed winding can be slightly improved with this optimizing tool, by searching the best coil pitch and number of turns.

The user can also use this software to downsize the motor in order to increase its efficiency and power factor (optimized rewinding), as well as to evaluate the impact in the stator winding Joule losses and check the feasibility of reducing the coil head length and by increasing the conduction section.

The stator winding design improvement may lead to motor efficiency gains of up to 4% and a much better MMF waveform. In the cases where the motor is strongly oversized, which are quite common, if the stator winding is adapted to the actual motor load, efficiency gains up to 15% may be obtained.

The presented software tool allows saving and exchanging with other users the key technical information of the winding design through an editable electronic file. It also helps organizing in a standard format the technical information associated with each rewinding service. Moreover, technical reports can be generated automatically.

BobiSoft can be used in repair shops, industrial maintenance departments/companies and motor manufacturers for professional purposes and in electrical engineering schools/universities for teaching/training purposes.

In the case of the motor rewinding shops, it may help gross errors in the winding redesign, since automatic alert messages are generated if the typical/recommended values of key parameters, such as current density, induction/flux and/or slot fill factor, are exceed. Moreover, the automatic tool to optimize simultaneously the coil pitch and number of turns allows improving the performance of the motor even if the nominal torque, number of poles, frequency and voltage are to be maintained.

The motor market is moving to premium and super-premium motors, which are inherently more expensive. Since, in general, SCIMs over 4 kW are rewound 2 to 4 times during their useful lifetime, and the repair/rewinding cost is not likely to increase, the percent price in relation to the new motors is nowadays lower and, therefore, such services become more competitive and represent a way to maintain or even increase significantly the motor efficiency by means of an optimized winding redesign. BobiSoft is an excellent software tool for that purpose, requiring only basic knowledge on electric machines to be used effectively.

1. Acknowledgments

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References

[1] A. T. de Almeida, F. J. Ferreira, A. Duarte, "Technical and economic considerations on super high-efficiency three-phase motors", IEEE Transactions on Industry Applications, Vol. 50, No. 2, March/April 2014, pp. 1274-1285.

[2] A. T. de Almeida, F. J. Ferreira, G. Baoming, "Beyond induction motors technology trends to move up efficiency", IEEE Transactions on Industry Applications, Vol. 50, no. 3, pp. 2103-2114, 2014.

[3] A. T. de Almeida, et al., "Ecodesign Assessment of Energy-Using Products - EuP Lot 11 Motors", Final Report for the EC, Inst. of Syst. and Robotics, Univ. of Coimbra, April 2008.

[4] Alex Chausovsky, "Motor Market Update", Presentation Slides, Motor Summit 2014, Oct. 2014, Zurich.

[5] Conrad Brunner, "Efficient Electric Motor Systems", Presentation Slides, Motor Summit 2014, Oct. 2014, Zurich.

[6] Fernando J. T. E. Ferreira, Aníbal T. de Almeida, "Overview on Energy Saving Opportunities in Electric Motor Driven Systems – Part 1: System Efficiency Improvement", IEEE Industrial & Commercial Power Systems Technical Conf. (ICPS'16), Conf. Rec., May 2016.

[7] IEC 60034-30-1:2014, Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code).

[8] IEC 60034-30-2 TS Ed.1, Rotating electrical machines - Part 30-2: Efficiency classes of variable speed AC motors (IE-code). Technical Specification Committee Draft (CD) 2/1753A/CC, February, 2016.

[9] Rita Werle, "Swiss audit program Easy", Presentation Slides, Motor Summit 2014, Oct. 2014, Zurich.

[10] de Almeida, A.; Ferreira, F.: "Actions to promote energy-efficient electric motor repair", Inter. Journal of Energy Technology and Policy, Vol. 1, No. 3, pp. 302-314, 2003.

[11] Ferreira, F.; de Almeida, A.: "Considerations on the Custom Design of the Stator Winding of Low-Voltage, Three-Phase, Cage Induction Motors to Improve their Efficiency and Reliability", 17th Inter. Conf. on Electric Machinery (ICEM'06), Conf. Proc., Sept. 2006.

[12] Ferreira, F.; de Almeida, A.: "Induction Motor Downsizing as a Low Strategy to Save Energy", Journal of Cleaner Production, Elsevier, Vol. 24, pp. 117-131, March 2012.

[13] A. de Almeida, F. J. T. E. Ferreira, J. Fong, "Standards for Efficiency of Electric Motors", IEEE Industry Applications Magazine, Vol. 17, No. 1, pp. 12-19, Jan./Feb. 2011.

[14] Ferreira, F.; de Almeida, A.: "Electric Machinery Winding Design Software for Teaching and Rewinding", 16th Inter. Conf. on Electrical Machines (ICEM'04), Conf. Proc., Poland, Sept. 2004

Technology to support Circular Economy: will standardization limits the outstanding benefits of new motor technology with or without drive and the use of raw material content of electric motors.

Régis Giraud & Cédric Plasse

Nidec - Leroy Somer

Abstract

Market needs are evolving towards compact and high/very high efficiency design, and consequently, the new technologies are key to boost motors & drives developments. Leroy Somer is one technology leader in the domain of industrial electric motors and is offering best in class product thanks to his permanent magnet concept.

The choice of magnet energy density level can affect the behaviour of the driven machine. Consequently multi-physic simulations as well as test of prototypes have been used to tune both the control algorithms and the magnetic circuit to achieve the best performances of the drive package.

Strong pressure to increase motor efficiency in line with Directives has led motor manufacturers to use more material which is not in line with circular economy requirements.

Very high efficiency in a standard shaft height with reduced material content versus an induction motor is one of the key assets of low energy density magnet assisted synchronous reluctant motors and will support circular economy guidelines. However the ultra-compactness required for some applications and offered by new technologies such as high energy density magnet assisted synchronous reluctant motors, available or in development, requiring less material, will lead the question of stepping out from standardization of electric motors in place for many decades.

Through some examples, evaluating the pros and the cons, maintaining standardization could limit the shift towards circular economy compliant designs and could even reverse the current trend.
In conclusion, market will decide and standards cannot be too far from customer expectations, meaning that technology trends have to be considered, even if the products are not yet available.

Introduction

The motors and drives business is governed by standards mostly focussed on energy efficiency. Depending on its size, 80 to 90% of the total cost of ownership of an electric motor is the energy consumed during its use. Consequently, reaching high efficiency standards, today IE3/4 level with induction motors, tomorrow IE5+ with synchronous technologies are our main challenges.

But there is one new request due to resources scarcity which is becoming one of the main challenges we have to face. This will lead to new directives in the frame of circular economy (mandate M453) that will push for even more attention to bring for the use of raw material, the reuse of component, but also the durability and the reparability of the electric motors.

- At EEMODS 2015, we presented "Facing the Challenges of efficiency and sustainability with the low energy density permanent magnet assisted synchronous reluctance motor and its associated electronic inverter". It was dedicated to the bill of material optimization and we have showed in particular that it is possible to design a high efficiency (IE4/5) and compact synchronous motor range while avoiding expensive and highly polluting rare earth material.

- In this new article, we would like to share more on the constraints defined by the circular economy and the potential consequences on the design of future electrical motors.

Market needs have evolved towards compact and high/very high efficiency standard size design. Consequently, new technologies are key to boost motors & drive developments and Leroy-Somer, one of the technology leaders in the domain of industrial electric motors is offering best in class product thanks to optimized induction ranges and low energy density permanent magnet motors.

This has led us to deploy treasury of innovation to be able to offer the most efficient products to comply and often exceed the demand of the standards and directives. Pushed by Directives but also driven by our customers, we have introduced to the market new designs or improve the current ones. Main drivers were to cut electrical losses without increasing raw material content as per Figure 1.

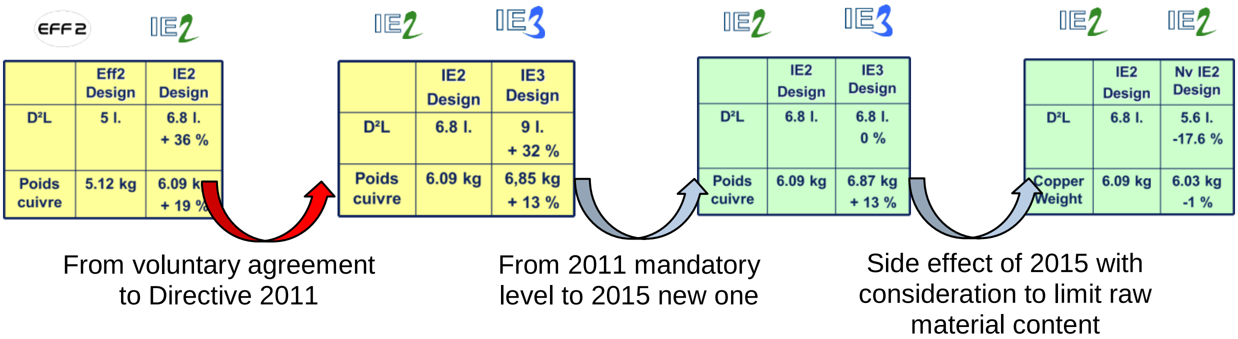


Figure 1: Stack volume evolution to comply with Directive and remain cost efficient.

In the near future, this trend will be a part of new package gathered under the umbrella of "Circular Economy" which will require our products to comply with new concepts, sometimes not easy to measure such as durability, upgradability, ability to repair, facilitate reuse, use of reused components, ability to re-manufacture, recyclability, RRR index, recycling, use of recycled materials, use of critical raw materials, recyclability of critical raw materials, as listed in Figure 2.

New Item Nr	Title of deliverable	Planned publicat° date	Lead (CEN or CENELEC)
1	Guide on how to use generic material efficiency standards when writing energy related product specific standardization deliverables	2019-03	CENELEC
2	Definitions related to material efficiency	2019-06	CENELEC
3	General method for the assessment of the durability of energy related products	2019-03	CEN
4	General method for the assessment of the ability to repair reuse and upgrade energy related products	2019-03	CEN
5	General method for the assessment of the ability to re-manufacture energy related products	2019-03	CENELEC
6	General methods for assessing the recyclability and recoverability of energy related products.	2019-03	CEN
7	General method for assessing the proportion of re-used components in an energy related product	2019-03	CEN
8	General method for assessing the proportion of recycled material content in energy related products.	2019-03	CEN
9	General method to declare the use of critical raw materials in energy related products	2019-03	CENELEC
10	Methods for providing information relating to material efficiency aspects of energy related products	2019-03	CENELEC
20	Overall coverage for a specific product group (ICT network infrastructure goods)	2016-11	ETSI
21	Overall coverage for a specific product group (ICT network infrastructure goods). Including aspects such as product durability, upgradability, reparability, reusability, recyclability, and re-manufacture, as well as re-use, recycling, recovery of materials and relevant metrics, indexes or criteria	2018-12	ETSI

Figure 2: List of standards expected by Mid-2019 to be the references for the future Circular Economy Directive.

Why it will be in a near future because most of the standards are to be written and delivered at least by March 2019. The purpose of this paper is not to claim after something not yet existing but to evaluate it is in line with the manufacturer's present goals to be involved in one more sustainable future for the planet. The idea is to inform people about the difficulties that can occur with one too strict regulation which may limit the innovation mandatory in our business to stay competitive and satisfy our customers.

For electric motors we have to also remind that our products are governed by standards (cf. Figure 3) issued from IEC 60034 & IEC 60072 series (in Europe for example) or from NEMA in some areas. These bunches of documents lead many aspects of electrical machine such as marking, definition and, key for our customers, the interchangeability thanks to the standardization of the frame size from IEC 56 to 315 for the most common ones covered by the Energy Efficiency Directives.

INTERNATIONAL AND NATIONAL STANDARD EQUIVALENTS

International reference standards		National standards				
IEC	Title (summary)	FRANCE	GERMANY	U.K.	ITALY	SWITZERLAND
60034-1	Ratings and operating characteristics	NFEN 60034-1 NFC 51-120 NFC 51-200	DIN/VDE 0530	BS 4999	CEI 2.3.VI.	SEV ASE 3009
60034-5	Classification of degrees of protection	NFEN 60034-5	DIN/EN 60034-5	BS EN 60034-5	UNEL B 1781	
60034-6	Cooling methods	NFEN 60034-6	DIN/EN 60034-6	BS EN 60034-6		
60034-7	Mounting arrangements and assembly layouts	NFEN 60034-7	DIN/EN 60034-7	BS EN 60034-7		
60034-8	Terminal markings and direction of rotation	NFC 51 118	DIN/VDE 0530 Teil 8	BS 4999-108		
60034-9	Noise limits	NFEN 60034-9	DIN/EN 60034-9	BS EN 60034-9		
60034-12	Starting characteristics for single-speed motors for supply voltages ≤ 660 V	NFEN 60034-12	DIN/EN 60034-12	BS EN 60034-12		SEV ASE 3009-12
60034-14	Mechanical vibrations of machines with frame size ≥ 56 mm	NFEN 60034-14	DIN/EN 60034-14	BS EN 60034-14		
60072-1	Dimensions and output powers for machines of between 56 and 400 frame size and flanges of between 55 and 1080.	NFC 51 104 NFC 51 105	DIN 748 (~) DIN 42672 DIN 42673 DIN 42631 DIN 42676 DIN 42677	BS 4999		
60085	Evaluation and thermal classification of electrical insulation	NFC 26206	DIN/EN 60085	BS 2757		SEV ASE 3584

Note: DIN 748 tolerances do not conform to IEC 60072-1.

Figure 3: List of current standards applicable to electrical motors.

Since the late 90's, the motor manufacturers have increased the efficiency of the products offered to the market, formerly through one voluntary action and then with new developments to comply with directive which requires minimum level of efficiency such as IE3 on fixed speed machines or IE2 with inverter supply to make the saving expected by the different treaties signed by our leadership like in Kyoto and Paris as some examples.

To conclude this introduction our engineering teams will have to find the right lane between:

- Standardization, as existing today and well appreciated by our customers

- Increasing demand and regulation for higher efficiency IE3, IE4 and why not more, often mandatory once it is set by directive

- New rules of "Circular Economy" to be published later on but that we need to take into account assuming the development and the industrialization of one new products range require usually 2 to 3 years depending on level of complexity.

Lessons from the past that can support our actions

Easy to say but a bit more complex to do! However, the expertise issued from WEEE in France is showing that our products are valued at their end of life, thanks to their raw material contents which is of interest to be recovered, gathered and recycled. We do not see industrial electric motors for given in the landscape or thrown in collectors as simple waste.

We have made a lot of efforts over the past decades to eliminate some materials from our motors such varnish components, when rejected in the air could increase danger for health of people surrounding areas of manufacturing.

There are many other examples of motor manufacturers' actions for one better planet.

Like other players in the motor business during last EEMOD's conference in 2015, we have presented new generation of ferrite magnet assisted synchronous reluctance motors with position sensorless electronic inverter drives. This proposed optimized package provides the same high torque and high efficiency as the rare earth permanent magnet motor and is as robust, as reliable, as easy to use and as environmentally friendly as the induction machine.

Two years before circular economy announcement, we were already sharing the high responsibility of motor manufacturers for one better planet. Aside of these advantages we were highlighting the possibility to propose one design optimization with NeFeB magnets for application where high power density is required.

The optimization of a complete motor range requires a lot of calculations. Consequently, a Multiphysics analytical model has been developed which reduces the magnetic circuit design time, compared with the finite element method. However, the model must take into account non-linear effects such as saturation to provide good accuracy. Validation has been done by comparison with finite element calculation as well as with experimental results. This methodology supports the adaptability the new Regulation may require.

Then, the analytical model of the machine has been coupled to the electronic inverter model to optimize the complete system with the control laws. In particular, the influence of the high frequency harmonic content due to Pulse Width Modulation (PWM) has been taken into account. Sensor-less operation has also been considered.

The design for supply chain and for manufacturing is based on maximizing the component re-use from the induction motor and limiting the number of different laminations which would require large stamping and winding investment costs.

This leads to an innovative motor & drive design optimization where optimum results are presented on a Pareto diagram. The multi-physic analytical model of the electrical machine and its electronic inverter is adapted to the chosen optimization algorithms. This is one key point to find the best compromise for raw material content, one of the priorities of the Circular Economy as per listed future standards. These different points are summarized in figure 4.

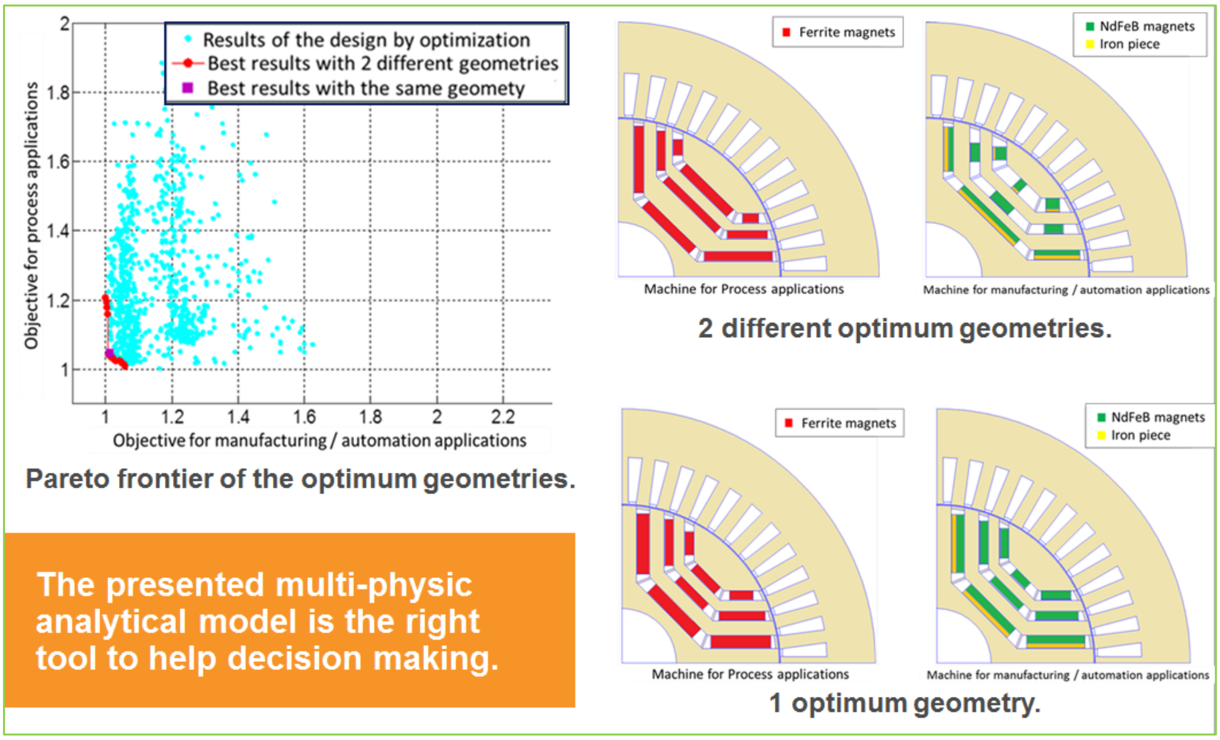


Figure 4: Choice of optimum geometry.

What to do in the future, future that, in reality, is starting today?

Today if we are requested to reduce the raw material content is electrical motors; we would consider again this possibility but what would occur with frame size standardization?

Customers' expectations can be really different depending on application requirements but also on product destination: OEM's for integration in machine or end-users for repairing or revamping existing installations.

In addition, minimum efficiency levels, mandatories for electric motors whether they are fixed or variable speed have changed the rules for designing machines.

As presented last year, the high improvement on microcontroller calculation capabilities has open many doors for highly innovative design. Nevertheless customers first care about reliability when they have to choose one product but standard compliance is not too far driving the market to evolve towards IE2 then IE3.

The objective is to reach the user needs with the lowest motor & electronic inverter package cost. A summary of objectives in relation to user needs is given in the hereunder table (figure 5) for process and manufacturing / automation market segments:

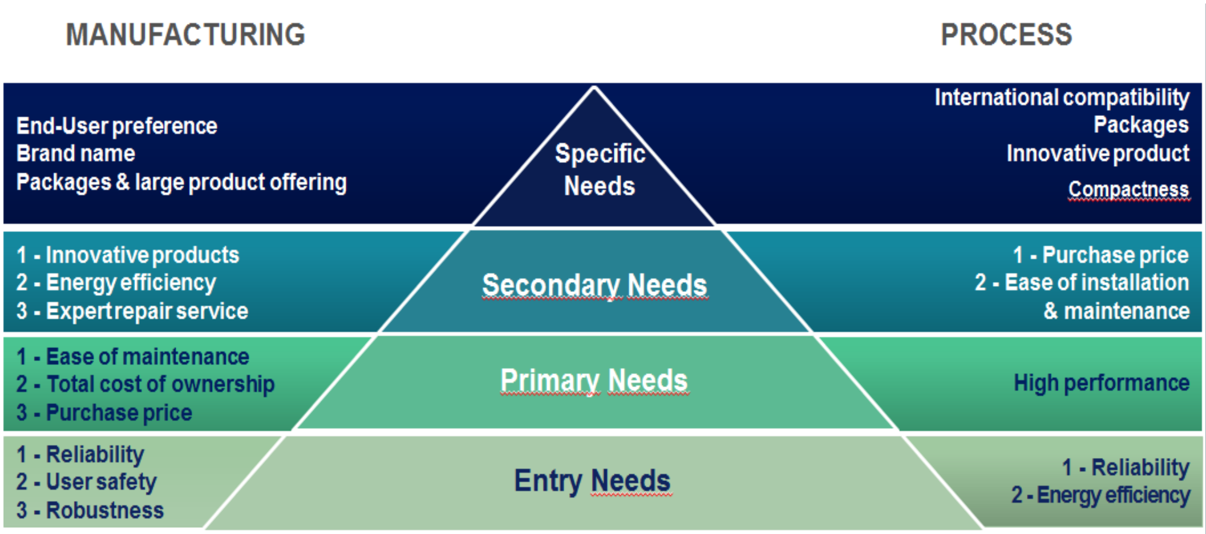


Figure 5: Market needs analysis.

If OEM's can be more sensitive to compactness specifically when it is driving differentiation on their business, end-user likes more the direct replacement machine for easy installation. All these well-known concern can be contradictory from engineering perspective. For example, raw material content is not any longer lead by the motor temperature rise but by the level of efficiency required. Then the difficulty will be to keep the standardization as per IEC 34000 series & 60072 series.

However such sizing will be in line with most of the request of Circular Economy like limitation of raw material content but will also support the end of life recycling that will be responsibility of our customers. Then the original question will be raised again, shall we continue keeping interchangeability or move towards the most compact solutions.

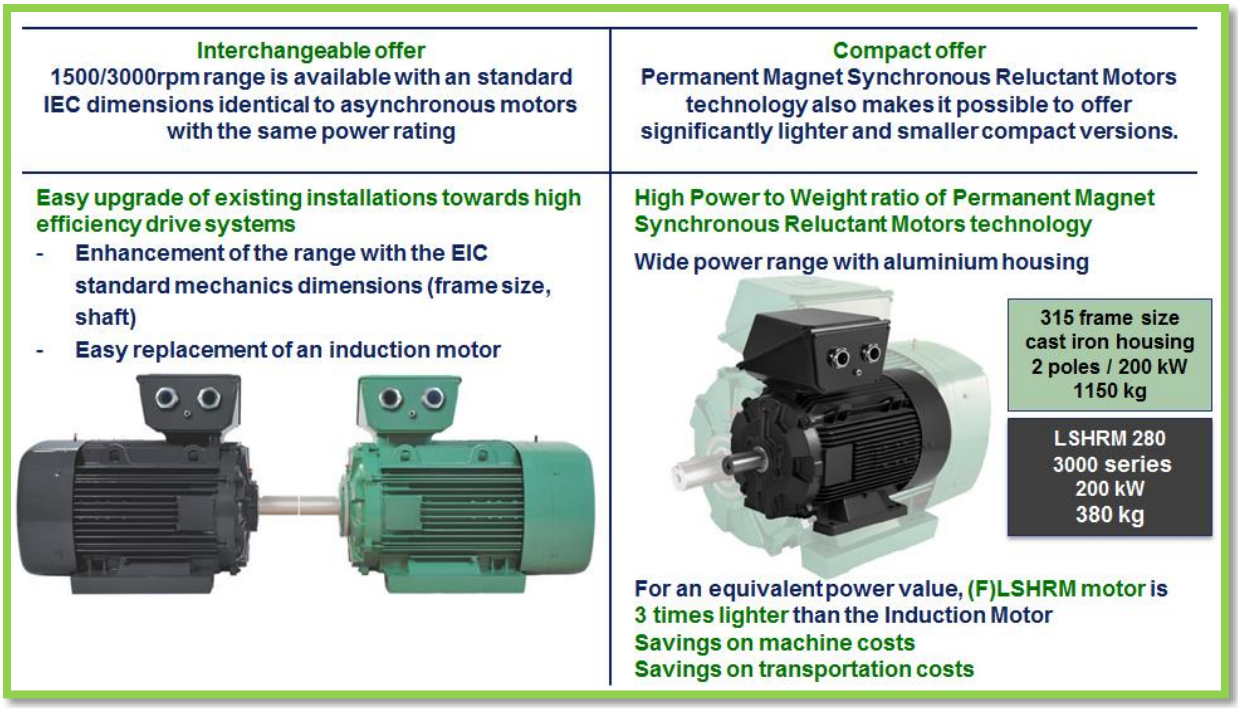


Figure 6: Trend in offering needed by market.

In some cases, the compactness & high torque of the synchronous permanent magnet technology enable system cost reductions. The elimination of the belt drive of a fan or of the gear reducer of an elevator and cantilever integration into high speed compressors are typical examples. In standard frame size ranges, its high efficiency compared to the massively produced induction machine leads to energy savings in many process applications (such as fans, pumps and compressors) working 24h a day, 365 days a year, resulting in a shorter pay-back (cf figure 7).

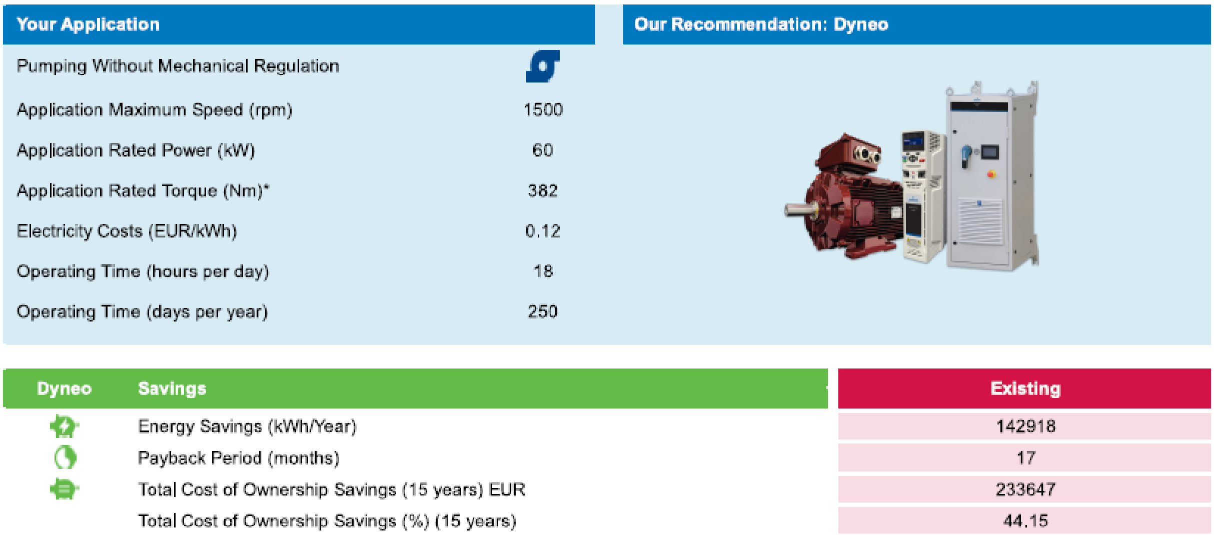


Figure 7: Weight of energy cost in the total cost of ownership.

However, as already mentioned, rare earth magnet price volatility limit the penetration of this permanent magnet machine technology on a large scale in industrial applications. This is why the use of ferrite magnets can be more in line with both our customer expectation and the trend of recyclability requested by Circular Economy.

We cannot offer the best in class drive system without the possible match between the motor and the drive. If drive ratings are pretty well fixed due to IGBT current capabilities, the optimization of the power factor will help to limit the content of raw material in the motor.

Maximization of the torque for a constant speed and a fixed raw materials content

	Torque (N.m)	Power output (kW)	Voltage (V)	Current (A)	Efficiency (%)	α (°)	Power factor	deterministic iterations	Genetic iterations
Initial Machine	206.9	65	345.1	137.2	95.2	23.42	0.850		
Optimization 1	253.5	79.6	340.0	169.8	95.4	24.11	0,851	45	5989
Optimization 2	274.1	86.1	340.0	167.7	95.3	26.99	0.937	45	5438

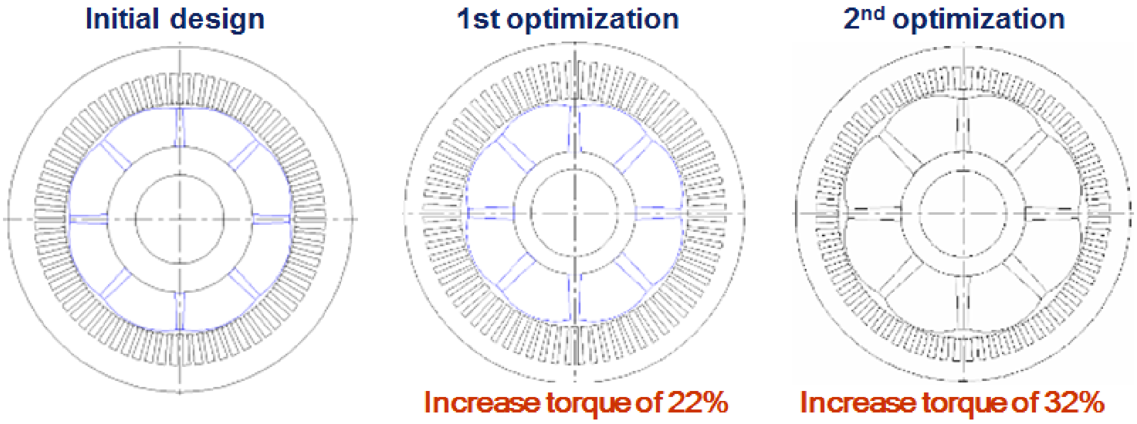


Figure 8: Maximization of torque by design selection.

As one result of this optimization, the improvement of power factor, thanks to the design, will support the limit of raw material content with smaller IGBT in the drive.

From manufacturing to repairing without forgetting service

Once the design is selected for the best in class performance according the customer needs, we have to take into account our own need for one efficient cost to manufacture added to the limitation of complexity. This last point is the key to have the capability to offer the service required by our customers and preserve quick delivery even with late stage customization, preventing huge stocks that jeopardized financial performance of our companies.

In theory, to raise the best efficiency of electric motors, we have to choose the highest grade of lamination but also to track and eliminate the losses where they are in the motor.

From design perspective, we have to increase as much as possible the density of copper inside stator slot as it enable raw material content reduction as well as performances increase.

Over the last two decades, thanks to the improvement of conventional winding techniques (cf. figure 9.a), the slot fill ratio was increased from 35% up to 45%. In the near future, organized winding with round wire as shown in figure 9-b or even better with flat wire as in figure 9-c will enable to achieve up to 65%. It will allow shortening both the rotor and stator lengths and consequently reducing the content of raw material while improving performances and in particular the efficiency. Thanks to these new winding techniques, we will comply with one of the future request of circular economy to reduce the content of raw material: less copper, less magnets and less steel.

This will also drive us to improve insulation and enamelling of copper wires and not consider them as already optimized for the use of electrical motors, but this is not covered in this article.

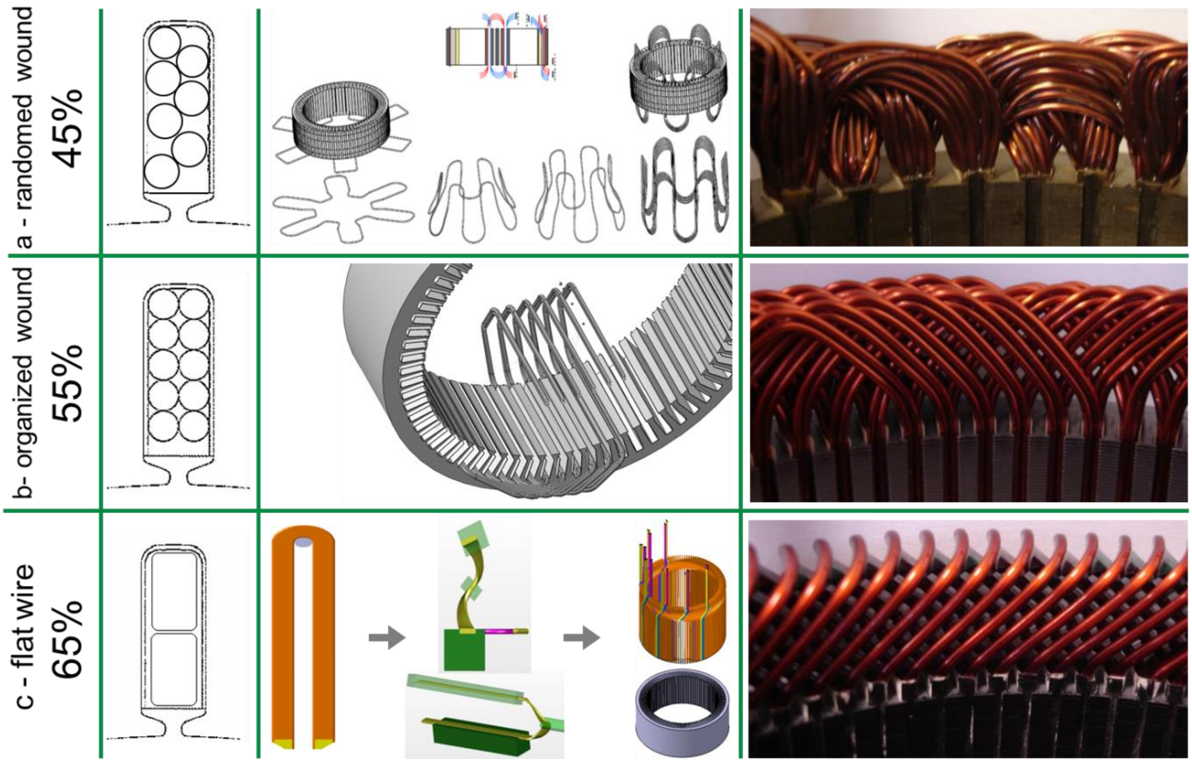


Figure 9: Evolution of slot fill factor.

However, are we going to meet the expectations of reparability and specifically the ability to repair such stator with high value of copper density? Our partners have made significant improvements to avoid loss of efficiency when repairing one motor.

When the need to increase efficiency has driven designers to choose high grade lamination materials, our services partners had to change their process to unwind motors and stop to heat the coil with blow torch. This was mandatory to prevent irreversible damages to lamination losses value.

We must confess that if we increase too much the copper density then the machines cannot be repaired by most the thousands of rewinding shops existing in the world unless without massive investment they cannot bear. Today we currently agree that maximum slot fill with hand winding cannot be higher than 85**%.** Then we could design one product, manufacturable at one competitive cost, compliant with efficiency rules, in line with customer expectations but could not be reparable if attention is not paid to current capabilities of service companies.

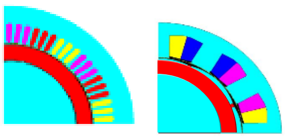
It is also of importance to note that electric motors have one average life time of twenty years, so the problem can occur for future generation even if decision must be taken now to give guidelines to our engineering and development teams.

One thing that will not change, due to forecasted copper scarcity, there will be always one market to recycle the copper included in electric motors like it is today, as proven by the first results of the WEEE.

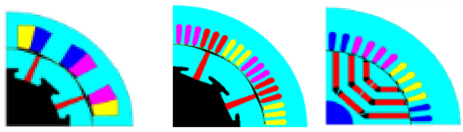
As presented early, adding magnets in rotor is driving the losses down in the rotating part of the motor. With more than twenty years of expertise in supplying permanent motors in industry but also for elevator market, we know the advantages of such technology but also the potential difficulties to repair them.

Glued magnet is one well-known issue with the need to use glue that has limited lifetime once it has been firstly used. The need of banding with impregnated fibber glass material on some rotors makes the reparability not easy to handle or limited to specialist.

However, the use of inserted magnet like presented during las EEMOD'S conference allows reparability even in small workshop of repairing companies assuming some of the basic precautions are taken. Because of their value, the recyclability is already well managed today.



Glued magnets (examples from servomotors)



Inserted magnets (existing and future examples of industrial motors)

Figure 10: Example of PM rotor designs.

Despite the lack of existing regulation, the recyclability of material has been organized mostly around copper and steel. But we cannot ignore that with around 100 million of vehicles sold every year in the world, each one equipped with one alternator using ferrite on rotor, the recycling of such component is organized and generates revenues all over the planet.

The Ferrite permanent magnet assisted reluctance motor has the same power density as the pure rare earth permanent magnet machine and is much more competitive and environmentally friendly. Because 2/3 of the torque is provided by the reluctance, such kind of motor is easy to dismantle without any special tooling allowing simple maintenance, like change of bearing which is the most common one, by any service centre or rewinding shop all over the world.

So, with permanent motors we can tick many boxes of circular economy request on top of induction motors current ones inclusive use of recycled materials. Thanks to the magnetization machines availability we can assembly the rotor easily and do the magnetization afterwards, just before assembly and at the level needed in the machine.

The main question to fix will be: if we make the highest compactness, we will lose the standardization that our customers like or even love, especially end-user.

Conclusion

To finish on one positive note, few years ago we, the motor manufacturers, we claim a lot with the increase of efficiency to IE3 that will drive us to loose standardization, thanks to the brilliant ideas of our engineering teams, it did not come to reality even some machines, especially the smallest power (up to 22 kW) have seen significantly increase of material content. Fortunately, the single phase motors were out of the directive, as well as the motors with high number of poles otherwise our fears would have come true.

So, the risk to loose frame size standardization is existing, thanks or because of the new technologies, either with or without inverter but our imagination will hopefully allow us to avoid it. Especially if standard to be written and published are integrating our concerns for B2B business and will not consider our products for B2C, with all the constraints attached to this business.

References

[1] Dany Prieto. Modélisation et optimisation des machines synchro-réluctantes à aimants permanents et de leur électronique – Application aux véhicules électriques et aux compresseurs. Thèse de Doctorat – Supélec, 2015.

[2] Dany Prieto, Benjamin Daguse, Philippe Dessante, P. Vidal, Jean-Claude Vannier. Effect of magnets on average torque and power factor of synchronous reluctance motors. IEEE 20th International Conference on Electrical Machines (ICEM) 2012, Marseille (France).

[3] Dany Prieto, Philippe Dessante, Jean-Claude Vannier, Xavier Jannot, Jacques Saint-Michel. Modélisation analytique d'un moteur synchro-réluctant assistée d'aimants permanents. Symposium de Génie Electrique 2014, Jul 2014, Cachan, France.

[4] Benjamin Daguse. Modélisation analytique pour le dimensionnement par optimisation d'une machine dédiée à une chaîne de traction hybride à dominante électrique. Supélec, 2013.

[5] Jacques Saint-Michel. Bobinage des machines tournantes à courant alternatif, Techniques del'Ingénieur, D3420, 10 Février 2001.

[6] B.Delinchant, D.Duret, L.Estrabaut, L.Gerbaud, H. Nguyen Huu, B. du poux, H.L. Rakotoarison, F.Verdiere, F.Wurtz, "An Optimizer using the Software Component Paradigm for the Optimization of Engineering Systems", COMPEL, Vol. 26, Issue 2, pp 368-379, 2007.

[7] CEN-CLC TCTCSec078aDC - M_543 - CEN CENELEC 1st annual report_V2017-04-10

[8] CEMEP Circular Economy working group CEMEP-TF-Cir-Eco_M543_Material-Eff-Standards_2017-05-11_rev2 (cf CEMEP website)

[9] GIMELEC Economie circulaire: Vision et engagement des entreprises de l'équipement électrique et de l'intelligence énergétique (cf GIEMELC website)

Parametric Analysis of Energy Efficient Motors

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Abstract

This paper presents a study on how the manufacturers are working to attend the International Efficiency standards of three-phase squirrel-cage induction-motors. One of the possibilities of improving the efficiency of induction motors is to reduce the stator and rotor resistances, and augmenting the magnetizing branch resistance. A methodology to obtain the parameters of the equivalent circuit of the induction motor from catalog data sheet is proposed. The variation in rotor parameters for deep bars in the rotor as a function of the slip is taken into account. The proposed methodology is applied to several motors from the most representative manufactures. The main parameters that regards to losses and energy efficiency, such as the resistances of the equivalent circuit, are compared, giving an idea on how each of the analyzed manufacturers deals with energy efficiency requirements and how their motors are designed to reach efficiency targets.

Nomenclature

E	Magnetizing branch voltage (V)
EFF	Efficiency of power conversion
g_r	Rotor resistance variation factor
g_x	Rotor reactance variation factor
I_0	No-load current (A)
I_1	Rated stator current (A)
I_2	Rated rotor current (A)
$\bar{I}_{st}$	Startup-to-rated current ratio
M_k	Breakdown torque (Nm)
$\bar{M}_k$	Breakdown-to-rated torque ratio
M_{st}	Startup torque (Nm)
$\bar{M}_{st}$	Startup-to-rated torque ratio
n_R	Rated speed (RPM)
n_S	Synchronous speed (RPM)
P	Mechanical loading power (W)
P_2	Rated full-load motor shaft power (W)
PF	Power factor for a given load
r_1	Stator resistance (Ω)

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r_2'	Rotor resistance referred to the stator (Ω)
r_{20}'	Rotor resistance at start-up (Ω)
r_{2k}'	Rotor resistance at maximum torque (Ω)
r_m	Magnetizing branch resistance (Ω)
s	Motor slip
s_R	Rated rotor slip
s_k	Rotor slip at the breakdown torque
V_1	Rated phase voltage (V)
x_1	Stator leakage reactance (Ω)
x_2'	Rotor reactance referred to the stator (Ω)
x_{20}'	Rotor reactance at start-up (Ω)
x_{2k}'	Rotor reactance at maximum torque (Ω)
x_m	Magnetizing branch reactance (Ω)

Introduction

Three-phase squirrel-cage induction-motors have been widely used since the beginning of the modern industry due to their reliability, robustness, easy application, flexibility, ability to work in harsh environments, low cost, and generally better overall performance when the kW-to-RPM ratio is lower than one. As such motors are responsible for about 40% of the entire consumption of an industrialized country, efficiency is a major issue. If in one hand oversized motors and imbalance of voltage can be found, reducing the overall efficiency, on the other, every tenth of gained efficiency is important.

In order to increase the efficiency of the motors, the Commission Regulations implemented directives with regard to eco-design requirements instituting minimum energy performance standards (MEPS), the so-called three-phase squirrel-cage induction-motor International Efficiency (IE), from one to fourth order, available in the market, in a mandatory fashion [1-2].

IEC 60034-30-1:2014 specifies efficiency classes for single-speed electric motors that are rated according to IEC 60034-1 or IEC 60079-0, for operation on a sinusoidal voltage supply [3]. This standard establishes a set of limit efficiency values based on frequency, number of poles and motor power. No distinction is made between motor technologies, supply voltage or motors with increased insulation designed specifically for converter operation even though these motor technologies may not all be capable of reaching the higher efficiency classes. This makes different motor technologies fully comparable with respect to their energy efficiency potential.

According to this standard, the Standard Efficiency motor (IE1) is the normal motor for general application. The High Efficiency motor (IE2), ranging from 0.75 to 375 kW, and the Premium Efficiency (IE3) ranging from 7.5 to 375 kW. The Super Premium Efficiency (IE4) ranging from 0.75 to 375 kW, target the high motor efficiencies seem until now. The minimum efficiencies are depicted in Figure 1.

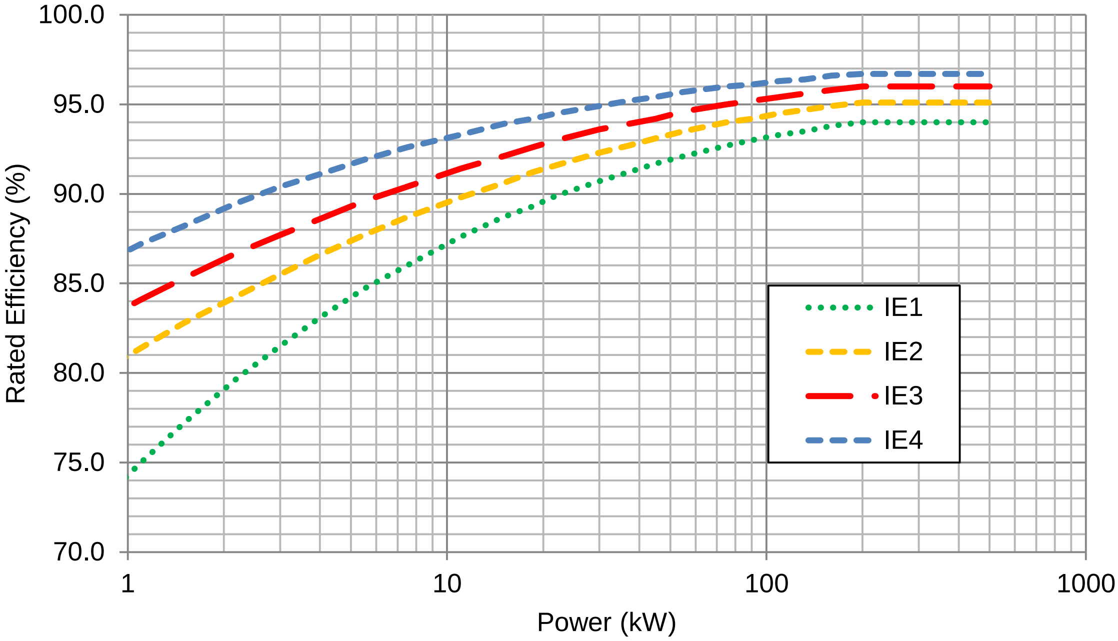

Figure 1 - Efficiencies of the several Induction Motor Classes

Figure 1 shows the rated efficiency for different powers, for IE1 to IE4, 4 poles, 50 Hz. It is worth do notice that EU regulation 640/2009 regards to 0.75 to 375 kW [1-2]. The American counterpart regards to general purpose motors and is referred as NEMA Premium Efficiency EISA Subtype I that is related to the IE3 Premium Efficiency motor, the NEMA Energy Efficiency EPAct Subtype II and NEMA Design B is related to the IE2 High Efficiency, and motors below standard efficiency relates to the IE1 Standard Efficiency [4]. Other similar regulations are available in local regulations.

Figure 2 shows the comparative efficiency gain of a class to another. It can be noticed that a great improvement from class IE1 to IE2. In lower power motors a gain of about 10% can be reached. From IE2 to IE3 and from IE3 to IE4 there is also a gain of the order of 3.5% on the lower powers. In all the cases, the gain is about 1-3% for powers greater than 10 kW. These gains in efficiency can relate to a gain of losses of about 20% from one class to another. It can be notice a greater gain from class IE3 to IE4, than from IE2 to IE3, showing a greater improvement in the first than in the former.

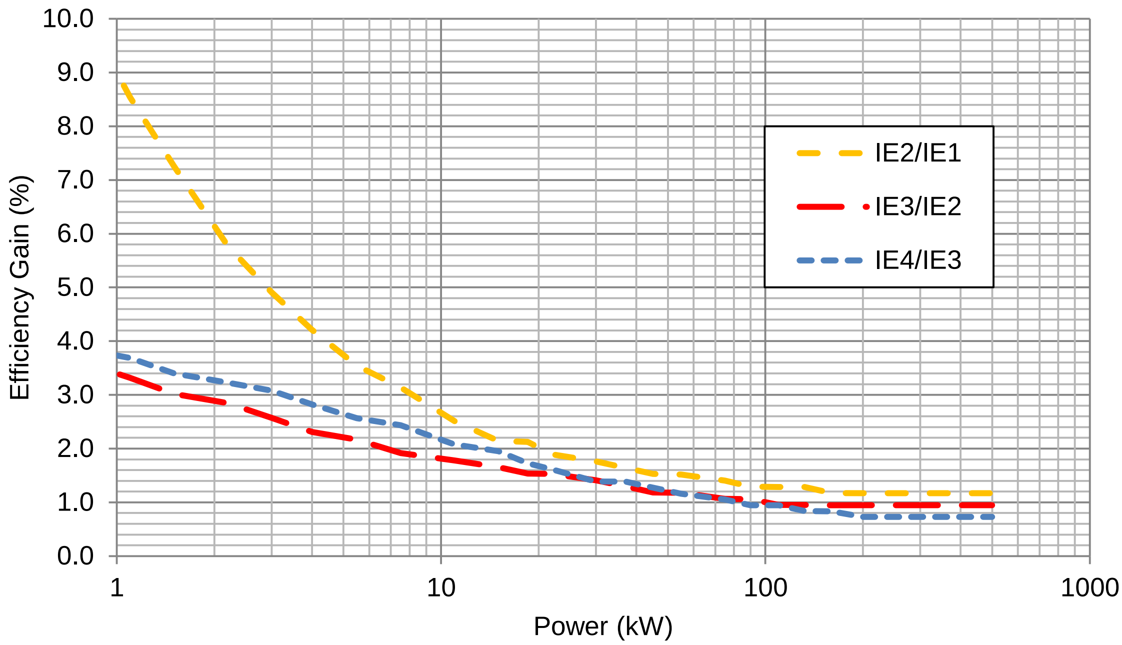

Figure 2 - Efficiency gain between classes

Due to the new materials and design procedures, International Efficiencies are well reachable today. The next level is the IE5 efficiency class, the Ultra-Premium motors, and its goal is to reduce the losses some 20% relative to IE4. Some manufacturers present their solution on IE5, such as ABB, WEG, and KSB, but in general they are reluctance motors. Further energy-efficiency optimizations will have to focus on improved system efficiency throughout the entire operating load cycle including all system-losses such as converter, filter, cables, motor technology, etc.

Equivalent Circuit and Parameter Identification

This work presents a different equivalent circuit in which the rotor parameters, rather than constant, varies with the slip to catch up the high starting torque with low losses at the rated speed. For the modern motors, the variation of the parameters follows the skin effect and is accomplished using deep bars or double cage in the rotor. In order to use regular transient programs, this effect normally is considered by the use of d-axis synchronous machine models without rotor voltage, which is not used here. The used motor equivalent circuit is shown in Figure 3.

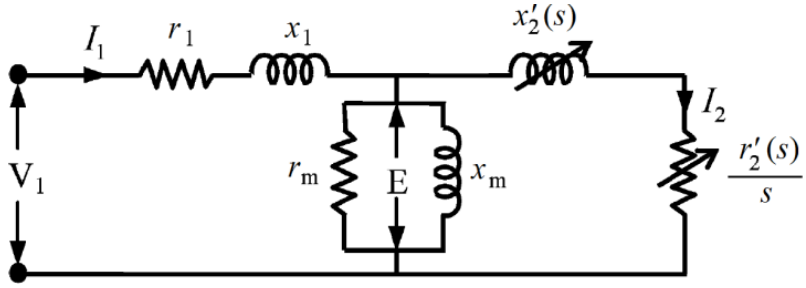

Figure 3 – Equivalent Circuit with variable rotor parameters.

The rotor parameters variation follows the equations (1) and (2). Notice that the parameter varies with the square root of the sleep, which is accordance with the theory [5].

$$r_2'(s) = r_{20}' \exp\langle g_r\sqrt{1-s}\rangle \quad (1)$$

$$x_2'(s) = x_{20}' \exp\langle g_x\sqrt{1-s}\rangle \quad (2)$$

The following items show how the parameters are determined. Methods for the determining the parameters based on catalog data are presented [6]. The value of additional information from the manufacturer data sheet is considered in the improved formulation.

A. Determination of the resistances

In every operating condition, there is a power balance in the motor in which the electromagnetic power is the result of subtracting the rotational losses and the stator copper loss from the power input.

$$3r_1I_1^2 + P_{rot} = \frac{P_2}{Eff} - \frac{P_2}{1-s} \quad (3)$$

The rotational loss is the summation of the core losses (hysteresis and eddy currents), windage, friction, and stray losses. Despite the shaft speed changes with the machine loading, the summation of the aforementioned losses is practically constant for all the loading conditions, mainly due to the constant rotation speed of the revolving field. In other words, as long as the windage and friction losses decrease with the increasing loading (shaft speed reduction), the core and stray losses increase in almost the same proportion, such that the rotational losses are kept nearly constant for all the machine loadings in the operating region. Rewriting (3) for the three operating conditions of the motor, i.e., half, three quarters, and full load. The stator resistance is the slope of the linear fit obtained from ordinary least-squares techniques.

$$r_1 = slope\,\langle\frac{P_2}{EFF} - \frac{P_2}{1-s}; 3I_1^2\rangle \quad (4)$$

The slip for any loading condition between no load and full load can be obtained as

$$s = \frac{1}{2}\left[1 - \sqrt{1 - 4s_R(1-s_R)P/P_2}\right] \quad (5)$$

For the rotor resistance, it is considered that the power dissipated in the resistance due to the current I_2 is lower than the power dissipated in the resistance due to the current I_1 by a constant. Again, writing this balance for the three known operating conditions of the motor, the rotor resistance referred to the stator can be obtained as the slope of the equation by using least-squares linear fit techniques.

$$r_2' = slope\,\langle P_2\frac{s}{1-s}; 3I_1^2\rangle \quad (6)$$

The value of the rotor resistance referred to the stator at the start-up can be determined by considering that all the electromagnetic power in this condition is dissipated in the rotor resistance.

$$r'_{20} = \frac{P_2 \bar{M}_{st}}{3(I_2 \bar{I}_{st})^2} \frac{n_S}{n_R} \tag{7}$$

If a limited catalog is available, the stator resistance per phase may be determined by (8).

$$r_1 = \frac{15V^2}{\pi M_k n_s} - \frac{r'_2}{s_k} \tag{8}$$

The rotor resistance is determined by knowing that its variable parcel dissipates rated power at rated conditions.

$$r'_2 = \frac{s_R}{1 - s_R} \frac{P_2}{3I_2^2} \tag{9}$$

The rated rotor current is calculated based on the full-load power factor:

$$I_2 = I_1 PF \sqrt{1 + (s_R/s_k)^2} \tag{10}$$

With s_R and s_k given by:

$$s_R = \frac{n_s - n_R}{n_S} \tag{11}$$

$$s_k = s_R \left(\bar{M}_{st} + \sqrt{\bar{M}_{st}^2 - 1} \right) \tag{12}$$

From (1), the rotor resistance variation factor is

$$g_r = \frac{\ln(r'_{20}/r'_2)}{\sqrt{1 - s_R}}. \tag{13}$$

Therefore, the resistance of the rotor at the breakdown torque is:

$$r'_{2k} = r'_{20} \exp\langle g_r \sqrt{1 - s_k} \rangle. \tag{14}$$

B. Determination of the reactances

The short-circuit reactance is calculated to attend the starting current.

$$x_s = \sqrt{\left(\frac{V_1}{\bar{I}_{st} I_1}\right)^2 - (r_1 + r'_{20})^2} \tag{14}$$

In a simple manner, the relationship between x_1 and x_{20} depends on the relationship between M_{st} and M_k, according to (15) and (16).

$$x_1 = \left(0{,}6 - 0{,}3\ \frac{M_{St}}{M_k}\right) x_s \tag{15}$$

And

$$x'_{20} = x_s - x_1 \tag{16}$$

Taking the derivative of the torque in relation to the slip [5], the reactance x_{2k} can be calculated when s is equal to s_k.

$$x'_{2k} = \frac{r'_{2k}}{s_k} \tag{17}$$

The rotor reactance variation factor is given by

$$g_x = \frac{\ln(x'_{20}/x'_{2k})}{\sqrt{1 - s_k}}. \tag{18}$$

And the rotor reactance in rated conditions is

$$x'_2 = x'_{20} \exp\langle g_x \sqrt{1 - s_R}\rangle. \tag{19}$$

C. Determination of magnetizing parameters

The magnetizing branch voltage is obtained from the voltage drop in the stator impedance.

$$E = V_1 - I_1 (r_1^2 + x_1^2)^{1/2} \tag{20}$$

The magnetizing resistance is determined by considering that it will assume all the rotational losses.

$$r_m = \frac{P_2}{3}\left(\frac{1}{EFF} - \frac{1}{1 - s_R}\right) - r_1 I_1^2 \quad (21)$$

With the no-load current, the reactance of the magnetizing branch is given by

$$x_m = \frac{E}{\sqrt{I_1^2 - I_2^2 - (E/r_m)^2}}. \quad (22)$$

Parametric Analysis

Different manufactures take different actions to accomplish the efficiency standard requirements. In general the better motor efficiency is obtained by increasing the mass of copper on the stator, enhancing motor behavior due to their higher electrical conductivity; greater amount of conductor material on the rotor; new motor designs do reduce noise, vibration levels, and mechanical losses; reduced operating temperatures through optimized cooling system designs, i.e., fan, fan cover, and frame; thinner laminations and greater silicon concentration reducing eddy current losses in the core. As an example, Figure 4 shows the full load approximate losses distribution of a regular motor, in which the main efforts of increasing efficiency are spent.

Therefore, the methodology presented in the previous topic is applied in International Efficiency motors of several powers, levels, and manufactures. The stator, rotor and magnetizing branch resistances are evaluated and conclusion is reached from that. Different manufacturers are analyzed. Figures 5 to 7 present the main cause of losses in motors there are stator, rotor and core losses of manufacturer WEG as it manufactures motor classes 1 to 4. Figures 8 to 10 present WEG, ABB, SIMENS, and LS comparisons for IE2 due to its large influence in the European market. Figures 11 to 13 present the same analysis for IE3 motors.

The motors were select with the following characteristics: Direct mains fed, cast iron, general purpose motor, 50 Hz, 400 V, delta connected, with one to four pole pairs, efficiency classes from one to four, rated output from one to one hundred kilowatts, insulation class F, temperature rise class B, protection class 55, and continuous mode of operation S1.

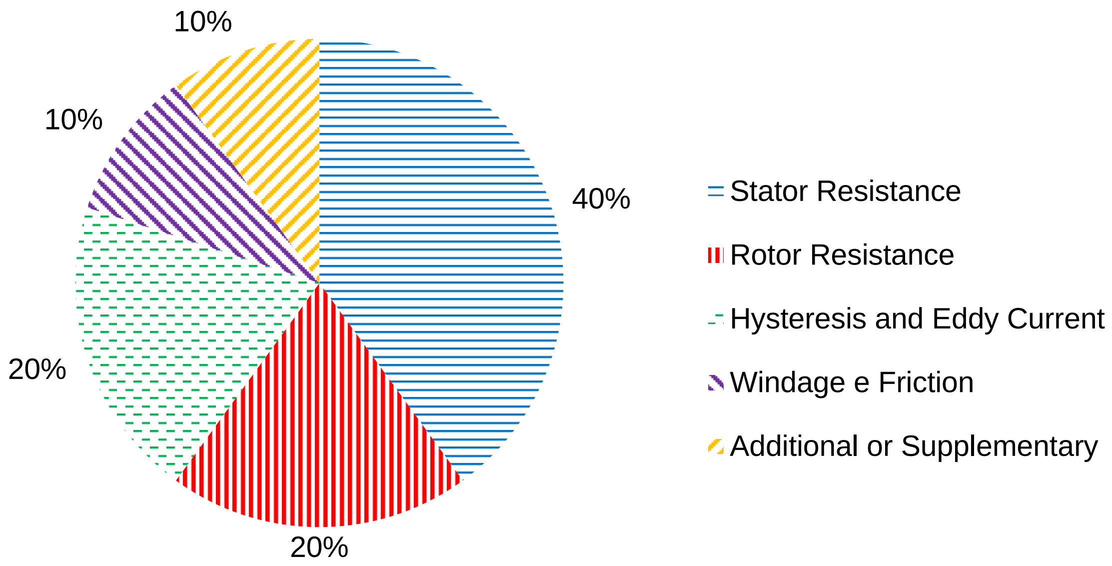

Figure 4 - Approximate full-load distribution of the losses in a regular motor.

A. Stator Resistance

The copper losses in the stator represent something about 25-40% of the losses in the motor. The reduction of stator resistance is one of the taken measures to have a more efficient motor. It is made increasing the cross section and the copper content of used conductor. Figure 4 shows how the more the stator resistance decreases the more the efficiency increases for WEG motors. It can be seen that, in general, the stator resistance of IE4 is lower than IE3 that is lower than IE2, which is lower than IE1.

From 1 to 100 kW, the rate of decay of the resistance, equal for the four efficiency classes, is approximately 1.25.

B. Rotor Resistance

The rotor losses are due to the passage of the current through the rotor material and accounts of 15-25% of the total losses of the motor. In the equivalent circuit, almost all the stator current flows to the rotor, excepting the no-load current. Therefore, the rotor losses will be proportional to resistance of the rotor, forcing the reduction of rotor resistance. The rotor is constructed of copper, aluminum, or a hybrid cage.

Figure 5 shows the behavior of the rotor resistance as a function of the motor power for different international classes for motors WEG.

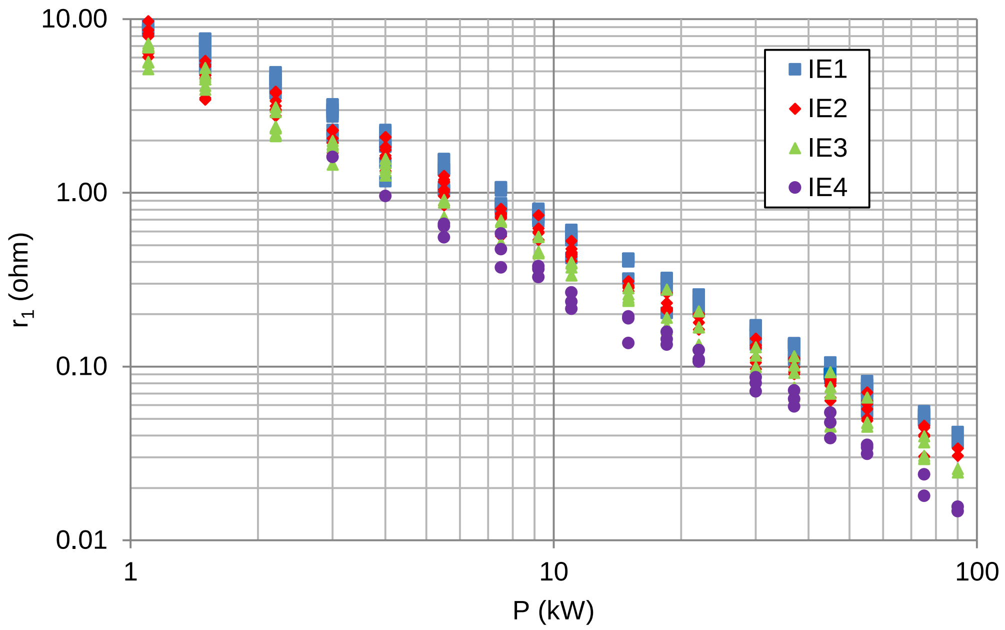

Figure 5 - Calculated stator resistance of motor WEG.

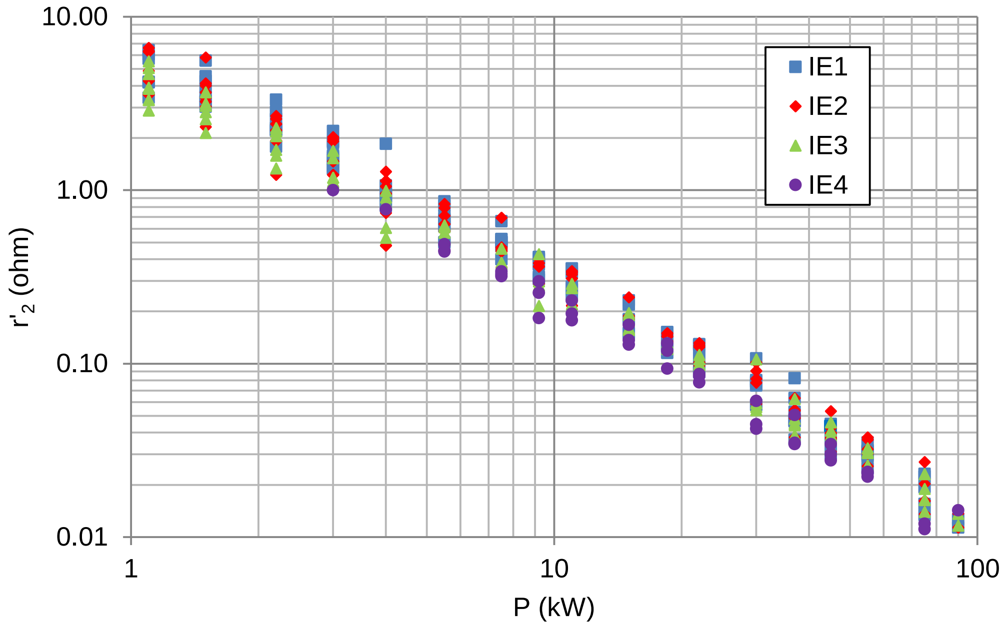

Figure 6 - Calculated rotor resistance of motor WEG.

C. Magnetizing Branch Resistance

The magnetizing branch losses is connected to eddy currents, a Joule nature therefore, and hysteresis. It accounts of 10-20% of the total losses of the motor. The way to reduce it is to improve the magnetic material used in the core of the machine, increasing its silicon contents. Also, it is common to reduce the size of the slice of the material, reducing the current through it and the proportional copper losses. The described measures result in less magnetic losses, which can be represented for greater magnetizing resistances. When looking to the circuit of Figure 3, the magnetizing resistance can be realized as a shunt resistance.

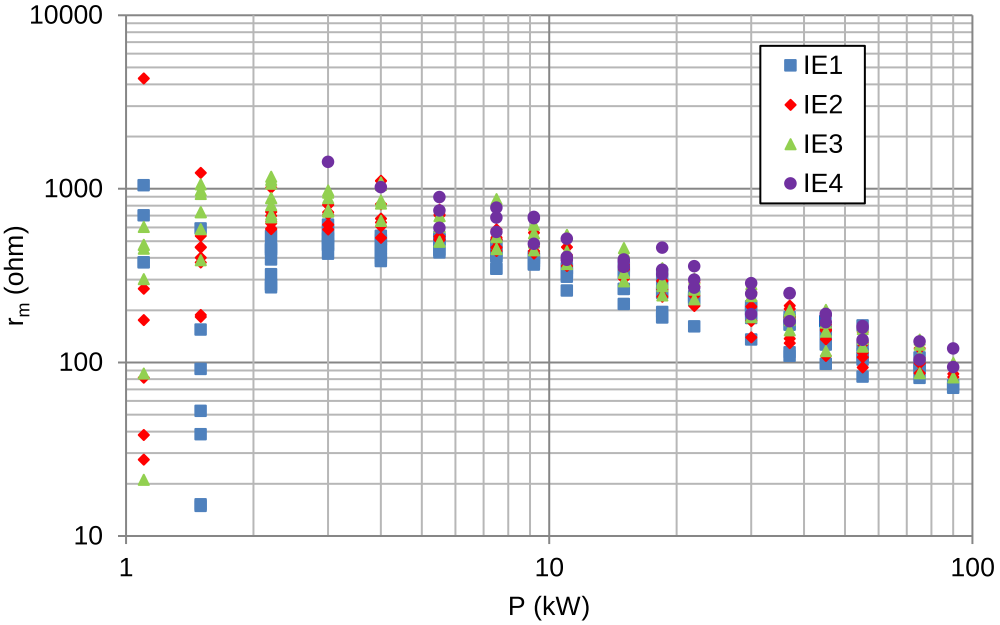

Figure 7 - Calculated magnetizing branch resistance of motor WEG.

This affirmation can be noticed in Figure 7, as the efficiency increases, the resistance does not decrease. It is important because the rotor resistance increases with efficiency, as the amount of no-load current reduces, reducing the no-load losses. It was also noticed a strong influence of the rotational speed over the magnetizing branch resistance calculated value.

D. Manufacturers Comparison

Regarding to the stator resistance, for motors IE class 2, it was noticed that LS has the greatest stator resistance value in almost all the range. On the other hand, WEG, ABB and SIEMENS have the lowest value in that range. There are some changes between the manufacturers when calculating the rotor resistance in IE2 motors. For lower powers, the SIEMENS presents the lower values of rotor resistance. For medium powers ABB shows the lowest resistances, and for high powers the LS and WEG show the best results with lower rotor resistances.

When analyzing the magnetizing branch, according to the spread catalog, the SIEMENS motor has the lower magnetizing branch resistance, followed by ABB and WEG. The LS brand has the highest magnetizing branch resistance in almost all the powers range. It must be noticed that it is good to have a high value of magnetizing branch resistance, as the magnetizing current will be lower and the losses are proportional to the square of the current. Figures 8, 9 and 10 depict the presented.

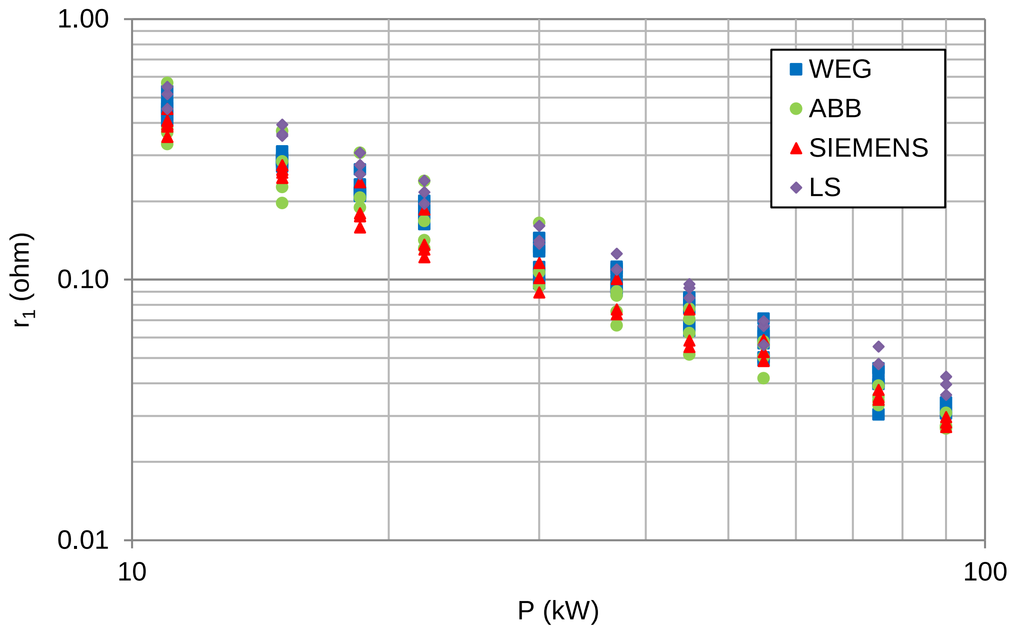

Figure 8 – Stator resistance variation for IE2 motors.

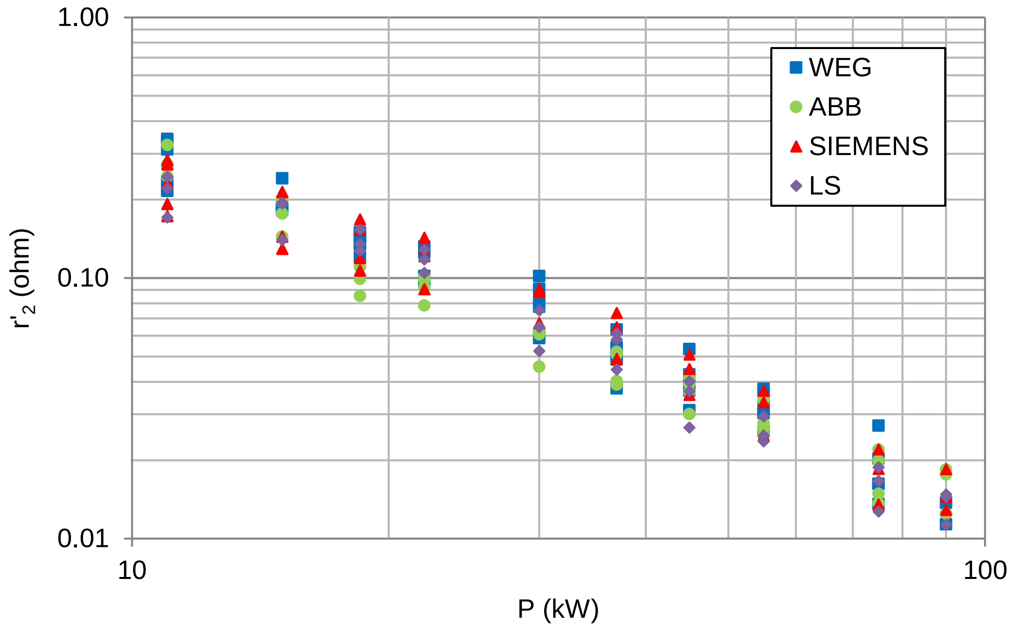

Figure 9 - Rotor resistance variation for IE2 motors.

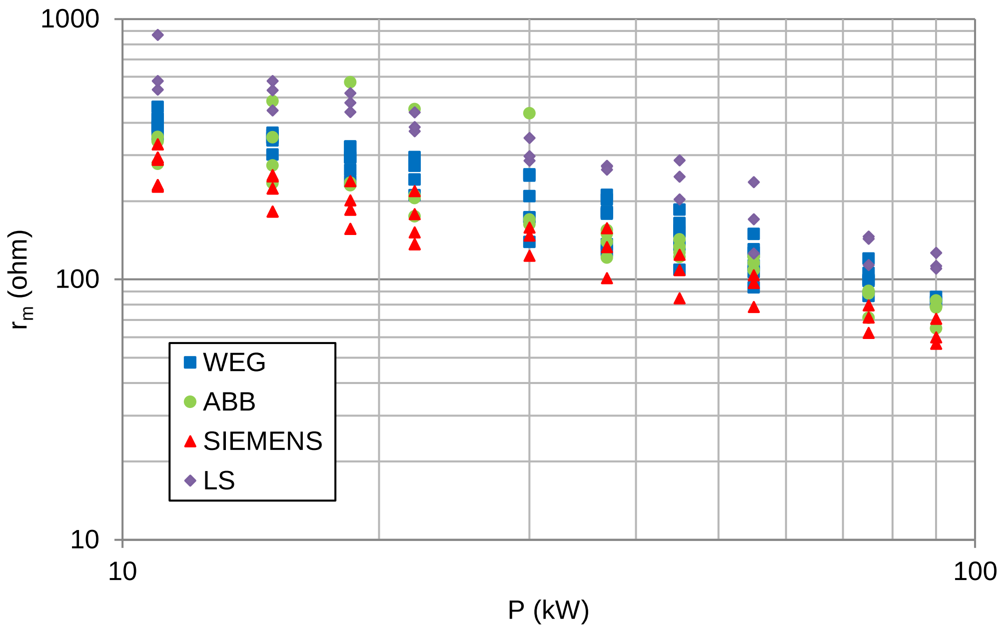

Figure 10 – Magnetizing branch resistance variation for IE2 motors.

Figures 11, 12, and 13 show the results of the resistances obtained for the calculations of IE3 class motors. It has been showed that WEG and LS have the highest stator resistance, while SIEMENS and ABB have the lowest. A lower stator resistance helps largely in a loss reduction, as the stator losses accounts for about 40% of the three-phase induction motor total losses.

Regarding rotor resistance, SIMENS has the higher value at lower powers, and WEG for the higher powers. In general, ABB has the lower value of rotor resistance for all the powers, and LS has an average value. In the same line of the stator losses, the rotor losses are current losses in its majority and accounts of about 20% of the total losses. Therefore, a lower rotor resistance value allows a lower rotor loss.

The magnetizing branch influences in the no-load current and in the magnetic losses, i.e., eddy current and hysteresis losses. Therefore, a higher value of magnetizing branch resistance means lower losses. In all the studied range, LS motor has showed a higher value of magnetizing branch resistance, and ABB and SIEMENS have showed a smaller value of magnetizing branch resistance. WEG has showed intermediate values.

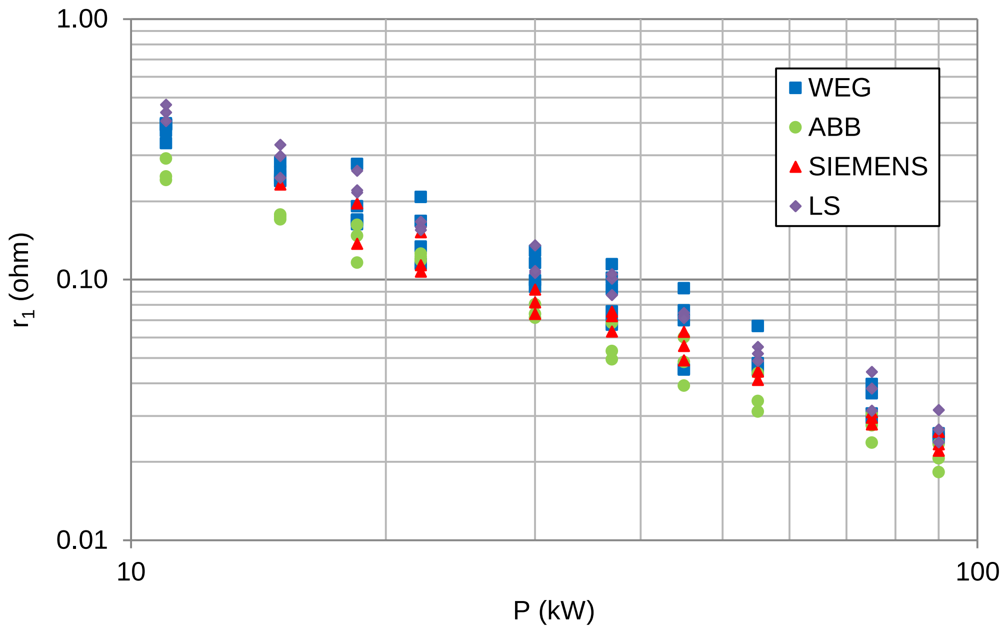

Figure 11 – Stator resistance variation for IE3 motors.

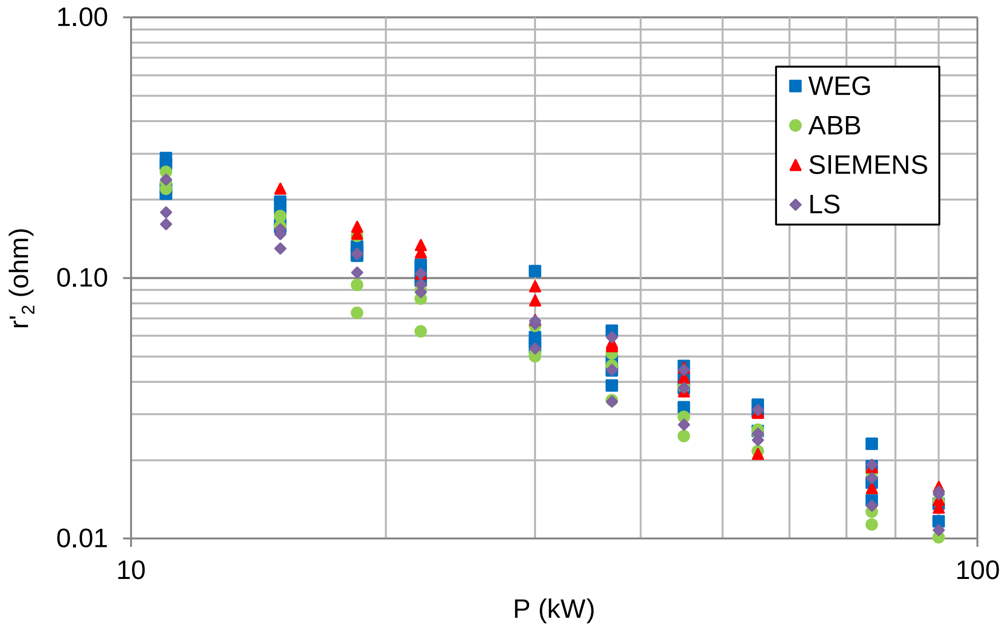

Figure 12 – Rotor resistance variation for IE3 motors.

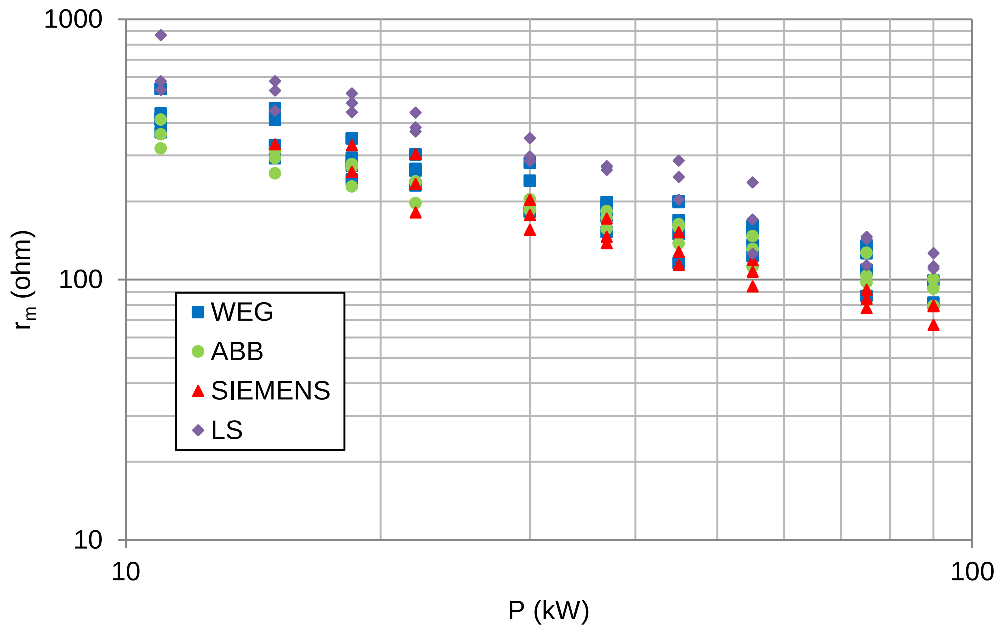

Figure 13 – Magnetizing branch resistance variation for IE3 motors.

Conclusions

The paper showed a methodology to evaluate the equivalent circuit of a three-phase induction motor. The methodology is algebraic and there is no dependence on optimization techniques and can be implemented straightly in a specific software or spreadsheet. The results of its application to the most important manufacturers have showed how they have dealt with the efficiency required by the most important standards. The methodology is applied to the available catalog data for dozen or motors and the results are analyzed in terms of how the resistances vary: stator resistance, rotor resistance, and magnetizing branch resistance. As it is wanted to reduce the losses of the motor, minimizing the stator and rotor resistances would reduce the current losses. In the same way, it is wanted to increase the magnetizing resistance, reducing the no-load current and the magnetic losses. When moving from IE2 to IE3, LS changed for the higher stator resistance value to the lowest resistance, while WEG, ABB and SIEMENS showed an average to low behavior of the stator resistance. Regarding to rotor resistance, SIEMENS moved from the lower value to the highest value in the low power range for the transition of IE2 to IE3 efficiency classes, and ABB maintained the lower values for about all the powers. WEG moved from the small values in the IE2 class to average values in IE3 class, and LS has an average value for all the powers and classes. Also, LS has maintained its branch resistance high value for all the powers and classes, and the lower value in both classes belongs to SIEMENS. ABB and WEG have shown intermediate branch resistances in the transition from IE2 to IE3 classes. It is concluded that, while reaching the efficiency requirements of the international standards, the several manufactures follow different paths to obtain the desired results, either reducing the series resistances or increasing the shunt resistance. The application of the proposed method may throw lights the reach better efficiencies.

Acknowledgement

The authors appreciate FAPEMIG, CNPq, INERGE, and CAPES, for their support to conduct research.

References

[1] Commission Regulation (EU) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors.

[2] Commission Regulation (EU) No 4/2014 of 6 January 2014 amending Regulation (EC) Nº 2 640/2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors.

[3] IEC 60034-30-1:2014. Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code), 50 p.

[4] A. Bonnett, C. Yung, "A Construction, Performance, and Reliability Comparison for Pre- EPAct, EPAct, and Premium-Efficiency Motors." IEEE Paper #PCIC-2006-7, 2006.

[5] M. Kostenko, L. Piotrovsky. Electrical machines – Part 2. Mir Pub. Moscow, 1977.

[6] J.M.C. Guimarães, J.V. Bernardes Jr., A.E. Hermeto, E.C. Bortoni. Parameter Determination of Asynchronous Machines from Manufacturer Data Sheet. IEEE Trans. on Energy Conversion, Vol. 29(3), Sept. 2014, pp. 689 - 697.

Energetic Performance Analysis of Soft Magnetic Materials for High Efficiency Electric Motors

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Abstract

Electrical machines efficiency is a key issue for the reduction of the absorbed electrical power in the industry sector with consequent benefit on pollutant emissions. For this reason, the accurate evaluation of power losses assumes a significant role during the design stage of electric motors. Among the different loss sources, iron losses represent one of the most difficult contributions to be evaluated as they depend on the non-linear soft magnetic material characteristics. Electrical engineers as well as Finite Element Software dedicated to electrical machine analyses, usually recur to the energetic model that represents the total iron losses through three main contributions: hysteresis, eddy current and excess losses. Nevertheless, this approach relies on some empirical coefficients that are not provided by the material producers. This paper reports the analytical procedure for the empirical coefficients computation starting from the data reported in the material datasheet. On the basis of this procedure, the paper discusses the energetic performance of different silicon iron materials suitable for electric motors. In particular, the analysis considers silicon iron magnetic steels having different quality and different lamination thickness, reporting the empirical coefficients suitable for the computation of the hysteresis, eddy current and excess loss contributions.

Introduction

Electrical machines are the main electrical load in the industrial sector with a consumption that is around 70% of the absorbed electrical power, with an impact of about 40% on the worldwide electricity production [1]. The global need of reducing the CO_2 emissions, together with the necessity of reducing the energy cost whatever is the company size, unquestionably drive the main target of the electrical machine design towards higher efficiency solutions. This concept is also endorsed by several studies reported in technical literature which show that relevant energy savings can be obtained using electrical machines with higher efficiency [2]-[4].

In the industry sector, the induction machines can be considered the backbone of the electromechanical conversion and for this reason, in the last decades different countries have promulgated set of rules dedicated to the efficiency measurement and machines labeling within defined efficiency classes. For instance, in EU the International Electrotechnical Commission (IEC) promulgated the International Standard IEC 60034-30 [5], [6] that defines three efficiency classes for low-voltage induction motors: Standard Efficiency (IE1), High Efficiency (IE2) and Premium Efficiency (IE3). In 2014 the IEC issued the second edition IEC 60034-30-1 [7] that substantially extends its applicability to a wider range of low voltage induction motors and introduces the Super-Premium Efficiency class (IE4). Fig. 1 shows the comparison between the efficiency classes defined by the European IEC Standards and those defined by the American NEMA Standards.

In addition to the above mentioned efficiency classes, a new Ultra-Premium (IE5) efficiency class has already been envisaged for the next edition of the IEC standard. The foreseen target for the IE5 is to further reduce by 20% the losses compared to the IE4. Nevertheless, researchers agree that achieving this target for the Ultra-Premium efficiency class requires further improvements on motor technologies together with the development of new materials [1].

It has to be remarked that, although the above mentioned International Standards are limited to three phase industrial motors, the high efficiency target also concerns electrical machines dedicated to transportation applications. Indeed, in transport sector the energy storage is limited and, as a consequence, increasing demands are put on maximized efficiency and minimized losses.

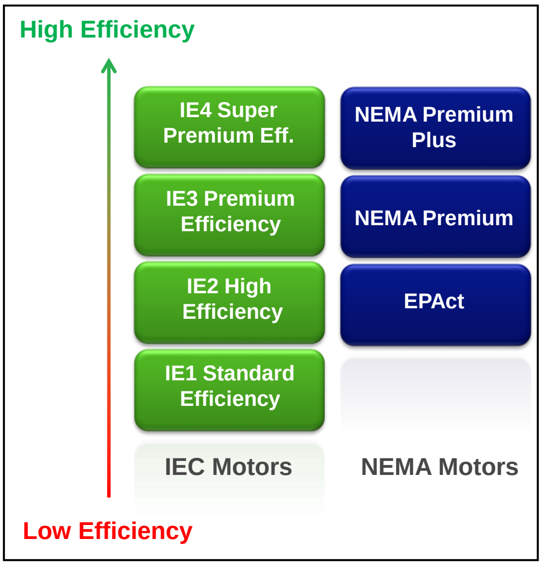

Figure 1: Efficiency classes defined by IEC and NEMA Standards for three-phase industrial induction motors.

In this perspective, an accurate evaluation of the efficiency assumes a key role in the electrical machine design. Aside to the copper losses, a significant attention is put on the magnetic losses, also known as *'iron losses'*. This loss source represent one if the most difficult to be evaluated as they depend on the non-linear characteristics of the soft magnetic material. In literature different approaches have been proposed to evaluate the energetic behavior of soft magnetic materials used in electrical machines, considering both sinusoidal and non-sinusoidal power supply [8]-[11]. Among them, the most suitable for an immediate application by the electrical machine designers is based on the representation of the iron losses by means of three main contributions, namely the hysteresis losses, excess losses and eddy current losses. As discussed in this paper, often this approach is used for the iron losses computation algorithms in the most common Finite Element Analysis "FEA" commercial software for the motor electromagnetic design. Nevertheless, this energetic model relies on some empirical coefficients that depend on the chemical and physical features of the considered soft magnetic material. Usually, these coefficients are not reported in the datasheet provided by the material producers and their identification is delegated to the machine designer.

This paper proposes an analytical approach for the identification of the empirical coefficients used in the energetic model based for the segregation of the total iron losses in the hysteresis, eddy currents and excess contributions. The energetic model considered in this paper has been originally proposed in [8]. However, for the reader convenience a brief description of the three main contributions is reported together with the formulations used in some commercial FEA software adopted for electrical machine design. The analytical approach for the empirical coefficients computation is applied to different silicon iron soft magnetic materials suitable for electrical machine design, considering different grades and different lamination thickness. The paper reports the iron losses and the energetic performance analysis of the considered materials providing the empirical coefficients suitable for the computation of the hysteresis losses, excess losses and eddy current losses.

Energetic model and iron loss contributions

With reference to the energetic model proposed in [8], the total iron losses in a soft magnetic material can be computed as the sum of three main contributions as shown in the following equation:

$$P_{iron} = a \cdot f \cdot B_{\max}^{x} + b \cdot f^{2} \cdot B_{\max}^{2} + e \cdot f^{1.5} \cdot B_{\max}^{1.5} \text{ [W/m}^3\text{]} \quad (1)$$

where *f* is the magnetization frequency, B_{max} is the maximum value of the magnetic flux density and the coefficients '*a*, *b, x, e'* depends on the chemical and physical characteristic of the material. The formulation expressed in (1) allows evaluating the specific iron losses expressed in Watts per kilogram for sinusoidal voltage supply.

The first term of (1) corresponds to the '*hysteresis losses*'. This contribution is due to the steady–state losses of the Weiss domains when a magnetic material is magnetized with a variable magnetic field. This term depends linearly on the magnetization frequency, while the peak value of the magnetic flux density depends on the Steinmetz coefficient *x*.

The second term of (1) is related to the eddy currents circulation in the magnetic materials. It has a quadratic dependence both on the magnetization frequency and on the maximum value of the magnetic flux density. This term is commonly denominated *'eddy current losses'* in the engineering world, while the physic community refers to this contribution as *'classical losses'*.

When a variable magnetic field is applied to a magnetic material, the Weiss domains are also subject to dynamic losses, with consequent discontinuous movements of the Block walls that produce the Barkhausen jumps. As [8] describes in detail, the very fast Barkhausen jumps produce eddy currents and related Joule losses. The contribution to the iron losses due to this phenomenon is accounted by the third term of (1), which is referred as '*excess losses*'.

It has to be remarked that the validity of (1) is restricted to sinusoidal supply only. Indeed, non-sinusoidal waveform introduces other phenomena that contribute to the iron losses depending on the applied waveform. For instance, it is worth mentioning the creation of minor hysteresis loops. Although the area of minor loops is much smaller than the major one, they are covered several times resulting in a significant impact on the hysteresis losses contribution. The technical literature reports many studies and approaches for the extension of (1) to non-sinusoidal waveforms. For example, [10] proposes an engineering approach based on harmonic series decomposition for predicting iron losses in soft magnetic materials with arbitrary voltage supply. This energetic model extension nevertheless requires the computation of the empirical coefficients of (1). Nevertheless, during the machine design stage, the FEA analyses are usually performed considering sinusoidal supply voltages. For this reason, the focus of this paper is restricted to the evaluation of the empirical coefficients '*a*, *b, x, e'* of the energetic model in (1).

Typical formulations for the iron losses computation in commercial FEA software

Nowadays, FEA are widely adopted in the electrical machines' design process. These tools allow evaluating with high accuracy the peak value of the flux density for each node of the mesh. Most of the commercial FEA software used for electrical machines magnetic analysis approach the iron losses computation with algorithms that are substantially based on the formulation expressed in (1). As a consequence, the accuracy of the results strictly depends on the accuracy of the empirical coefficients inserted by the designer. This section provides a brief excursus on the typical formulations adopted by these software in order to put in evidence their similarities with (1), without the intention of being a discussion about what is the best formulation.

To compute the total iron losses, the commercial FEA software *Flux* [12] uses the following formulation:

$$P_{tot} = c_1 B_{\max}^2 f + c_2 (B_{\max} f)^2 + c_3 (B_{\max} f)^{3/2} \quad [\mathrm{W/m^3}] \qquad (2)$$

where 'c_1' is coefficient of losses by hysteresis, 'c_2' is the coefficient of eddy current losses and 'c_3' is the coefficient of excess losses. In this software, the coefficient 'c_2' and 'c_3' are expressed in function of the material properties and the lamination thickness, leading to the formulation expressed in (3).

$$P_{tot} = \left(k_h B_{\max}^2 f + \sigma \frac{\pi^2 d^2}{6} \left(B_{\max} f \right)^2 + 8.67 \cdot k_e \left(B_{\max} f \right)^{3/2} \right) \cdot k_f \quad [\mathrm{W/m^3}] \qquad (3)$$

where k_f is the lamination filling factor. This expression is similar to (1) except for the term related to the eddy current losses. In particular, (3) directly relates the eddy current contribution to the conductivity 'σ' and to the thickness 'd' of the lamination sheet. It has to be highlighted that the Steinmetz coefficient in (3) is fixed equal to 2 (typical values for this coefficient are in the range 1.8 – 2.2 [10]). A further extension of (3), introduces for all the three contributions the empirical coefficients α and β at the exponent of B_{max} and f, respectively. Besides this extension, it is evident that the computation of the total iron losses by means of (3) requires at the user the introduction of the empirical coefficients for the hysteresis losses 'k_h' and for the excess losses 'k_e'.

The FEA software *JMAG* [13] uses the following formulation:

$$W = K_h B^{\alpha} f^{\beta} + K_e B^{\gamma} f^{\delta} \quad [\mathrm{W/m^3}] \qquad (4)$$

Again this expression is similar to (1) except that (4) does not explicit the contribution related to the excess losses. Over the coefficients at the exponent of 'B' and 'f', also in this case the user has to insert the empirical coefficients 'K_h' and 'K_e'.

As evident from (5), also *ANSYS Maxwell* [14] approaches the iron losses computation with the sum of the three above mentioned contributions. Also in this case the user has to insert the empirical coefficients related to the hysteresis losses (K_h), to the eddy current losses (K_c) and to the excess losses (K_e).

$$P_{vol} = P_h + P_c + P_e = K_h f B_{\max}^2 + K_c f^2 B_{\max}^2 + K_e f^{1.5} B_{\max}^{1.5} \quad [\mathrm{W/m^3}] \qquad (5)$$

The FEA software *MagNet* [15] uses the formulation in (6), which separates the iron losses in the hysteresis and eddy current loss contributions.

$$P = K_h f^{\alpha} B_{peak}^{\beta} + K_e \left(s \cdot f \cdot B_{peak} \right)^2 \quad [\mathrm{W/m^3}] \qquad (6)$$

In (6) 's' is the lamination thickness ratio and it is not empirical value. It allows using the same empirical coefficients for different material thicknesses. Again, also in (6) the user has to insert the hysteresis (K_h) and the eddy current (K_c) empirical coefficients.

Equations (2)-(6) show that the considered FEA software evaluates the total iron losses using formulations that are similar to (1). This approach requires to the user the insertion of empirical coefficients related to the different iron losses contributions. The following section describes the analytical approach proposed to determine the empirical coefficients for the computation of the iron losses contributions.

Equations (2)-(6) show that the magnetic loss formulations used by most of the FEA software are substantially based on (1). Thus, it is rather straightforward to evaluate the total iron losses once the empirical coefficients '*a*, *b, x, e*' have been determined. The following section describes the analytical approach proposed for their computation.

Procedure for the empirical coefficients computation

The analytical approach to evaluate the unknown coefficients is based on the analysis of the core loss curves (Watts per kilogram) at different frequencies that are provided in the material datasheets. In particular, it consists on computing the unknown coefficients '*a*, *b, x*, *e*' that minimize the mean square error between the total iron losses predicted by

(1) with respect to the values measured by the producer. The objective equation that has to be minimized is the following:

$$\frac{1}{n}\sum_{k=1}^{n}\left(\frac{P_{ir\_meas}-P_{ir\_pred}}{P_{ir\_meas}}\right)^2 \qquad (7)$$

where P_{ir_meas} are the measured iron losses provided in the material datasheet and P_{ir_pred} are the iron losses predicted by (1), and n is the number of measured points (i.e. the different values of intrinsic induction for which the manufacturer has tabulated the measurements).

Producers of soft magnetic materials typically report in their datasheet the core loss values for different measurement points (intrinsic induction values) at different frequency levels. For instance, Figure 2 shows some core loss curves obtained by the data tabulated in the datasheet of a fully processed non-oriented M400-50A silicon steel [16].

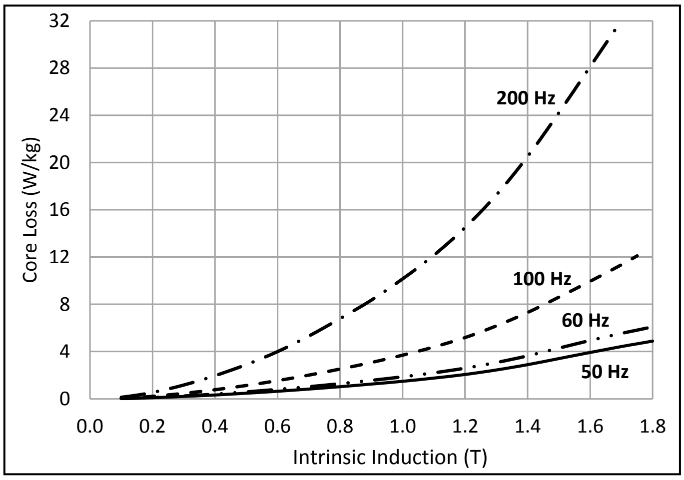

Figure 2: Total core loss for different frequencies provided in the material datasheet for a fully processed non-oriented M400-50A silicon iron steel [16].

Starting from arbitrary values for '*a*, *b, x*, *e*', the proposed procedure consists in finding a set of these coefficients that allows minimizing (7) for each frequency level. Nevertheless, from the electrical machine designer viewpoint, it would be useful to have a set of empirical coefficients that is suitable for different frequency level. In this way, the designer can perform FEA for different working points (i.e. different speeds and supply frequencies) without the necessity of setting different empirical coefficients for the iron losses evaluation. Thus, to find a set of empirical coefficients '*a*, *b, x*, *e*' suitable for different frequency levels, equation (7) is modified in:

$$\frac{1}{m}\sum_{j=1}^{m}\left[\frac{1}{n}\sum_{k=1}^{n}\left(\frac{P_{ir\_meas}-P_{ir\_pred}}{P_{ir\_meas}}\right)^2\right] \qquad (8)$$

where the index '*j*' represents the different frequency levels considered for the empirical coefficients identification. In other words, (8) minimizes the average value of the mean square error for the considered frequencies.

It has to be highlighted that often is not convenient to define a unique set of coefficients '*a*, *b, x*, *e*' for all the frequency levels. Indeed, the phenomena that contribute to the total iron losses in the low frequency range are rather different compared to that at the high frequency levels. For instance, hysteresis losses predominate in the low frequency range, while at higher frequencies the impact of the eddy current losses becomes relevant. For this reason, to have a good match between predicted and measured values, it is often useful to define few sets of the coefficients '*a*, *b, x*, *e*' valid for a restricted range of frequency levels.

Computational example of the empirical coefficients for a M400-50A silicon steel

To minimize (8) for identifying the '*a*, *b*, *x*, *e*' coefficients, the authors use the Solver embedded in Microsoft Excel, but obviously any other tools or programming language can be used. Figure 3 shows the comparison between measured and predicted total iron loss at 50 Hz for a fully processed non-oriented M400-50A silicon steel.

The measured iron losses are those provided in the material datasheet [16], while the predicted ones have been obtained by (1) applying the following coefficients:

a=0.0223; b=0.0001413; x=1.82; e=0.000335

For this material, the producer provides the iron loss measurements for several frequency levels in the range 10 Hz - 1.2 kHz. Nevertheless, the above coefficients have been determined considering a restricted range of frequencies (10 Hz – 100 Hz) in order to obtain a better match between measured and predicted iron losses. In particular, for this material the authors found satisfactory results defining three sets of empirical coefficients '*a*, *b*, *x*, *e*', as listed in Table 1.

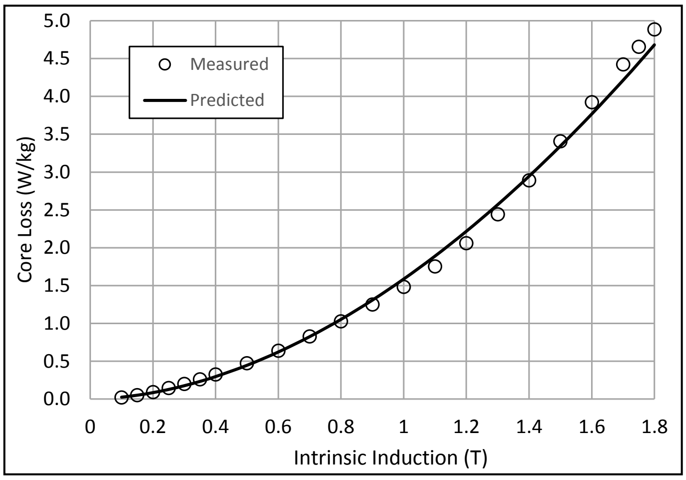

Figure 3: Comparison between measured [16] and predicted total iron loss at 50Hz for a fully processed non-oriented M400-50A silicon iron steel.

Table 1. Empirical coefficients determined for the M400-50A soft magnetic silicon iron steel.

Frequency levels	**a**	**b**	**x**	**e**
10Hz - 50Hz - 60Hz - 100Hz	0.0223	0.0001413	1.82	0.000335
200Hz - 400Hz - 700Hz	0.0335	0.0001138	1.87	0
1kHz - 1.2kHz	0.0159	0.00009581	2.07	0.0006072

Figure 4 shows the comparison between predicted and measured iron losses at 60 Hz and 100 Hz, while Figure 5 shows the same comparison for 200 Hz and 1.2 kHz frequency levels. Also in these cases, the predicted total iron losses have been obtained by (1) applying the empirical coefficients listed in Table 1, depending on the considered frequency level.

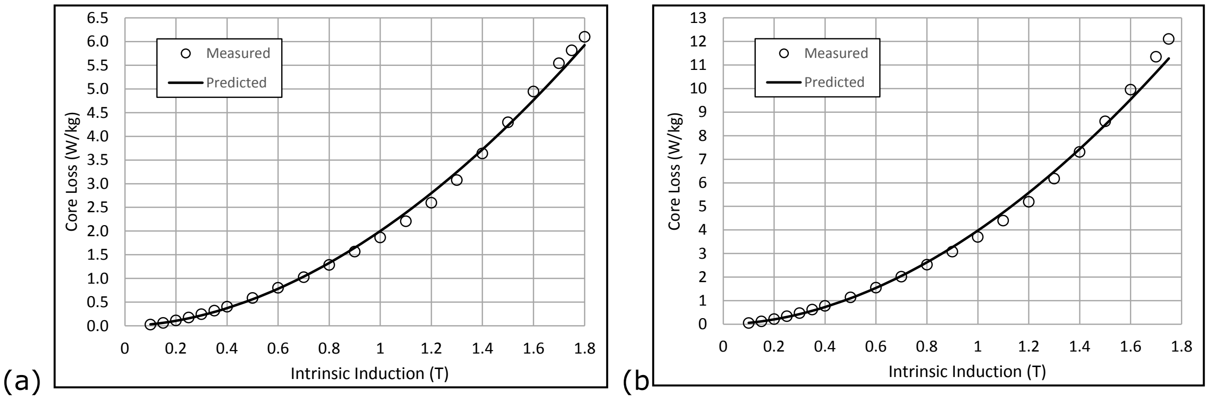

Figure 4: Comparison between measured [16] and predicted total iron loss at 60 Hz (a) and 100 Hz (b) for a fully processed non-oriented M400-50A silicon iron steel.

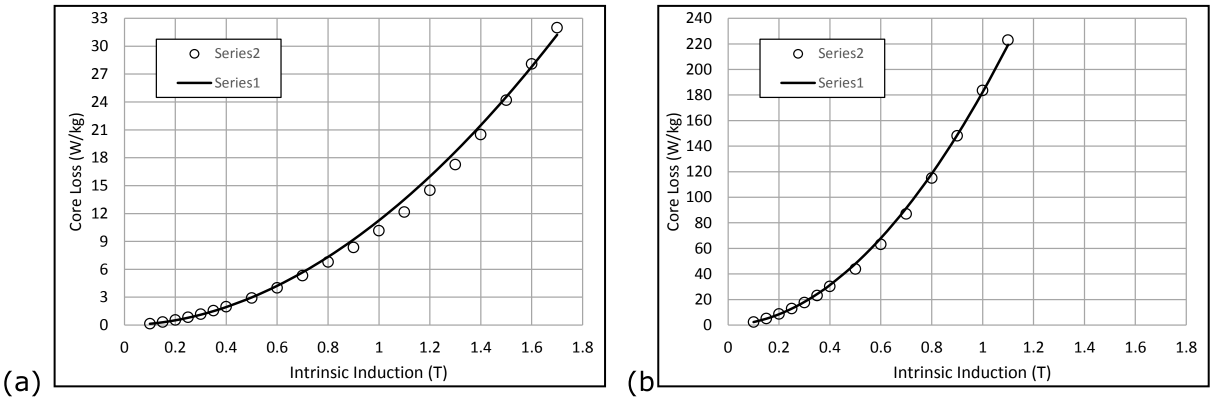

Figure 5: Comparison between measured [16] and predicted total iron loss at 200 Hz (a) and 1.2 kHz (b) for a fully processed non-oriented M400-50A silicon iron steel.

The calculation of total iron losses by (1) allows separating the contributions due to the hysteresis, eddy current and excess losses. For instance, Figure 6 shows the three contributions versus the intrinsic induction at 50 Hz for the M400-50A silicon steel considered in the previous section. As evident, for all the considered intrinsic induction values, the largest contribution at the total iron losses is due to the hysteresis. Figure 7 shows the impact of each term evaluated at 1.5 T – 50 Hz, while Figure 8 depicts the percentage impacts at 1.5 T for 60 Hz, 100 Hz, 200 Hz and 1.2 kHz.

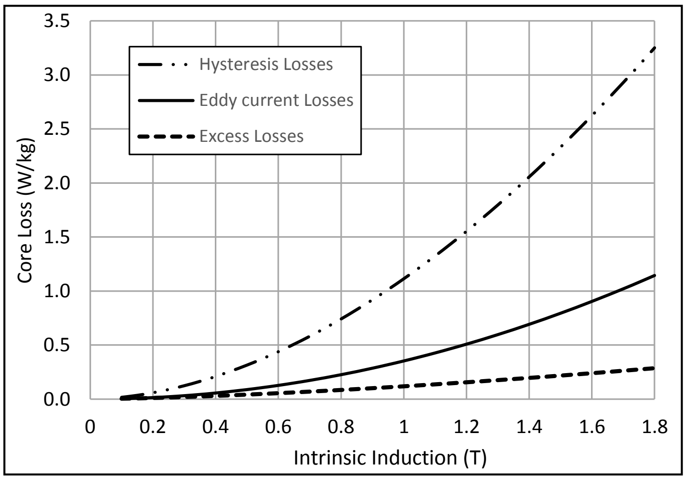

Figure 6: Predicted contributions at the total iron losses at 50Hz for a fully processes non-oriented M400-50A silicon iron steel.

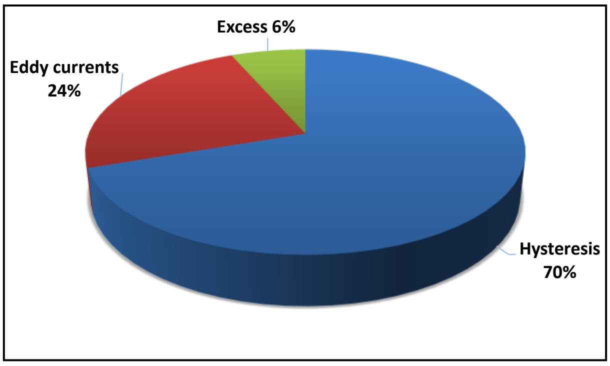

Figure 7: Percentage impact of the predicted iron loss contributions at 1.5T - 50Hz for a fully processed non-oriented M400-50A silicon iron steel.

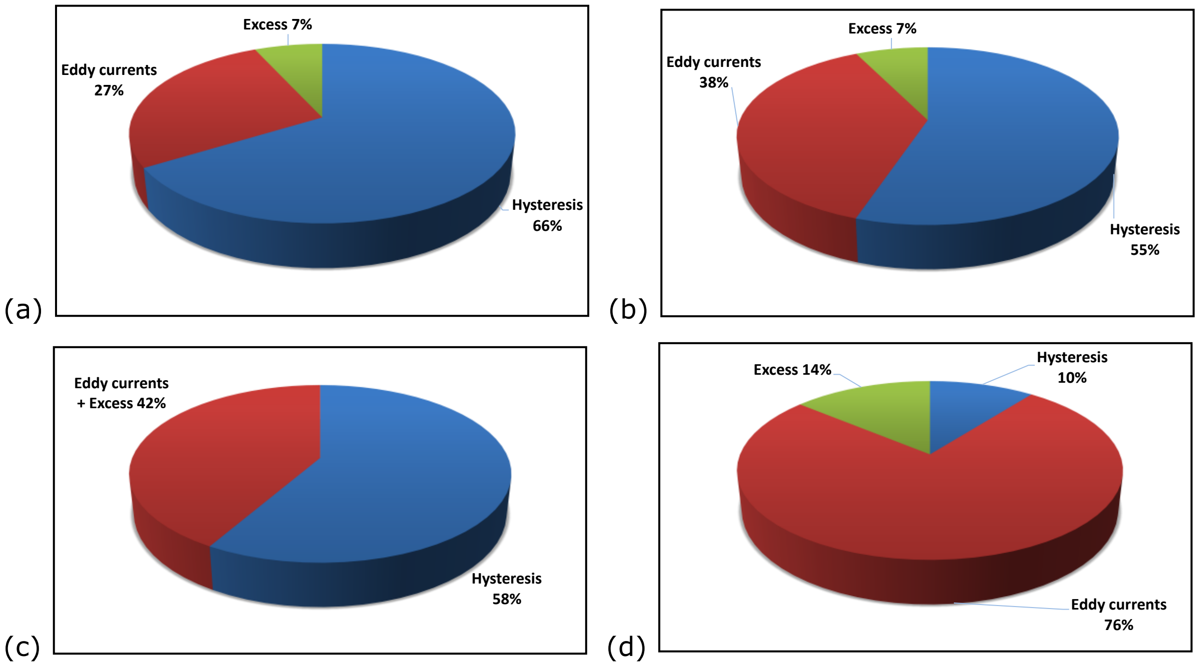

Figure 8: Predicted iron losses contribution at 1.5T at 60 Hz (a), 100 Hz (b), 200 Hz (c) and 1.2 kHz (d) for a fully processed non-oriented M400-50A silicon iron steel.

Looking at Figure 7 and Figure 8, the percentage impact of the eddy current losses and excess losses increase for higher frequency values, as expected. It is interesting to note that, at 200 Hz, the percentage impact of the excess losses has been englobed on the eddy current contribution. The reason is that, for this frequency value, the coefficient '*e*' has been set equal to zero as its value resulted very small. This mean that, for this case, the provided measurements do not allow us to separate the eddy currents due to the classical losses and those due to the excess losses; nevertheless this does not mean that the excess losses are equal to zero. Thus, from an engineering point of view, the excess losses contribution can be combined with the classical losses (eddy currents + excess losses) for the computation of the total iron losses.

Iron losses analysis for different silicon iron soft magnetic materials

The proposed analytical approach for the estimation of the empirical coefficients used in (1), has been applied to several silicon iron soft magnetic materials having different quality and different lamination thickness. The datasheets for all the considered materials can be found in [16].

Figure 9 shows the predicted iron loss contributions at 1.5 T and 50 Hz for fully processed non-oriented silicon iron steel with 0.5mm lamination thickness. In particular, the figure reports the loss contributions predicted for a high quality material (M250-50A), a medium quality material (M400-50A) and a low quality material (M800-50A), considering two different producers that are referred as '*Producer A*' and '*Producer B*', respectively. For the M800-50A only the Producer A has been considered since the data from Producer B were not available for this specific material. Table 2 lists all the empirical coefficients '*a*, *b, x*, *e'* that have been determined for the materials reported in Figure 9. It is important to remark that the reason for considering two different producers is not aimed to a quality comparison between them, but is aimed at supporting the technical discussion.

As expected, materials with a higher quality (i.e. with a low loss digit) feature lower total iron losses compared to those with lower quality (i.e. with a high loss digit). In particular, it can be observed that there is almost a linear dependence between the hysteresis contribution and the loss digit, whereas eddy current and excess loss contributions do not change significantly because of constant frequency and constant thickness. Table 3 summarizes the total iron losses and the percentage impact of each contribution.

Figure 10 shows the average iron losses separation at 1.5T and 50Hz versus lamination thickness. It has to be highlighted that the results shown in Figure 10 are not restricted to the materials listed in Table 2, but have been obtained considering almost all the fully processed non-oriented silicon iron steels reported in [16]. The reason for reporting the average loss for each thickness lies on the necessity of having an easy-to-read graph; moreover, those values that are far away from the graph's trend are softened by the averaging operation.

As can be observed, the average values shows that the hysteresis contribution slightly increases with the thickness; nevertheless, the eddy current contribution is the most influenced by the material thickness as they depend on the square of the lamination thickness (see equation (3)). Regarding the excess losses contribution, it does not present a high influence on the lamination thickness. Table 4 summarizes the total iron losses and the percentage impact of each contribution.

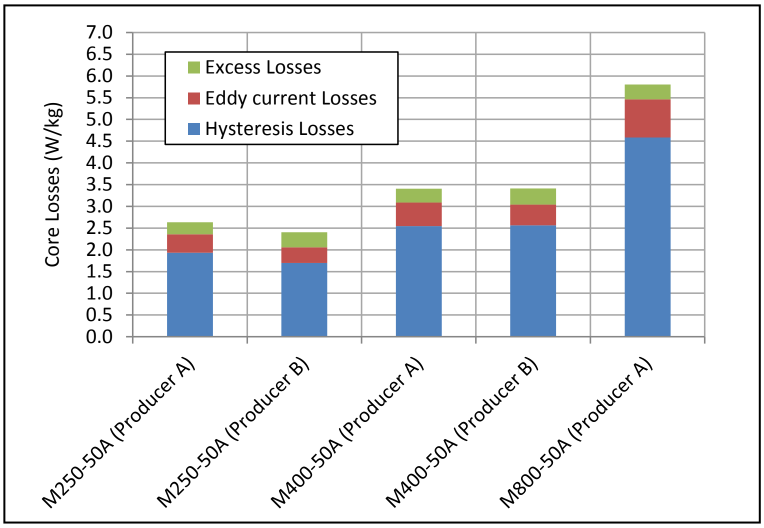

Figure 9: Predicted iron loss contributions at 1.5 T – 50 Hz for fully processed non-oriented silicon iron steels with 0.5 mm lamination thickness and different quality.

Table 2. Empirical coefficients for the materials in Figure 9 (f=50 Hz).

Sample	a	b	x	e
M250-50A (Producer A)	0.0167	0.0001256	1.75	0
M250-50A (Producer B)	0.0141	0.000135	1.69	0.00008328
M400-50A (Producer A)	0.0223	0.0001413	1.82	0.0003353
M400-50A (Producer B)	0.0231	0.000140	1.69	0.00013896
M800-50A (Producer A)	0.0406	0.0002873	1.71	0

Table 3. Total iron losses and contribution percentage impacts for the materials in Figure 9.

Sample	Total iron Losses (W/kg)	Hysteresis Losses (%)	Eddy current Losses (%)	Excess Losses (%)
M250-50A (Producer A)	2.63	73%	16%	11%
M250-50A (Producer B)	2.41	71%	15%	14%
M400-50A (Producer A)	3.42	75%	16%	9%
M400-50A (Producer B)	3.41	75%	14%	11%
M800-50A (Producer A)	5.80	79%	15%	6%

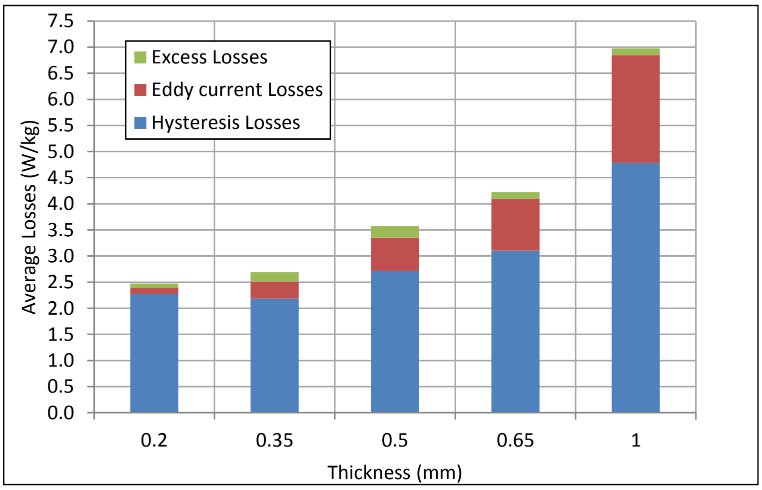

Figure 10: Average iron loss contributions at 1.5 T – 50 Hz vs. thickness for fully processed non-oriented silicon iron steels.

Table 4. Total iron losses and contribution percentage impacts for the materials in Figure 10.

Thickness	Total iron Losses (W/kg)	Hysteresis Losses (%)	Eddy current Losses (%)	Excess Losses (%)
0.2 mm	2.48	92%	5%	3%
0.35 mm	2.69	81%	12%	7%
0.5 mm	3.57	76%	18%	6%
0.65 mm	4.22	74%	23%	3%
1 mm	6.98	69%	29%	2%

Conclusions

This paper presented the analytical procedure for the evaluation of the empirical coefficients necessary to evaluate the total iron losses with the energetic model based on the separation of hysteresis, eddy currents and excess losses. The proposed procedure is based on the analysis of the magnetic loss measurements reported in the material datasheet. It has be highlighted that, the material producers usually performs these measurements on the Epstein frame using material strips. This implies that the magnetic losses can slightly differs when the material is punched for its utilization in a rotating electrical machine. To obtain more accurate results, the designer can perform experimental measurements directly on the machine core samples when available, as described in [17]. Moreover, the validity of the considered energetic model is restricted to a sinusoidal supply. Its extension to arbitrary supply voltage waveforms is beyond the scope of this paper and dedicated literature reference are provided for the reader convenience.

The proposed procedure provides a practical way for evaluating the total iron losses during the machine design stage. Indeed, most of the commercial FEA software require the insertion of these coefficients for the numerical computation of the iron losses. In this perspective, the coefficients provided in this paper are a valuable reference for the designers facing the iron losses computation in electrical machines. Obviously, the empirical coefficients are strictly dependent on the considered material, but the proposed procedure is a practical tool that the designer can use to compute the coefficients of any different soft magnetic materials for electrical machines.

The determination of the empirical coefficients '*a*, *b, x*, *e'* allows separating the total iron losses in the hysteresis, eddy currents and excess loss contributions. On the basis of this separation, the paper reported and discussed the energetic performance of different silicon iron soft magnetic materials suitable for electrical machine design. In particular, the analysis highlighted the impact of each iron losses contribution in function of the material quality and lamination thickness. Energetic analyses on different soft magnetic materials for electrical machines, such as cobalt iron and nickel iron, are part of the authors' today activities and will be presented in future research papers.

References

[1] A.T. d Almeida, F.J.T.E. Ferreira, A. Duarte, "Technical and Economical Considerations on Super High-Efficiency Three-Phase Motors", *IEEE Trans. Ind. Appl.*, Vol. 50, No. 2, Mar./Apr. 2014, pp. 1274-1285.

[2] E.B. Agamloh, N. Kaufman, K. Butler, "The economics of pre-EPAct motors operating in industry", Conf. Rec. of Pulp and Paper Industry Technical Conference, pp. 212-219, 2007.

[3] ABB Brochure, "Boosting industrial profitability with energy efficient drives and motors", *2016*.

[4] A. Krings, A. Boglietti, A. Cavagnino, S. Sprague, "Soft Magnetic Material Status and Trends in Electrical Machines", *IEEE Trans. Ind. Electron.*, Vol. 64, No. 3, March 2017, pp. 2405-2414.

[5] International Standard IEC 60034-30:2008, Rotating Electrical machines – Part 30: Efficiency classes of single speed, three phase, cage induction motors.

[6] CEMEP, European Committee of Manufacturer of Electrical Machines and Power Electronics, "Electric motor and Variable Speed Drives – Standards and legal requirements for the energy efficiency of low-voltage three-phase motors", 2011.

[7] International Standard IEC 60034-30-1:2014, Rotating Electrical machines – Part 30-1: Efficiency classes of line operated AC motors.

[8] G. Bertotti, "General Properties of Power Losses in Soft Ferromagnetic Materials", *IEEE Trans. Magn.*, Vol. 24, No. 1, pp. 621-630, Jan. 1988.

[9] R. Kaczmarek, M. Amar, F. Protat, "A general formula for prediction of iron losses under non sinusoidal supply voltage waveform", *IEEE Trans Magn.*, Vol. 31, pp. 2505-2509, Sept. 1995.

[10] A. Boglietti, A. Cavagnino, M. Lazzari, M. Pastorelli, "Predicting Iron Losses in Soft Magnetic Materials With Arbitrary Voltage Supply: An Engineering Approach", *IEEE Trans. Magn.*, Vol. 39, No. 2, March 2003, pp. 981-989.

[11] D. Eggers, S. Steentjes, K. Hameyer, "Advanced Iron-Loss Estimation for Nonlinear Material Behavior", *IEEE Trans. Magn.*, Vol. 48, No. 11, pp. 3021-3024, Nov. 2012.

[12] http://www.cedrat.com/software/flux/

[13] https://www.jmag-international.com/

[14] http://www.ansys.com/products/electronics/ansys-maxwell

[15] http://www.infolytica.com/en/products/magnet/

[16] S. Sprague, *Lamination Steel Third Edition*. South Dartmouth, MA, USA: The Elect. Motor Educ. Res. Found, CD-ROM, Second printing 2009.

[17] M. Cossale, A. Krings, J. Soulard, A. Boglietti, A. Cavagnino, "Practical Investigations on Cobalt-Iron Laminations for Electrical Machines", *IEEE Trans. Ind. Appl.*, Vol. 51, No. 4, pp. 2933-2939, July/August 2015.

Efficiency increase of a single-phase induction motor with permanent capacitor for household appliances

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Abstract

In this paper, we study the effect of several electromagnetic parameters on the performance of a single-phase induction motor with permanent capacitor for household appliance application.

A lumped model of such motor is defined to this aim: the model results are compared to experimental data, to validate the model itself, and the sensitivity analysis is then carried out.

This analytical model allows the following optimization of the induction motor while the Finite Element Analysis (both electromagnetic and mechanical) allows the study of the vibration.

Lumped model definition using SPEED

The study starts with an electric motor manufactured by FIME (a company of the Elica group).

As already mentioned, it is a single-phase induction motor with 4 µF permanent capacitor for household appliance application.

The motor is designed to be supplied with 220÷240 V ~ 50 Hz or 220 V ~ 60 Hz and it can reach about 3000 rpm or about 3600 rpm being a two-pole motor.

The SPEED (by Siemens PLM Software) software is used to define a lumped model of such device and the model results are compared with experimental ones at the maximum efficiency point.

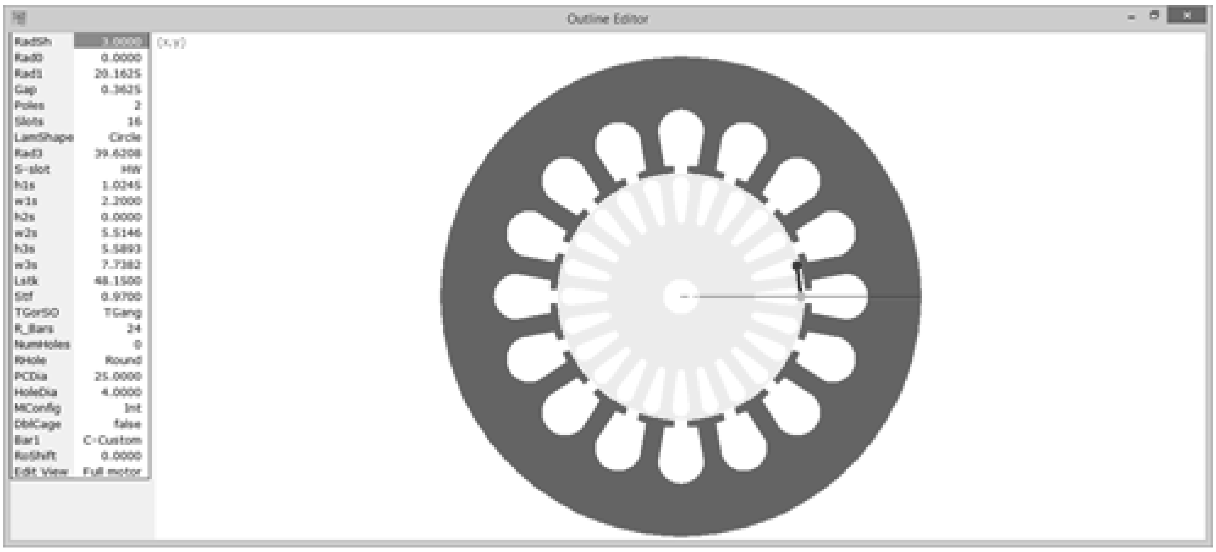
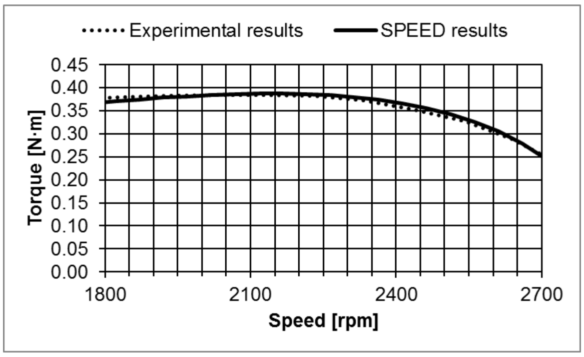


Figure 1: Definition of the motor radial section inside SPEED

Table 1: Comparison between the experimental results and the SPEED model ones

	Experimental results	SPEED results
Speed [rpm]	2638	2635
Torque [N·m]	0.289	0.290
Output Power [W]	80	80
Input Power [W]	122.1	122.1
Efficiency [%]	65.5	65.5
Voltage [V]	229.1	229.1
Current [A]	0.543	0.541
Power factor	0.981	0.986
Losses [W]	42.1	42.1

The motor characteristics versus speed are analytically computed as well: they show, between 1800 rpm and 2700 rpm, a good match with the measured ones.



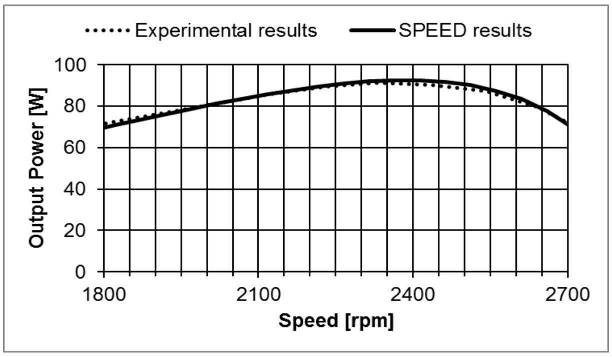
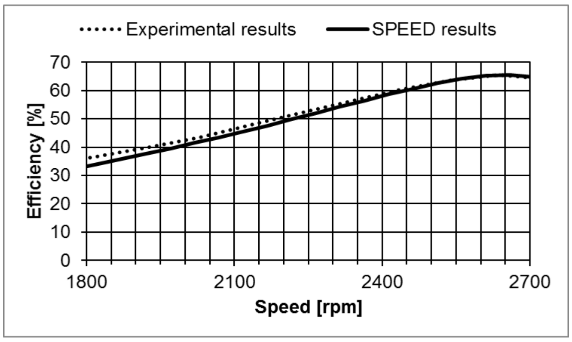


Figure 2: Comparison between the experimental results and the SPEED model ones: Torque and Output Power curves versus Speed



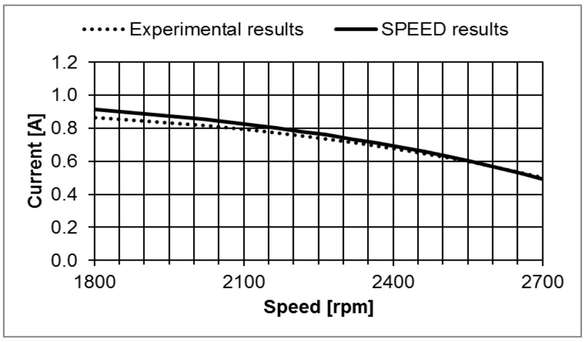


Figure 3: Comparison between the experimental results and the SPEED model ones: Efficiency and Current curves versus Speed

Having thus verified that the SPEED model simulates the behaviour of the real motor, its losses can be analysed to find the best way to increase its maximum efficiency.

Table 2: Computation of the motor power balance and of losses contribution

	SPEED results [W]	**Percentage of Input Power [%]**	**Percentage of Losses [%]**
Output Power	80	65.5%	-
Windage and Friction losses	2.7	2.2%	6.3%
Iron losses	4.0	3.3%	9.4%
Joule losses in stator winding	23.2	19.0%	55.1%
Joule losses in squirrel-cage	12.3	10.0%	29.1%
Losses	42.1	34.5%	100.0%
Input Power	122.1	100.0%	-

The Windage and Friction losses are the less important ones: they are considered invariant during the following analysis.

The amount of Iron losses makes it reasonable to assume that no benefit can be obtained using a different grade of laminations in the magnetic circuit (no benefit at all if laminations with higher specific losses are used!).

The Joule losses inside the stator winding and in the squirrel cage are obviously the most important ones: then they should be reduced to increase the motor maximum efficiency.

Sensitivity analysis

In compliance with maintaining the motor typology, the following parameters are analyzed:

1. the material used for the die-casting of the squirrel cage (Copper instead of Aluminum),
2. the length of the stator stack,
3. the axial thickness of the rotor rings.

Furthermore, the effect of the number of conductors in the main winding and in the auxiliary one and the capacitor value are considered.

Table 3: Sensitivity analysis results on aluminum squirrel cage motor

Current motor - Aluminum squirrel cage				
Rotor rings axial thickness [mm]	2.0	3.5	5.0	6.5
Speed [rpm]	2561	2635	2709	2709
Torque [N·m]	0.280	0.290	0.270	0.284
Efficiency [%]	63.1	65.5	66.2	66.5

Table 4: Sensitivity analysis results on copper squirrel cage motor

Current motor - Copper squirrel cage				
Rotor rings axial thickness [mm]	2.0	3.5	5.0	6.5
Speed [rpm]	2709	2759	2759	2808
Torque [N·m]	0.269	0.270	0.288	0.248
Efficiency [%]	66.1	66.4	66.0	65.3

Table 5: Sensitivity analysis results on aluminum squirrel cage motor with increased stator stack length

Increased stator stack length - Aluminum squirrel cage				
Rotor rings axial thickness [mm]	2.0	3.5	5.0	6.5
Speed [rpm]	2561	2660	2660	2709
Torque [N·m]	0.274	0.271	0.293	0.274
Efficiency [%]	62.7	65.1	65.8	66.1

Table 6: Sensitivity analysis results on copper squirrel cage motor with increased stator stack length

Increased stator stack length - Copper squirrel cage				
Rotor rings axial thickness [mm]	2.0	3.5	5.0	6.5
Speed [rpm]	2660	2759	2759	2759
Torque [N·m]	0.294	0.260	0.277	0.286
Efficiency [%]	65.8	65.9	65.8	65.2

The use of a Copper die-cast rotor and/or the increase of the axial thickness of the rotor rings reduce the rotor resistance and the Joule losses in the squirrel cage.

At the same time, if there is no action on the winding, such modifications lead to the increase of the Joule losses inside the stator winding.

Thus, the increase in efficiency is no more than 1%; furthermore, the maximum efficiency point is moved to the right, toward a speed value higher than the present one.

On the other side the torque, the output power and the efficiency at lower speed values get worse.

The reducing the axial thickness of the rings can compensate such behaviour, but this makes worse the gain on the maximum efficiency.

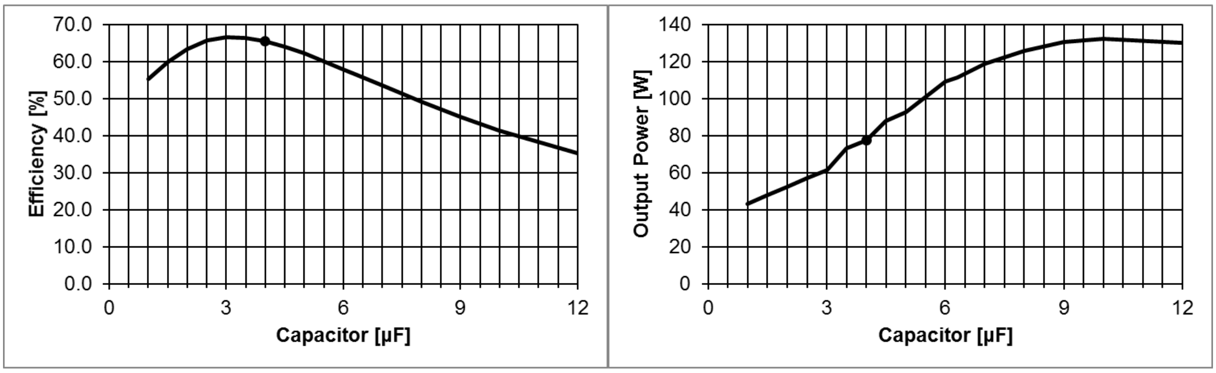


Figure 4: Effect of capacitor value on Efficiency and Output Power of the motor

On the electrical side, decreasing the value of the capacitor, the increase in the efficiency is concomitant with the reduction of the output power.

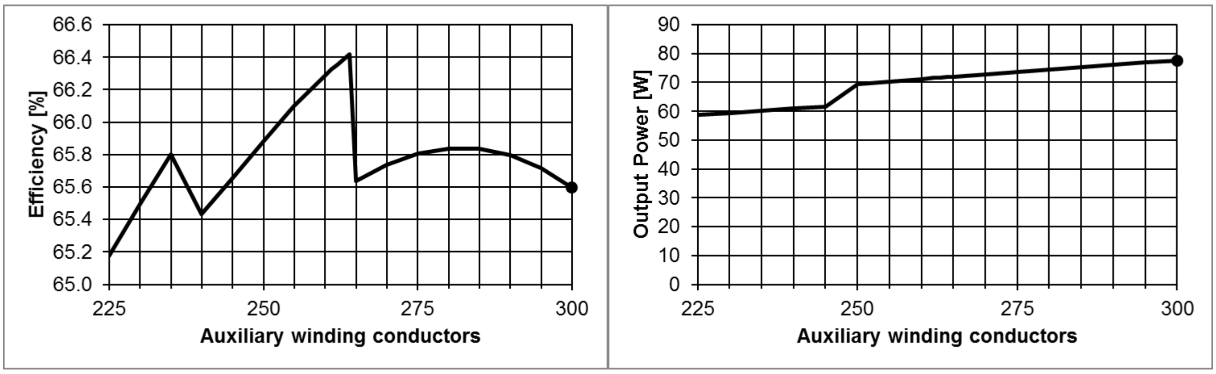


Figure 5: Effect of number of conductors in the auxiliary winding on Efficiency and Output Power of the motor

The decrease in the number of conductors in the auxiliary winding produces the same behaviour.

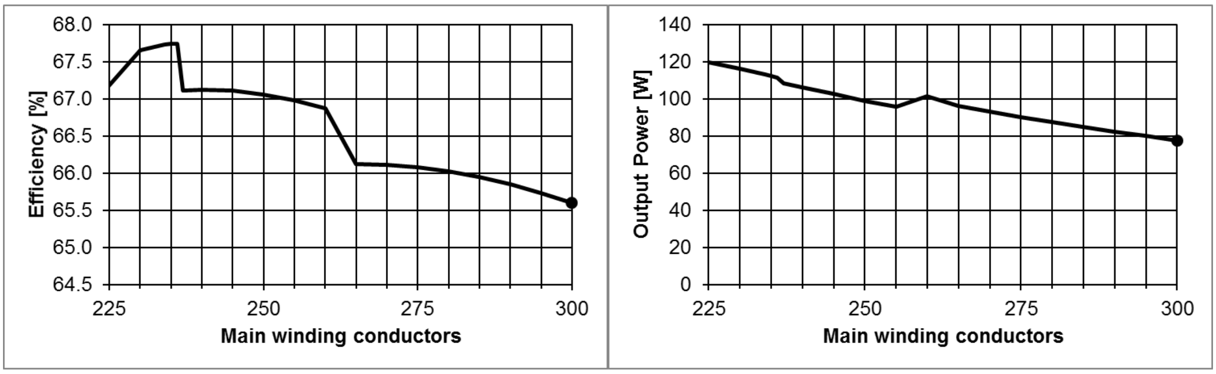


Figure 6: Effect of number of conductors in the main winding on Efficiency and Output Power of the motor

Positive results are provided by the decrease in the number of conductors in the main winding: indeed, this increases both the efficiency and the output power.

When reducing the number of conductors in the main winding and in the auxiliary one, the wire diameter may increase: then attention must be paid not to exceed the maximum slot-fill.

Motor optimization

Concerning the optimization of the induction motor, the main goal is the increase of the efficiency, while the output torque, of a specified speed range, is constrained to avoid a loss of performance and guarantee the mechanical power required for the application.

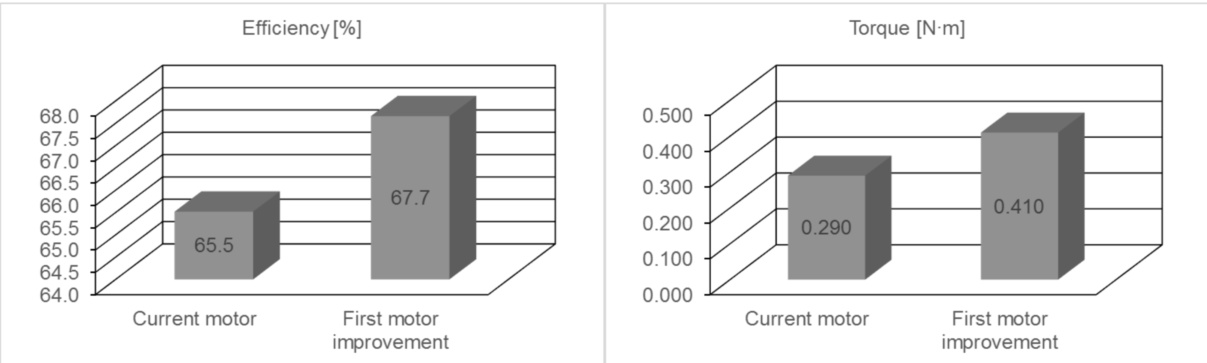


Figure 7: First motor improvement, just involving the decrease in the number of conductors in the main winding and the wire diameter increase (without exceeding the maximum slot-fill)

A first motor improvement is detected through the previous sensitivity analysis.

It just involves the decrease in the number of conductors in the main winding and the wire diameter increase (without exceeding the maximum slot-fill).

The efficiency increases by 2.1% while torque increases by 41.4%

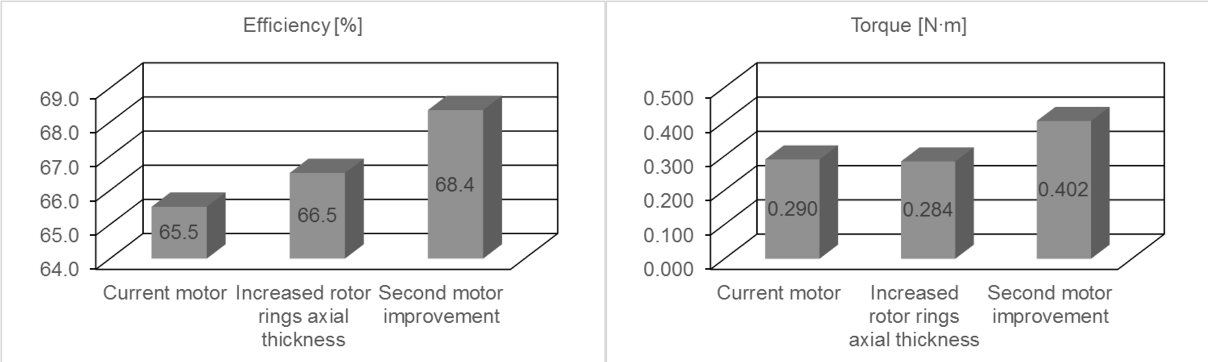


Figure 8: Further motor improvement, involving a motor with increased axial thickness of the rotor rings and the decrease in the number of conductors in the main winding and the wire diameter increase (without exceeding the maximum slot-fill)

A further improvement starts from a motor with increased axial thickness of the rotor rings.

This motor achieves 1% efficiency increment while torque is slightly lower.

Decreasing again the number of conductors in the main winding and increasing the wire diameter (without exceeding the maximum slot-fill), efficiency and torque are 1.8% and 41.6% higher.

Hence, we get the 2.8% increase in the efficiency and the 38.8% increase in torque.

Vibration analysis

The vibration analysis provides the following steps:

1. magnetic finite element modelling of the induction motor using Flux (by Altair),
2. mechanical finite element modelling of the induction motor using OptiStruct (by Altair).

Flux model

The Flux model of the induction motor is based on the analytical model provided by SPEED.

The electromagnetic FEM model of the motor is built using Flux-Skew module, which considers the effect of the skewing of the rotor bars.

Periodicity and symmetries are introduced, according to the topology of the motor, to reduce the size of the model and speed up the computation.

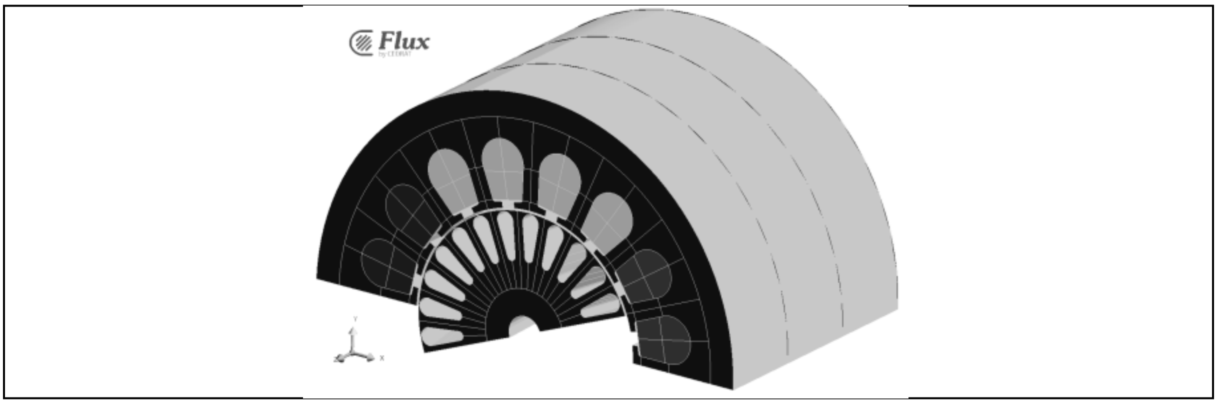


Figure 9: Flux-Skew model of the motor

The Flux-Skew model of the motor requires the definition of the corresponding 2D section and consequently the preparation of the 2D mesh.

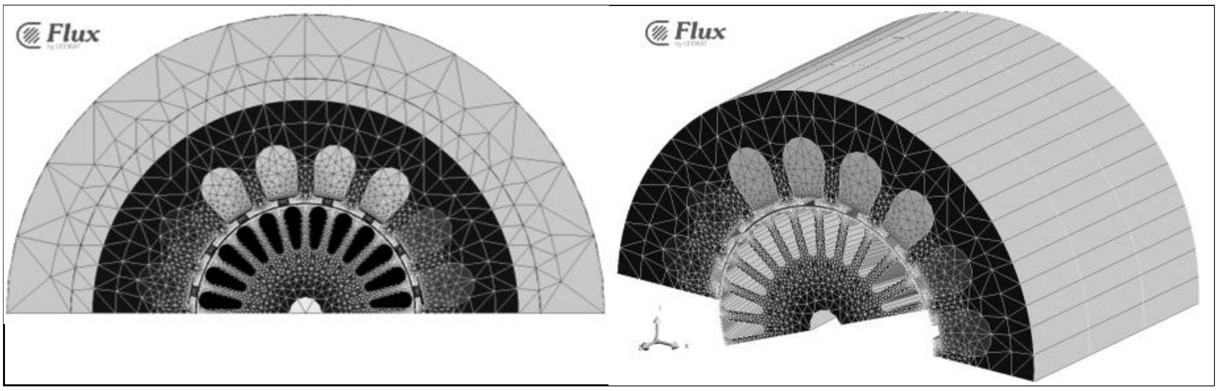


Figure 10: Meshed Flux-Skew model of the motor

Then the Skew model is automatically generated by extruding the 2D original section and applying the required skewing of the rotor bars.

The result is a full 3D model with second order mesh elements.

The main objective of the Flux computation is the extraction of the electromagnetic sources of vibration, such as torque ripple and oscillation in the attraction forces acting over stator and rotor teeth across the airgap.

In this paper two working points are analyzed and compared: **Table 7** summarizes the main parameters of these working points.

Table 7: Main working points

Measured at Intensive Speed (230V AC applied to the Blue and Black clamps)							
Speed [rpm]	Torque [Nm]	Output Power [W]	Input Power [W]	Eff. (%)	Voltage [V]	Current [A]	Power Factor
2638	0.289	80	122.1	65.5	229.1	0.543	0.981

Measured at Low Speed (230V AC applied to the Blue and White clamps)							
Speed [rpm]	Torque [Nm]	Output Power [W]	Input Power [W]	Eff. (%)	Voltage [V]	Current [A]	Power Factor
1073	0.047	5.3	138.3	3.8	230.4	0.6	0.998

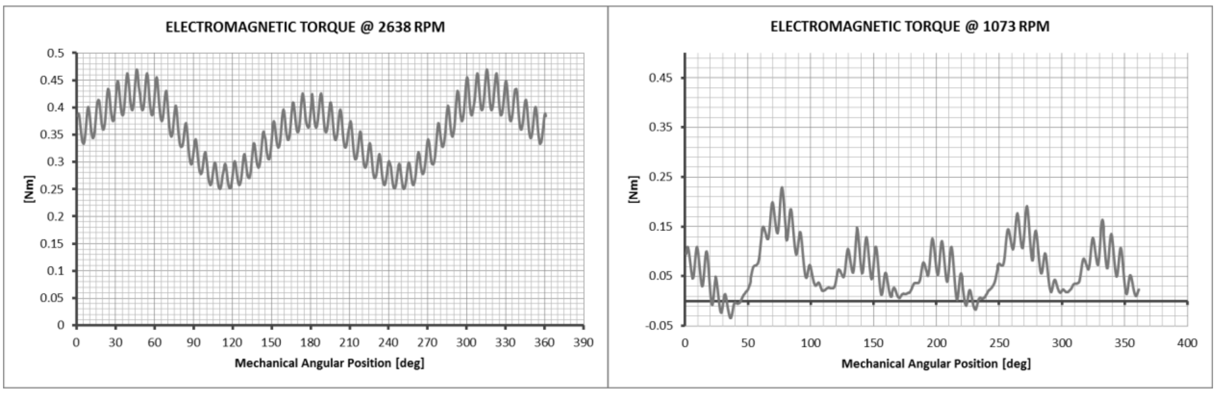


Figure 11:Torque ripple at 2638 rpm (Intensive Speed) and 1073 rpm (Low Speed)

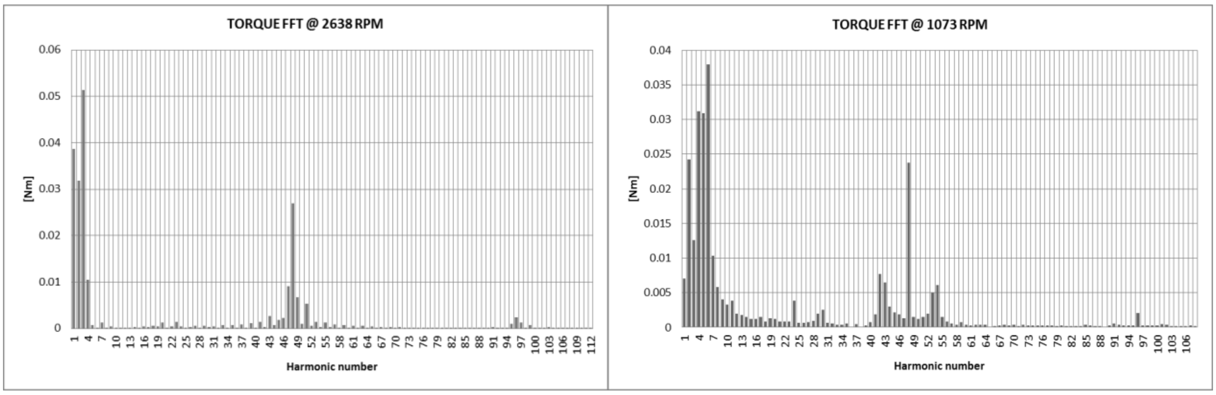


Figure 12: Harmonic content of torque ripple at 2638 rpm (Intensive Speed) and 1073 rpm (Low Speed)

The above diagrams highlight the harmonic content of the torque ripple in the selected working points.

It can be noticed the behavior of the motor is completely different: motor working at Low Speed introduces oscillations with a larger number of harmonic components than motor working at Intensive Speed.

Furthermore, the amplitude of each component is higher compared to the average value of the torque.

The attraction forces between stator and rotor across the airgap can be computed using two different methods:

1. Virtual Work method,
2. Maxwell Tensor method.

Method N.1 is more accurate than N.2, but it gives back only the resultant value of the force over an entire region of the motor.

Method N.2 can be slightly less accurate than N.1, but it allows the extraction of the local forces on each node of the mesh.

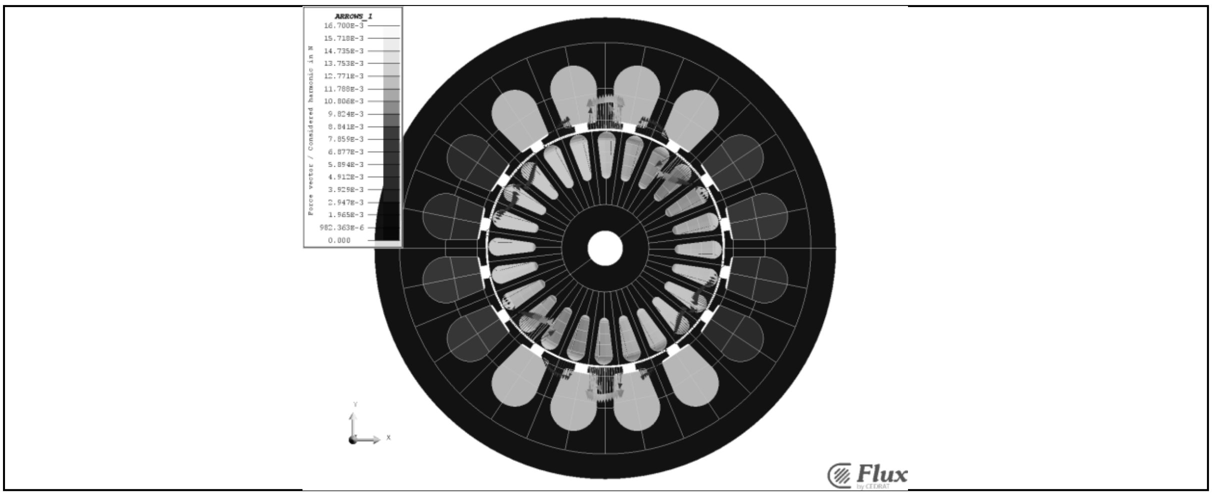


Figure 13: Local forces acting along the stator teeth

Then the local forces acting on a single stator tooth may be integrated along the boundary of the tooth to obtain the resultant vector.

In **Figure 14**, the force vector is split in its Cartesian components w.r.t. the main coordinate system of the model.

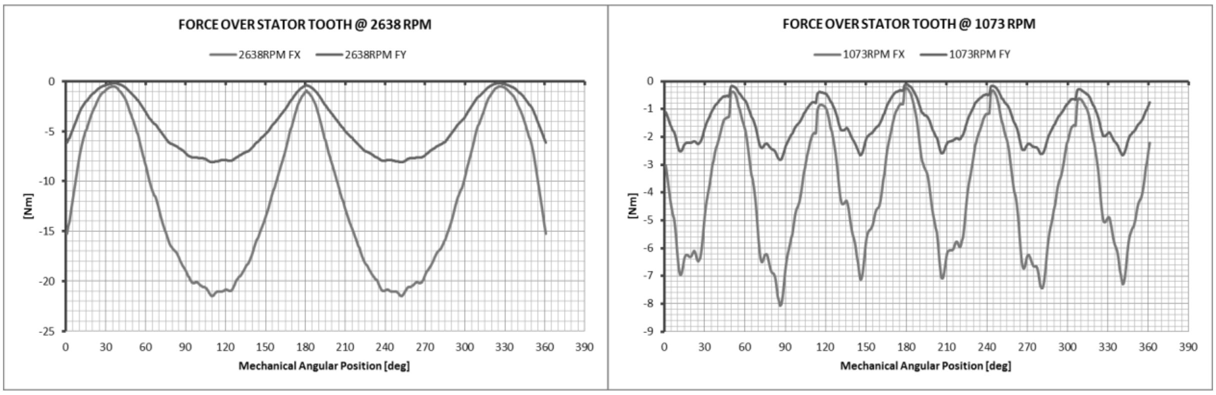


Figure 14: Force acting over a stator tooth at 2638 rpm (Intensive Speed) and 1073 rpm (Low Speed)

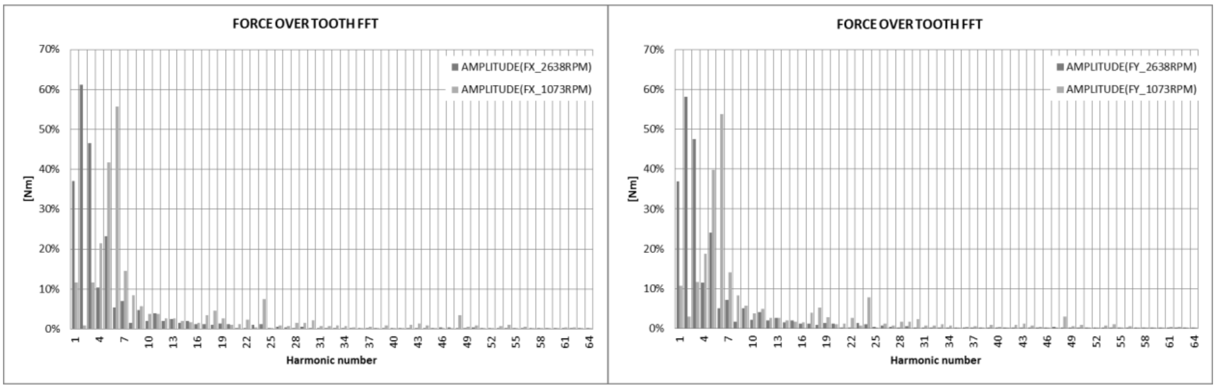


Figure 15: Harmonic content of force acting over stator tooth at 2638 rpm (Intensive Speed) and 1073 rpm (Low Speed)

The above computed force vector acts on any single tooth of the stator lamination, providing the necessary phase shift due to temporal and spatial displacement of the force.

Flux allows to export the local force vector acting on any node of the model and automatically generates a load file which is compatible with OptiStruct.

The load file contains the list of nodes which describes the boundary surface of the stator or rotor teeth.

For each node, this file lists the magnitude and phase shift of the harmonic components of the force vectors in the frequency domain.

OptiStruct model

The mechanical model of the motor is built to compute the harmonic response and estimate displacement, velocity and acceleration of the various parts.

It is not required to match the mesh of the mechanical model with the electromagnetic model one.

The forces computed using Flux are projected onto OptiStruct's mesh using a specific algorithm.

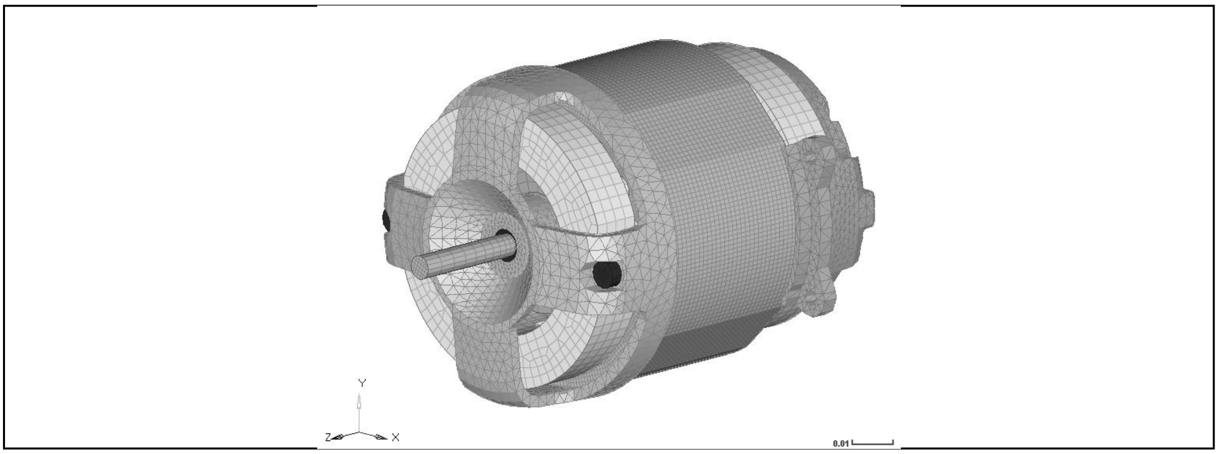


Figure 16: Mechanical model of the motor

The parts of the motor considered critical in terms of vibration response are meshed with higher accuracy than the remaining sections.

For example, the teeth of stator lamination are described with a larger number of nodes to accurately catch the higher harmonic components of vibration.

The modal analysis is linear and it requires the introduction of at least the following properties:

1. Young Modulus (E [MPa]),
2. Poisson's ratio (mu),
3. mass density (Rho [kg/m³]).

Table 8 summarizes the main parts of the model with their properties.

Table 8: Motor parts list

PART	E [MPa]	mu	Rho [kg/m³]
STATOR	200000	0.298	7800
ROTOR	200000	0.298	7800
ROTOR BARS	70000	0.33	2795
BOLTS AND SCREWS	199900	0.29	7850
SPACERS	105000	0.3	8400
BUSHINGS	96530	0.35	8780
SHAFT	199900	0.29	7850
FRONT SHIELD	70000	0.33	2795
BACK SHIELD	70000	0.33	2795

The mechanical model is used to perform the following analysis:

1. modal analysis,
2. modal based harmonic response analysis.

The modal analysis determines the natural frequencies, the mode shapes (eigenvalues and eigenvectors) and the modal participation factors, together with the modal effective mass associated with every resonant frequency.

The above results are stored in a database and establish the basis for the subsequent step.

The modal based harmonic response analysis determines the actual displacement of the system caused by the applied forces in the frequency domain. Thus, velocity and acceleration for every node of the mesh can be computed, together with stress and strain.

The modal analysis is performed on the unconstrained model, to exclude the effect of mechanical constraints on it.

Table 9 summarizes some of the natural frequencies and the modal effective masses: these quantities are useful to highlight the significance of the mode shapes and isolate the most important ones.

Table 9: Summary of modal analysis results

MODE	**[Hz]**	**T1**	**T2**	**T3**	**R1**	**R2**	**R3**
1	205	-2.48635E-09	-1.87403E-09	-4.59489E-10	0.028979	0.03016782	4.27381E-05
…	…	…	…	…	…	…	…
3	368	2.08467E-09	-2.96432E-09	1.03408E-11	3.64E-05	4.20811E-05	-0.04118648
4	924	-1.02748E-09	2.50662E-10	1.71496E-09	2.1E-06	2.4412E-06	2.26886E-06
…	…	…	…	…	…	…	…
6	1148	5.90301E-10	-2.77793E-09	9.29057E-09	9.97E-06	2.19009E-05	4.56895E-06
7	1285	8.5586E-10	7.42063E-09	-1.12374E-09	-1.3E-08	4.70605E-07	-0.0033487
…	…	…	…	…	…	…	…
13	2757	-2.58599E-10	5.68029E-09	-4.93573E-09	-1.2E-05	1.66239E-08	9.74123E-07
14	3257	4.51853E-11	-6.24894E-10	5.01792E-10	-1.3E-07	-2.67654E-06	6.07835E-07

15	3300	6.91452E-11	-1.83625E-09	1.73265E-09	-4.5E-07	-1.59862E-05	-1.4851E-06
16	3326	1.87164E-10	-5.20354E-09	4.01354E-09	4.56E-05	-1.69541E-05	3.52117E-06
17	3713	7.90082E-12	-2.43489E-10	2.90544E-10	4.69E-06	-2.17449E-06	-2.001E-07
18	5087	-7.22877E-12	-3.6993E-11	-8.38553E-11	-8.6E-08	-4.65162E-08	1.69532E-06
19	5183	5.34042E-11	-9.78111E-10	6.80261E-10	6.69E-07	-1.79615E-07	-8.4507E-06
…	…	…	…	…	…	…	…
56	12483	8.53596E-12	-2.89626E-10	2.20274E-10	1.07E-06	1.82872E-06	2.32191E-07
57	12527	1.15509E-12	-1.04847E-11	1.95911E-11	2.29E-07	-5.1715E-07	3.75655E-06
58	12692	5.34862E-12	-1.23661E-10	1.03398E-10	-7.6E-07	-3.75484E-07	-1.9332E-06
59	13324	-1.12417E-11	2.73016E-10	-2.16019E-10	-4.4E-07	6.72976E-07	5.51117E-07
60	13432	5.50419E-12	-1.21827E-10	6.24891E-11	6.98E-07	-3.31356E-07	-1.3064E-07
61	13497	7.63102E-13	-5.69375E-11	4.02844E-11	9.26E-07	2.7966E-07	1.50455E-06
62	13624	6.92238E-12	-9.28841E-11	8.80834E-11	1.09E-06	-5.28709E-07	2.21136E-07
63	13656	-6.73159E-12	1.41896E-10	-8.81999E-11	-8.9E-07	2.08041E-06	-1.7963E-07
64	14220	4.79491E-12	-1.15528E-10	9.63458E-11	-4E-06	7.70203E-06	8.40862E-07
65	14407	-3.18445E-12	1.03094E-10	-7.23113E-11	1.96E-06	-3.83353E-06	-3.071E-08
66	14809	3.73555E-12	-6.52367E-11	4.29161E-11	-2.2E-07	2.09344E-06	-5.0662E-07

Note: columns marked T# and R# show Translational modal effective masses (T#) and Rotational modal effective masses (R#).

Figure 17 displays some of the mode shapes.

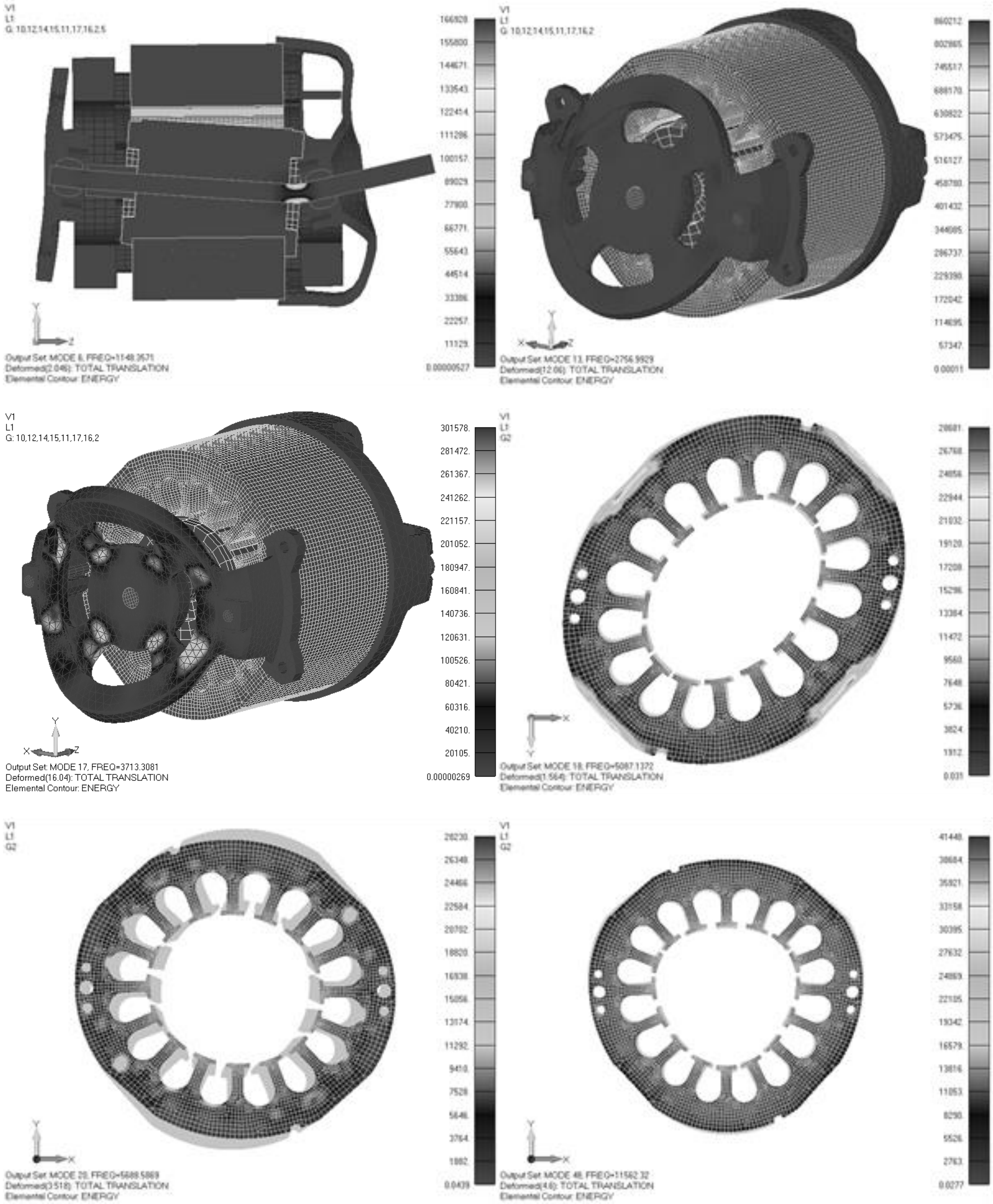


Figure 17 Modal analysis results

Displacement, velocity and acceleration of every node of the model are computed because of the application of the electro-magnetic forces coming from Flux.

The values of the acceleration of the following three virtual sensors are displayed.

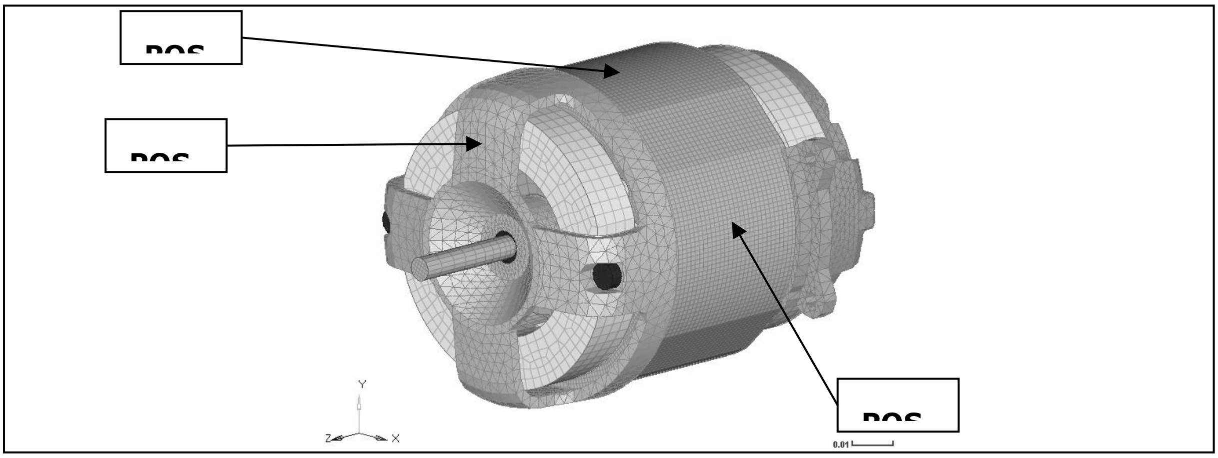


Figure 18: Virtual sensors position

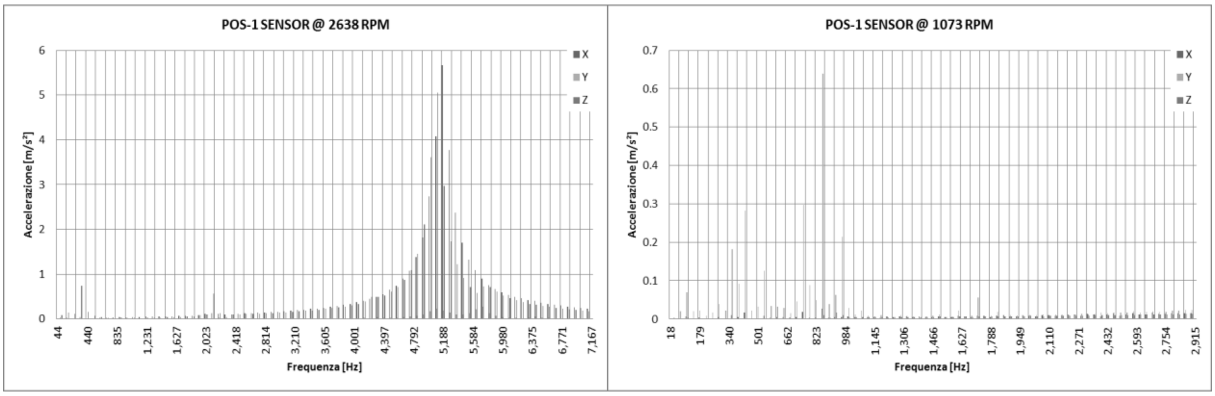


Figure 19: Acceleration level on POS-1 sensor at 2638 rpm (Intensive Speed) and 1073 rpm (Low Speed)

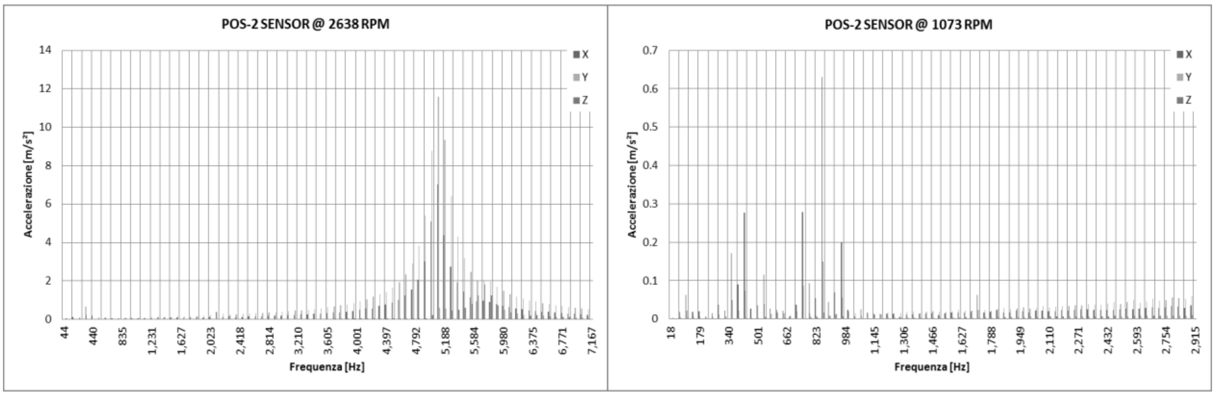


Figure 20: Acceleration level on POS-2 sensor at 2638 rpm (Intensive Speed) and 1073 rpm (Low Speed)

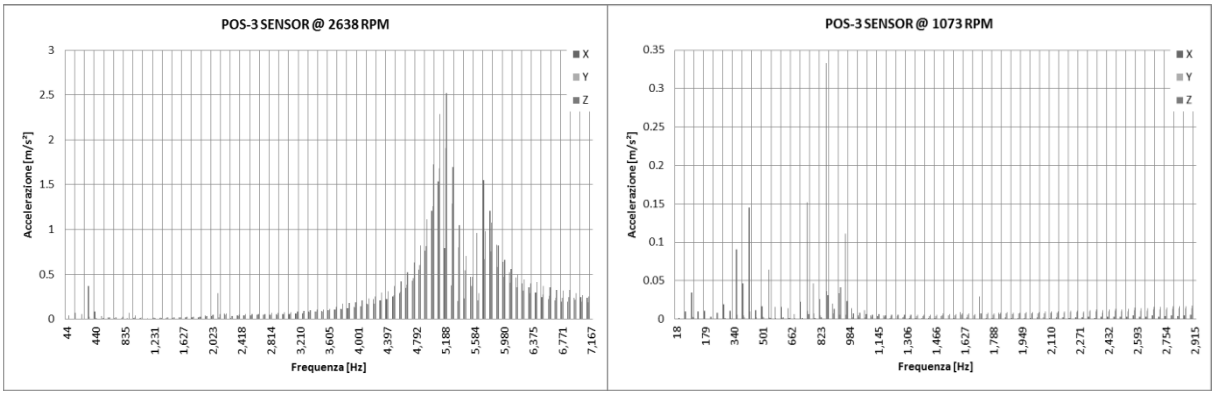


Figure 21: Acceleration level on POS-3 sensor at 2638 rpm (Intensive Speed) and 1073 rpm (Low Speed)

Conclusions

In this paper, the virtual prototyping strategy has been used to analyse the effect of several electromagnetic parameters on the performance of a single-phase induction motor with permanent capacitor for household appliance application.

A lumped model of such motor has been defined to this aim using SPEED software: the model results have been compared to experimental data, to validate the model, and the sensitivity analysis has been carried out, to find the most affecting design parameters.

The analytical model has been used also for optimizing the induction motor.

A prototype version of the motor has been built according to the results of the sensitivity and the optimization analysis.

This prototype has been tested and the experimental data agree with the simulations results.

Thanks to the finite element analysis with Flux and to the use of specific tools it has been possible to extract the electromagnetic sources of vibration in different working points and compare the results in terms of harmonic response.

The different connection of main and auxiliary winding coils, required to obtain a specific working speed, introduces unbalanced forces across the airgap that generate high vibration.

Considering the increasing importance of noise and vibration in house appliance application, the future developments of this motor shall not only consider the increase of the efficiency and the reduction of cost but also the reduction of the noise and vibration level across the overall speed range.

References

[1] SPEED (by Siemens PLM Software) User's Manuals and Examples.

[2] TJE Miller. *SPEED's Electric Machines.*

[3] Jacek F. Gieras, Chong Wang and Joseph Cho Lai. *Noise of Polyphase Electric Motors.* December 12, 2005 by CRC Press. ISBN 9780824723811. Can be ordered at https://www.crcpress.com/

[4] https://connect.altair.com/ for Flux and OptiStruct User's Manuals and Examples.

Does Higher Motor Efficiency Necessitate Higher Production Costs?

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Consultant

Abstract

It is generally accepted that achieving higher motor efficiency results in higher motor manufacturing cost. This paper investigates the possibility of achieving high motor efficiency without the associated higher motor cost. This problem was approached by reviewing motor loss mechanisms and then examining candidate motor designs that could minimize these losses, thereby leading to greater motor efficiency. These designs were then analyzed to determine which ones could be manufactured inexpensively. One possible candidate, a unique dual rotor, single stator axial design was investigated in detail.

Introduction

It is commonly assumed that to increase the efficiency of a motor, the associated cost of manufacturing will increase for the more efficient motor. This paper attempts to investigate the possibility of achieving high motor efficiency with a motor that has lower manufacturing costs. While this is a simple concept to state, it is actually quite difficult to accomplish. There are many reasons for this difficulty which include both limitations due to the laws of physics and subjective assumptions and biases.

To evaluate motors on the basis of efficiency per unit of cost (dollar or euro), one must set ground rules that cover a number of complex real world decisions. In the industrial world, induction motors are often utilized without any electronic controls or drives. The first decision then is to decide whether or not to include the cost of the drive with the motor, if a candidate motor needs a drive to operate. In other words, is the comparison to be based on total system cost of a specific application, on the motor plus any electronic controls, or only the motor? And, for what specific application is the comparison to be made? Then there are issues such as installation costs, cabling costs, training, maintenance and so forth. Each of these may differ depending on the type of motor chosen because of variations in motor size, weight, starting torque and other motor characteristics. To simplify this complex issue and make this task feasible, the author decided to compare only motor material and assembly costs. This approach is admittedly limited in applicability, but makes the problem more tractable.

Even with this limited approach, it is very difficult to directly compare motor manufacturing costs for the wide range of motor types that are available in the marketplace. Some motor types have high material costs but lower production costs, while others may have low material costs but high labor assembly costs. Material costs vary from year to year with some trending up and some down, and labor costs vary widely from region to region. Also, motor manufacturing costs are highly dependent on volume sold and the amount of specialized tooling and automation utilized in the manufacturing process. Should the capital cost of the manufacturing be factored into the motor cost? Therefore, in order to investigate efficiency per unit of motor cost, a different approach might need to be employed.

The author's approach to this problem was to analyze the basic loss mechanisms that limit motor efficiency and to examine a variety of existing and possible motor designs to see how well losses could be minimized to achieve high motor efficiency. Then one or more of the best possible candidate designs were selected on the basis of the expected manufacturing cost and potential cost reductions that might be obtained. By employing this approach, the goal of finding motor designs with high efficiency while maintaining low manufacturing cost was more likely to be achieved.

Motor Loss Mechanisms and Loss Segmentation

Losses in electric motors are relatively easily segregated into four specific categories. These are (1) conduction losses, (2) iron losses, (3) frictional losses and (4) other losses, sometimes referred to as stray losses, such as losses from higher harmonics and stray eddy currents. Each of these can be broken down into subcomponents and located in specific parts of the motor structure.

Conduction losses are mainly located in the windings of the stator, but can also be in rotor windings, such as are found in induction machines or doubly fed separately excited machines. Conduction losses increase as motor temperature increases, which can lead to thermal runaway as the windings heat up. Conduction losses are often the largest source of loss for most motors.

Iron losses are found wherever magnetic permeable material is used and is exposed to changing magnetic flux levels. This loss consists of both hysteresis and eddy current loss. In general, a majority of iron losses are associated with the stator, but they also exist in the rotor. Rotor iron losses can range from nearly zero to a major contributor to overall iron loss, depending on machine type. Iron losses depend heavily on the machine construction, type of materials and magnetic design, which sets the operating flux levels in the motor. They also depend significantly on both the flux density and the frequency of the flux changes in the motor. Iron losses are generally the second highest loss in modern motors. It should be noted that while hysteresis loss only occurs in magnetically permeable materials, eddy current losses are not limited to magnetic materials and can occur in any conductive material used in the motor.

Friction loss results from bearing friction from whatever bearings are used to support the rotor and also from rotor windage loss due to the rotating structures of the motor. This is usually a rather small contributor to the overall loss in a motor, especially in machines running at relatively low rpm.

The fourth category, stray loss, is a bit of a misnomer as it is used in the industry as a catchall category of losses that generally results from the difference in the prediction of each of the three primary losses compared to the total measured loss in the actual motor. Therefore, much of the loss attributed to stray loss can be from the first three primary loss mechanisms. In an actual motor, it is difficult to precisely predict and/or measure the losses in each category, and so the industry standard is to predict or measure each loss and then, if the complete motor testing shows higher loss than the sum of these expected losses, the excess losses are attributed as stray loss.

The loss due to AC impedance effects on the conductors can also contribute to stray loss. The winding resistance of most motors is specified as a DC resistance, but motors are operated with AC voltages and currents. Conduction losses increase as the frequency of the drive signals increases and are especially significant when higher frequency harmonic currents are present. In addition, eddy current or hysteresis losses in the motor casings and bearings are hard to quantify and can contribute to the stray losses, especially when non-sinusoidal waveforms are present. There can also be eddy currents in the conductive motor windings if they are exposed to a changing magnetic field from an external source.

Table 1 shows each loss and where it usually occurs. As can be seen, most of the total loss occurs in the stator, and conduction loss and iron loss are the main losses that limit the efficiency of a motor.

` Loss Type	Stator	Rotor	Notes
Conduction	Main loss area	With induction motor	Usually largest percentage loss
Iron Loss	-------------------	-------------------	-------------------
Hysteresis	Main loss area	Some loss	Can occur in iron casing
Eddy current	Main loss area	Some loss	Can occur in conductive casing
Friction	-------------------	-------------------	-------------------
Bearing	None	All rotor	Less than 1 percent
Windage	None	All rotor	Usually very small
Stray loss	Main loss area	Some loss	AC impedance, losses in casing

Table 1: Motor losses and their physical location

Review and Selection of Candidate Motors

Given that conduction loss and iron losses are the dominant sources of loss in a motor, in searching for a motor that has high efficiency it makes sense to focus on motors that, by the nature of their design, minimize conduction and iron losses while still providing adequate output power. In this search, all types of motor designs were initially considered. However, because the most commonly available traditional motor designs (induction, standard permanent magnet and reluctance) achieve good efficiency and have already been effectively cost reduced, the approach taken was to focus efforts on less commonly produced designs and non-traditional approaches. Many possible designs were considered, including various forms of axial motors, 3-dimensional approaches, transverse flux designs, line start reluctance and permanent magnet motors and others. The author has a reasonable familiarity with many of these designs and has followed the development of these motor types into the commercial market.

After a look at a number of these design options, the author decided to explore in detail a subset of axial motor designs. This subset is a permanent magnet dual rotor, single stator motor without iron in the air gap (air core motor). This type of design nearly eliminates all of the iron losses. It is also unusual in that it has an equal number of stator and rotor poles and generally utilizes a wide magnetic air gap.

There are a number of interesting aspects of this type of motor. Since both rotors rotate together and there is no iron associated with the conductors in the air gap, this design nearly eliminates all the iron losses associated with more traditional designs. This leaves the designer free to focus on conduction losses which can be minimized by optimizing the conductor volume with respect to the width of the larger than normal air gap.

The initial impetus for examining this motor design was the evaluation of a motor built by Mr. Paul Butterfield in California. He built and patented a specialized winding that can effectively drive this motor to reasonable performance using neodymium iron boron magnets (1). A form of this motor is currently the drive motor for a home-built electric car driving around the Silicon Valley area of California. A picture of this motor is shown in Figure 1.

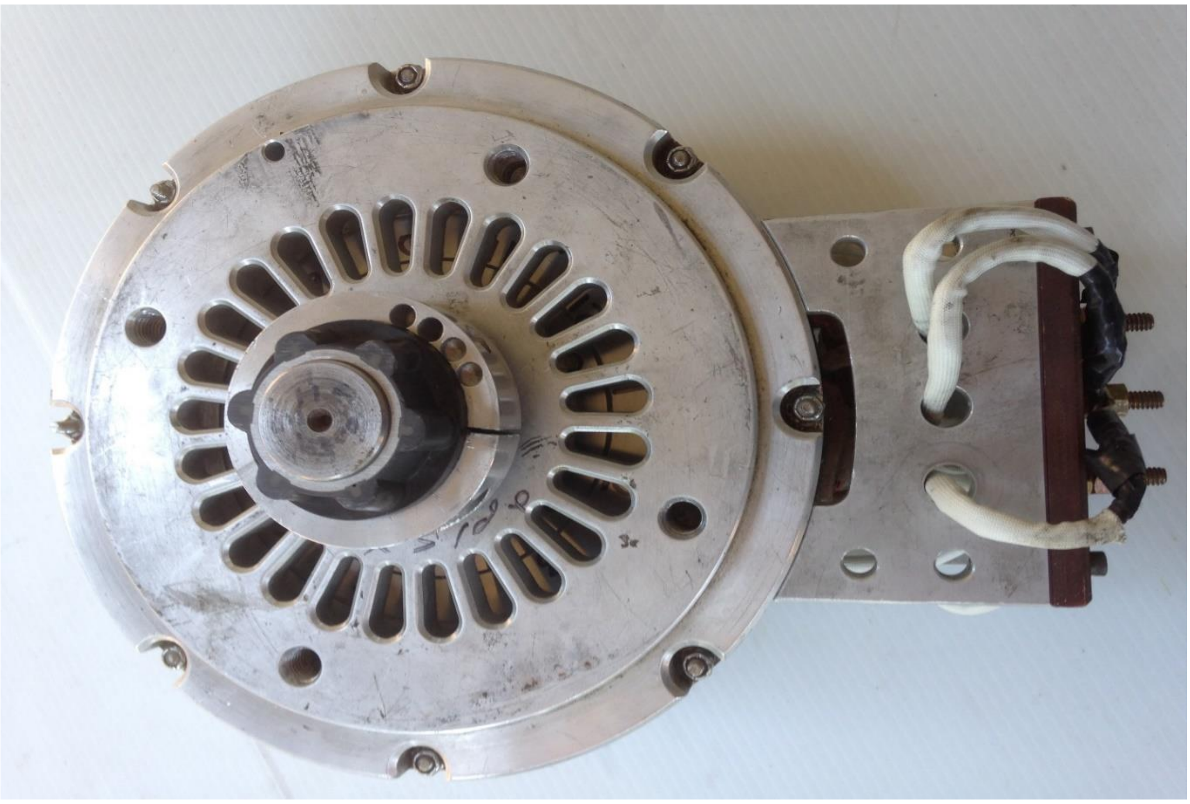

Figure 1: Butterfield Air Core Motor

Design Features

This motor design has some very interesting characteristics. Since the two rotors rotate together and no iron is used in the gap, there are minimal iron losses and zero detent torque. The result is a motor that is incredibly smooth. Since the only friction is from the bearings and air drag on the rotors, the motor spins freely and easily when turned by hand.

The motor is constructed with an equal number of stator and rotor poles and creates torque by the generation of force which is directly proportional to the magnetic field (B), the current (I) and the length of the conductor (L). This is similar to the standard equations used for force in brush DC motors. This type of motor tends to have a larger air gap and low resistance and low inductance values for the windings. This makes this type of motor very responsive, and it is similar in operation to printed circuit type servo motors. Another characteristic is that the peak torque can be 10 or more times the continuous running torque, allowing for very high acceleration. This is very useful in applications where short accelerations require high power, but the average power is normally much lower.

Some other physical characteristics are that this motor tends to have relatively high inertia, due to the fact that there are two identical rotors that face each other. The design of the rotors allows the magnets to be securely retained, which permits relatively high rotation speeds for this motor design. Another characteristic is that as the motor gets larger in diameter, the optimum number of poles increases. This increase in the number of poles is not required, but the motor performs best with specific pole dimensions based on magnetic design and rotor gap. This design feature in combination with the axial motor format results in larger diameter motors performing better than smaller motors. In fact, it is difficult to make small motors (less than 60 mm in diameter) work well with this design. High pole count, larger diameter motors of this type work very well at lower speeds, especially in the range of 100 to 600 rpm.

In terms of overall efficiency, this motor design performs quite well. There is one additional loss mechanism in this motor that is not generally an issue in traditional motors. The conductors experience the full changing magnetic field from the rotors. This then causes eddy currents in the conductive windings. This can be mitigated by using groups of smaller gauge wire twisted together rather than one larger diameter conductor. This multiple strand approach is commonly used in the motor industry to achieve greater current-carrying capacity, but in this design this winding technique is especially useful for reducing eddy currents in the conductor assembly. The Butterfield motor uses multiple strands to minimize this problem. The winding patented by Paul Butterfield is shown in Figure 2 below.

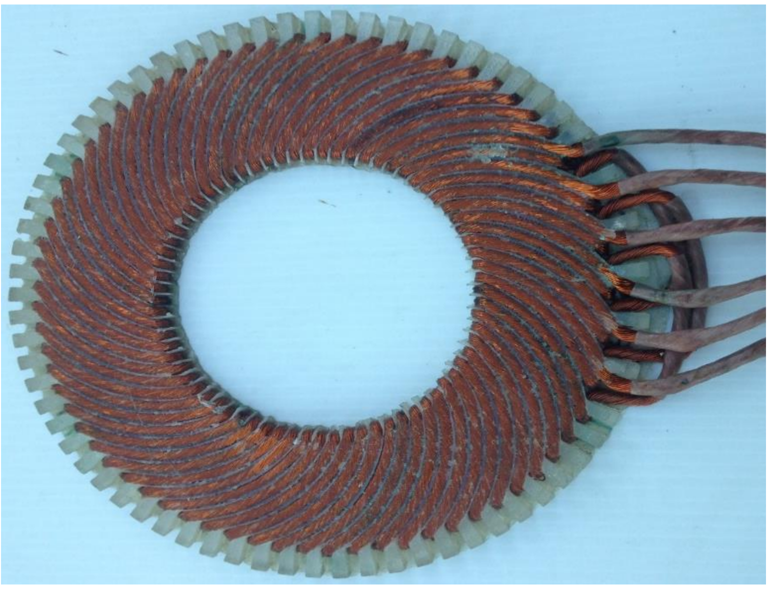

Figure 2: Patented Air Core Motor Winding

The particular implementation of this motor that was analyzed by the author included a high velocity fan incorporated into both rotors because this motor was cooled only with airflow in the demanding application of automobile propulsion. Most car drive motors are water or oil cooled. This fan feature added to the no load speed losses and reduced the overall efficiency when running at nominal power levels. Also, stray flux generating losses in the motor casing also resulted in somewhat lower efficiency than would be expected from a motor of this design.

The motor was tested on a dynometer test stand, as shown in Figure 3. The test results are presented in Table 2.

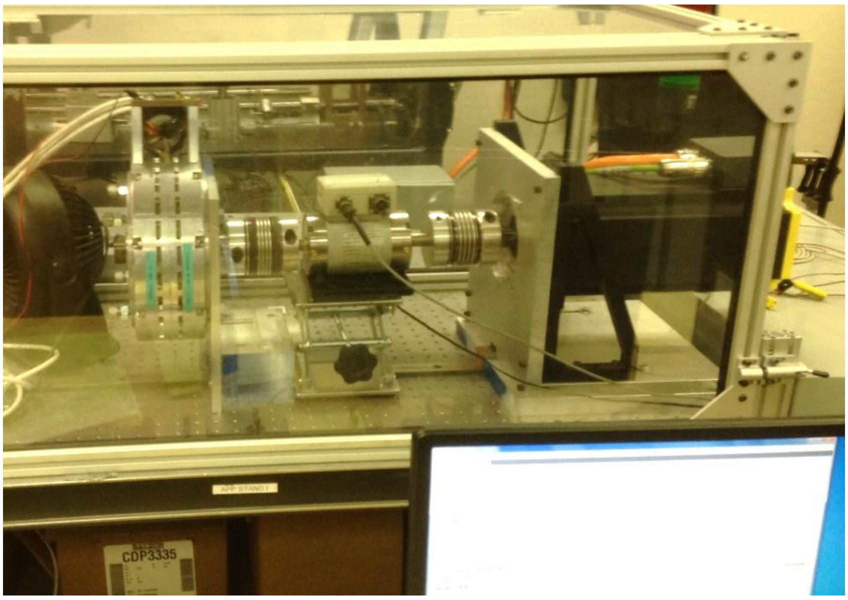

Figure 3: Motor on test stand.

Item	Units	Value	Notes
Winding resistance	Ohms	0.017	Phase to Phase Y
Winding inductance	milliHenries	0.008	Phase to Phase Y
Voltage constant	Volts per radian per second	0.105	
Torque constant	Newton meters per amp	0.1	
Rated speed	RPM	7500	
Rated torque	Newton-meters	15	At 150 amps
Rated power	Kilowatts	11.8	
Maximum speed	RPM	9,000	
Maximum torque	Newton-meters	75	
Maximum efficiency	Percent	92	At 3000 rpm
No load loss	Watts	146	At 3600 rpm
Diameter	mm	250	
Length	mm	100	
Weight	Kilograms	19	

Table 2: Test results

The very low winding resistance and inductance make this particular motor implementation operate at low voltages and higher currents. This can present a challenge to electronic motor drives, but was chosen to match the lower battery voltage supply available for this specific car application.

Design Challenges

This motor is not a highly power dense motor. It has a pancake form factor where the diameter is much larger than the length, and it does not have as high a torque output as a traditional radial motor of the same diameter. But given the short length, it does achieve an efficient use of total material. Multiple sections can be stacked together to arrive at similar torques and form factors as traditional radial motors. However, with this type of design, if one can tolerate a larger diameter, it is always more efficient in terms of material usage to achieve torque gains with increased diameter rather than by adding additional stacks.

This motor type also has some unique design challenges. One of these is the optimization of the width of the air gap. Clearly, too small of a gap results in very little conductor volume and therefore high conduction losses and poor overall performance. Too large of a gap results in the magnetic field dropping off and having undesirable flux paths so even with the resulting large volume of conductor associated with a wide gap, the motor does not perform well. For every magnetic configuration, there is an optimum gap width and conductor volume. This optimum gap width also depends on the speed of the motor, since many losses are highly dependent on speed.

The rotating magnetic flux passes through the conductor volume in the rotor gap and generates eddy currents. The eddy current losses in the conductors are, of course, dependent on the flux density, the rotational speed of the motor, as well as the number of poles and other factors. This loss can become a major contribution to overall loss if not properly addressed in the motor winding design. Making the winding structurally sound is another design challenge with this motor, since ideally the entire distance between the rotors would be filled with conductor material except for the required clearance gaps to permit rotation.

Another issue with this motor design is the control of the stray magnetic flux that can generate losses in the metal casing and other structural parts of the motor. The no load speed losses of the tested motor were indeed higher than expected, mostly due to this stray flux issue. This problem can be minimized with improved magnetic design and the use of some non-magnetic, non-conducting materials close to the rotating magnet assembly.

While the motor tested used disc-shaped neodymium iron boron magnets to achieve the desired power density, other magnet configurations could be utilized. Ferrite magnets would reduce the overall magnet cost, especially for larger diameter machines with a drop in power density. The lower BH product of ferrite can be partially mitigated by using these magnets in a Halbach type arrangement. This can increase the gap flux density by over 1.5 times, while actually reducing the total volume of magnets required. However, more magnetic pieces need to be assembled to achieve this improvement.

Possible Modifications to the Candidate Motor

Given that this motor has minimal iron losses, it is a promising candidate for achieving high efficiency. Also, given the simple construction, it could achieve the low cost goal. The key to achieving both high efficiency and low cost with this motor is to use the permanent magnets in a very cost effective manner or use inexpensive ferrite magnets. After looking at the motor design that was available, the author investigated alternative ways to utilize less expensive materials and alternative conductor designs that might be less expensive to produce. The most obvious cost reduction in materials would be to move from neodymium iron boron magnets to ferrite. However, given the much lower energy product of ferrite, better flux concentration and focusing would be required to achieve even a portion of the magnetic field produced by the magnets that were originally used. After several design iterations, a Halbach array of ferrite magnets was modeled for the rotors using a reasonable grade of ferrite. This design still only achieved about one-half of the flux density of the original magnets, but the cost savings would be substantial. Again, the most effective way to increase torque is with an increase in motor diameter and, in this case, the torque effectiveness lost by using ferrite can be regained by increasing the diameter of the motor by only 1.26 times the original diameter. If the application of this motor does not require high power density, then there would be a clear economic advantage to using ferrite magnets for this design.

Besides magnets, the other primary place for cost savings is in the conductor assembly. While the Butterfield winding design works well, it may not be the most cost effective. The original motor performs rather well with the use of a slightly twisted, multiple-stranded cable. The difficulty of this approach is the complexity of making the winding and the mechanical strength of the winding assembly.

Therefore, a search was undertaken to uncover various other winding techniques for this motor design. Several have been proposed in the literature, including using ribbon-style conductors, printed circuit conductors, other flat plane conductors, and discrete solid wires like the "hairpin" conductors that are often used in modern automotive drive motors. Each of these has advantages and disadvantages that are detailed below.

Using flat ribbon conductors results in a standard concentrated winding that can provide good torque per amp ratings. However, the fill factor is rather low, given that the conductors start on an inside diameter and end up in a much larger diameter. A configuration like this has been recently patented by Gabrys (2). Given the constant cross section of this style of conductor, if the outside diameter is twice the inside diameter of the active part of the motor, then the conductor fill factor at the outside diameter is less than 50 percent, even if it is near 100 percent at the smaller diameter. Even with this limitation, Gabrys's patent claims efficiencies of above 98 percent.

This conductor space utilization can be mitigated by using printed circuit conductors, but this approach is limited by the amount of conductor that can be applied to and formed on a printed circuit structure. Also, the base printed circuit material that holds the conductor takes up valuable space that ideally is filled with conductors. This again leads to relatively low conductor fill factors. There are many smaller printed circuit motors available on the market, and again they achieve very high efficiencies (3, 4).

Using "hair pin" style conductors is an interesting approach which could be very space-efficient in terms of conductor volume, but involves separate structures both on the inner diameter and outer diameter to hold these discrete conductors in the proper location. Also, the electrical interconnects between all the individual conductors poses a significant problem.

Of course, one obvious option for reducing the cost of the conductor assembly would be to switch to aluminum conductors from the currently used copper wire. This would reduce the cost and the weight of the assembled motor, but increase the losses in the conductors by about 20 percent. This also would reduce the structural strength of the conductor assembly.

Conclusion

From examining this specific dual rotor axial motor design, it was determined that it could, with appropriate modifications, indeed meet the goal of high efficiency and low production cost, but that such a motor would not provide a highly power-dense motor. Also, the pancake form factor limits this motor to a subset of applications. Therefore, the primary market for such a motor would be one where the overall size and weight of the motor were not the most important considerations.

In evaluating motors there are a number of possible metrics that can be used. This paper has focused on efficiency per unit of motor cost. Other important metrics are power density in terms of both size and weight, efficiency over a broad speed or torque range, reliability, commercial availability including multiple source options, and many others. The investigations conducted by the author lead to a conclusion that a high efficiency motor with low manufacturing costs in terms of both materials and labor can indeed be achieved, however, such motors are not likely to be power dense or have high power per unit weight. However, the search should be continued as the need for higher motor efficiency at an attractive cost will continue to be of interest to the commercial marketplace.

References

[1] US Patent 7,375,449 Optimized Modular Electrical Machine using Permanent Magnets, Paul Butterfield, May 20, 2008

[2] US Patent 8,933,607 High Efficiency Air Core Motor-Generator, Christopher Gabrys, January, 13, 2015

[3] http://www.printedmotorworks.com/brushless-pancake-motors/, Printed Motor Works

[4] http://www.astli.com/cds_series.html, AST, Automation Source Technologies

Performance evaluation of induction motors fed by PWM voltage with magnetic equivalent circuits.

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Abstract

Three-phase induction motors fed by frequency inverters have become an increasingly used solution for applications that require torque and speed control. The harmonic content of inverter output voltage generates harmonics in the motor current. Both harmonics produce harmful effects on motor performance. The accurate estimation of these effects in the design stage of electric motors is not a simple task. Not all the phenomena that occur in electrical machines are fully modeled, especially when considering the voltage harmonics of non-sinusoidal supply.

The numerical methods that currently have satisfactory results penalize the project with expensive computational cost and time. Analytical models are very common and useful for analyzing small changes in current projects, but they have limitations to deal with new project evaluation. An alternative modeling approach is Magnetic Equivalent Circuit (MEC), which has the main advantages of the previous two.

The main goal of this work is to show the capability of MEC to estimate the efficiency of three-phase induction motors with PWM voltage. The necessary considerations in the modeling to take into account the effects of the high order voltage harmonics on the motor performance are presented.

Introduction

Electric motors in industrial applications consume about 40% of all the generated electrical energy worldwide. In the European Union (EU), electric motor systems are, by far, the most important type of load in industry, using about 70% of the consumed electricity [1]. Part of these motors are supplied by inverters in applications requiring variable speed and torque. Some features of induction motors (such as mechanical robustness and reliability, reasonably low production costs and easy availability on the market) make this machine topology an attractive alternative for this type of application [2].

The introduction of energy efficiency regulations around the world [3] emphasizes the importance of the determination of losses and energy efficiency of the induction motor [4]. The optimization of the design of electrical machines fed by complex waveforms has deserved the attention of experts.

Figure 1 shows an infographic of a motor supplied by a converter and typical curves. While the input voltage of the inverter has almost no harmonic content, its output voltage has a large harmonic content that results in current distortion.

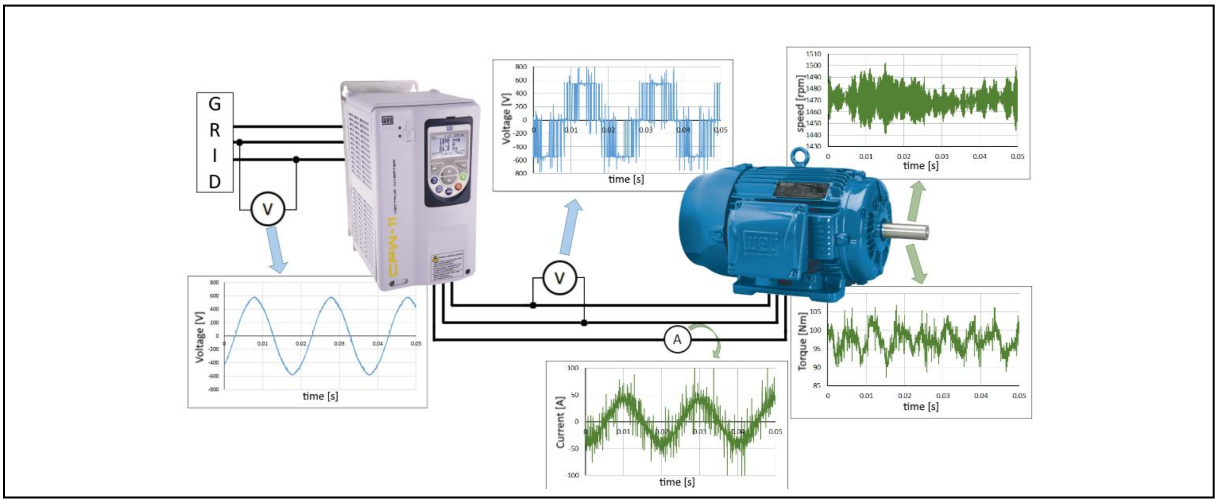


Figure 1 - Infographic: motor supplied by a converter (author).

Although the general design principles of electric machines such as induction motors have been well defined over the years by theory and practice, it is increasingly common for machine designers to search for alternatives to improve the performance of these machines. Therefore, other than experience, developments may be based on “trial and error” or computer simulations. Ideally, the simulations make it possible to consider the analysis of a much larger number of project changes without the cost of the experimental analysis practices (prototypes).

The development of simulation software suitable for advanced design purposes has been restricted by the geometrical complexity of most electrical machines. In principle, numerical approaches such as the Finite Element Method (FEM), are able to give precise and complete machine performance by providing both the detailed behavior of the field and the overall performance of the machine. However, the computational resources available to designers are not always suitable for this task. Consequently, the designer is often forced to compromise performance on steady state by considering simplifications in the model. A comprehensive literature review on the subject and a comparison of the three main approaches to machines modeling is presented in [5].

Currently, the overall performance of the machine can be obtained by tests, but the segregation of losses is possible only through simulation [6]. In this case, the main difficulties for the realization of simulation are:

- difficulty in defining an adequate model for estimating iron losses;
- data for these models are obtained in most cases for low frequencies; and
- the simulation is time-consuming and expensive when using the small time-steps required for high frequency switching waveforms.

This work aims to analyze the capability of MEC, with the model proposed in [11], to be used as a CAD tool to estimate the efficiency of three-phase induction motors with PWM voltage. The test results of 6 motors of different powers are compared with simulated values.

Despite typical switching frequencies are 5 to 18 kHz, the analyses in this work deal with low switching frequencies (1.25 and 2.5 kHz), due the fact that these frequencies cause greater losses in the motors and are very common in industrial applications, mainly for motors above 90 kW. To derate motor power properly, the losses need to be estimate correctly.

Electrical Machines Modeling Approaches

Modeling is an important task in the new electric machine design. The geometrical discretization level of an efficient model should be: (a) sufficiently detailed to give good accuracy, even in regions with high flux gradients; and (b) generic to require little computation time.

An accurate model should be able to consider non-linear magnetic effects, such as saturation and losses, hysteresis and eddy currents, even in complex structures of electrical machines. The requirements for an analysis tool are precision, computing resources, 3D capability and parameterization.

The three most common approaches to modeling and design of electric machines are: Analytical Models (AM), FEM, and Magnetic Equivalent Circuit (MEC).

Analytical Models - AM

Electrical machines performance assessments based on analytical models were introduced in the 1970s. These models are the most common, mainly because of their simplicity. The parameters and performance characteristics (e.g. torque, losses and current) are based on the average magnetic field in the air gap and laminations. Analytical models are based on equivalent circuits with lumped parameters. Therefore, depending on the machine saturation level, neglecting the saturation effects will result in significant errors.

For some system operating conditions, these approaches do not provide the desired accuracy. Complex geometries are difficult to simulate using classical analytical procedures as well as saturation, eddy current and hysteresis losses, and the skin effect.

This method is useful for analyzing small changes in existing and known projects, but it has limitations in new project evaluation. The great advantage is related to computational resources, but have drawbacks in accuracy, flexibility and 3D simulation capability.

Finite Element Method - FEM

To design machines with optimized efficiency, FEM tools are very flexible, especially in cases involving new projects that incorporate new topologies; but they have the disadvantage of requiring long processing time.

The modeling of an induction machine, in the time domain with a typical commercial tool, takes hours to reach the solution in steady state, simulating 1 second operation time.

Despite some limitations, FEM models allow simulations in 3D. In these cases, the models become more computationally expensive (further increasing processing time). Other advantages of FEM models are the possibility to consider stator and rotor slots, spatial distribution of stator winding and nonlinear behavior of the magnetic core.

Magnetic equivalent circuit - MEC

Modeling by MEC has been developed and used since the beginning of last century. V. Ostovic adapted a version based on computer models for induction motors in the 1980s, later published in [7]. This method has been used to model the non-linear magnetic field in electrical machines, on both dynamic and steady-state conditions.

MEC modeling can consider saturation, once the locations where the phenomenon is expected to occur are known and modeled. By using this method, the leakage and saturation, as well as iron losses, can be modeled accurately and calculation times are smaller than FEM. The number of elements implemented in this method is usually less than for the FEM. This is especially true for 3D models, where the MEC uses pipe elements instead of point elements.

The simulation of the eddy current is a challenge in the modeling by MEC, and its inclusion in the formulation significantly increases the complexity of the model. This is because the Magnetomotive Force (MMF) formulation has a magnetic scalar potential without the geometric properties necessary to induce eddy currents.

The main advantages of the MEC method are precision, low complexity of the model, easy parameterization, 3D capability and low computational time.

Criteria for defining the modeling method

MEC approach is gaining increasing popularity in the design optimization and transient simulation of electrical machines where repetitive computations are required in a short time. The method has been successfully applied to different types of magnetic devices, including induction machines [8].

However, in addition to this trend, it is important to base the choice with qualifying criteria. In [9] there is a list of criteria and their corresponding qualitative ratings. These values are presented in Table 1, where "+" denotes an advantage, "0" a neutral rating, and "-" a disadvantage. According to this classification MEC method is appropriate for CAD of electrical machines.

Table 1 – Criteria of a Modeling Tool Feasible for Design

Criteria	AM	FEA	MEC
Model accuracy	-	+	0
Computational effort	++	-	0
3-D capability	-	0	+
Parameterization	+	0	+
Simplicity of implementation	0	0	0
Interpretation of results	+	0	0

Table adapted from [9].

MEC Modeling of Induction Machines

Flux Tube

MEC networks consist of permeances, MMF sources, and magnetic flux sources, analogous to resistive electric networks. Permeances represent flux tubes in the geometry of the modeled machine. A flux tube connects two points (nodes) in an object where a scalar magnetic potential u is defined. The flux Φ flows in uni-axial directions between these points. The general definition of a flux tube is shown in Fig. 2. It has length l, cross-sectional area A, and permeability μ. Its permeance P is

$$P = \frac{1}{R} = \frac{1}{\displaystyle\int_0^l \frac{dl}{\mu A(l)}} \tag{1}$$

assuming that μ is constant within the flux tube.

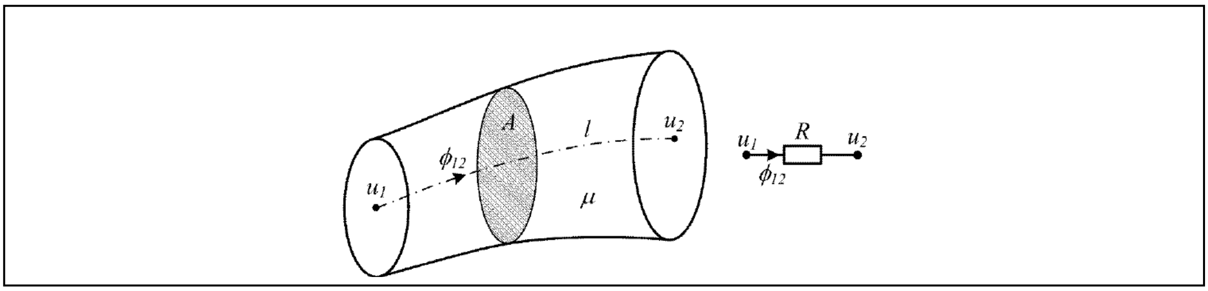


Figure 2 - Definition of a flux tube and the corresponding reluctance [11].

The MEC method is based on the decomposition of an electromagnetic system into flux tubes. Each tube is characterized by its permeability, and all the permeances are linked creating a magnetic circuit model in which the magnetic flux and the MMF are the variables.

Model Formulation

MEC implemented in this work is similar to one used in [11]. In this method, most parts of stator and rotor structures are approximated by cubic elements whose permeance can be defined as:

$$P = \frac{\mu A}{l} \quad (2)$$

where *P*; μ, *A* and *l* are permeance, permeability, cross-section area, and length of an element, respectively.

Stator Permeances

Figure 3 shows part of an induction motor MEC. Main flux paths in the stator are represented by stator yoke (*Psb*), stator tooth (*Pst*) and stator tooth-tip-to-tooth-tip (*Pstst*) permeance elements. These individual permeances can be calculated with the material properties and geometric parameters of the machine, according to (2):

$$P_{sb,i} = \frac{\mu_{Fe} N_{ss} (s_{od} - s_{id} - 2s_{sd}) L}{\pi (s_{od} + s_{id} + 2s_{sd})} \quad (3)$$

$$P_{st,i} = \frac{4\mu_{Fe} s_{tw} L}{s_{od} - s_{id} + 2s_{sd}} \quad (4)$$

$$P_{stst,i} = \frac{\mu_0 N_{ss} s_{tft} L}{\pi (s_{id} + s_{tft}) - N_{ss} s_{tfw}} \quad (5)$$

where μ_{Fe} and μ_0 are permeabilities of iron core and air, respectively; s_{tw} is the stator tooth width; s_{od} and s_{id} are the stator outer and inner diameters, respectively; s_{sd} is the stator slot depth; s_{tft} and s_{tfw} are stator tooth face thickness and stator tooth face width, respectively; L is the axial length of motor; N_{ss} is the number of stator teeth.

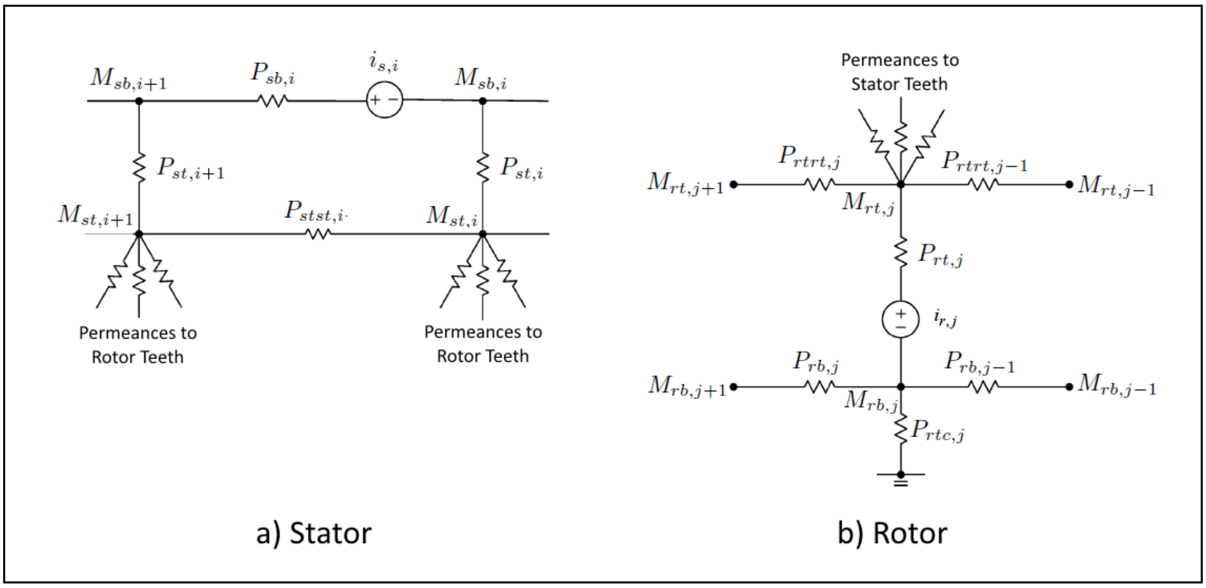


Figure 3 - (a) Stator and (b) rotor MEC [11].

Rotor Permeances

Rotor permeance elements, similar to stator ones, rotor tooth-tip-to-tooth-tip (*Prtrt*), rotor tooth (*Prt*), rotor yoke (*Prb*), and rotor yoke-to-center (*Prtc*) can be defined as follows:

$$P_{rtrt,j} = \frac{\mu_0 N_{rs} r_{tft} L}{\pi(r_{id} - r_{tft}) - N_{rs} r_{tfw}} \tag{6}$$

$$P_{rt,j} = \frac{\mu_{Fe} L r_{tw}}{r_{sd} + r_{bdn}} \tag{7}$$

$$P_{rb,j} = \frac{2\mu_{Fe,lin} L r_{dbn} N_{rb}}{\pi(r_{od} - 2r_{sd} - 2r_{bdn})} \tag{8}$$

$$P_{rtc,j} = \frac{2\pi\mu_{Fe,lin} L}{N_{rb} \ln((r_{od} - 2r_{sd} - 2r_{dbn})/r_{id})} \tag{9}$$

where r_{tft}; r_{tfw}; r_{od}, and r_{id} are rotor tooth face thickness, rotor tooth face width, rotor outer diameter, and rotor inner diameter, respectively; r_{tw} is the rotor tooth width, r_{sd} is the rotor bar depth; r_{bdn} is the depth of rotor yoke nodes and is defined as:

$$r_{bdn} = \frac{1}{2} + \sqrt{\frac{\pi(r_{od} - 2r_{sd})r_{tw}}{N_{rb}}} \tag{10}$$

Air-gap permeances

The stator–rotor permeance, $Prtst_{i,j}$, depends on the area of overlap between the teeth and must be computed for every stator–rotor tooth combination:

$$Prtst_{i,j} = \frac{a_{i,j} \times \mu_0}{g} \tag{11}$$

where g is the air gap length and $a_{i,j}$ is the area of overlap between the i^{th} stator tooth and the j^{th} rotor tooth. In this work, the skew is considered according to [7].

Leakage Permeances

Some stator and rotor leakage permeances are not considered in the MEC of Fig. 3. In this case, they must be considered by analytical expressions based on the method proposed in [11].

MMF Sources

The specification of MMF sources in MEC, in addition to permeance elements, is done across the geometry of the machine where electric currents flow inside the stator windings or the rotor bars. These stator MMF sources are obtained by multiplying the current in each phase by the number of turns in each stator slot. Rotor MMF sources are equal to rotor loop currents. The setup of these equations is discussed in detail in [7] and [11].

Differential equations

A MEC dynamic solution requires the differential equations formulation that governs the external electrical circuits of the stator windings and the rotor cage. The states are the stator (λ_{qd0}) and rotor (λ_r) flux linkages, which depend on the applied voltages and currents. Details of stator and rotor differential equations are shown in [11].

In this work, the skin effect is considered by the correction of rotor bars resistance and leakage reactance values. These factors are based on rotor speed and are defined in [12].

Torque Calculation

Finally, mechanical differential equations for induction motor are:

$$\tau_e - \tau_{load} = J\frac{d\omega}{dt} \quad , \quad \omega = \frac{d\theta}{dt} \tag{12}$$

where τ_{load} is the mechanical load in *N.m*, J is the rotor inertia, ω is the motor speed in *rad/sec*, and Θ is the rotor angle (position) in *rad*. Electromechanical torque τ_e is given as:

$$\tau_e = \frac{P}{2}\left(\lambda_d i_q - \lambda_q i_d\right) \tag{13}$$

where P is number of poles in a machine. Stator flux linkages (λ_{qd0}) and stator currents (i_{qd0}) are calculated in *qd0* stationary reference frame.

Material Characteristics

Like in [11], the steel is characterized by permeability, μ_{fe}, and is computed as a function of the magnetic field intensity H in accordance with

$$\mu_{\mathrm{fe}}(H) = \begin{cases} \frac{K_2 \ln(K_1|H|+1)}{|H|} & H \neq 0 \\ K_1 K_2 & H = 0 \end{cases} \tag{14}$$

where $H = \Delta M/l$, and where ΔM the magnetic potential across the iron section and l is the length of the iron section.

Performance Estimation

To evaluate the induction motor performance, it is necessary to estimate the power losses. Resistive losses can be determined from the dynamic solution of the stator and rotor winding currents, and knowledge of the resistance.

The main problem consists of core loss estimation that can be calculated with empirical equations based on the magnetic field solution in the reluctance elements. In this work, the core losses are estimated according to [13] after simulation is finished.

Core loss

The core loss components (hysteresis loss p_h, eddy current loss p_c, and excess loss p_e) are computed for all MEC network elements as proposed in [13]:

$$p_h(t) = H_{irr}\frac{dB}{dt} \tag{15}$$

$$p_c(t) = \frac{k_c}{2\pi^2}\left(\frac{dB}{dt}\right)^2 \tag{16}$$

$$p_e(t) = \frac{k_e}{C_e}\left(\frac{dB}{dt}\right)^{1.5} \tag{17}$$

where B is magnetic field density, H_{irr} is irreversible component of magnetic field (defined in [13]), and k_c, k_e e C_e are material characterization constants. The determination of these values is described in detail in [13].

Comparative Analysis

The main aim of this work is to analyze the induction motor performance at steady-state operation. So, except as noted, all values analyzed are for this condition.

The validation of MEC modeling is done with data of 6 three-phase induction motors (see Table 2), comparing the experimental and simulated results.

Table 2 – Motor List

id	P_N [kW]	IEC Frame	f [Hz]	V_L [V]	poles	I_N [A]
1	1.5	90L	50	400	4	3.31
2	5.5	132S	50	400	4	10.5
3	15	160L	50	400	4	28.8
4	30	200L	50	400	4	57.8
5	45	225S/M	50	400	4	82.8
6	110	280S/M	50	400	4	197

Three voltage waveforms were considered in analysis: sinusoidal (grid) and two PWM voltages (with different switching frequencies: 1.25 kHz and 2.5 kHz), always keeping fundamental rms voltage level in 400V. Four load conditions (100%, 75%, 50% and 25%) were analyzed at nominal frequency of 50Hz.

Base values used in analyses are P_N for power and losses, and I_N for currents.

Simulation

MEC model described above has been programmed in python. Steady state values were based on the last 2 cycles of the supply voltage (fundamental component).

All motors use the same magnetic material. The magnetization parameters used in (14) are K_1= 0.04197 m/A and K_2 = 0.32989 T. For core loss estimation, parameters were defined as proposed in [13]: k_c = 1.6247, k_e = 2.3827 e C_e = 8.7634.

Tests

Tests were performed in laboratory benches equipped with power analyzers (Yokogawa WT1800). Torque was measured with torque transducers (HBM T40), speed with encoders and temperatures were monitored with resistance temperature detector (PT-100) installed on the end windings.

When testing electric motor under load, fluctuations in the output power and other measured quantities may be unavoidable. Therefore, for each load point, several measurements over a period of time (approximately 30 s) were simultaneously sampled to determine the average of quantities, as suggested in [14]. Before running the load tests, the motors reached thermal stability.

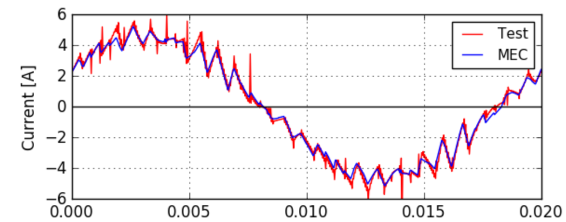
Overall Performance

The overall performance of the motors is analyzed by means of two quantities of the motor: current and power losses. The current waveforms in the time domain show the capability of the MEC simulation to reproduce transient effects. Another study analyzes the capability of the MEC model to estimate the tendency of current and losses variation as a function of load.

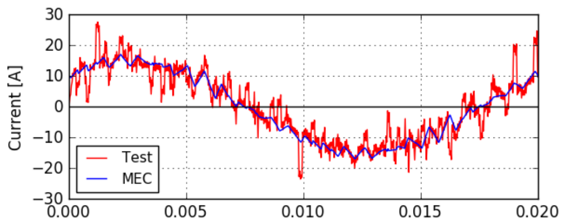
Input Current Waveforms

The current waveforms for the six motors fed by PWM voltage, at nominal load, are depicted in Fig. 4 and 5, for switching frequencies of 1.25 kHz and 2.5 kHz, respectively.

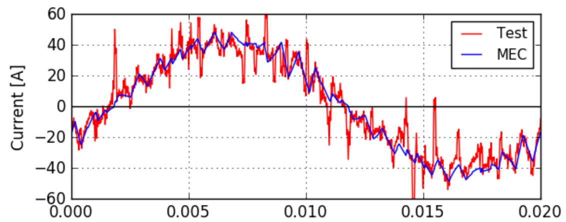
In general, the MEC model provides a reasonable estimate of the amplitude and wave shape of the current. As expected, one can observe that the current harmonic content is greater for switching frequency of 1.25 kHz (Fig. 4), and the model has correctly reproduced this effect.



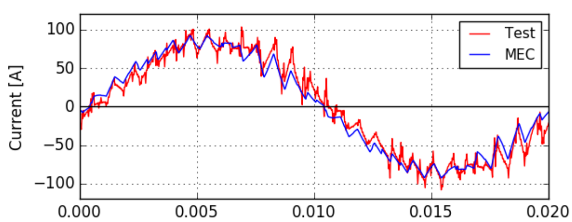
(a) Motor 1 - PWM 1.25 kHz



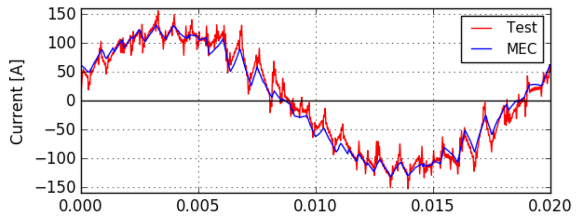
(b) Motor 2 - PWM 1.25 kHz



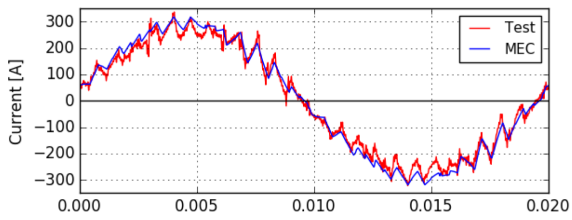
(c) Motor 3 - PWM 1.25 kHz



(d) Motor 4 - PWM 1.25 kHz

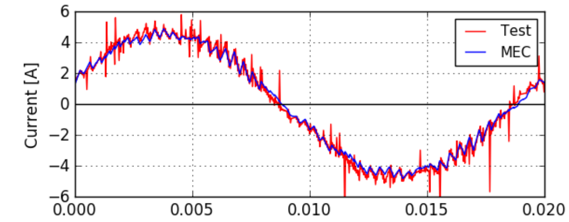


(e) Motor 5 - PWM 1.25 kHz

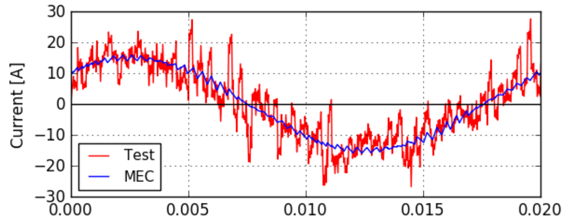


(f) Motor 6 - PWM 1.25 kHz

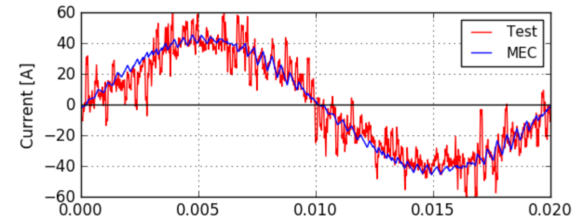
Figure 4 – Motor currents @100% load with PWM voltage – 1.25 kHz.



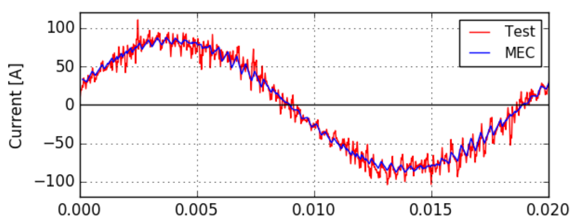
(a) Motor 1 - PWM 2.5 kHz



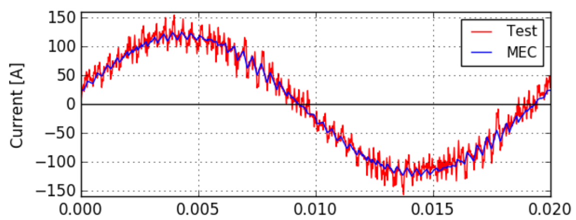
(b) Motor 2 - PWM 2.5 kHz



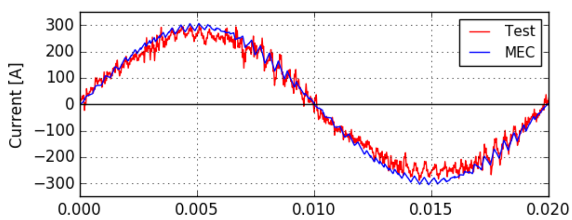
(c) Motor 3 - PWM 2.5 kHz



(d) Motor 4 - PWM 2.5 kHz



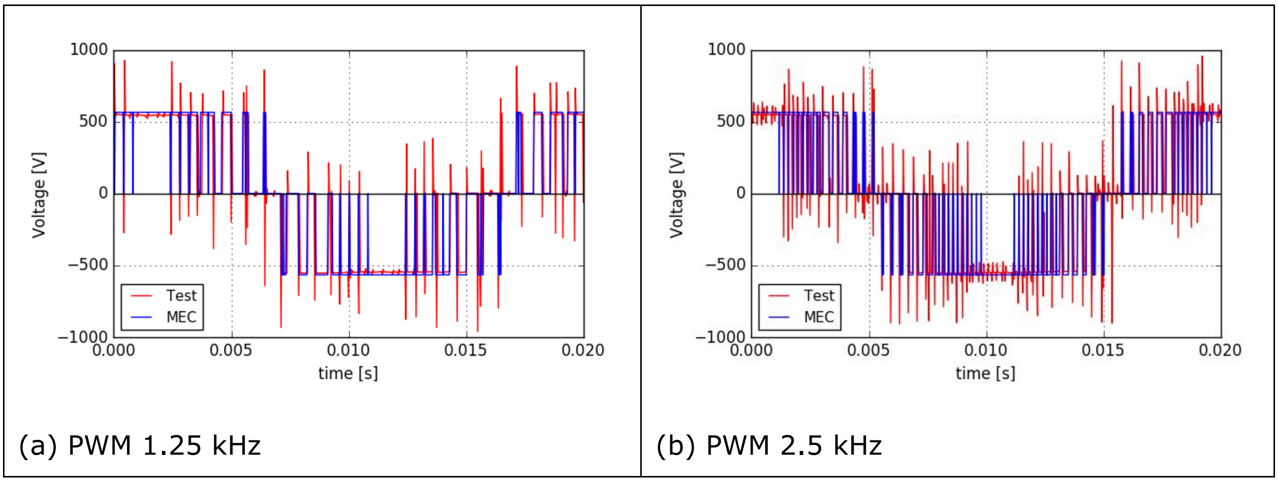
(e) Motor 5 - PWM 2.5 kHz



(f) Motor 6 - PWM 2.5 kHz

Figure 5 – Motor currents @100% load with PWM voltage – 2.5 kHz.

In both figures, measured curves present a considerable "noise" not simulated by MEC. Apparently, this noise is higher for switching frequency of 2.5 kHz (Fig. 5). The explanation for this phenomenon is motor supply: simulation considers ideal PWM voltage, different from real one, as shown in Fig. 6.



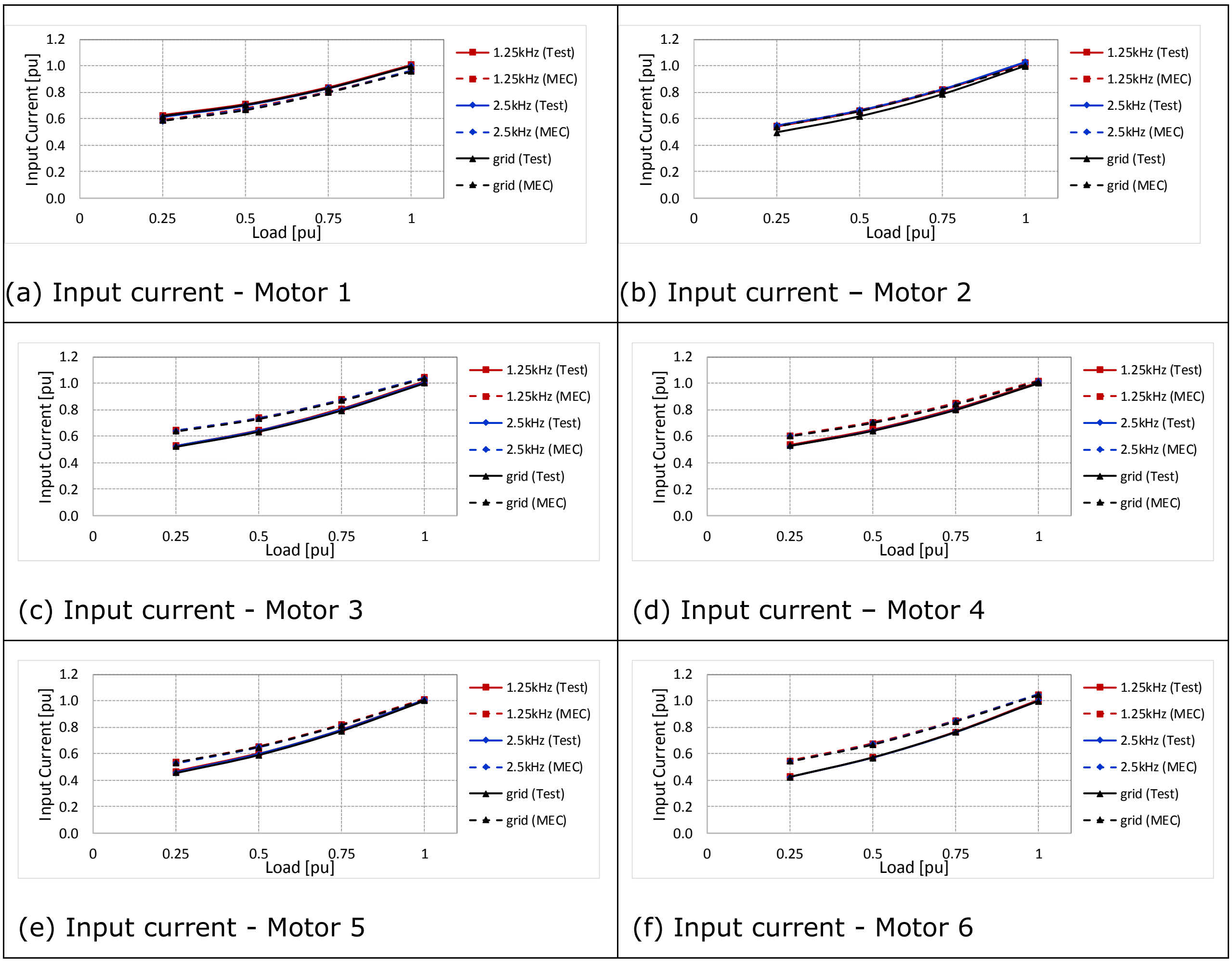
(a) PWM 1.25 kHz

(b) PWM 2.5 kHz

Figure 6 – PWM voltage – Test x MEC.

Input Current

The input current increase due to the PWM voltage is practically imperceptible in the visual analysis of the current variation, as can be seen in Fig. 7, which shows the rms values measured and estimated for all motors, in p.u.[58]



(a) Input current - Motor 1

(b) Input current – Motor 2

(c) Input current - Motor 3

(d) Input current – Motor 4

(e) Input current - Motor 5

(f) Input current - Motor 6

Figure 7 – Input current (rms) variation with load and voltage waveform, in p.u.

[58] Current base value is equal to nominal current I_N for each motor, defined in Table 2.

Comparing estimated and measured values one can observe that except for motor 1, the estimated values are greater than measured. The difference is small at nominal load and increases for low loads, as can be observed in Fig. 8 for grid supply.

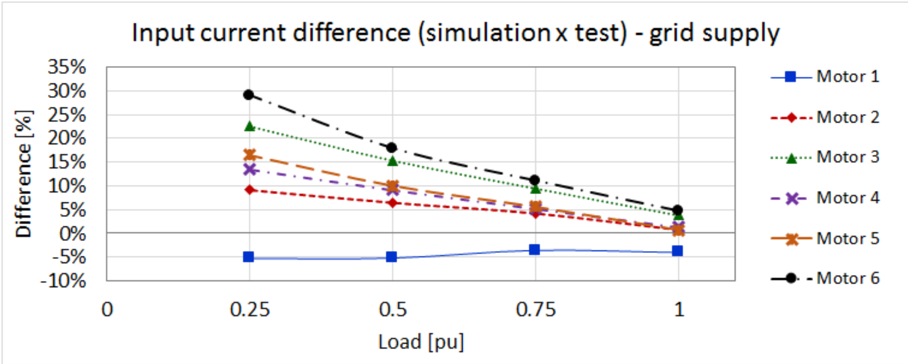


Figure 8 – Input current difference between simulation and test, for grid supply.

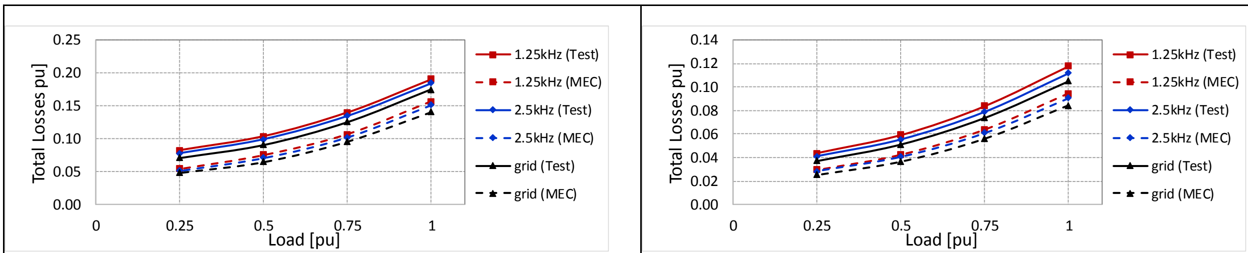
The input current differences found in simulation values may have been caused by the characterization of BxH curve used in motor modeling.

Total Losses

The total losses, in p.u.[59], for the six motors are depicted in Fig. 9. The measured and estimated losses variation with load for each motor are shown, for three different voltage waveforms: sinusoidal (grid) and PWM voltage with two different switching frequencies, 1.25 KHz and 2.5 kHz.

Both measured and estimated values show the same trend: (i) motor losses increase when fed by inverter and (ii) lower switching frequency present higher losses. As the amplitudes of the voltage harmonic components of the PWM waveform are equal for both switching frequencies, 1.25 kHz and 2.5 kHz, but component frequencies are lower for 1.25 kHz, it is possible to conclude that the lower the voltage harmonic frequency, the greater will be the contribution on losses increase.

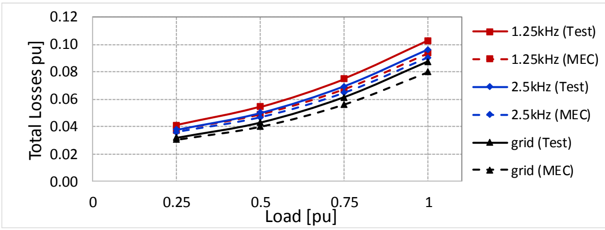
In general, it seems that the loss difference between switching frequencies is smaller for the estimated values. This observation is further confirmed by the comparison of additional losses.



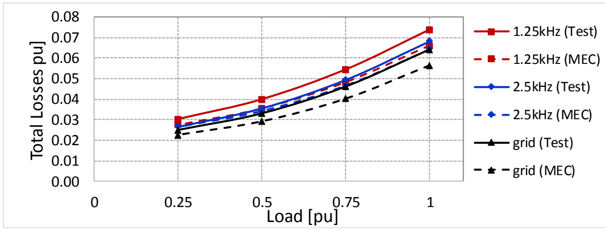
(a) Total losses - Motor 1

(b) Total losses – Motor 2

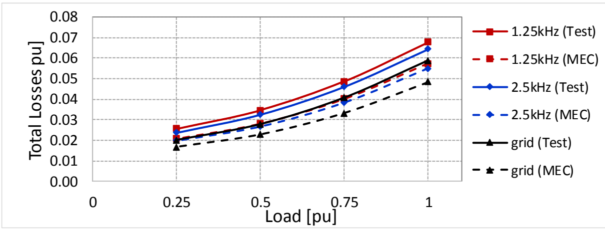
[59] Power base value is equal to nominal power P_N for each motor, defined in Table 2.



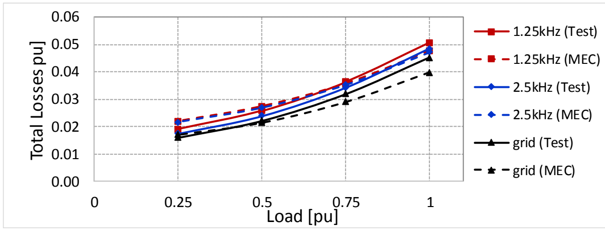
(c) Total losses - Motor 3



(d) Total losses – Motor 4



(e) Total losses - Motor 5



(f) Total losses - Motor 6

Figure 9 – Total losses variation with load and voltage waveform.

Comparing estimated and measured values one can observe that except for one load condition of motor 6, Fig. 9(f), estimated values are smaller than measured. There are 3 types of loss variation with reducing load: (i) for motors 1 and 2 the difference increases; (ii) for motors 3, 4 and 5 the difference decreases slightly ; and (iii) for motor 6 the difference decreases until 50% of load, increasing again at 25% of load. These trends are plotted in Fig. 10 for grid supply.

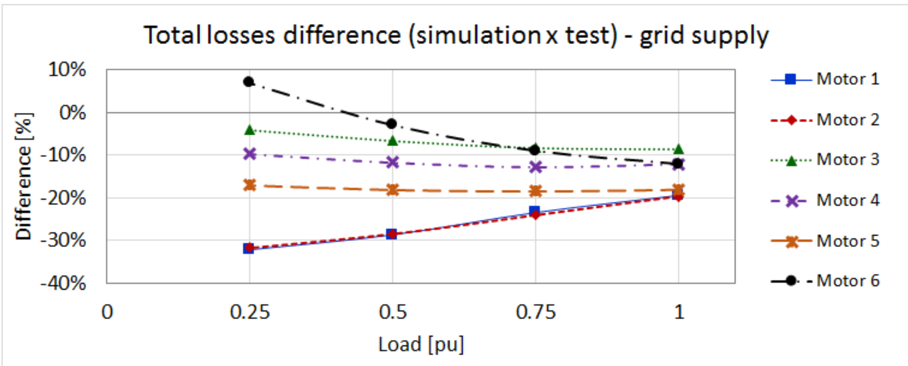


Figure 10 – Total losses difference between simulation and test, for grid supply.

Figures 8 and 10 shows that even for sinusoidal voltage MEC model needs improvements. Simulations used same model for all six motors.

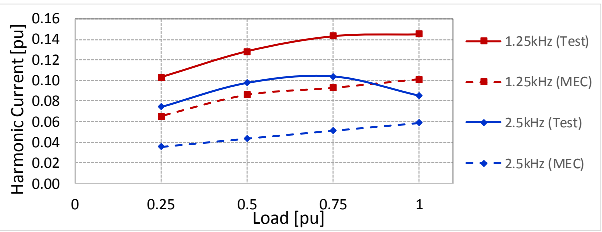
Current difference with load (Fig. 8) can explain, in part, losses variation, mainly for motors 3 to 6. However, the main reason must be related to core losses estimation. In this case, there are two factors to be improved: (i) MEC model mesh refinement, and (ii) model for core loss estimation.

Additional Losses and Harmonic Current

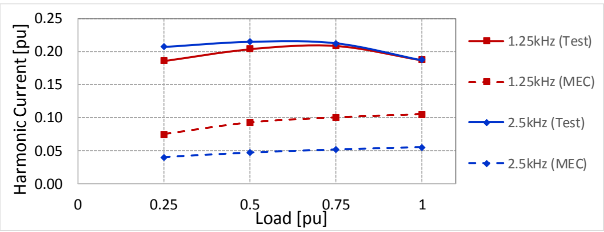
In practice, the performance of induction motors supplied by sinusoidal voltage (grid) is estimated quite accurately. The major difficulty is the estimation of the losses increase when the motor is supplied by PWM voltages. In this way, the proposed model must correctly calculate losses and current harmonics to be characterized as a good CAD tool.

Harmonic Current

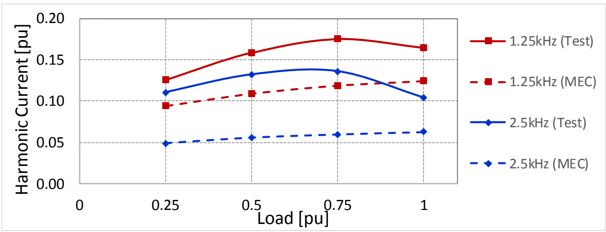
Figure 11 summarizes the variations of harmonic currents for the analyzed motors. Except for the test results of motor 2, for other motors both results, tests and simulation, show that harmonic currents with 1.25 kHz are greater than with 2.5 kHz.



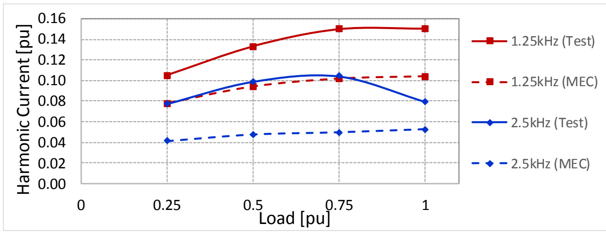
(a) Harmonic current - Motor 1



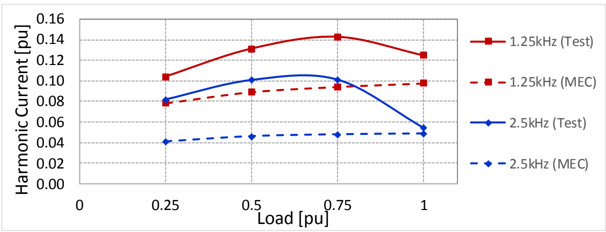
(b) Harmonic current – Motor 2



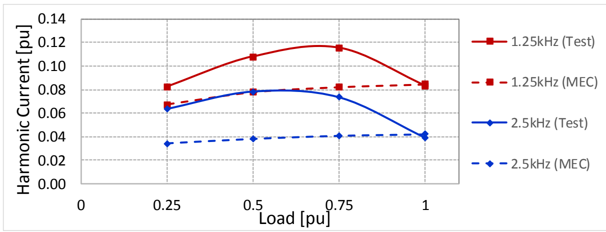
(c) Harmonic current - Motor 3



(d) Harmonic current – Motor 4



(e) Harmonic current - Motor 5



(f) Harmonic current - Motor 6

Figure 11 – Harmonic current (rms) variation with load and voltage waveform, in p.u.

While simulation values present a linear variation trend, the test ones present a parabolic trend. MEC model need improvements to reflect this phenomenon.

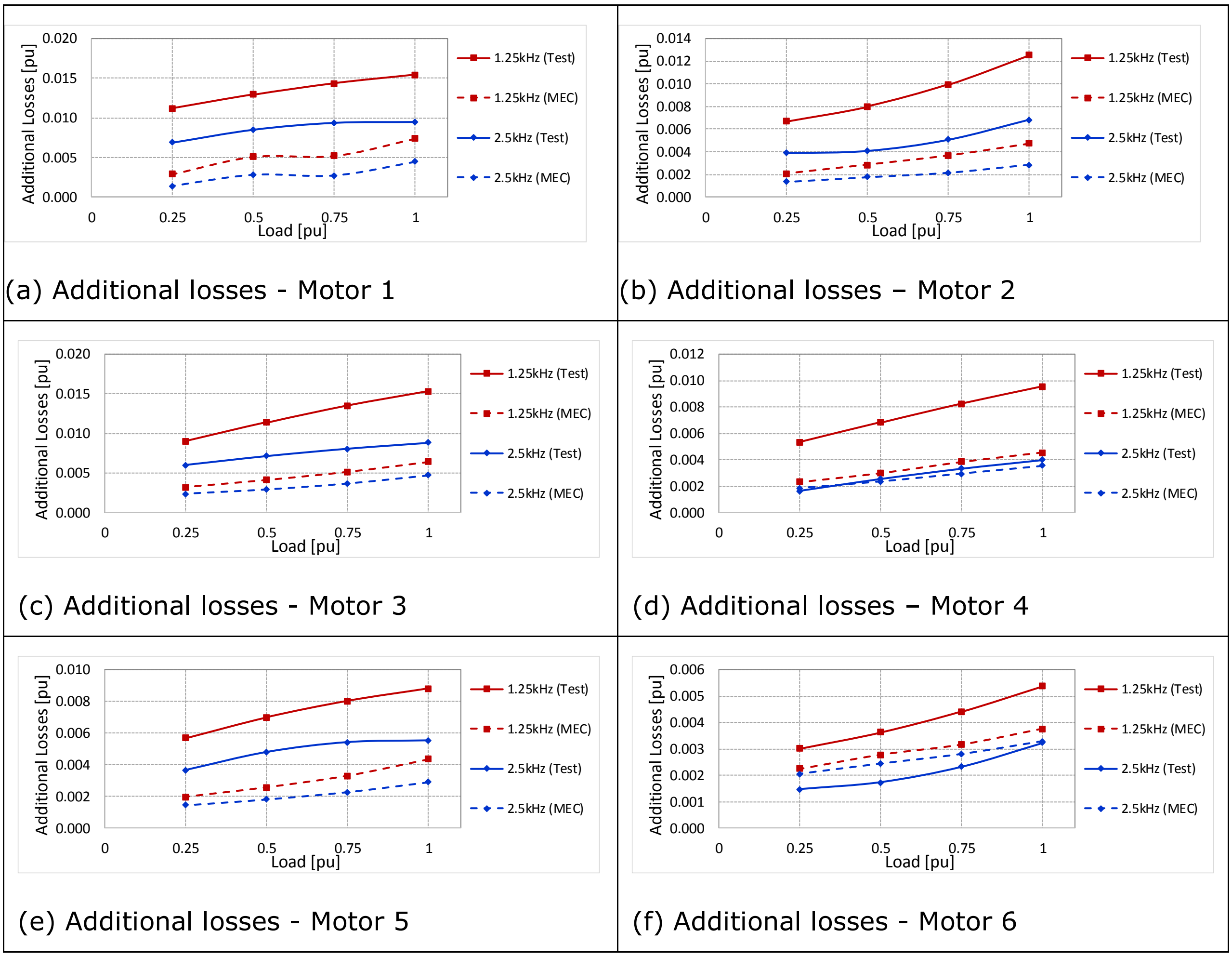
Additional losses

In the IEC/TS 60034-2-3, the additional harmonic losses caused by the PWM converter supply are understood as the difference in the motor losses with frequency converter supply and with sinusoidal supply [15].

In this paper the term "additional losses" was chosen instead of "harmonic losses" because loss increase in PWM fed motors is composed by: increase of fundamental losses (due the temperature increase) and the arising of harmonic losses caused by voltage harmonics. Segregation of these components is not a simple task.

Additional losses variation for all six motors are depicted in Fig. 12. Except for motors 4 and 6, with 2.5 kHz PWM, simulation values are lower than tested ones. On the other hand, when additional losses variation trend is analyzed, both values present good agreement since all test curves can be considered linear and simulation curves have reproduced this trend.

Core loss estimation is a great challenge to modeling. Some points must be investigated to improve simulation of this loss component. As iron loss is a function of time derivative of magnetic induction, the first step is to improve magnetic field calculation in some MEC elements (by mesh refinement). Another step is to look for other iron losses models for cases with great harmonic content.



(a) Additional losses - Motor 1

(b) Additional losses – Motor 2

(c) Additional losses - Motor 3

(d) Additional losses – Motor 4

(e) Additional losses - Motor 5

(f) Additional losses - Motor 6

Figure 12 – Additional losses variation with load and voltage waveform, in p.u.

Conclusion

The paper presented an experimental verification of MEC model capability to estimate the performance of induction motors fed by PWM voltage. The analyses deal with low switching frequencies (1.25 and 2.5 kHz), due to the fact that these frequencies cause greater losses in the motors and are very common in industrial applications.

Although the results show that MEC model can reproduce the trends with reasonable accuracy, the use of a single simplified model for simulation of a wide motor range is a challenge. Permeance network proposed in [10] is a quite simple method to simulate some motor effects, mainly for the desired accuracy level.

The following points must be investigated to improve MEC model analyzed in this work: (i) improve material characteristic modeling, mainly for low magnetic field values, to correct the currents estimation at low loads; (ii) refine MEC mesh to better reproduce the magnetic field behavior in saturated regions; and (iii) carry out a complementary study to define the most appropriate iron loss modeling for cases with high frequencies.

References

[1] A. de Almeida, F. Ferreira, and A. Quintino Duarte, "Technical and Economical Considerations on Super High-Efficiency Three-Phase Motors," *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 1274–1285, 2014.

[2] M. Hafner, M. Popescu, A. Boglietti, and A. Cavagnino, "Analytic Modeling of Inverter-Fed Induction Machines - A Practical Approach for Matching Measurement and Simulation Data," *IEEE Transactions on Industry Applications*, vol. 52, no. 6, pp. 4710–4718, Nov 2016.

[3] J. Malinowski, W. Hoyt, P. Zwanziger, and B. Finley, "Motor and Drive-System Efficiency Regulations: Review of Regulations in the United States and Europe," *IEEE Industry Applications Magazine*, vol. 23, no. 1, pp. 34–41, Jan 2017.

[4] L. Aarniovuori, A. Kosonen, M. Niemela, and J. Pyrhonen, "Frequency Converter Driven Induction Motor Losses," in *Industrial Electronics Society, IECON 2013 - 39th Annual Conference of the IEEE*, Nov 2013, pp. 2881–2886.

[5] M. Yilmaz and P. Krein, "Capabilities of Finite Element Analysis and Magnetic Equivalent Circuits for Electrical Machine Analysis and Design," in *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE*, June 2008, pp. 4027–4033.

[6] T. Green, C. Hernandez-Aramburo, and A. Smith, "Losses in grid and inverter supplied induction machine drives," *IEE Proceedings - Electric Power Applications*, vol. 150, pp. 712–724(12), November 2003.

[7] V. Ostovic, *Dynamics of Saturated Electric Machines*. Springer Science & Business Media, 1989.

[8] B. Asghari and V. Dinavahi, "Permeance Network Based Real-Time Induction Machine Model," in *Proceedings of the International Conference on Power Systems Transients (IPST 2009), Kyoto, Japan*, 2009, pp. 1–6.

[9] M. Amrhein and P. Krein, "Induction machine modeling approach based on 3-d magnetic equivalent circuit framework," *Energy Conversion, IEEE Transactions on*, vol. 25, no. 2, pp. 339–347, June 2010.

[10] M. Amrhein and P. T. Krein, "Magnetic Equivalent Circuit Modeling of Induction Machines Design-Oriented Approach with Extension to 3-D," in *2007 IEEE International Electric Machines Drives Conference*, vol. 2, May 2007, pp. 1557–1563.

[11] S. Sudhoff, B. Kuhn, K. Corzine, and B. Branecky, "Magnetic Equivalent Circuit Modeling of Induction Motors," *Energy Conversion, IEEE Transactions on*, vol. 22, no. 2, pp. 259–270, June 2007.

[12] P. L. Alger, *Induction Machines: Their Behavior and Uses*. Gordon and Breach, 1970.

[13] D. Lin, P. Zhou, W. N. Fu, Z. Badics, and Z. J. Cendes, "A Dynamic Core Loss Model for Soft Ferromagnetic and Power Ferrite Materials in Transient Finite Element Analysis," *IEEE Transactions on Magnetics*, vol. 40, no. 2, pp. 1318–1321, March 2004.

[14] *Rotating Electrical Machines – Part 2-3: Specific Test Methods for Determining Losses and Efficiency of Converter-Fed AC Induction Motors*, Ed. 1, IEC/TS 60034-2-3, 2013.

[15] H. Karkkainen, L. Aarniovuori, M. Niemela, and J. Pyrhonen, "Converter-Fed Induction Motor Efficiency: Practical Applicability of IEC Methods," *IEEE Industrial Electronics Magazine*, vol. 11, no. 2, pp. 45-57, June 2017.

High starting Torque LSPM Motor for wide range of Industrial Applications

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Advanced Motors Electromagnetics

Louie Finkle
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Abstract
In contrast with typical design of Line Start Permanent Magnet (LSPM) new patented dual rotor construction LSPM motor is able to develop high starting torque and able to handle high inertial loads practically equivalent to D-design AC Induction Industrial motors. New LSPM design is also able to significantly reduce Total Harmonic Distortion (THD) of the motor current draw. Presentation will discuss FEA and test results of a prototype motor delivering IE7 efficiency, high starting torque and ability to drive high inertia loads.

I. Traditional LSPM and its performance shortcomings

Line-Start Permanent-Magnet motors (LSPM) have been proposed several decades ago [1, 2] but only recently have drawn more attention as a candidate technology to be capable deliver IE4 and higher requirements [2, 3]. In fact some authors conclude that LSPM is the only valuable candidate to deliver IE4 efficiency requirements for a line driven industrial motors [3].

LSPM technology is now commercially available, but still is not able to become a truly common Industrial application motor. LSPM short fallings are well known and accepted.

Here are the main performance issues slowing use of LSPM:

1. Inability to synchronize load with high inertia. According to some the maximum load inertia for LSPM is between 25 to 30 times the rotor own inertia.
2. The initial "kick" torque is quite violent, and often can cause damage in the coupled load or coupling itself.
3. Line current draw harmonic are often far greater than comparable Squirrel Cage Induction Motors (SCIM)
4. Risk of permanent magnet demagnetization during start in cases with high load inertia
5. High power factor of LSPM at full load drops quickly at partial loads that causes higher current draw and I^2R losses, and eventually diminishes savings is case LSPM running lower than full load [4].

The reason behind offering new Dual Rotor LSPM is to significantly improve listed above weak characteristics of traditional LSPM designs.

II. Dual Rotor LSPM Construction

Construction of a four pole Dual rotor LSPM can be seen on the Fig. 1. This motor has two rotors, but only one of them is mechanically coupled with the motor shaft. Dual rotor LSPM shaft is coupled only with the Inner Rotor. The Outer Rotor is not coupled with the motor shaft, and it has ability to rotate around the inner rotor and its shaft on the set of additional bearings. This construction was proposed and described in US Patent [8].

As shown on the Fig.1 Inner Rotor carries a squirrel cage and slot cuts creating distinct d/q reluctance structure similar to rotor of synchronous reluctance motor. Outer Rotor also has a squirrel cage and permanent magnets installed on its inner surface. Stamped in the outer rotor lamination Flux barriers are made to reduce magnet flux leakage. In presented example both Outer Rotor and Inner Rotor Cages have the same number of slots and bars.

Additional details the rotor components and rotor assembly can be seen of the Fig. 2.

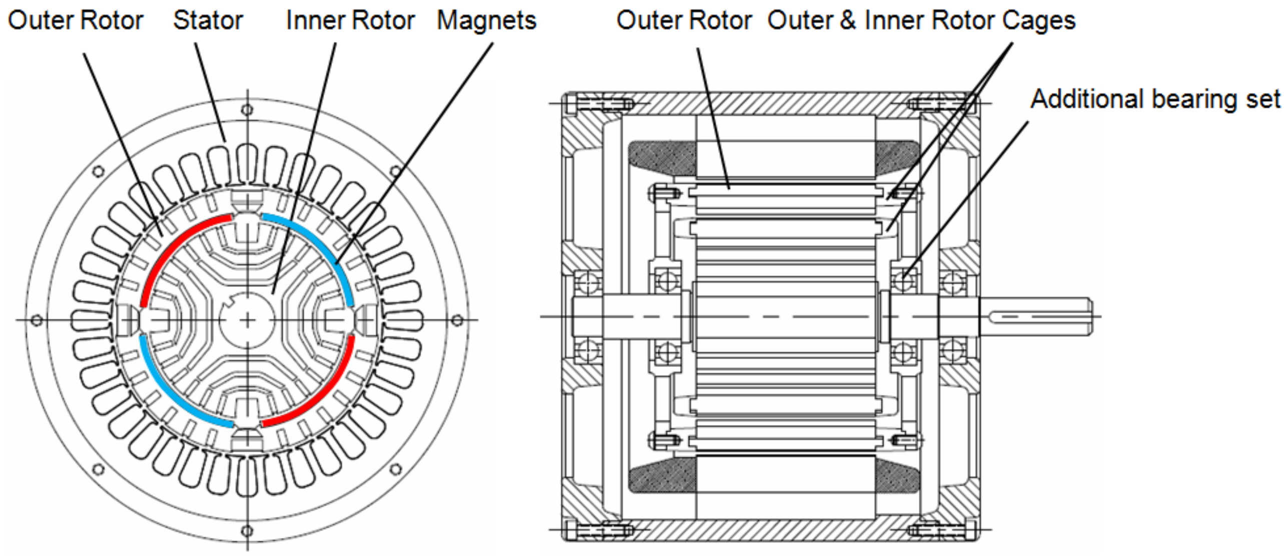
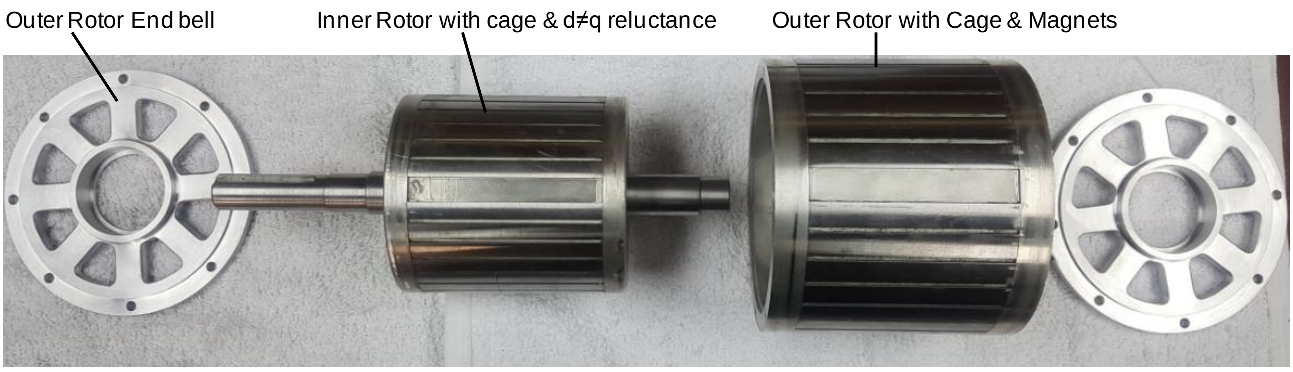


Fig.1. Dual Rotor LSPM Construction



(a)

(b)

Fig.2. Dual Rotor LSPM Rotor components (a) and assembly (b)

Permanent magnets of the Outer Rotor have electromagnetic coupling with both, asynchronous and synchronous coupling with Stator, and also asynchronous and synchronous interaction with Inner Rotor. The absence of the hard mechanical coupling of the rotor with permanent magnets enables successful synchronization of high inertia loads, much higher than traditional single rotor LSPM.

III. Analysis of Torque in Dual Rotor LSPM

To optimize electromagnetic design of the proof of concept Dual Rotor LSPM we used FEA Flux2D.
Fig. 3 shows flux distribution in the motor for two cases, (a) - aligned inner rotor (zero load), and (b) – inner rotor is misaligned by load torque relative to outer rotor magnets.

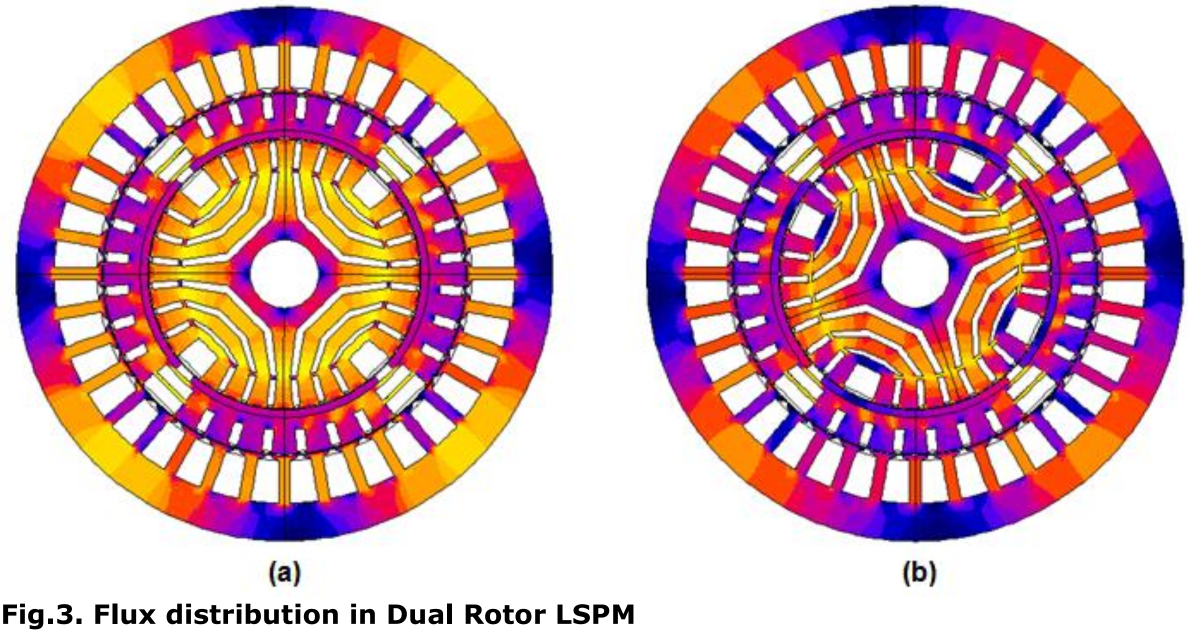


Fig.3. Flux distribution in Dual Rotor LSPM

The synchronous torques calculated with FEA are shown on Fig. 4. The analysis was conducted in two stages. At first, we evaluated the reluctance torque between Outer Rotor magnets and the inner rotor for various static positions between the Inner Rotor and Outer Rotor (blue curve), with no stator MMF present. At second stage we left Inner rotor in fully aligned position and rotated Outer Rotor relative to stator with rated current

MMF (red curve). These two torques have to be in certain relationship to achieve optimum operation of the motor. The fact that Inner Rotor torque (due to its reluctance nature) has period two times shorter than synchronous torque between the stator MMF and permanent magnets of the Outer Rotor is helping to reduce transient load torque spikes, one of the concerns/limitations with traditional LSPM.

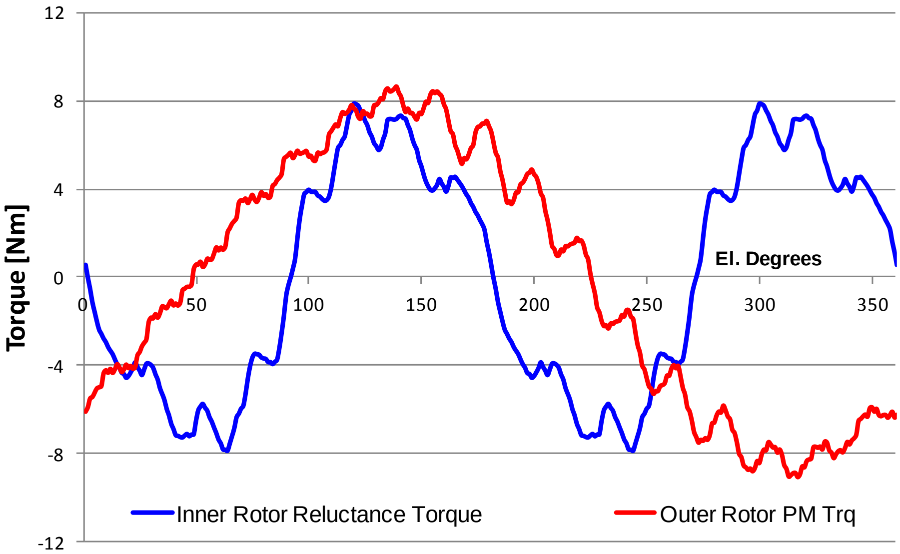


Fig.4. Dual Rotor LSPM Synchronous Torques

In order to validate the concept we have built a three phase test motor with the following parameters:
Rated power =0.75kW; Rated speed=1800rpm; OD=172 mm; Lst=76mm; 35UH NeFeBr magnet arks are 2.5mm thick; stator stack has a 1 tooth pitch skew; Rated voltage =220V. The sketch of the motor construction is presented on the Fig. 1.

IV. Dual Rotor LSPM Startup Test

Since one of the main aspects of any LSPM motor is its startup performances, i.e. ability to synchronize in presence of load torque and inertia, we built a special test bench where both parameters can be adjusted, see Fig.6. Inertia of the one disk plate is 0.0534 kgm^2 that about 27 times greater than inertia of the Internal Rotor, and we have tested up to 4 plates at the time.

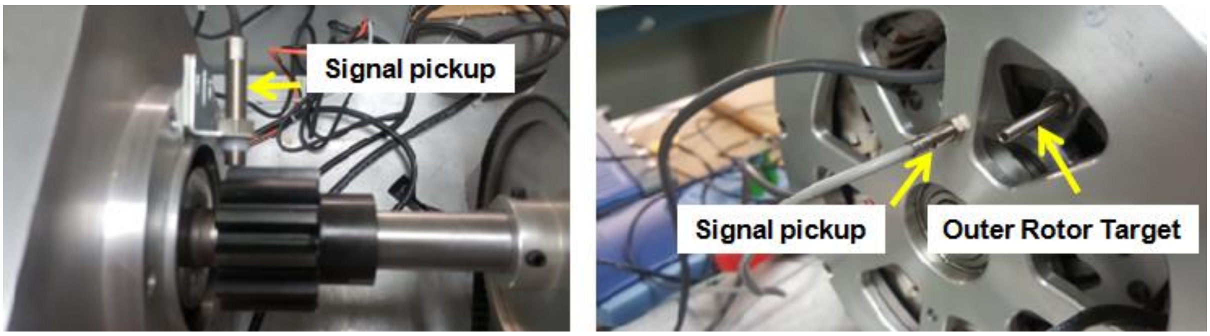


Fig.5. Rotors RPM measurement

Both rotors of the motor were equipped with magnetic RPM counters based on magnetic proximity sensors, see Fig. 5. Pulses of these sensors during startup tests were recorded and converted to RPM.

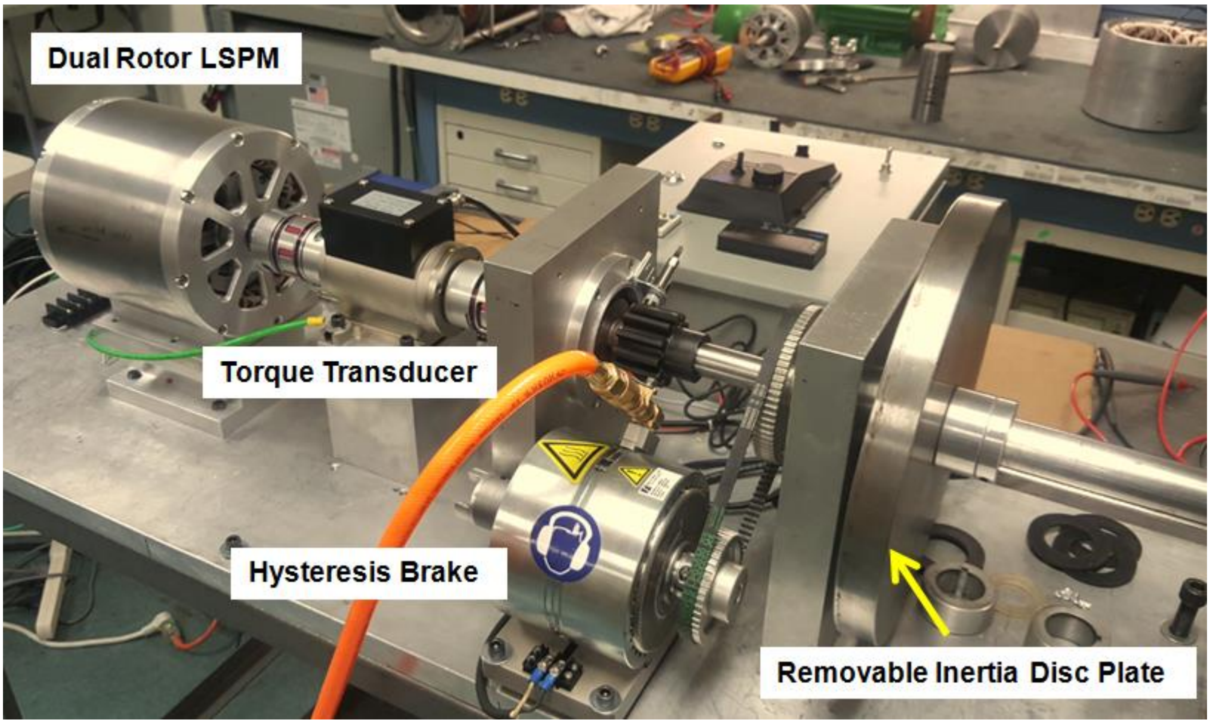


Fig.6. Dual Rotor LSPM Test Bench

Load torque was adjusted prior to startup recording. On the Fig. 7 below are recording of the startup with one inertia disk plate and 4Nm load torque corresponding to 0.75 kW nominal load.

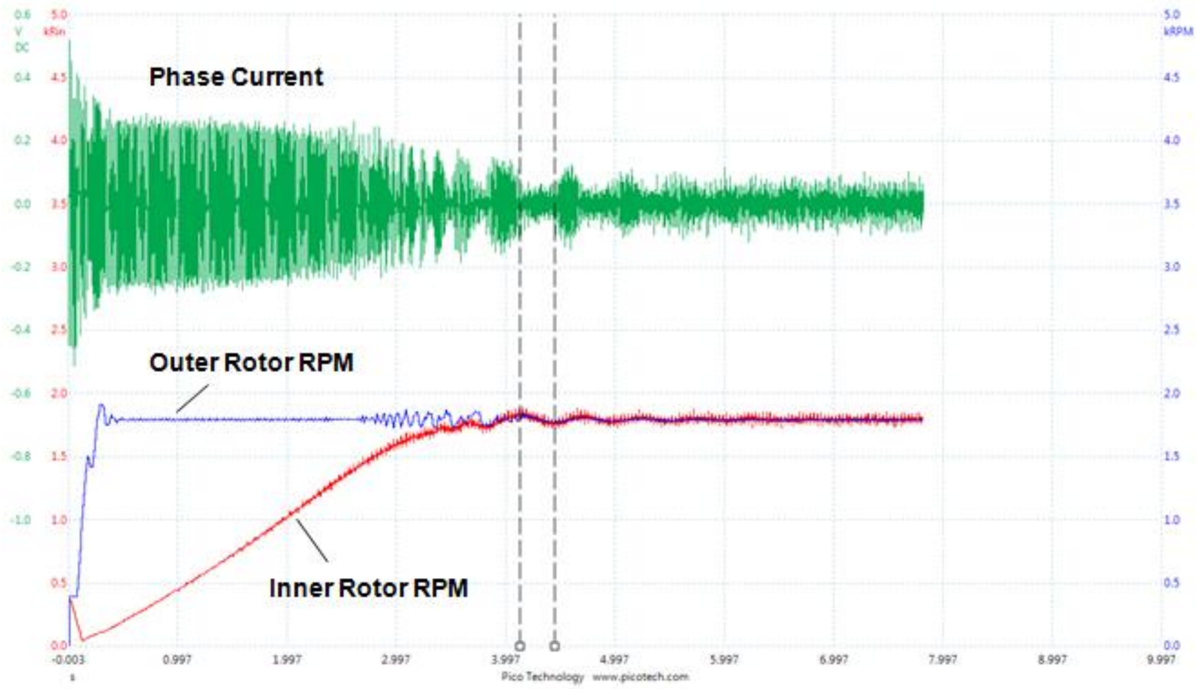


Fig.7. Dual Rotor LSPM Startup with 4 Nm load with 27 times higher than motor inertia

To find out full potential in ability to synchronize grater inertia, we have tested and successfully synchronized at nominal load torque up to 3.5 inertia disks, that is 94 times greater than motor own inertia. Startup recording for the 3.5 inertia plates is shown on Fig. 8.

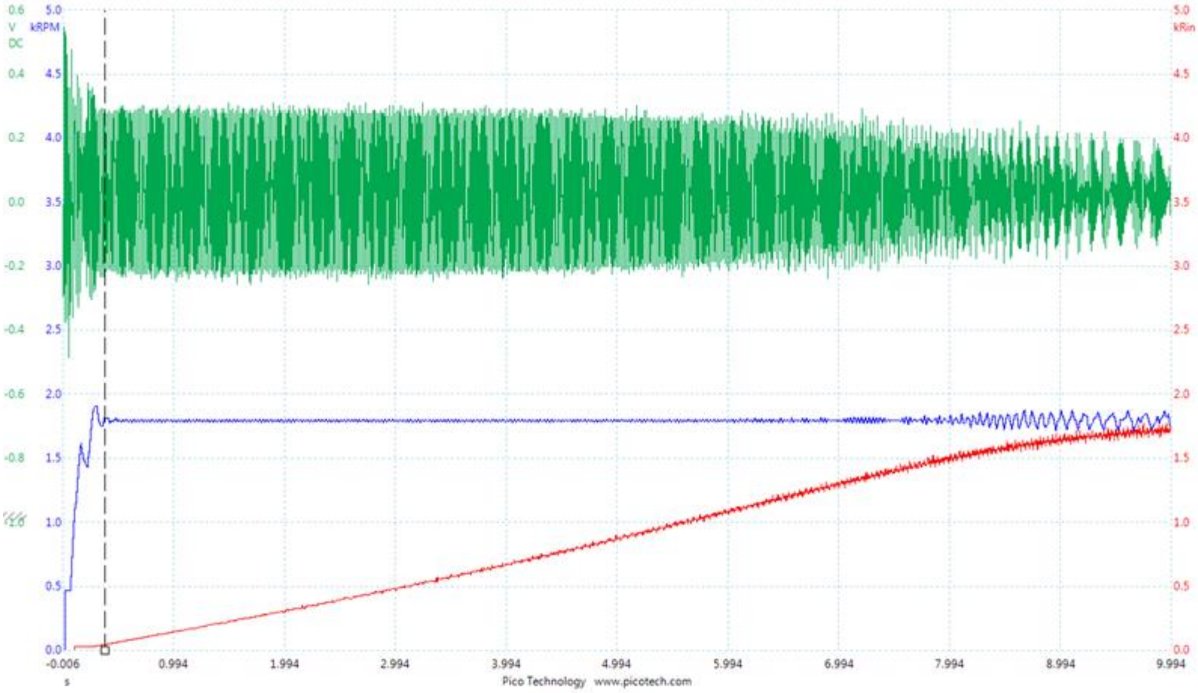


Fig.8. Dual Rotor LSPM Startup with 4 Nm load with 94 times higher than motor inertia

V. Dual Rotor LSPM Startup Observations

The first obvious difference between new design and traditional LSPM is the Load inertia that can be successfully synchronized. The maximum load inertia of LSPM is stated in several publications as 25 to 30 times the motor rotor own inertia [4, 6]. The Dual Rotor LSPM test results proof ability to successfully synchronize the load with at least 94 times higher inertia than motor own.

The second important observation is a very smooth load acceleration or in other words absence of the so called LSPM starting "kick" that in some cases can lead premature wear of the load gears and bearings [4]. According to our startup data analysis the maximum dynamic torque applied to load is about 50% of the load torque. In contrast, even optimized traditional LSPM design [2] has achieved reduction of this startup "kick" from 1700% to 700%.

As a result of a smooth motor acceleration Dual Rotor LSPM startup does not produce so much noise and vibration vs. typical traditional design LSPM. This fact should benefit LSPM in many additional industrial applications.

The reason for a high starting torque "kick" and "violent" oscillation of load torque [4] during synchronization is laying in the fact that in majority practical situation motor load cannot be brought to synchronous speed in the quarter of supplied voltage cycle, that means that in some moments the EMF from rotor magnets will cause negative torques, and high current spikes. And the longer it takes to get to synchronous RPM, the longer is potentially harmful load torque oscillation will exist.

In the presented design, the Outer Rotor carrying magnets accelerates and reaches synchronous rpm in fraction of second, practically independent of the load inertia. As can be seen from the two startup recordings, Outer Rotor is reaching synchronous RPM in about 300 milliseconds in both cases. And the load is being accelerated at the rate according to its inertia and load torque. It takes longer for high inertia load to reach synchronous RPM.

VI. Dual Rotor LSPM Lock Rotor Test

Lock rotor performance is important part of characteristics of any industrial application motor. Lock rotor test recording for our proof of concept Dual Rotor LSPM is shown of Fig.9.

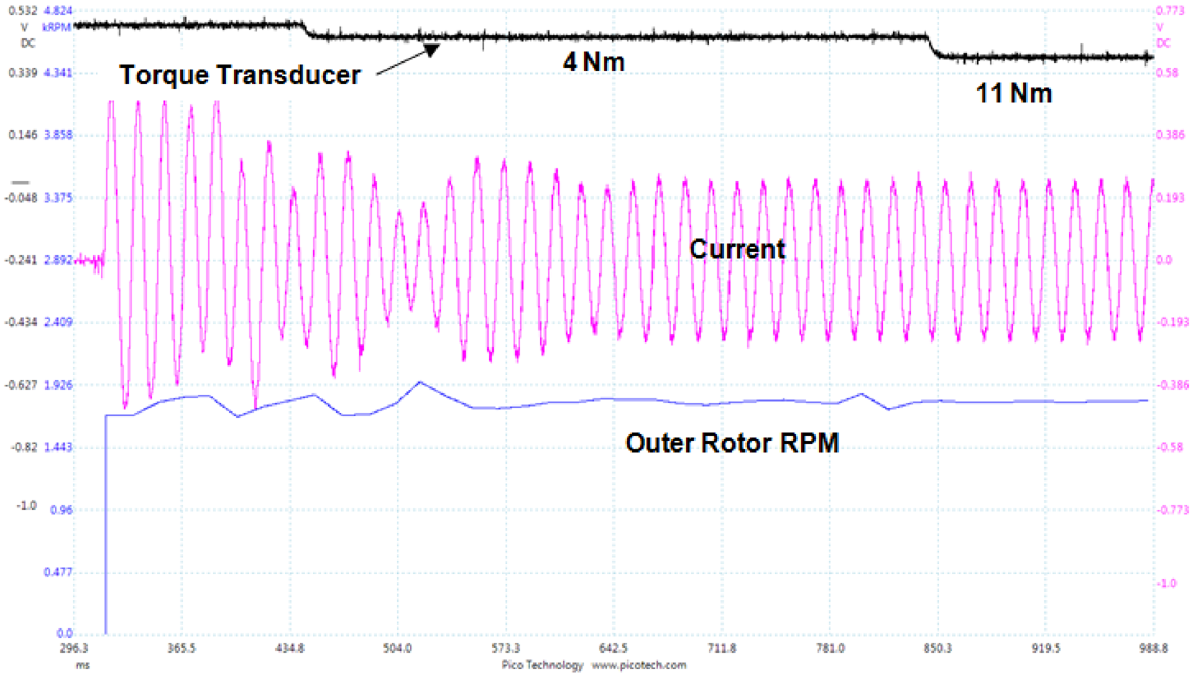


Fig.9. Dual Rotor LSPM Lock Rotor Test

The proof of concept Dual Rotor LSPM produces 11 Nm of torque at lock rotor which is 2.8 times the rated torque, at 850% of the rated current draw which on par with AC Induction Super Premium Efficiency Motors [7]. The corresponding parameters for the 1HP motor in [7] are LRT = 2.6 and Lock Rotor current is 840%.

The Outer Rotor of Dual Rotor LSPM at Lock output shaft did synchronize in similar fashion (in about 180ms) as in startup recordings described earlier.

It does appear that the Dual Rotor LSPM full Lock Rotor Torque is being developed in two stages. The torque transducer shows two distinctive plateaus, initial 4 Nm and reaching 11 Nm in about 540 milliseconds. The transient torque in each of these plateaus is fairly steady and completely stabilizes in 0.55 second after applying power.

The test was using Torque transducer ZHK810 with 0.1% accuracy and 50 Nm rated torque.

VII. Dual Rotor LSPM Efficiency and Power Factor

Superior efficiency of LSPM is available due to presence of permanent magnet, that provides near unity power factor and very low rotor losses, this is commonly accepted among electric machine specialists. Adding additional rotor and air gap in Dual Rotor LSPM does not create any significant loss of the flux linkage with stator winding. Larger effective air gab in fact even can help to reduce parasitic eddy current losses in the LSPM cage bars.

LSPM motor Efficiency test procedure is not formalized yet, but most experts agree that input-output or direct method is the most applicable at the moment. This is how we have conducted the test of our motor efficiency. Test results of the Dual Rotor LSPM (DR-LSPM) with Y winding connection are shown in the Table 1. Power and torque measurements were recorded with power analyzer Tektronix PA3000 and torque transducer ZHK810.

Table1. Dual Rotor LSPM Steady State Performance

DR-LSPM Operating point	Load Torque	Line to Line Voltage	Phase Current	Power Factor	RPM	Input Power	Output Power	Efficiency
	Nm	Vrms	Arms	PF	rpm	W	W	%
LSPM @ No load	0	221	0.25	0.40	1800	38.9	0.0	**0.0**
LSPM @ 3/4hp	2.97	221	1.61	0.98	1800	607.8	559.9	**92.1**
LSPM @ 1hp	3.96	221	2.06	0.99	1800	800.3	746.5	**93.3**
LSPM @ 1.5 hp	4.95	221	2.62	0.99	1800	1002.6	933.1	**93.1**

As can be seen the motor prototype rated load efficiency is far exceeding the IE4 level, it is probably close to IE7 (if we extrapolate the 0.75 kW IE4 efficiency with 20% loss reduction per level). The name plate of the 0.75 kW IE4 AC IM is only 87.5%, WEG catalogue [7], so the DR-LSPM has significant reserves to meet efficiency of the future more demanding regulations.

VIII. Dual Rotor LSPM technical and economical considerations

Our work with presented Dual Rotor LSPM has shown some robustness of the construction and no problems of holding additional airgap between inner and outer rotor. Both air gaps are in a range of 0.3 to 0.45 mm, are typical for this power AC IM. The Outer Rotor does not have any connection with the load nor any associated with it radial forces (for example, from a belt driven load). Axial distance between outer rotor bearings is very close with the motor stack length, that increases overall stiffness of the dual rotor itself.

Since we do not have solid manufacturing economics at the moment, we can consider its economics based on the active material use. This approach from our experience is quite applicable for many mass production motors.

When we benchmark this 0.75 kW DR-LSPM versus IE4 AC IM we see significant reduction of required steel and winding copper due to the axial stack length reduction. For example the stack length of our 1hp DR-LSPM was only about 65% of IE4 AC IM. This helps to offset the cost of magnets and additional bearings to support the outer rotor.

If we compare the single rotor LSPM vs. DR-LSPM, the weight of the diecast aluminium is probably similar if not reduced, due to absence of the LSPM startup torque “kick” that cage torque must be able to overcome. DR-LSPM does not exhibit such startup issue, thus the torque of the cage(s) does not have to be as high as in traditional LSPM.

IX. Conclusions

New Dual Rotor LSPM has been presented. This new type LSPM is able to overcome some major problems with use of line-start motors for general industrial applications. The starting LSPM torque “kick” and load inertia limitation have been practically eliminated. These improvements can widen up the range of use LSPM for IE4, IE5 applications, beyond traditionally accepted 10-15 kW. The new design is exhibiting excellent Efficiency and power factor even at low load level.

References

[1] Rahman M. A. and Osheiba A.M. *Performance of Large Line-Start Permanent Magnet Synchronous Motors*. IEEE Transaction on Energy Conversion, Vol. 5, No.1, March 1990, pp. 211-217

[2] Doppelbauer M. *Line-Start Permanent -Magnet Motors and Their Use in Typical Industrial Applications*. Proceedings of the 8th Energy Efficiency in Motor Drive Systems (EEMODS'2013) Rio de Janeiro, Brasil, pp. 204-212

[3] Rajarm T.U., Bhalchandra N.C. and Ashutosh P. *Overview of research evolution in the field of line start permanent magnet synchronous motors*. IET Electr. Power Applications, 2014, Vol.8, Iss. 4, pp.141-154

[4] De Almedia A., Ferreira F. and Quintino A. *Technical and Economical Considerations on Super High-Efficiency Three-Phase Motors*. Industrial & Commercial Power Systems Technical Conference (I&CPS), 2012 IEEE/IAS 48th

[5] De Almedia A., Ferreira F. and Baoming G. *Beyond Induction Motors - Technology Trends to Move up Efficiency*. IEEE Transactions on Industry Applications, Vol. 50, No. 3, May/June 2014pp. 2103-2114

[6] Bork B.C., Martins C.E.G. *Performance evaluation a Line-Start Permanent Magnet Motors using finite element analysis and experimental tests*. 7th Energy Efficiency in Motor Drive Systems (EEMODS'11) Alexandria, USA, pp. 301-311

[7] WEG Motor Catalogue, *"WQuattro Super Premium Efficiency Motor",* 2011

[8] Finkle L.J. *Hybrid Electric Motor with Self Aligning Permanent Magnet and Squirrel Cage Rotors* US Patent Application 2015/0194868 A1, Jul. 9, 2015

Line-start synchronous reluctance motors: Overview on latest developments on technology and suitable applications

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ABB IEC low voltage motors

Abstract

Magnet-free synchronous reluctance motor technology with line-start capability, namely *direct-on-line SynRM* (DOLSynRM) was presented in the "Magnet-free motor technology for fixed speed applications reaching IE5 efficiency level" – paper [1] published at EEMODS 2015. This new paper continues DOLSynRM study by presenting the latest results related to a range of motors from 1,1kW to 55kW with IE4 efficiency level. Starting characteristics, suitable applications and operation in variable speed drive duty are also discussed.

Introduction

Following the industry needs for efficient and sustainable motor solutions, recent developments have addressed the possibility to utilize new motor technologies also for direct-on-line operation.

Line-start permanent magnet (LSPM) motors, for instance, are already present in the market. On the other side, magnet-free direct-on-line synchronous reluctance motors (DOLSynRM) have already been proposed as a valid alternative to magnet-based solutions, aimed furthermore at solving typical drawbacks of PM motors, such as cost, sustainability and maintainability.

When dealing with direct-on-line applications, though, the legacy of well-rooted induction motor technology can influence the common user's perception of the new technological proposals, often perceived as complicated; hence, it is important to clarify common points and differences between the traditional solutions and the innovative ones.

The performance values presented in this paper are based on extensive prototype program. Verified data on performance and starting capability enable motor users to evaluate the usability of DOLSynRM for different applications.

This paper includes power levels up to 55kW and IEC frame size 250. However DOLSynRM technology enables also higher power levels. Especially 4-pole versions would probably provide good alternatives to induction motors at least up to IEC frame size 315.

DOLSynRM technology in brief

In simple terms, a DOLSynRM could be understood as two motors in one. There is an induction cage within the rotor which is used for starting. At the end of the starting phase reluctance torque pulls the motor to synchronous speed. When the motor is running at synchronous speed the induction cage becomes "invisible" in the electrical sense because there is no voltage induced into the cage, hence no current. This means that there are no cage-related losses in the rotor, which in turn enables high overall efficiency during normal operation. [1]

It seems that 2-pole and 4-pole versions are most feasible for DOLSynRM technology. That's why this study is focusing on those two alternatives.

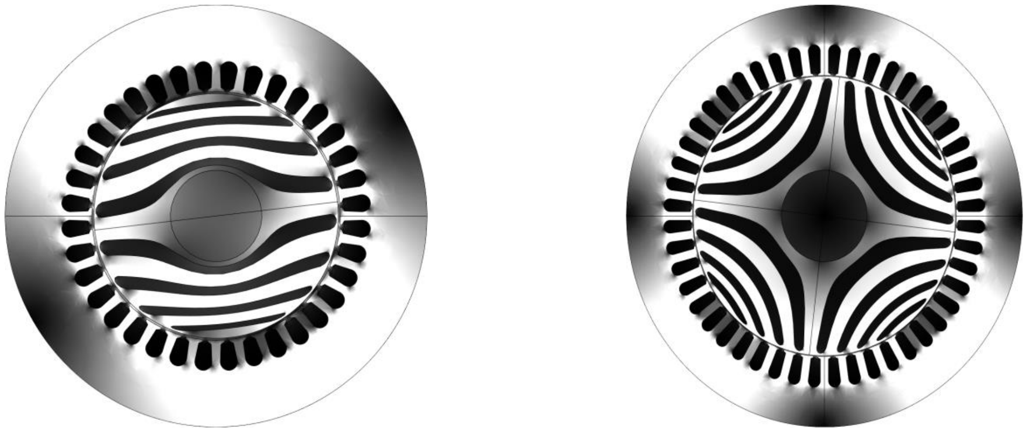

Figure 1. Principal pictures of 2- and 4-pole DOLSynRM rotor constructions.

DOLSynRM motor starting and overloadability characteristics

One of the major differences between induction and DOLSynRM motors is the starting process. Start-up of the DOLSynRM can be roughly divided into three phases: inrush, oscillation and synchronization. The inrush phase is very similar and almost comparable to that in an IM motor. The rotor cage is excited by the magnetic field provided by the stator, causing a large start-up current to flow through the cage. In this phase, the starting current taken by the motor is in general a little higher than with an IM as the cage is not as symmetrical and optimized as the IM's rotor cage. During this time the motor accelerates towards the synchronous speed. The next phase is oscillation, where the motor either reaches nominal speed or remains in oscillation due to load torque and inertia. In cases where the motor reaches synchronous speed the oscillation phase is passed very quickly. Finally in the synchronization phase, the motor speed might fluctuate around the synchronous speed before settling on it [1], [3].

In the "Magnet-free motor technology for fixed speed applications reaching IE5 efficiency level" [1] – paper it was concluded that further investigation of DOLSynRM starting behavior was needed. Such study was carried out and summary of the results is collected in the next chapter.

Analysis of DOLSynRM motor start by using torque decomposition method

An electromagnetic analysis on starting behaviour was conducted during 2016 with Tampere University of Technology [2]. The study consisted of using so called torque decomposition method to split simulated motor's torque into components of torques between different parts of the motor. For example what is the torque component between stator winding and rotor iron or what would be the torque between stator iron and rotor aluminium cage. These questions cannot be answered with traditional simulation methods or even with measurements as both produce total torque. With this new method the split between reluctance torque and cage torque could be obtained and analysed. These torque components are shown in figure 2.

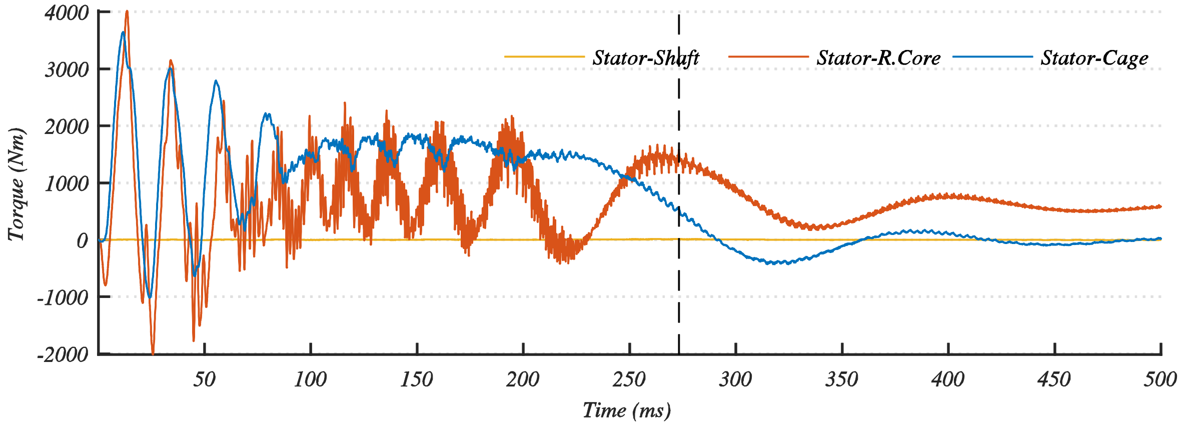

Figure 2. Plot of torque components on successful start-up of DOLSynRM motor.

The plot shown in figure 2 is a representation of three major torque components during the start-up. During the start-up the motor reaches the synchronous speed on dashed line an 275ms. The plot provides three interesting new findings on DOLSynRM and SynRM motor technologies.

Firstly, the cage torque actually does not reach zero when the slip reaches the zero at dashed line. This suggests that the inductances in the system keeps rotor current flowing upon reaching synchronous speed allowing the motor the motor to lock on to synchronism.

Second behavioural note is that normally it is assumed that with DOLSynRM the average torque is zero on start-up phase. However, the splitted torque analysis shows that the reluctance torque is constantly above zero resulting non-zero average torque.

Last point to be highlighted from the torque analysis is the final phase of starting sequence. Here the torque levels ease up to steady state operation. This is where the cage torque fades out and reluctance torque takes over. At this point the cage losses are eliminated.

This analysis together with following tests and simulations show that there is no "dead" point in torque curve just before synchronization as suggested in the "Magnet-free motor technology for fixed speed applications reaching IE5 efficiency level" – paper [1].

Overloadability during synchronous operation and re-synchronization

The "Magnet-free motor technology for fixed speed applications reaching IE5 efficiency level" – paper [1] suggested that there could be a significant dip in the torque curve just below synchronous speed. This would lead to situation where a de-synchronized motor could not re-synchronize without being stopped. Latest tests and simulations show that this is not the case. A motor can re-synchronize without being stopped. These results were obtained by analyzing a 37kW, 2-pole, 117,8Nm DOLSynRM motor. In addition to inertia, also voltage level and load torque impact on starting and re-synchronization capabilities.

In this analysis load torque was the same as motor's nominal torque of 117,8Nm. Inertia J was 2,9 kgm^2. Voltage was 360V, which is 10% below nominal network voltage of 400V. Reduced voltage naturally decreases the overloadability. The behavior is shown in figure 3. Load torque is gradually increased by 5% increments and finally at 135% load the motor de-synchronizes. Torque and speed start to fluctuate and average speed is around 2930rpm. When the load is reduced back to 100% level the motor re-synchronizes.

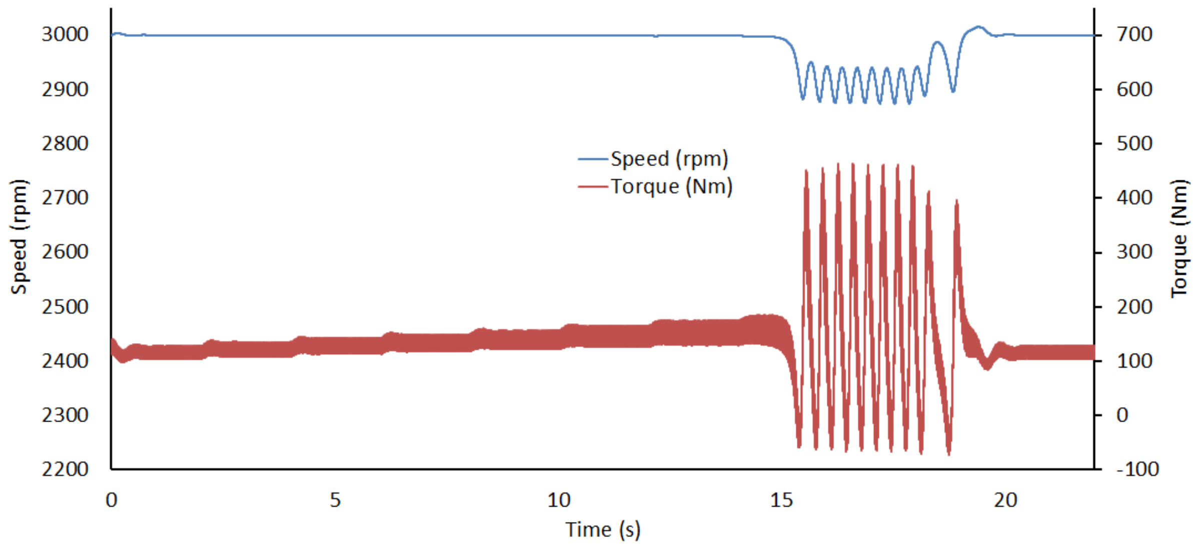

Figure 3. Motor de-sychronization and re-synchronization

Synchronization capability of the same motor, load and inertia was also simulated with different voltage levels. For practical purposes the simulation was focused to 2400rpm to 3000rpm speed range. As shown in fugure 4 the motor synchronizes with 360V and 380V voltage levels whereas lower voltage levels reduce motor torque too much for successful synchronization. Fluctuating speed below 3000rpm synchronous speed mean unsuccessful synchronization.

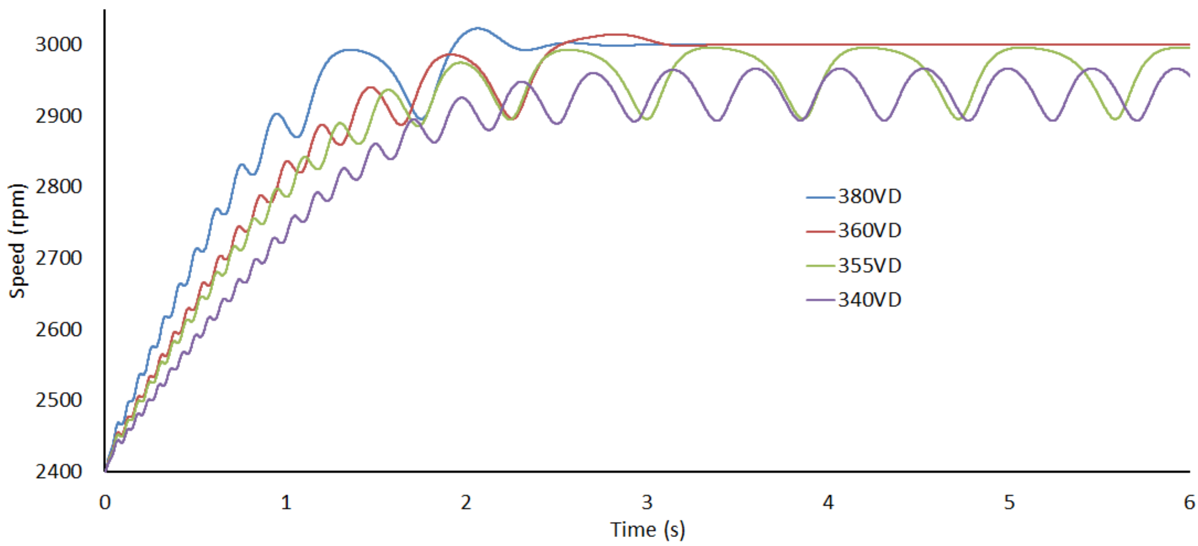

Figure 4. Starting capability with different voltage levels

This analysis indicates that capability for full start from zero speed to synchronization and re-synchronization after load peak are linked to each other. If motor can start successfully with certain voltage, load and inertia then also re-synchronization would be successful when load torque is reduced back to motor nominal torque after load peak.

Motor range

This section presents possible motor designs for IE4 efficiency level. In addition to typical performance values there are number of values related to load inertia. As explained in the starting characteristics- section, DOLSynRM technology in line-start duty has limited capability when it comes to load inertia. The load inertia must be low enough for successful start. (notice that this limit does not apply when operating DOLSynRM with frequency converter). In the tables the "Max J" is the maximum load inertia for different designs with 100% network voltage. Maximum inertia according to IEC is also listed together with comparison to inertia limit of the motor. IEC values for load inertia are originally intended for induction motors. For induction motors the load inertia is just related to starting time whereas for DOLSynRM it's not a matter of time but a matter of successful synchronization. In the section for applications it can be seen that typical load inertia can be higher of lower compared to IEC limit values.

It should be noted that motor design is always a compromise between starting characteristics and steady-state full load performance. Also with DOLSynRM technology it's possible to fine-tune characteristics to some extent by modifying the electrical design to find a better compromise for specific need. These tables give a good impression of typical characteristics that can be reached with DOLSynRM technology.

Table 1. Potential product designs with calculated performance values for 2-pole motors.

2-pole 400V 50 Hz													
General			Dimension	Steady-State					Starting				
Pn [kW]	Speed [RPM]	f [Hz]	Frame Size	Un [V]	In [A]	PF	Eff 100 [%]	Tmax / Tn	Is/In	Ts/Tn	max J [kg m^2]	Max J / IEC J [%]	IEC J [kg m^2]
1,5	3000	50	90	400	3,1	0,80	87,3	2,3	6,4	2,3	0,007	12	0,058
2,2	3000	50	90	400	4,6	0,77	89,1	2,6	7,4	2,9	0,023	28	0,081
3	3000	50	100	400	6,2	0,77	90,1	2,3	7,4	2,8	0,075	70	0,108
4	3000	50	100	400	7,9	0,80	90,4	2,0	6,6	2,4	0,070	50	0,139
5,5	3000	50	132	400	11,1	0,78	91,2	2,1	7,8	3,5	0,14	74	0,186
7,5	3000	50	132	400	14,8	0,79	91,9	1,8	7,3	3,2	0,15	62	0,245
11	3000	50	132	400	21,7	0,78	92,7	1,8	7,0	3,0	0,26	74	0,346
15	3000	50	160	400	27,3	0,85	93,6	1,8	8,7	2,3	1,1	229	0,458
18,5	3000	50	160	400	34	0,83	94,0	1,8	8,6	2,4	1,4	253	0,553
22	3000	50	160	400	41	0,82	94,2	1,9	8,7	2,4	1,8	279	0,646
30	3000	50	200	400	54	0,84	95,1	1,5	8,5	2,6	2,4	275	0,854
37	3000	50	200	400	67	0,84	95,2	1,5	8,7	2,7	2,9	281	1,03
45	3000	50	200	400	83	0,82	95,0	1,4	7,6	2,3	2,9	236	1,23
55	3000	50	250	400	106	0,82	95,3	2,1	8,6	2,5	3,5	241	1,47

Table 2. Potential product designs with calculated performance values for 4-pole motors.

4-pole 400V 50 Hz													
General			Dimension	Steady-State					Starting				
Pn [kW]	Speed [RPM]	f [Hz]	Frame Size	Un [V]	In [A]	PF	Eff 100 [%]	Tmax / Tn	Is/In	Ts/Tn	max J [kg m^2]	Max J / IEC J [%]	IEC J [kg m^2]
1,1	1500	50	90	400	2,6	0,69	87,2	2,7	7,2	1,7	0,003	1,2	0,247
1,5	1500	50	90	400	3,5	0,71	88,2	2,5	7,0	1,7	0,005	1,6	0,326
2,2	1500	50	100	400	5,0	0,71	89,5	2,6	8,3	2,3	0,009	2,0	0,460
3	1500	50	100	400	6,7	0,71	90,4	2,4	7,5	1,9	0,009	1,5	0,608
4	1500	50	100	400	8,8	0,72	91,1	2,5	7,7	2,0	0,02	2,5	0,788
5,5	1500	50	132	400	11,7	0,74	91,9	2,2	8,0	2,5	0,07	6,9	1,05
7,5	1500	50	132	400	15,8	0,74	92,6	2,4	8,8	2,7	0,15	11	1,39
11	1500	50	132	400	22,7	0,75	93,3	2,2	8,5	2,5	0,20	10	1,96
15	1500	50	160	400	30	0,76	93,9	2,1	10,6	2,8	1,5	58	2,59
18,5	1500	50	160	400	37	0,76	94,2	2,0	9,9	2,6	1,6	50	3,13
22	1500	50	180	400	44	0,76	94,5	2,2	9,6	3,0	1,4	39	3,65
30	1500	50	200	400	59	0,77	94,9	1,9	10,0	2,6	5,0	103	4,83
37	1500	50	200	400	72	0,78	95,2	2,1	10,6	2,8	7,3	124	5,83
45	1500	50	200	400	87	0,78	95,4	2,1	11,8	3,4	7,0	100	6,96
55	1500	50	250	400	106	0,78	95,7	2,0	10,7	2,8	7,5	90	8,34

Applications and synchronization

The motor designs presented in the motor range – section represent one type of design approach. However it should be understood that there is some freedom in motor design and for specific cases it is possible to fine tune motor characteristics to fit application needs.

Evaluating the feasibility of DOLSynRM on specific applications implies an accurate analysis of the parameters impacting the synchronization process, i.e the required locked-rotor torque, the load profile, the equivalent moment of inertia seen on motor shaft, the possible need for frequent repeated starts and the possible presence of voltage drops during startup.

Although these parameters can widely change from application to application, it is clear that a theoretical standardization of starting conditions can lead to more normalized evaluations and comparisons of typical synchronization performance among different machines.

Following the well-rooted tradition of induction motors standard, a simple way to describe such parameters and evaluate synchronization capabilities seems to derive from IEC 60034-12, in which minimum limits of moment of inertia are introduced.

In particular, the assumptions behind the proposed limits involve the presence of quadratic load profile. Keeping the same hypotheses, it is then possible to describe the limit of the moment of inertia that DOLSynRM motors with certain rating and pole number can pull-up to synchronization as a percentage of the corresponding limit on the IEC standard

It must be remarked that, although within the mentioned IEC standard inertia limits are introduced with an eye on thermal behavior of induction motors during starting, in DOLSynRM case the limitation is here referred to the synchronization capability, whereas thermal evaluations are not in the scope of this discussion although in general still relevant and important.

Important applications involving quadratic load profile are clearly pumps, fans. The proposed approach seems however extendable to describe inertia requirements of applications where load profile is not quadratic, like compressors, keeping in mind that further checks using proper profile are needed in this case.

Typical inertia from targeted applications are reported in the following table, both as absolute value and as a percentage of limits as in IEC 60034-12.

Table 3. Typical moment of inertia in targeted applications, 2-pole motors.

Power [kW]	Typical motor frame size	Approximate max moment of inertia limit for the motor [kg m^2]	IEC 60034-12 limit of moment of Inertia [kg m^2]	Typical moment of inertia for pumps		Typical moment of inertia of plastic fans		Typical moment of inertia for metal fans		Typical moment of inertia of compressors	
				[kg m^2]	[%]	[kg m^2]	[%]	[kg m^2]	[%]	[kg m^2]	[%]
1.5	FS 90	0.007	0.058	0.005 – 0.006	8.6 – 10.3			0.007 – 0.15	12.1 - 259		
3.0	FS 100	0.075	0.108	0.005 – 0.006	4.6 – 5.6			0.02 – 0.5	18.5 - 462		
7.5	FS 132	0.15	0.245	0.0283	11.6			0.1625 – 0.7	66.3 - 285		
15	FS 160	1.1	0.458	0.0382	8.3			0.55 – 2.6	120 - 567		
30	FS 200	2.4	0.854	0.0663	7.8			1.9 - 3	222 - 351	0.046	5.4
55	FS 250	3.5	1.474	0.0801	5.4						

Table 4. Typical moment of inertia in targeted applications, 4-pole motors.

Power [kW]	Typical motor frame size	Approximate max moment of inertia limit for the motor [kg m^2]	IEC 60034-12 limit of moment of Inertia [kg m^2]	Typical moment of inertia for pumps		Typical moment of inertia of plastic fans		Typical moment of inertia for metal fans		Typical moment of inertia of compressors	
				[kg m^2]	[%]	[kg m^2]	[%]	[kg m^2]	[%]	[kg m^2]	[%]
1.5	FS90	0.005	0.326	0.0057	1.8	0.0291	8.9	0.02 – 0.725	61.4 - 222		
3.0	FS100	0.009	0.608	0.0219	3.6	0.0524	8.61	0.095 – 2.3	15.6 – 378		
7.5	FS132	0.15	1.387	0.0239 – 0.263	1.7 – 18.9	0.1898	13.7	0.1375 – 6.0	9.91 – 432		
15	FS160	1.5	2.589	0.0646	2.5	0.2431	9.4	0.475 – 9.25	18.3 - 357		
30	FS200	5.0	4.831	0.3432	7.1			10 - 13	207 - 269	0.046	1%
55	FS250	7.5	8.336								

Operation with frequency converter

Synchronous motors (permanent magnet motors or synchronous reluctance motors etc.) designed for frequency converter operation require more advanced control software compared to induction motors. These synchronous motors don't have dampening windings in the rotor, which means that the frequency converter must follow rotor position and load angle very well for proper control performance. Control algorithms developed for these motors are usually not suited for motors with rotor cage. These being induction motors, line-start permanent magnet motors or DOLSynRM motors.

Having a rotor cage can also have advantages. That's because the rotor cage acts also as dampening winding in frequency converter operation. This means motor physics "stabilize" the operation in somewhat similar way compared to induction motors and advanced control algorithms are not needed. This is often commented also with line-start permanent magnet motors.

The DOLSynRM motor synchronization process in VSD duty is very similar to the direct-on-line operation. The three phase voltage supplied to the stator produce rotating field that induces current in the rotor cage which interacts with stator field producing torque. The cage torque helps the rotor to accelerate close to synchronism and the reluctance torque pushes the rotor into synchronism. Hense, the rotor rotates synchronously with stator supply frequency.

Tests show that also DOLSynRM can be driven with simple scalar control available practically in all frequency converters. Motor-drive system was able to cope with load changes seen in typical pump and fan applications. Advanced applications with dynamic performance needs and operation with various control methods should however always be verified with particular frequency converter model.

Preliminary tests show that DOLSynRM can be a good alternative also for variable speed applications. And when operating these motors with frequency converter there are no limits for load inertia. However more testing would be recommended in order to understand behavior in VSD duty better.

Conclusions

Range of designs proven with wide prototype program shows that DOLSynRM can be a good alternative to other motor technologies both in line-start duty as well as in variable speed duty.

In line-start duty the inertia limit excludes many fan applications whereas pumps and compressors have typically low enough inertia for successful operation.

Inertia limit does not apply in variable speed operation and simple scalar control seems to work well also with DOLSynRM motor.

References

[1] Tammi A.; Känsäkangas T.; Termini P., *Magnet-free motor technology for fixed speed applications reaching "IE5" efficiency level*, EEMODS 2015 paper # 098

[2] Tampio J.; Känsäkangas T.; Suurniemi S.; Kolehmainen J.; Kettunen L.; Ikäheimo J., *Analysis of Direct-On-Line Synchronous Reluctance Machine (DOLSynRM) Start-up Using a Magnetic Field Decomposition*, IEEE Transactions on Industry Applications , vol.PP, no.99, pp.1-1

[3] Gamba, M.; Pellegrino, G.; Vagati, A.; Villata, F., *Design of a line-start synchronous reluctance motor*, 2013 IEEE International Electric Machines & Drives Conference (IEMDC), pp.648-655, 12-15 May 2013.

Novel Flexible-Blade Centrifugal Fan for Variable-Speed Motors

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Abstract

In the developed countries, it is expected that, by the year 2020, half of the industrial motors will be controlled by variable-speed drives. In variable-speed self-cooled motors, the steady-state motor torque limit decreases significantly with the rotational speed. For general purpose motors, the preferred cooling fan type is centrifugal with rigid blades. In this paper, a novel centrifugal flexible-blade cooling fan concept is purposed to move up the torque limits at speeds lower than rated and to avoid excessive cooling fan power and airflow at speeds higher than rated. This solution leads, on one hand, to a decrease of the losses and acoustic noise of the motor at higher speeds (economic and technical benefits) and, on the other hand, to a higher torque capability at lower speeds, allowing the user to use a motor with a lower rated power, which is inherently cheaper (economic benefit). Experimental results are presented for a 7.5-kW, 4-pole, induction motor, demonstrating clearly that the proposed fan concept works, increasing the motor speed range for a given constant load torque, being a quite promising solution for variable-speed motors.

Introduction

World industrial electric motor market is moving toward super-premium/IE4 and ultra-premium/IE5 efficiency classes [1, 2]. Due to the well-known technical and economic benefits associated with variable-speed drives (VSDs), their use in the industrial sector is increasing fast. In the developed countries, it is expected that, by the year 2020, half of the industrial motors will be controlled by VSDs. The centrifugal (bidirectional) fan with nonflexible or rigid blades is the preferred cooling fan type for general-purpose self-cooled/fan-cooled/self-ventilated electric motors, whose diameter and blade shape and number varies as a function of the motor efficiency class, as it can be seen in Fig. 1. The fan is directly coupled to the motor shaft. In rigid-blade centrifugal fans, the volumetric airflow rate, Q_{air} (m^3/s), is proportional to the angular/rotational speed, ω_{fan} (rad/s or r/min), and the mechanical power, P_{fan} (W), required by the fan is proportional to the cube of the rotational speed [3].

Fig. 1. Cooling fans of 7.5-kW, 4-pole, self-cooled, three-phase induction motors of different efficiency classes (IE1-IE4).

In variable-speed self-cooled motors, to avoid exceeding the motor nominal temperature, for a rotational speed lower than the base or nominal, the motor torque in steady-state (thermal equilibrium) should not exceed a certain limit/capability, which decreases significantly with the rotational speed, as it can be seen in Fig. 2. This is due, in part, to the reduction of the airflow rate produced by the external cooling fan. The lower air flow is, the lower the heat dissipation by convection will be, ultimately leading to an increase in the equivalent thermal resistance between the frame and the surrounding environment/air [4]. For a rotational speed higher than and up to twice the nominal, due to the voltage limitation of the VSD output and the increase of the motor impedance and back-electromotive force at higher frequencies, the power capability is approximately constant. In this operating regime, there is an excessive cooling airflow and the acoustic noise produced by the fan is very high. In fact, the centrifugal cooling fan power (which account for most of the windage losses[60]) increases significantly due to its cubic relation with the rotational speed.

In this paper, a novel centrifugal flexible-blade cooling fan concept is purposed to move up the torque limits at speeds lower than nominal and to avoid excessive cooling fan power at speeds higher than nominal. It can be anticipated that this solution leads, on one hand, to a decrease of the motor windage losses (as shown in Fig. 3) and acoustic noise at higher speeds and, on the other hand, to a higher torque capability at lower speeds, allowing the user to use a motor with a lower rated power, which is inherently cheaper.

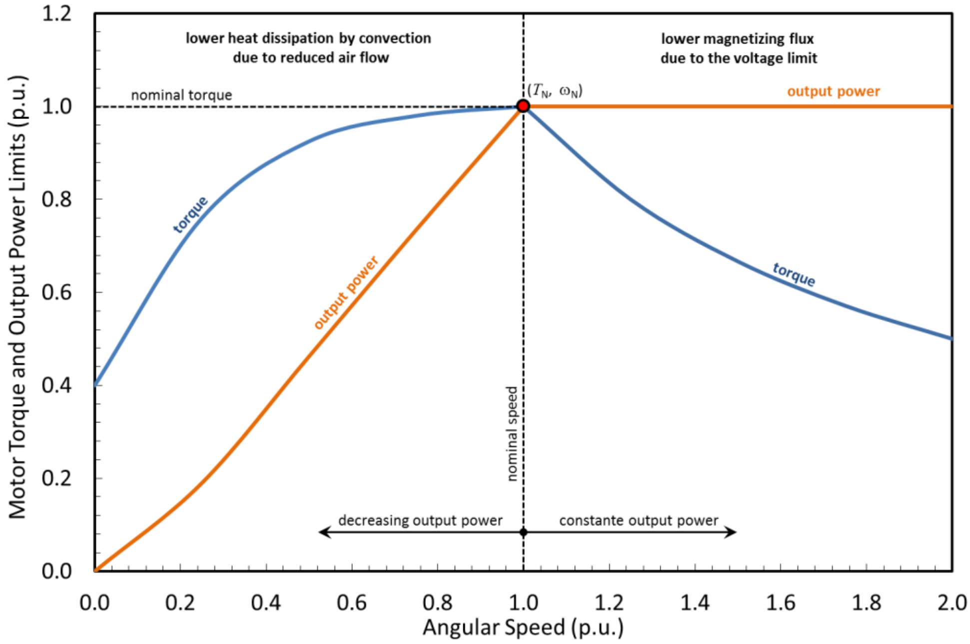


Fig. 2. Steady-state torque capability/limit of self-cooled motors to avoid exceeding nominal operating temperature.

60 A small part of the windage losses is also associated with the inner air movement due to the rotor end-ring blades (if any).

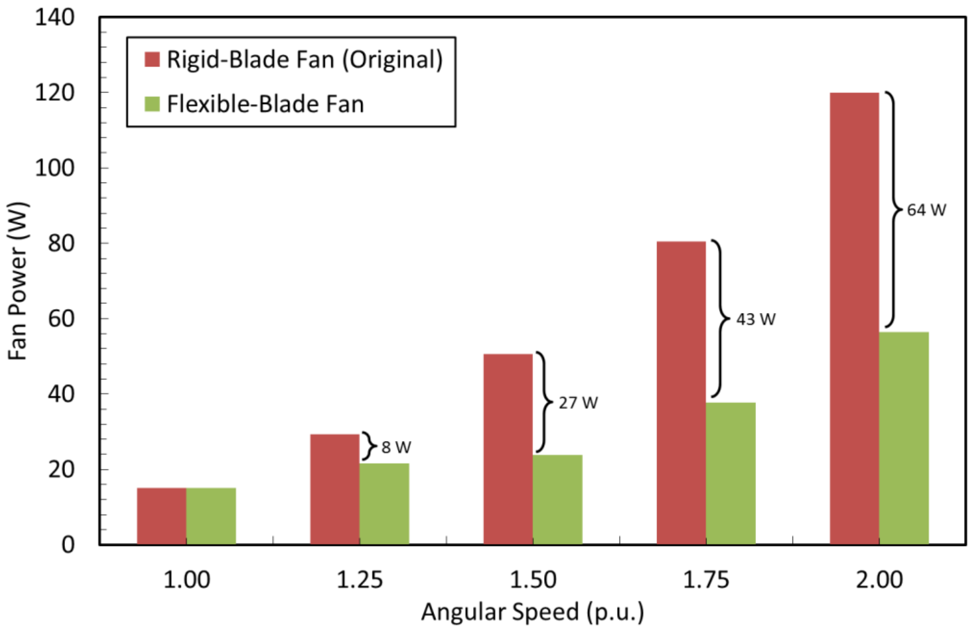


Fig. 3. Power required by the external cooling fan of a 7.5-kW, 4-pole, 50-Hz, 3-phase induction motor.

Flexible-Blade Centrifugal Fan

Concept

The basic concept being proposed in this paper is a flexible-blade centrifugal fan with a flatter airflow rate to angular speed curve, instead of the proportional relation offered by the conventional rigid-blade centrifugal fans, as illustrated in Fig. 4.

The flexible blades of the proposed fan gradually bend with the increase of the angular speed, reducing therefore the resulting output airflow in relation to a conventional rigid-blade fan. As a result, such a fan produces additional airflow at lower speed and requires less power at higher speed.

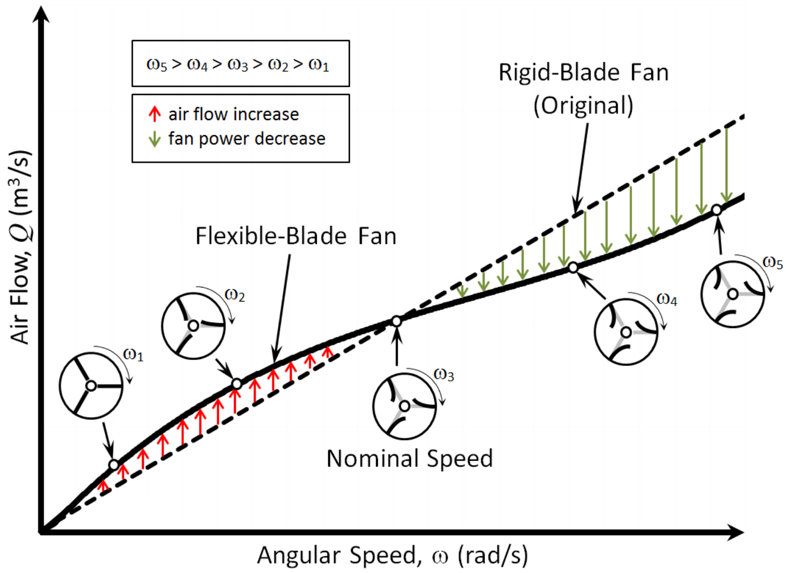


Fig. 4. Flexible-blade centrifugal fan concept: airflow rate as a function of the angular speed.

Design

Being the flexible-blade fan design a novel case, without any background in the literature, an empirical approach has been used to achieve a fully operation design and to understand the phenomena that influence on the dynamic behavior of the centrifugal fans with bending blades.

Before moving to the design and prototyping steps, a preliminary computational analysis of the original impeller geometry, has been performed with the commercial CFD code ANSYS CFX (an Element-based Finite Volume Method (EbFVM), with a Cell Vertex Formulation [5]), in order to visualize the pressure field on the blades. In Fig. 5, the total pressure field (static plus dynamic pressure) for the original impeller rotating counter-clockwise at the rated speed in a straight ideal flux tube, is shown.

This study has provided insight on the forces acting on the blades, which was quite useful in the flexible-blade fan design process since it provided clues to reach the desired blade deformation effect.

The first objective in the design process was to evaluate/quantify how much the blades can bend for different blade shape, size, flexibility, and number. Although it is extremely difficult to find the balance point between those parameters with an empirical approach due to the elevated number of variables, some preliminary experiments were performed and the respective results have led to key conclusions.

Firstly, a fan with semi-bending blades, with flexible blade tips in the outer part (Fig. 6), was prototyped and tested. The suction of the air in the centrifugal impeller occurs in the center of the fan (air intake), in axial direction, and then the air direction changes flowing from the center to the periphery of the fan, in a radial direction. Therefore, the forces in the blades imposed by the air movement will be concentrated in the region where the airflow direction changes from axial to radial, i.e., in the center region of the fan. As a result, adding flexible parts to the outer part of the blades (Fig. 6) does not produce the desired effect since the blade extremities are maintained straight regardless the angular speed. Two aspects contribute to the non-bending of the flexible part of the blades, the reduced tangential forces associated with the air movement and the centrifugal forces that tend to maintain the flexible part of the blades straight. When the air reaches the flexible part of the blade its flow direction is already radial.

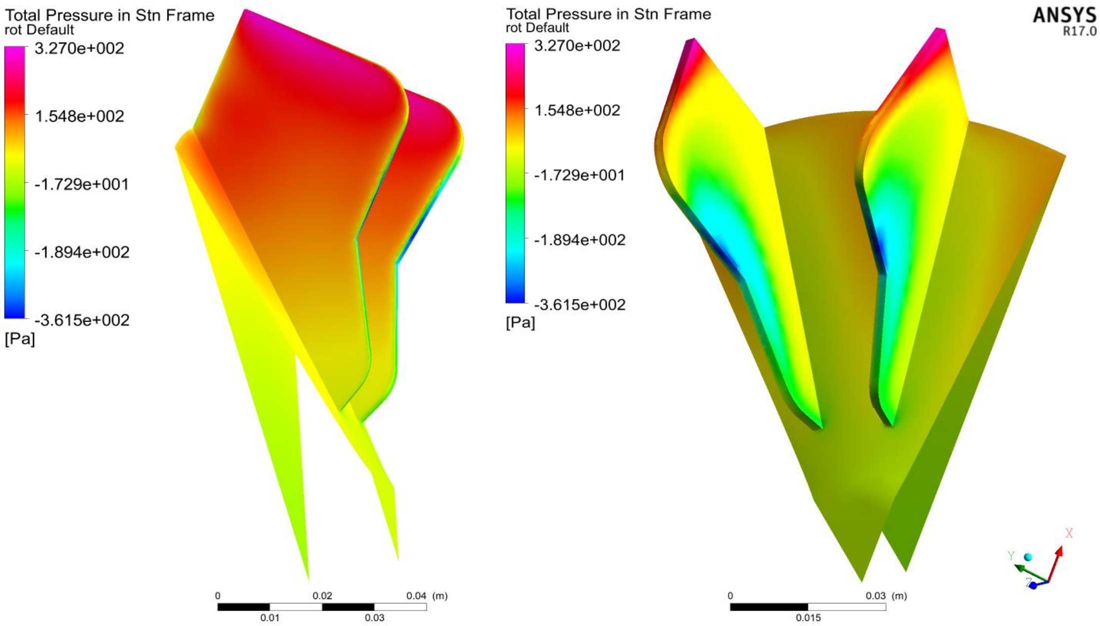


Fig. 5. CFD-based analysis of the total pressure field (static plus dynamic pressure) in the original rigid-blade centrifugal fan rotating counter-clockwise at 1500 r/min (base speed) in a straight ideal flux tube.

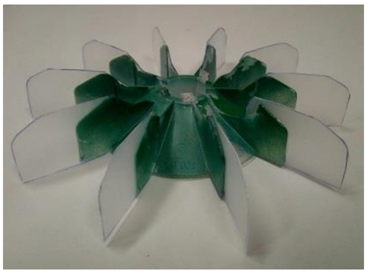


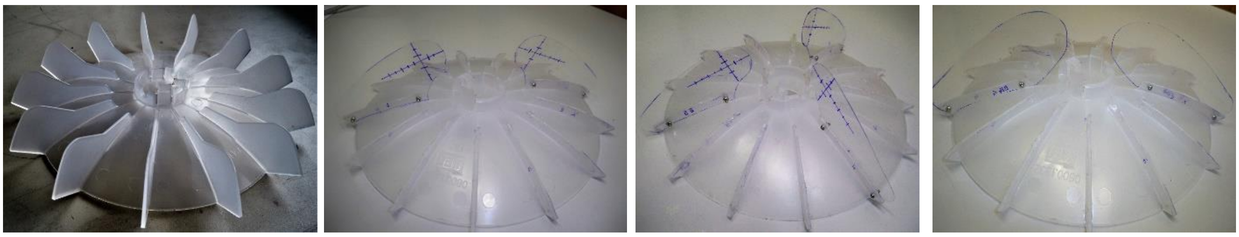
Fig. 6. First prototype of a centrifugal, flexible-blade, cooling fan for a 7.5-kW, 4-pole, self-cooled motor.

Secondly, a fan with blades designed to maximize the bending in the inner region of the fan (the region where the airflow changes its direction) was also prototyped and tested. In this case, the results were promising since a progressive blade bending with the increase of the angular speed was observed, proving that this design strategy can produced the desired behavior. A key conclusion for this test is that the more the bending part of the blade is concentrated near the fan center, the more the bending effect with the increase of the angular speed.

On the basis of the previous conclusions, two different blade shapes were designed (shown in Figs. 7b and 7c), prototyped in a flexible material, and then fixed in a rigid base. The larger area of the blades is concentrated near the fan hub. Moreover, the total area of the flexible blades is larger than that of the original one, in order to increase the airflow at low speed. Three different fan solutions/designs were prototyped (Fig. 8b, fan #1; Fig. 8c, fan #2; Fig. 8d, fan #3) and experimentally tested. Their behavior and performance was compared to the original fan of an IE1-class motor (Fig. 8a). The experimental results are presented in Section 2.3. It can be anticipated that these new blades bend almost completely at twice the motor nominal speed.

(a) (b) (c)

Fig. 7. Fan blade shape: (a) original rigid-blade fan; (b) novel flexible-blade fan #1 and fan #2; (c) novel flexible-blade fan #3.



(a) (b) (c)
(d)

Fig. 8. Different centrifugal fans: (a) original rigid-blade fan of an IE1-class motor, with 13 blades of the shape shown in Fig. 7a; (b) prototype of the novel flexible-blade fan #1, with 2 blades of the shape shown in Fig. 7b; (c) prototype of the novel flexible-blade fan #2, with 3 blades of the shape shown in Fig. 7b; (d) prototype of the novel flexible-blade fan #3, with 2 blades of the shape shown in Fig. 7c.

Experimental Tests

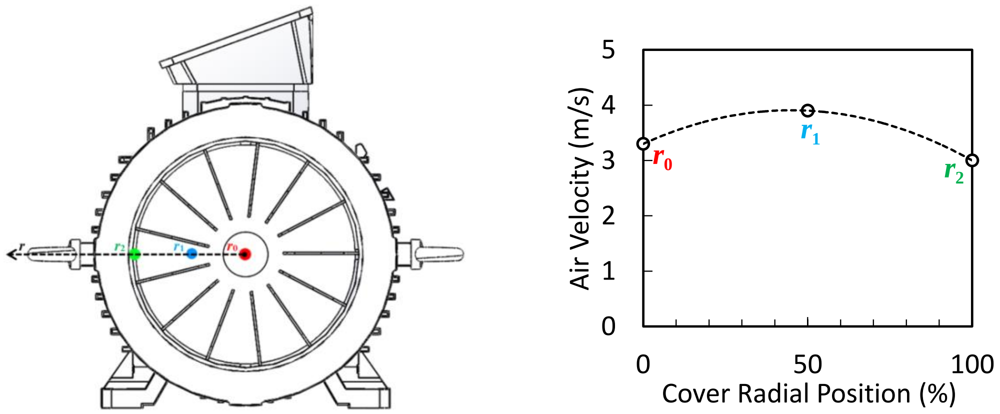
The original rigid-blade centrifugal fan of the IE1-class motor (Fig. 8a) and three different flexible-blade fan prototypes were all tested in an IE3-class, 7.5-kW, 4-pole, 50-Hz, 3-phase induction motor. The motor was fed/controlled by a VSD (Yaskawa Varispeed F7) and tested at no-load for different rotational speeds. To measure the motor input power, a high-precision power analyzer (Yokogawa WT1800), was used.

For the estimation of the airflow rate at the fan cover entrance/inlet, a high-precision solid-state anemometer was used to measure the air velocity, v_{air} (m/s), in three different radial points, r_0, r_1, r_2, with different radial distance, r (m), from the cover center of the inlet section of the fan cover, as illustrated in Fig. 9a. For each triad of values, a polynomial trend line of second order has been fitted to the experimental points (e.g. $v_{air}(r)=-0.0003r^2+0.027r+3.3$), as shown in Fig. 9b. Then, an average air velocity, v_{avg}, in the inlet section of the cover, has been calculated dividing the integral[61] of the $v(r)$ from r_0 to r_2 by the total area of the cover inlet, A_{cover}, according to (1). The volumetric airflow rate, Q_{air}, is given by (2).

$$v_{avg} = \frac{\int_{r_0}^{r_2} 2\pi \cdot r \cdot v(r) \cdot dr}{A_{cover}} \tag{1}$$

$$Q_{air} = A_{cover} \cdot v_{avg} \tag{2}$$

Even if the values obtained with this procedure cannot be assumed as the real numerical quantity of the airflow, they are, at least, precise enough to perform a comparative analysis. Furthermore, the values obtained with this strategy reflect fairly the real behavior of the airflow in such a complex geometry as the self-ventilation system with a centrifugal fan enclosed by a cover. Note that this ventilation system also has air recirculation, as shown in the smoke test presented in Fig. 10, which is a quite complex fluid dynamical aspect to analyze.



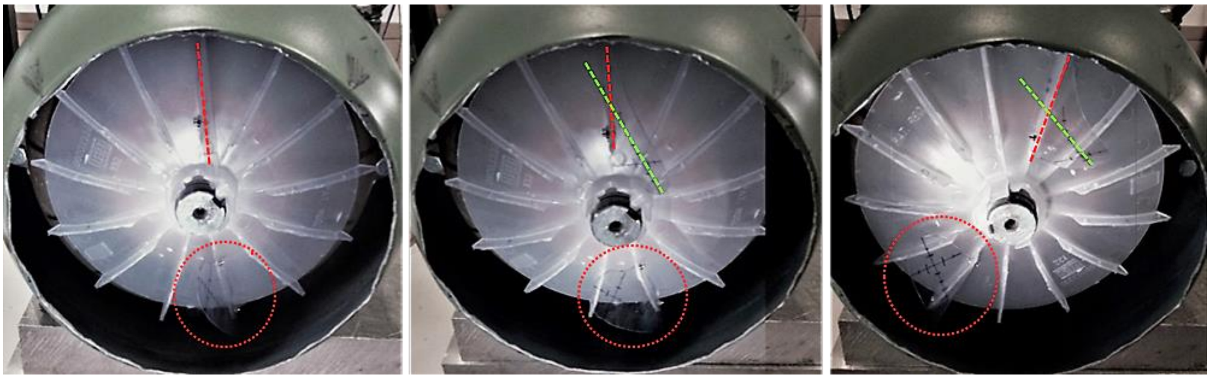
(a) (b)

Fig. 9. (a) Representation of the point where the velocity has been measured with the solid-state anemometer; (b) Typical trend line of the velocity in function of the radius of the cover ($v_{air}(r)=-0.0003r^2+0.027r+3.3$).

[61] In the numerical integration, the trapezoidal method was used [6].

Fig. 10. Smoke test performed on the original ventilation system (centrifugal fan plus cover) of a 7.5-kW, 4-pole, 50-Hz, 3-phase, self-cooled, induction motor to observe the airflow behavior and visualize the recirculation inside the cover.

In Fig. 11, a snap-shot, taken using a stroboscope, of the fan #1, rotating at three different speeds (in ascending order), is shown. It can be noted that the blades are perfectly straight at half of the nominal speed, start bending at the nominal speed, and are completely bended at twice the nominal speed.



(a) (b) (c)

Fig. 11. Snap-shot of the novel centrifugal flexible-blade fan, taken at 3 different speeds in order to visualize the different grade of bend: (a) 25 Hz, 725 r/min, the blades are perfectly straight; (b) 50 Hz, 1450 r/min, the blades start to bend; (c) 100 Hz, 1900 r/min, the blades are completely bended.

For each solution, the airflow has been estimated on the basis of the method previously explained, and the no-load input power, for six different values of the frequency[62], has been measured.

In Fig. 12, the airflow rate as a function of the rotational speed, in per unit (p.u.), is presented, considering the airflow rate produced by the original fan at no-load and 50 Hz, as reference/base.

Except for the curve of novel fan #3, all the curves take really close values of the flow at the no-load speed. This peculiarity enables to see at a glance the advantages in terms of flow compared to the original solution, which shows a linear pattern, as expected.

In Fig. 13, the input power as function of the rotational speed is shown, presenting two different trends. Up to the base angular speed, the power increases almost linearly, then it starts to increase cubically, as expected. This difference is caused by the mix of the friction losses, predominant for low speed, and the windage losses, predominant for high speed.

[62] In this paper it is considered that, at no-load, the slip of the induction motor is negligible. Actually, that has been experimentally confirmed even for the highest speed when the windage power is notable. The slip is so close to the unit value that, for the purpose of this paper, it is fair to assume that the motor speed is proportional to the supply frequency.

Fig. 14 shows the trend of the acoustic noise for the original fan and the novel fans #1 and #2, measured at the inlet section of the cover. The largest difference can be notice at high speed, where the flexible-blade fans produce less noise.

The straight trend of the original fan in Fig. 12 and the overlapping of the values at low speed (when the friction losses are prodominant and they can be assumed equal for each fan) in Fig. 13, demonstrate the fair accuracy of the measurements and of the comparative analysis carried out.

The most favorable solution seems to be the fan #1, both in terms of airflow and input power. With regard to the air flow, the area between the characteristic curve of original fan and fan #1, increases 20% at low speed (Figs. 4 and 12) and decreases 15% at high speed (Figs. 4 and 12). Concerning the input power, it decreases 17% at twice the base speed.

The novel flexible-blade fan #2, which has one additional blade compared to the fan #1, does not produce any flow gain at low speed and the flow reduction (due to blade bending) at higher speed is lower.

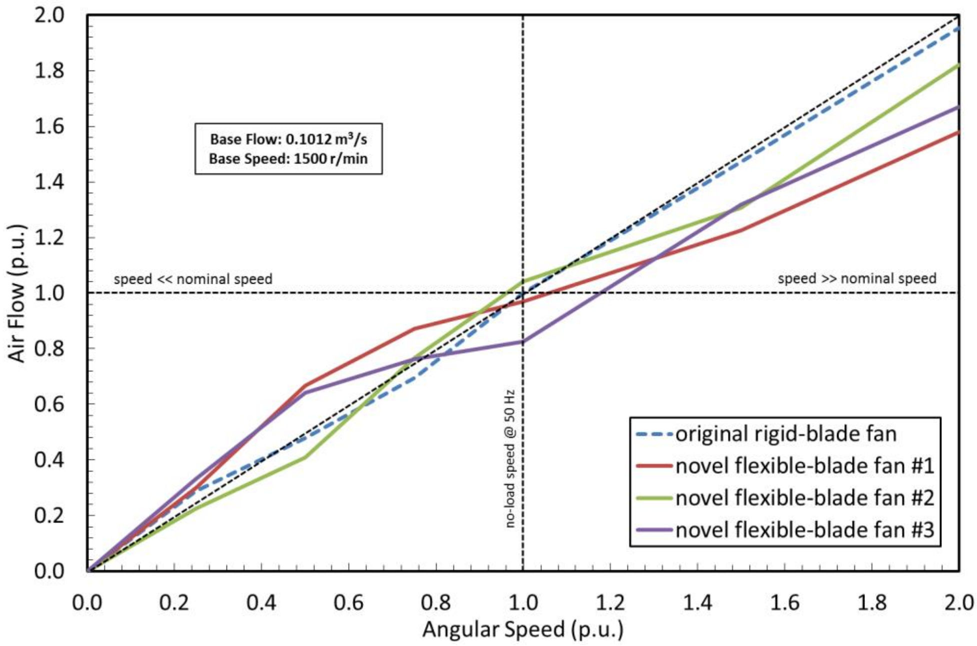


Fig. 12. Volumetric airflow rate as a function of the angular speed of the fan.

The fan #3, although leading to a flow gain at low speed, the blades start bending too early and move less air at no-load speed. This is due to the excessive area of the blades near the fan hub.

Finally, the flexible-blade fans produce less acoustic noise than the original fan.

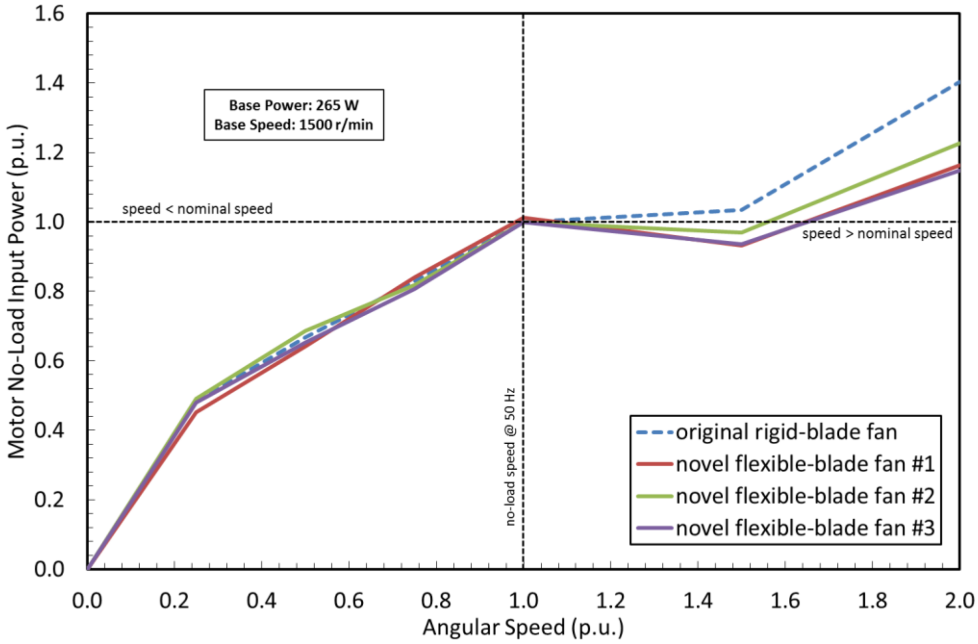


Fig. 13. Motor no-load input as a function of the angular speed of the fan.

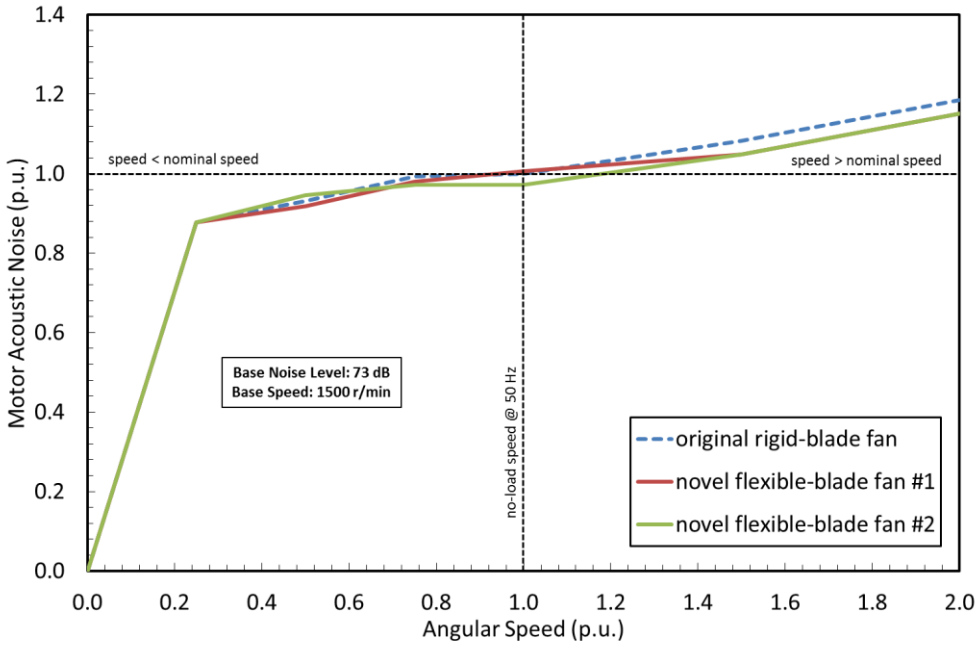


Fig. 14. Motor acoustic noise as a function of the angular speed of the fan.

Possible Design for an Axial Fan with Variable-Blade Angles

Following the same line of design, it is under development a novel axial fan with variable blade angles.

This solution is intended to combine the benefits associated with the flexible-blade fan concept and with the axial fans, which are in general more efficient than centrifugal fans [7].

In this case, referring to Fig. 15, the blade (point 2) changes position thanks to the flexible element (point 4), put between the body (point 1) and the blade (point 2), that increasingly flexes backwards with the increase of the rotational speed of the fan.

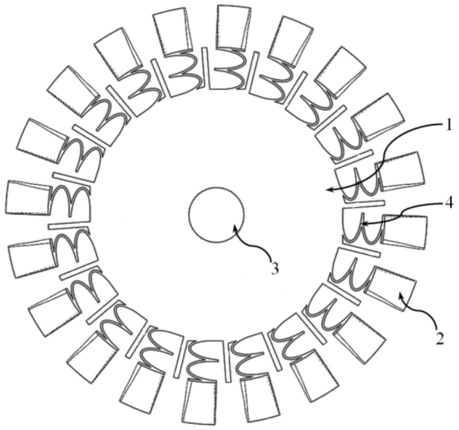


Fig. 15. Proposed axial fan with variable blade angles.

Technical and Economic Considerations

The proposed centrifugal flexible-blade cooling fan concept allows to move up the motor steady-state torque limits at speeds lower than rated and to avoid excessive cooling fan power and airflow rate at speeds higher than nominal. As previously referred, this solution leads, on one hand, to an increase of the motor efficiency and to a reduction of the produced acoustic noise at higher speeds (economic and technical benefits) and, on the other hand, to a higher steady-state torque capability at low speeds, allowing the user to use a motor with a lower rated power, which is inherently cheaper (economic benefit).

In Fig. 16, the approximate torque capability/limit curves[63] for two self-cooled motors, one of 7.5 kW and one of 11 kW, is presented. It is also presented an estimated curve for the 7.5-kW motor considering the airflow gain expected with the flexible-blade centrifugal fan #1.

As an example, the curves of constant-torque and quadratic-torque loads are also included in Fig. 16.

Considering the constant-torque load, with 85% of the motor nominal torque, in steady-state (thermal equilibrium), the 7.5-kW can only drive the load down to 40% of the nominal speed. If the user wants to operate the constant-torque load down to 20%, without using a forced external cooling system, it has to use a motor with higher rated power (in this case, of 11 kW). However, this solution is expensive and leads to a significant motor oversizing. If a flexible-blade centrifugal blade is used in the 7.5 kW motor, due to the airflow gain at lower speed, the torque limit is higher than the original, allowing the motor to drive the constant-torque load down to 20%. This is a better and cheaper solution to extend the motor speed range for a given torque. For an IE3-class induction motor, the difference between 5.5-kW and the 7.5-kW motor is approximately 100 €. Moreover, for speeds higher than nominal, the flexible-blade fan leads to a reduction of the windage losses/power and acoustic noise.

The proposed flexible-blade fan can retrofit directly the original one, as it can be seen in Fig. 17.

Regarding the mass production, the proposed fan design is likely to be manufactured at a cost equal or lower than that of the conventional rigid-blade centrifugal fan.

[63] For an angular speed lower than the nominal, these curves define the maximum shaft torque that can be developed by the motor in steady-state operation (considering the thermal equilibrium) without exceeding the stator winding nominal temperature.

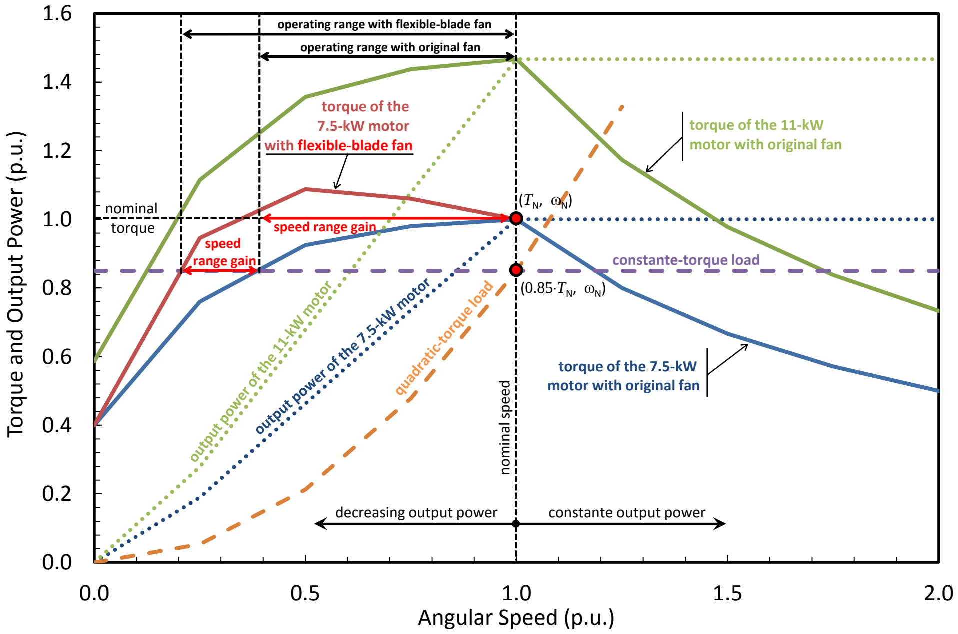


Fig. 16. Approximate torque capability/limit curves at steady-state for 7.5-kW and 11-kW self-cooled motors.

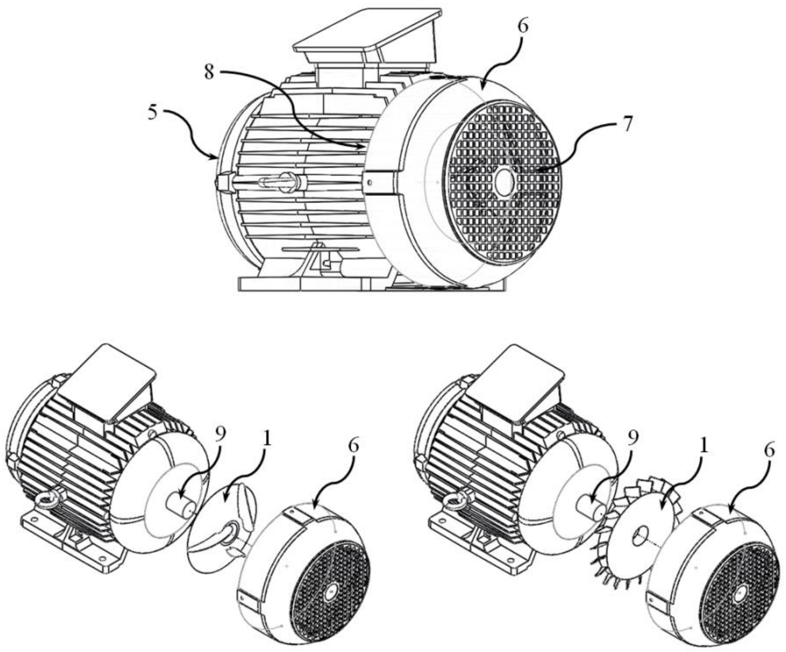


Fig. 17. Installation of the proposed fans in the motor.

Conclusions

On the basis of the presented experimental results, it can be concluded that the proposed novel centrifugal flexible-blade cooling fan is a promising solution to move up the motor steady-state torque limits at speeds lower than rated and to avoid excessive cooling fan power and airflow rate at speeds higher than nominal. Its use can, on one hand, increase of the motor efficiency and reduce the acoustic noise at higher speeds (economic and technical benefits) and, on the other hand, increase the steady-state torque limit at low speeds, allowing the user to use a motor with a lower rated power, which is inherently cheaper (economic benefit) than the alternative solutions, namely, the integration of an external forced-cooling system or the increase of the motor rated power.

The proposed concept leads to a consistent gain/reduction of airflow at low/high speed obtained with a really simple design that could be particularly easy and cheap to industrialize, particularly if the simplicity of the design is taken into account.

Even if the results presented are quite good, the design of the fan/blades requires an accurate optimization.

The innovative idea of the blade that bends presents a problem that involves a specific area of the material engineering. The material used, not only has to withstand the constant bend without deforming itself permanently, but has also to guarantee a minimum lifespan of 80000 hours. A blade with a variable thickness, made of strong plastic with anisotropies proprieties, could be a suitable solution.

The flexible-blade fan concept has been patented in the Portuguese Patent Office (INPI, National Patent No. 109849).

Acknowledgments

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References

[1] A. T. de Almeida, F. J. Ferreira, A. Duarte, "Technical and economic considerations on super high-efficiency three-phase motors", IEEE Transactions on Industry Applications, Vol. 50, No. 2, March/April 2014, pp. 1274-1285.

[2] A. T. de Almeida, F. J. Ferreira, G. Baoming, "Beyond induction motors technology trends to move up efficiency", IEEE Transactions on Industry Applications, vol. 50, no. 3, pp. 2103-2114, 2014.

[3] S. L. Dixon and C. Hall, "Fluid mechanics and thermodynamics of turbomachinery", Butterworth-Heinemann, 2013.

[4] Fernando J. T. E. Ferreira, A. T. de Almeida, J. Carvalho, "Experiments to Observe the Impact of Power Quality and Voltage-Source Inverters on the Temperature of Three-Phase Cage Induction Motors using an Infra-Red Camera", 2009 IEEE Inter. Electric Machines and Drives Conf. (IEMDC'09), Miami, Florida, USA, May 2009.

[5] "Solver theory guide", Ansys CFX Release, Vol. 11, pp.1996-2006,

[6] W. Ambrosini, "Notes from the Computational Thermo-Fluid Dynamics course", University of Pisa, Academic Year 2014/2015.

[7] M. Roffi, F. J. T. E. Ferreira, A. T. de Almeida, "Comparison of Different Cooling Fan Designs for Electric Motors", 2017 IEEE Inter. Electric Machines and Drives Conf. (IEMDC'17), Miami, Florida, USA, May 2017.

Comparative analysis of the effects of voltage unbalance on the performance of IE 4 electric motors

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Abstract

In this paper, we study the behavior of line start permanent magnet synchronous motors (LSPMSM) and squirrel cage induction motors (IM) under different voltage unbalance levels and different load conditions. To this end, we carried out different tests on a 5.5 kW, 4 pole, 1500 rpm, IE4 efficiency LSPMSM and on a 5.5 kW, 4 pole, 1475 rpm, IE4 efficiency IM. We analyzed the behavior of currents and losses on the electric motors under different levels of unbalance. In addition, we present results about the effects of voltage unbalance on the power oscillations, estimated electromagnetic torque and mechanical vibrations.

Keywords

Electric Motors, Energy efficiency, IE4, Unbalanced voltages, Power Quality.

Introduction

Nowadays, higher efficiency electric motors (EM) are used to increase the productivity in industry [1]. In the super-premium efficiency class (IE4), there are EM with different constructive characteristics; one of them is the squirrel cage induction motor (IM) while the other one is the line start permanent magnet synchronous motor (LSPMSM). The stator of LSPMSMs is similar to the stator of IMs, however rotor combines a squirrel cage with permanent magnets inserted into the rotor core [2][3]. Then, the LSPMSM operates at synchronous speed at steady state, and it uses the squirrel cage to start up and under load transients and supply voltage changes. These facts allow LSPMSMs to have higher energy efficiency and higher power factor than the traditional IM. As a disadvantage with regard to the IM, LSPMSMs require a special methodology to replace the bearings and a particular care if the coupled load may cause a rotor lock, due to the minimum-time of locked rotor that LSPMSMs allow.

Another disadvantage of LSPMSMs is related to its behavior under power quality problems [4]. In [4] the authors studied, by finite-element modeling and experimental results, the influence of supply voltage distortion on the energy efficiency of LSPMSM [4]. They concluded that harmonic distortion lead to important variations on the rotor losses of the LSPMSM [4]. Voltage unbalance is another power quality problem that may lead to negative effects on the EMs performance. Voltage unbalance induces currents in the squirrel cage at steady state, thus increasing losses and temperature in the rotor which may in turn lead to damage of the EMs [5][6].

Therefore, even when higher efficiency EM could produce great benefits to the industry due to the savings in energy costs under good power quality, these benefits may not be such when the motor works under voltage unbalance conditions.

In this paper, we study the behavior of LSPMSMs and IMs under different load conditions and different voltage unbalance levels. To this end, we carried out several tests on a 5.5 kW, 4 poles, 1500 rpm, IE4 efficiency LSPMSM and on a 5.5 kW, 4 poles, 1475 rpm, IE4 efficiency IM. We analyze the behavior of the currents and losses in these conditions. In addition, we present results of the effects of voltage unbalance on the input power oscillations, estimated electromagnetic torque and vibrations of the EM.

Characteristics of the analyzed EMs

In low- and medium- power EM there is a significantly increase in their efficiency between the super-premium efficiency class (IE4) and the standard efficiency class (IE1). These low- and medium- power EMs are widely used in the industry The Instituto de Tecnologia para o Desenvolvimento (LACTEC) and the Companhia Paranaense de Energia (COPEL), found that, out of 916 IMs in 12 industrial sites in Brazil, 423 (46%) were between 0.746 and 7.46kW (1-10 HP) [7]. Then, in order to analyze experimentally the behavior of the EM, we selected a 5.5 kW, 4 poles, 1500 rpm, IE4 efficiency LSPMSM and on a 5.5 kW, 4 poles, 1475 rpm, IE4 efficiency IM. Table I shows the nameplate data of the analyzed EMs.

Table I Nameplate data of the analyzed EMs

Electric Motor Type	**IM**	**LSPMSM**
Power (kW)	5.5	
Voltage (V)	220/380	
Frequency (Hz)	50	
Poles	4	
Frame	132	
Service Factor	1	
International Efficiency Class	Super Premium IE4	
Efficiency (%)	91.9	92.5
Rated Current (A)	11.1	9.72
Rated speed (R.P.M.)	1470	1500
Power factor	0.82	0.93
Rated torque (N.m)	35.8	35
Starting Current (p.u.)	8.8	8.2
Starting Torque (p.u.)	2.9	3.8
Maximum torque (p.u.)	3.5	2.5
Stator resistance (ohm)	0.55	

Table I shows that the LSPMSM has higher efficiency and power factor than the IM. In the same way, the LSPMSM has lower rated current. The IM has higher rated torque and maximum torque than the LSPMSM. The high starting current, in per unit of the rated current, of both EMs (Is≥8.2) implies low negative-sequence impedances, leading to large losses under unbalanced voltage conditions [8][9].

Test Bench

Figure 81 shows the test bench that we used to test the EMs [10]. The bench consists of a three-phase programmable source to create different voltage supply conditions [10]. The EM under test is coupled to an IM used as a load. This IM is fed by a variable speed drive (VSD) so that the load on the motor under test may be adjusted.

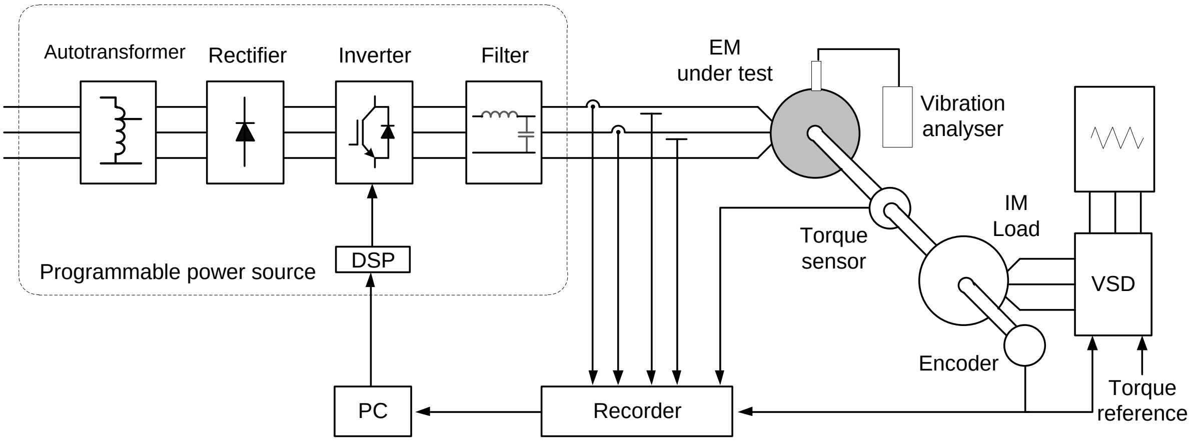


Figure 1 Test bench used to measure power, torque and vibrations.

We record two line voltages and two phase currents of the motor under test using a four-channel recorder (3.2s, 40kS) [10]. The remaining voltage and current are obtained adding the measured values. A rotating torque sensor (0-100 Nm) is used to measure torque and speed and a one-channel vibration analyzer is used to measure the vibrations in the frame of the EM under test [10].

We calculate the instantaneous active power using the voltages and currents supplied to the EM. Finally, we use the stator voltage, current and resistance to estimate the linked stator flux [11] and then we use the currents and the flux to estimate the electromagnetic torque as proposed in [11] [12].

We compute the voltage unbalance factor (VUF) using IEC 61000-4-30 standard, as the ratio between the modulus of the negative-sequence component of the voltage and the modulus of the positive-sequence component of the voltage in percentage [7][10].

We performed 25 tests in each EM supplied with sinusoidal voltage (THD_V < 2%), for different load levels (0-25-50-75-100%) and different voltage unbalance levels (0%-1%-3%-5%-7%). We introduce voltage unbalance by increasing the fundamental negative-sequence component of the supply voltage.

Negative-sequence currents measured on the EMs for different levels of voltage unbalance

Figure 2 shows the behavior of the negative sequence current (i_{ns}) in per unit of the rated current (i_r), for different values of voltage unbalance.

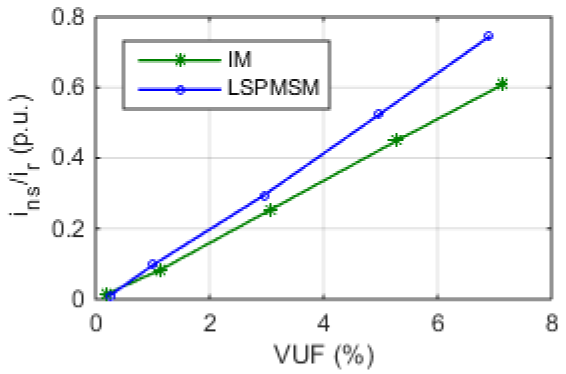


Figure 2 Negative sequence current as a function of the voltage unbalance. EM load 75%.

The figure shows that the negative-sequence current increased almost linearly with the voltage unbalance in both EMs. This behavior is similar to the one observed in others IMs, however, the increase in the negative-sequence current is higher than in standard IMs [9] [13] [14]. For approximately VUF = 5% the negative-sequence currents in the IM is close to 45% of the rated current (i_r), and close to 55% for the LSPMSM.

Increase of total power losses and instantaneous active power oscillations in EMs due to voltage unbalance

The negative-sequence current increase the power losses of EMs [9] [14] [15]. The increase of losses leads to an increase of the temperature and reduce the lifespan of the EMs [6] [9] [14] [15]. The interaction between the positive-sequence voltage and the negative-sequence current produce torque and power oscillations at twice the supply frequency. These oscillations are also produced by the negative-sequence voltage and the positive-sequence current [10] [16]. Then, with unbalanced voltage, the instantaneous power presents these oscillations a twice the supply frequency [10] [16].

In this section, we present the increase of losses in both motors and then the effects on power and torque for different voltage unbalance level.

Increase of total power losses due to voltage unbalance

Figure 3 shows the increase of power losses (expressed in percentage of the losses measured under ideal supply voltage) for different values of voltage unbalance. The figure shows that for voltage unbalance factors less than 3%, the increase of losses in the IM is less than 10%. However, the increase of losses is almost 20% in the LSPMSM. With VUF=7% the increase of losses in the EMs are 32% and 57% respectively.

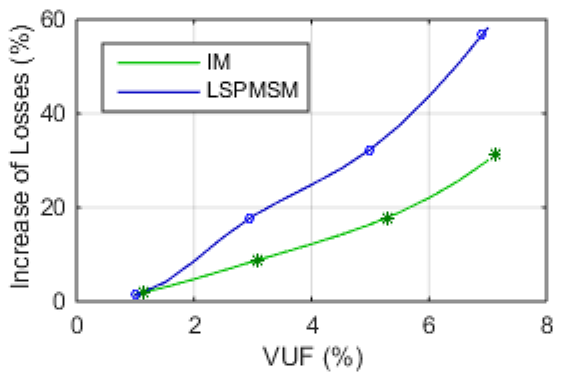
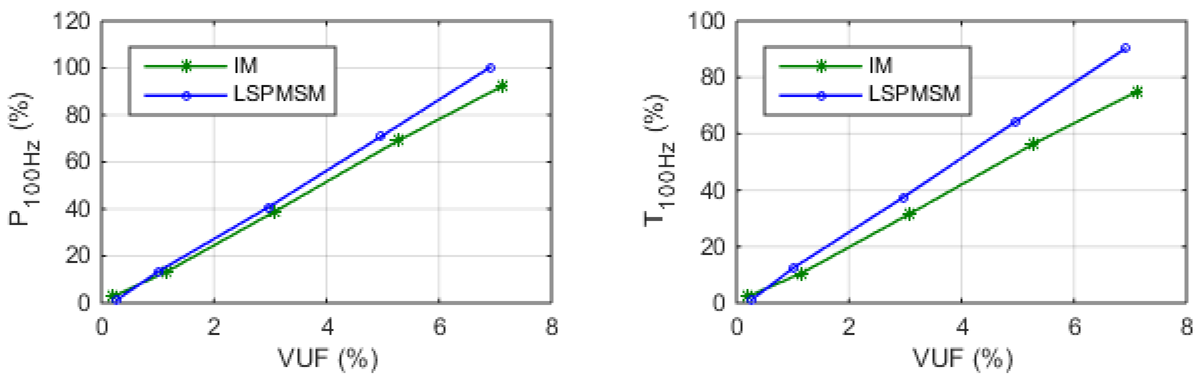


Figure 3 Increase of total losses as a function of the voltage unbalance. EM at no load.

Power and torque oscillations at twice supply frequency due to voltage unbalance

Figure 4(a) shows the instantaneous power oscillations at twice the supply frequency for different values of voltage unbalance. The figure shows that as the voltage unbalance goes from 0% VUF to 7% VUF, the oscillations on the LSPMSM grows from almost 0 to 100% of the rated power. The IM present a similar behavior; however, the oscillations are smaller than in the LSPMSM.

Figure 4(b) shows the amplitude of the oscillations of the estimated electromagnetic torque in per unit of the rated torque for different values of voltage unbalance. The figure shows that the torque oscillations increased almost linearly with the voltage unbalance in both motors. For the same level of unbalanced voltage, the LSPMSM produce greater torque oscillations than the IM.



(a) (b)

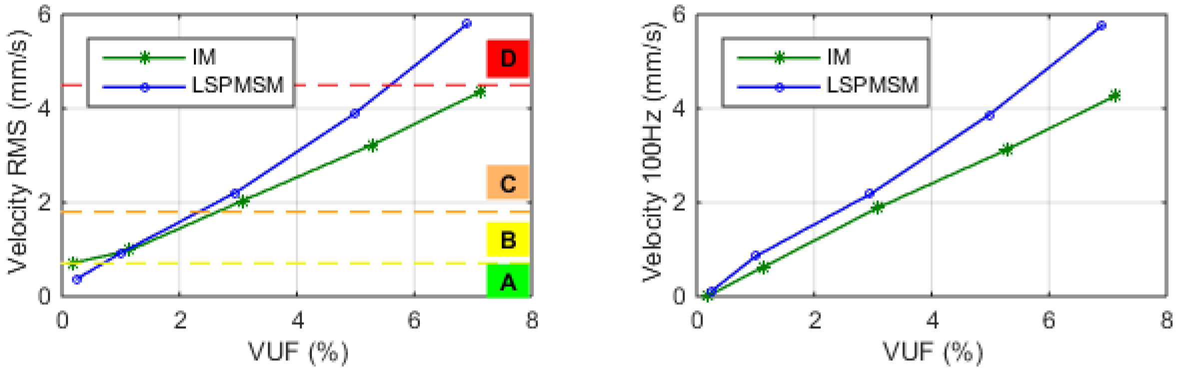
Figure 4 Amplitude of oscillations of the instantaneous active power (a) and electromagnetic torque (b) at twice supply frequency for unbalanced voltage conditions. EM load 75%.

Vibration analysis

The power oscillations and the torque oscillations at twice the supply frequency lead to the increase of RMS value of vibrations. The RMS value of vibrations is often used to assess the general health of rotating equipment [10] [17]. ISO 10816-1 and IEC 60034-14 standards establish tolerable levels of vibrations on IMs for different power ratings, foundation and load type [10][17].

According to the ISO 10816-1 standard, for this IM (Power<15kW), RMS vibration velocities between 0-0.71 mm/s (zone A) correspond to machines just put into service. Values between 0.71-1.8 mm/s (zone B) correspond to equipment which can operate continuously without any restrictions. Values between 1.8 and 4.5 mm/s (zone C) indicates that the condition is acceptable only for a limited period of time [10]. Finally, a value over 4.5 mm/s (zone D), indicates that the condition is not acceptable [10].

Figure 5(a) shows the RMS value of the vibrations velocity for different values of voltage unbalance. The figure also shows the vibration thresholds defined by the ISO 10816-1 standard. As the voltage unbalance goes from 0% VUF to 7% VUF, the RMS values of the vibrations velocity grows as a result of the increase in the 100Hz component of the vibration's velocity (see Figure 5(b)).



(a) (b)

Figure 5 Vibration velocity as a function of voltage unbalance. (a) RMS and (b) 100 Hz component. EM load 75%. A, B, C and D are the ISO 10816-1 levels of vibrations.

In the IM with ideal supply voltages, the vibration level corresponds to the upper level of zone A of the ISO 10816-1 standard (approx. 0.7mm/s), however, as the voltage unbalance goes from 0% VUF to 7% VUF, the vibration level grows to almost zone D (approx. 4.3 mm/s).

In the LSPMSM, for voltage unbalance factors less than 0.5%, the vibration level corresponds to zone A. On the other hand, for voltage unbalance ratios greater than 2.3%, the vibration levels exceed the threshold of vibrations acceptable under continuous operations (zone C of the standard) and for ratios greater than 5.5% they exceed the threshold of not acceptable vibrations.

Conclusions

In this paper, we measured the effect of voltage unbalance on the currents, power, losses and vibrations over two different super-premium efficiency class (IE4) EMs. We analyze a Squirrel Cage IM and a LSPMSM.

We found out that under ideal supply voltages the IE4 LSPMSM presents lower line currents and losses than the IM. However, the performance of the LSPMSM deteriorated most as the voltage unbalance grew. The IM presents lower negative-sequence current than the LSPMSM for the same level of voltage unbalance. The lower negative-sequence current of the IM lead to lower losses and lower power oscillations than in the LSPMSM.

The vibrations measured in the frame of the LSPMSM are smaller than the IM under ideal supply voltages. However, the higher power oscillations at two times the supply frequency in the LSPMSM increase more the vibrations in the LSPMSM than in the IM. The vibrations level measured in the LSPMSM is unacceptable for continuous operations with VUF≥ 2.3% and it should be out of service with VUF≥ 5.5%.

Acknowledgments

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References

[1] L. Siebert, E. Yamakawa, A. Aoki, L. Ferreira, P.Santos E. Silva, G. Klinguelfus and F. Filipini. Energy efficiency indicators assessment tool for the industry sector. Transmission & Distribution Conference and Exposition - Latin America (PES T&D-LA), 2014 IEEE PES. 2014.

[2] M. Kahrisangi, A. Isfahani, S. Zadeh and M. Sebdani, “Line-start permanent magnet synchronous motors versus induction motors: A comparative study” Frontiers of Electrical and Electronic Engineering, Nov. 2012.

[3] F. Ferreira, G. Baoming and A. Almeida, "Stator Winding Connection-Mode Management in Line-Start Permanent Magnet Motors to Improve Their Efficiency and Power Factor," IEEE Transactions on Energy Conversion, vol. 28, pp. 523-534, 2013.

[4] C. Debruyne, P. Sergeant and S. Derammelaere "Influence of Supply Voltage Distortion on the Energy Efficiency of Line-Start Permanent-Magnet Motors," IEEE Transactions on Industry Applications, vol. 50, pp. 1034-1043, 2014.

[5] F. Ferreira, B. Leprettre and A. de Almeida,, "Comparison of Protection Requirements in IE2-, IE3-, and IE4-Class Motors," IEEE Transactions on Industry Applications, vol. 52, pp. 3603-3610, 2016.

[6] E. Quispe, X.Lopez-Fernandez., A. Mendes, A. Marquez- Cardoso and J. A. Palacios. “Influence of the positive sequence voltage on the derating of three-phase induction motors under voltage unbalance”. In Electric Machines & Drives Conference (IEMDC), 2013 , IEEE International, pp. 100-105, 2013.

[7] A. Bonelli, A. Aoki, M. Teixeira, A. Langner, W. Souza, F. Filipini and R. Nehls, “Panorama do Impacto da Qualidade da Energia Elétrica Aplicada aos Motores das Indústrias do Estado do Estado do Paraná” IV Simpósio Brasileiro de Sistemas Elétricos (SBSE 2012). Goiânia, Brasil. 2012.

[8] R. Dugan, S. Santoso M. McGranaghan and H. Beaty, “Electrical Power Systems Quality”, Mc Graw Hill professional. 2002.

[9] P. Donolo, C. Pezzani, A. Bonelli, A. Aoki, R. Nehls, G. Bossio and G. García, “Performance of High Efficiency Induction Motors with Power Quality Problems” 45th CIGRE Session 2014. Paris, France. 24 to 29 August 2014.

[10] P. Donolo, G. Bossio, C. de Angelo, G. García and M. Donolo, “Voltage unbalance and harmonic distortion effects on induction motor power, torque and vibrations” Electric Power Systems Research, 140, pp. 866-873. 2016.

[11] D.W. Novotny, T.A. Lipo. Vector control and dynamics of AC drives. Clarendon Press 1996.

[12] M. Babaei, R. Asgharei and A. Ahmarinejad, “Electromagnetic Torque and Speed Estimators for Permanent Magnet Synchronous Motor Drive Systems”, Energy Procedia, Volume 100, November 2016.

[13] P. Donolo, G. Bossio, and C. de Angelo, “Analysis of voltage unbalance effects on induction motors with open and closed slots” Energy Conversion and Management, vol. 52, Nº 5, pp. 2024-2030. 2011.

[14] P. Gnacinski, “Derating of an induction machine under voltage unbalance combined with over or undervoltages”, Energy Conversion and Management, vol. 50, pp. 1101-1107, 2009.

[15] P. Gnacinski and T. Tarasiuk, “Energy-efficient operation of induction motors and power quality standards” Electric Power Systems Research, vol. 135, pp. 10-17. 2016

[16] Y. Wang; M. Lee and S. Sung, “Analytical modeling of pulsating torques of induction motors caused by supply voltage unbalance”, International Conference Utility Exhibition on Power and Energy Systems: Issues & Prospects for Asia (ICUE), 2011 28-30 Sept. 2011.

[17] IEC 60034-14:2003, Rotating electrical machines — Part 14: Mechanical vibration of certain machines with shaft heights 56 mm and higher — Measurement, evaluation and limits of vibration severity. 2003.

Numerical investigation of the heat dissipation improvement from the small power brushless electric motor

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Abstract

The paper covers a numerical investigation of the brushless motor thermal behavior. The first part of the research focuses on a numerical model validation that was developed for the small power electric motor cooled by the natural convection and radiation. The experiment was performed on two identical coupled machines. One of them worked in the normal motor regime and the second one in the generator mode. The measurements were performed on the motor using thermocouples mounted within the motor, on its housing and in the air above the machine. In the numerical model, the whole test rig was taken into consideration. One of the crucial aspects of the model was to include the anisotropic thermal conductivity of windings and the magnetic core. A good agreement between the measurement and model results has been obtained.

The second part of the research covered the analysis of heat dissipation improvement from the described machine. During the numerical tests, the air volume within the motor was converted into the solid volume with a higher thermal conductivity. In the numerical investigation, a resin material was taken under consideration. Its location was identified on the base of the highest temperatures that occur in the previous model. It allowed decreasing the windings temperature resulting in the electric resistivity reduction causing also copper loss reduction. Additionally, the suggested improvement could help to reduce a risk of the windings isolation overheating during the work under the overload condition.

Introduction

Ecological and economical regulations concerning eco-design instructions for electric motors manufacturers established by European Commission were collected and described in the following documents:

- Commission Regulation (EU) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council;
- Commission Regulation (EU) No 4/2014 of 6 January 2014 amending Regulation (EC) No 640/2009 implementing Directive 2005/32/EC of the European Parliament and of the Council.

According to these regulations, European policy aims to increase the average efficiency of the energy conversion of electric power to effective mechanical power. Therefore, the increase of the electric motor efficiency became a key goal in the electric engineering field in Europe and in the whole World.

Simultaneously, environmental policy intends to reduce usage of the low efficient internal combustion engines in the automotive industry. It can be realized by replacing this technology by a high efficient electric drive source in a public and individual transport. The main barrier to this goal implementation is still the limited possibility of the electric energy storage. Trends described in the literature show that this limitation will be decreased in following time [1],[2],[3].

Mobile technologies of the electric energy storage occur usually as the direct current source. Therefore, one of the natural ways is to use a motor which can be powered by this type of source and the most effective technology, in this case, are the permanent magnets Direct Current motors (PM BLDC).

One of the methods to achieve the objective of increasing electric motor efficiency is an improvement of the machine thermal behavior. Therefore, a method of heat dissipation intensification from the crucial components of the electric motor is proposed in this paper. In this case, intensification of heat dissipation could be realized by using a thermal gap filler in the vicinity of elements where hot spots occur. This way was also proposed for the radial flux electric machine in [4] and axial flux machine in [5].

Experimental test rig

Thermal measurements on the investigated motor were the first stage of the research. An experimental test rig contained two identical motors. The first one worked in the motor mode and the second one in the generator regime. These machines were coupled with each other by a universal bellow coupling. The rated output power of the motor was on the level of 430 W and rated input voltage with the electronic commutation of 24 V. The investigated machine was a PMBLDC motor. On the rotor, the neodymium magnets were applied. In the test rig, machines were mounted to the aluminum base by aluminum fixing using rubber distances between these elements. Rubber distances were used to limit the heat transfer from motors to the base and simulate natural work conditions. Moreover, around the machines, a transparent plastic cover was applied to reduce the fluctuations of air from the laboratory room. The cover had free air access from the bottom and from the top wall, air could exit this closed space via drilled hole of 0.008 m diameter. The photography of the main components is presented in 0. In the test rig, a system of resistors with external cooling was used to dissipate heat produced by a generator which was a load for the investigated motor.

Photography of the test rig.

Mathematical model

According to the experimental test rig description, the numerical models were prepared. In the previous studies, thermal and flow analysis describing numerical computations with experimental validation within a motor and the external surrounding air was performed [6], [7]. Similarly, in the following paper, the same governing equations of fluid mechanics and heat transfer were solved by means of the Ansys FLUENT® code.

Nonetheless, in the presented research, the series of User Defined Functions (UDFs) were implemented to reduce the thermal model by removing the air surrounding the motors. The implemented UDFs, used as the boundary conditions in the model referred to formulas based on empirical equations dedicated to natural convection [8], [9], [10]. Aluminum fixing in UDFs was treated, in this case, as horizontal plates. At the same time, the housing of electric motor was simplified to the cylinder shape for which the empirical equations for the dimensionless Nusselt numbers were created. Basing on the known heat fluxes from the specific surfaces from the previous models, some heat transfer coefficients (HTC) were calibrated for the specific surfaces of the model where part of forced convection appeared.

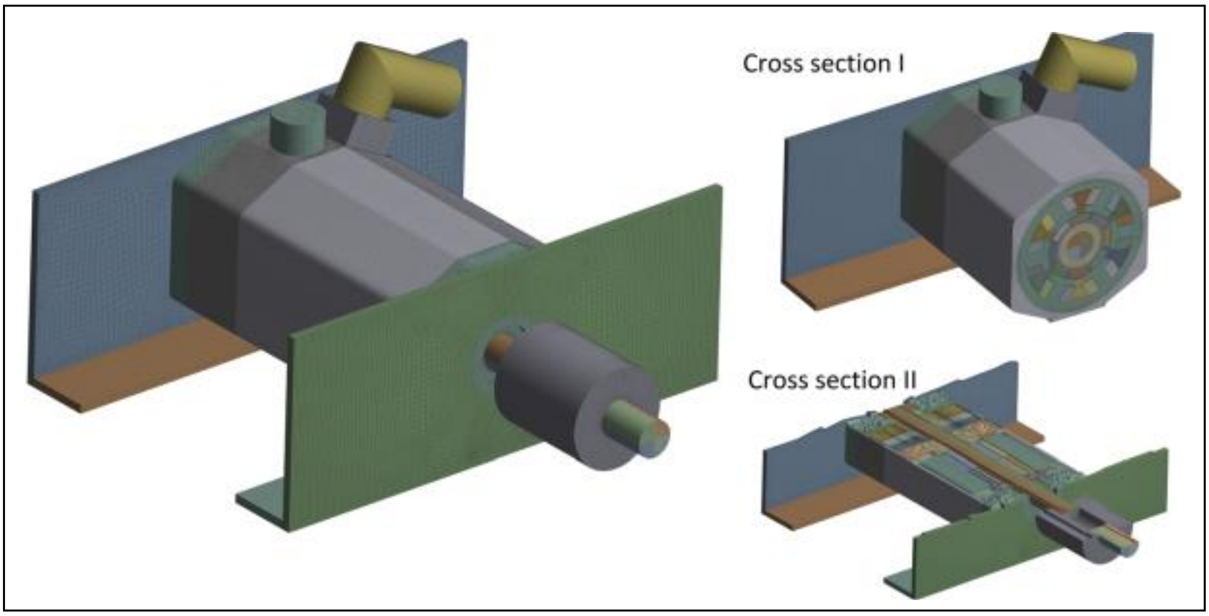
In the current research, two separate numerical models were created. Model A was built based on the original geometry according to the tested motor in laboratory conditions, while model B represented a geometry motor with the application of the resin thermal filler. The thermal filler was added on the whole length of the stator windings. In the model calibration process, the temperature field calculated from model B was consistent with a model containing a numerical analysis of air outside the motor.

One of the crucial elements of thermal analysis is an identification of the thermal conductivity of the specific materials used for a machine construction. In 0, a list of the materials assumed in numerical analysis with their thermal conductivities is presented. It is worth to mention that the windings and iron core materials were modeled as the anisotropic thermal conductivity.

Thermal conductivity in W m^{-1} K^{-1} of the specific elements assumed in the model

Identified construction material of specific elements	**Thermal conductivity, W m^{-1} K^{-1}**	**Literature or website source**
Isolated wires of windings - axial direction	167	[11]
Isolated wires of windings - radial direction	1.4	[11]
Laminated core - axial direction to the shaft position	4.9	[11]
Laminated core - radial direction to the shaft position	22	[11]
Aluminum housing	202	[12]
Aluminum fixing	202	[12]
Cast iron endcaps	50	[13]
Neodymium magnets	9	[14]
Printed Circuit Board connecting input wires with windings	0.55	[15]
Plastic cover located on the core	0.45	[16]
Assumed resin filler	2.5	[17]

In the paper, numerical analysis was conducted basing on the machine geometry presented in 0. Moreover, in this figure, two cross sections of the machine are shown on which all results in the following chapters will be presented. Cross-section I divided the analyzed machine using a plane perpendicular to the shaft. Cross-section II was created on the shaft axis and its plane was normal to the gravity direction.



External motor geometry used in the model (left) and two schematic cross-sections on which the results are presented (right).

In the presented models, the following assumptions were made:

- thermal gap filler has the same magnetic conductivity as air;
- only one thermal resistance occurs in the model between solid materials and it is located between windings and plastic cover of the magnetic core;
- the same values of generated losses were used in both described models.

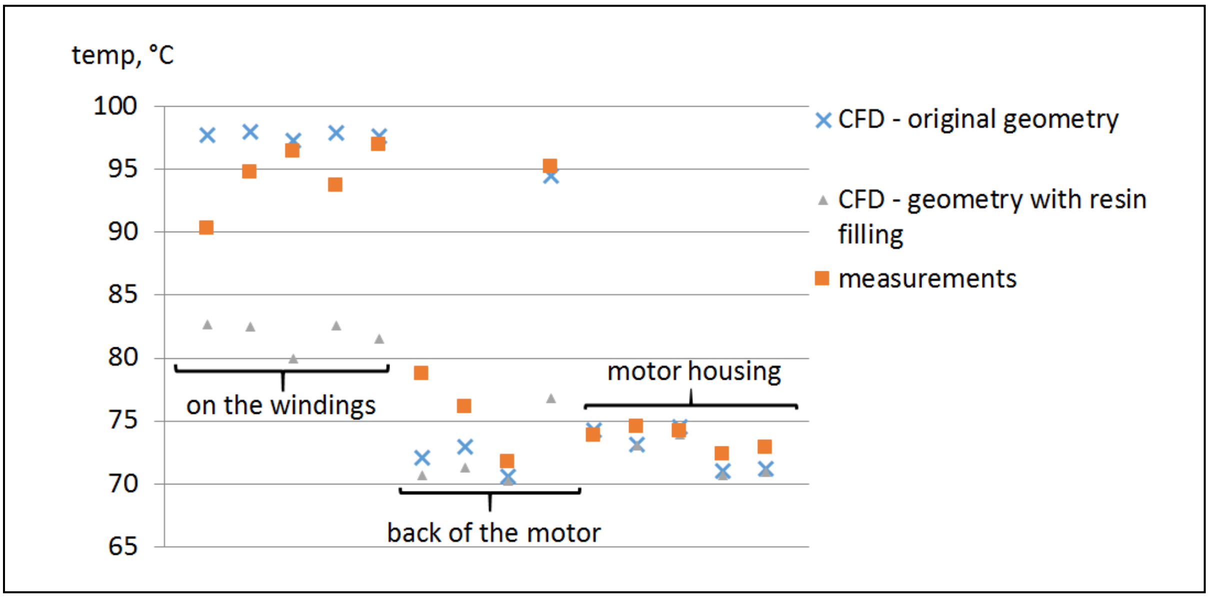
Results

In the following section, results obtained from the described models are presented.

In 0, the temperature in 16 points was compared between measurements and results from two CFD models. Model A, according to the previous description, represents the original geometry of motor which was investigated on the test rig. Model B was built on assumption that almost the whole free space in the front part of the motor was replaced by the resin thermal filler. In 0, presented points were categorized into 3 groups. The first group contains results from the windings surfaces. The temperature of these points in Model A was uniform and reached 97.5 °C. The biggest difference between CFD results and measurements, in this group, was at the first point and reached 7.5 °C. It could be caused by the assumption of homogeneous heat generation in the volumes of specific elements where losses occur. On the other hand, during the measurements, some thermocouples could have been detached from their original position. Hence, values of these points could not represent the surface temperature but of its close distance. The smallest differences occur in third and fourth point in this group and reach about 0.8 K. In the model B, the temperature in the analogical points on the windings decreased by approximately 12.5 K.

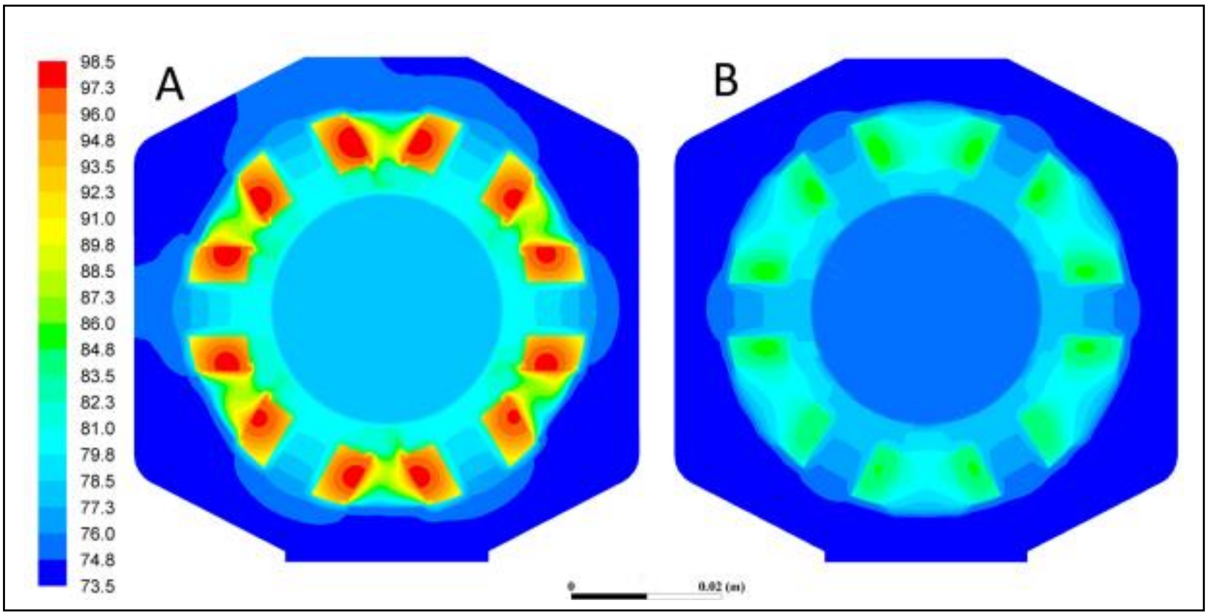
The second group of points, in 0, was located in the back part of the motor. First two thermocouples, measured air temperature. The third measurement in this group was conducted on the PCB plate. On the other side of the PCB plate, the copper paths were located. These paths were used to connect the power supply with windings. Therefore, the temperature at this point was much higher than at the other points from this group and reached 95.2 °C according to the measurements. At this point in Model A, the temperature was on the similar level and reached 94.8 °C. However, in Model B temperature at this point was lower and was equal to 76.8 °C. It was caused by the assumption that resin thermal filler was in a contact with front surface of PCB plate where copper paths were located. The last point in this group was attached to motor housing from the internal side.

In 0, the last group of points represents the measurements collected from the external part of the motor housing. At these points, the CFD results from Model A and B are consistent with each other. The maximum difference between measurements and the computational results was 1.6 K.



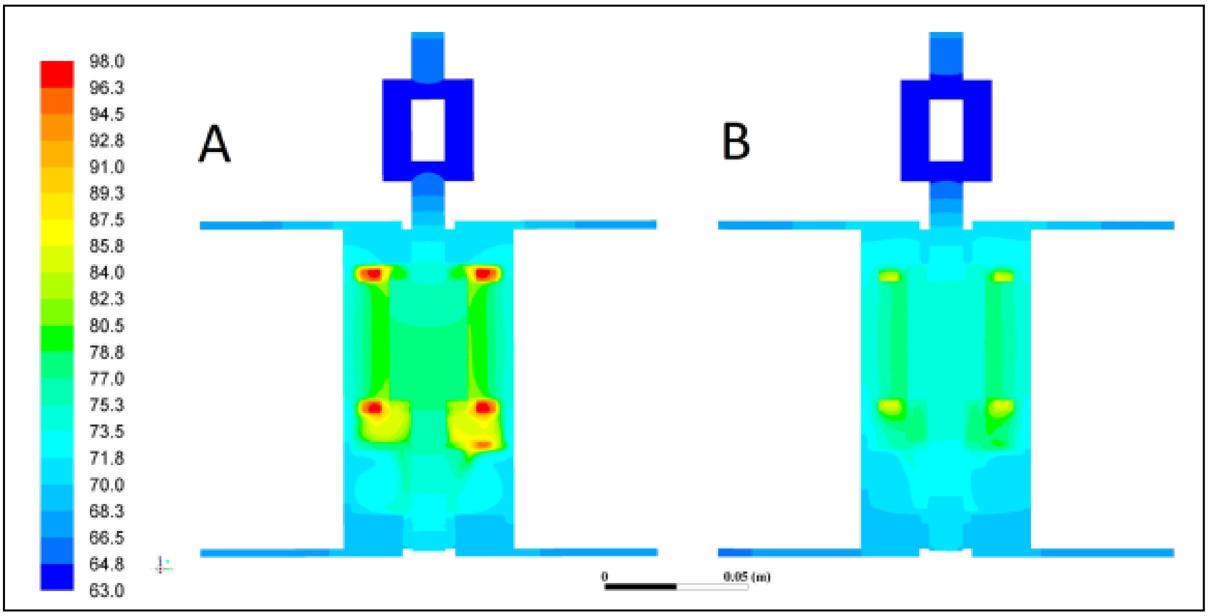
Comparison of the measured and computed temperature in °C at the specified points.

In 0, the temperature field for both models in Cross-section I is shown. The maximum temperature of this field in Model A occurs at the level of 98.5 °C. It occurred in the middle of the surface representing air and windings contact. The lowest temperature, in this cross-section, occurred in the vicinity of the external part of the motor housing and reached 73.5 °C.



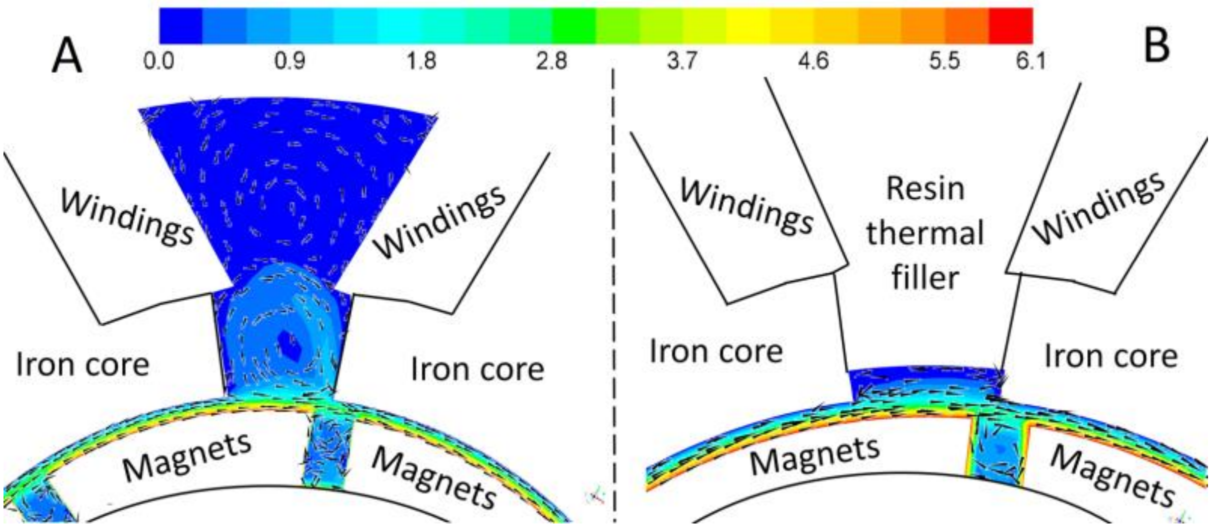
Temperature field in °C in Cross-section I for a model representing (A) real geometry and (B) a geometry with the resin filling.

In 0, the temperature field for both models in Cross-section II is shown. This cross-section cuts windings only in the place where end-windings occur. The maximum temperature of this field in Model A occurs on the level of 98 °C. This temperature level can be noticed in the windings region and in the PCB plate. The hot spot on PCB is caused by heat loss generation that occurred in the copper paths described earlier. Therefore in presented cross-section, asymmetrical temperature field can be noticed. The minimum temperature in this field can be observed in the region of universal bellow coupling and it is approximately 63 °C. It can be explained by the fact that this element rotates surrounded by fresh air. Force convection also takes place while analyzing cooling of the coupling. In the case of Model B, the maximum temperature occurs in the same places but its level is 85 °C. Temperature field in the Model B, where the thermal filler was applied, shows that the temperature gradient between specific elements in the stator space is smaller.



Temperature field in °C in Cross-section II for a model representing (A) real geometry and (B) a geometry with resin filling (B).

In 0, the velocity fields is shown for both models in the fragment of Cross-section I. This figure presents a comparison between two analyzed models in the region of the air gap between stator and rotor. Moreover, this visualization covers air space between different phases of windings in Model A and this zone filled with resin in Model B. According to the obtained results, the same speed can be observed in the close vicinity of rotating walls, where the magnets are marked. In Model A, the backward swirl to the rotation direction can be observed where the air is below windings level. The presented geometry assumed that part of the windings sticks out of the iron core edge. Therefore, the resulting velocity field shows that the next swirl occurred in the air between the winding of the other phases and this swirl is consistent with shaft rotation direction. The same tendency has repeated in the analogous air gaps.



Velocity field in m s^{-1} with marked vectors in Cross-section I for a model representing (A) real geometry and (B) a model representing geometry with resin filling.

Conclusions

The presented paper focuses on the comparative analysis of two thermal models of the electric motor. Model A was represented by the geometry of existing motor and was validated by measurements conducted on test rig dedicated for this purpose. Model B was created to test the conception of filling the free air gaps inside front part of the stator with a resin material. The aim of this attempt was an intensification of heat dissipation from windings and in consequence reduction of maximum temperature in hot spots in the motor. Additionally, the suggested improvement could help to reduce a risk of the windings isolation overheating during the work under the overload condition.

It was possible to reduce the average temperature of the windings by 12.5 K. It was assumed that the thermal resin filling was applied in maximum free capacity filled earlier by air and had ideal contact with solid elements of the stator. Moreover, the same heat losses were analyzed in both models and magnetic conductivity of the potting material was the same as the air.

In the future research, the analysis could be expanded on coupling with the electromagnetic field calculations. Moreover, the comparison of magnetic fields between proposed models could be implemented.

Acknowledgments

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Reference

[1] Gallagher K. G., Goebel S., Greszler T., Mathias M., Oelerich W., Eroglu D. and Srinivasan V. *Quantifying the promise of lithium–air batteries for electric vehicles*. Energy Environ. Sci. 7 2014, pp. 1555-1563.

[2] Chen L. and Shaw L. L. *Recent advances in lithium-sulfur batteries*. J. Power Sources 267 2014, pp. 770–783.

[3] Rezvanizaniani S. M., Liu Z., Chen Y. and Lee J. *Review and recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility*. J. Power Sources 256 2014, pp. 110–124.

[4] Polikarpova M., Lindh P. M., Tapia J. A. and Pyrhönen J. J. *Application of Potting Material for a 100 kW Radial Flux PMSM*. 2014, pp. 1–6.

[5] Polikarpova M., Lindh P., Gerada C., Rilla M., Naumanen V. and Pyrhönen J. *Thermal effects of stator potting in an axial-flux permanent magnet synchronous generator*. Appl. Therm. Eng. 75 2015, pp. 421–429.

[6] Melka B., Smolka J., Bulinski Z., Ryfa A., Hetmanczyk J. and Makiela D. *A validated numerical model of heat and mass transfer in a PM BLDC electric motor*. IEEE 2016 Int. Symp. Power Electron. Electr. Drives, Autom. Motion 2016, pp. 1409–1413.

[7] Melka B., Smolka J., Bulinski Z., Ryfa A., Hetmanczyk J. and Makiela D. *An experimental and numerical analysis of temperature and velocity field in PM BLDC motor*. Przegląd Elektrotechniczny 1(3). 2016, pp. 94–97.

[8] Çengel Y. A. *Heat transfer : a practical approach*. McGraw-Hill, 2003.

[9] Churchill S. W. and Chu H. H. S. *Correlating equations for laminar and turbulent free convection from a horizontal cylinder*. Int. J. Heat Mass Transf. 18(9). 1975, pp. 1049–1053.

[10] Churchill S. W. and Chu H. H. S. *Correlating equations for laminar and turbulent free convection from a vertical plate*. Int. J. Heat Mass Transf. 18(11). 1975, pp. 1323–1329.

[11] Wrobel R. and Mellor P. H. *A general cuboidal element for three-dimensional thermal modelling*. IEEE Trans. Magn. 46(8). 2010, pp. 3197–3200.

[12]http://www.matweb.com/search/DataSheet.aspx?MatGUID=0cd1edf33ac145ee93a0aa6fc666c0e0&ckck=1

[13]http://www.matweb.com/search/DataSheet.aspx?MatGUID=6291a24572754cae94ff365ed99b96f9

[14]http://www.matweb.com/search/DataSheet.aspx?MatGUID=7f8b78c89b054b16accee80f9a363626

[15] Azar K. and Graebner J. E. *Experimental determination of thermal conductivity of printed wiring boards*., in *Twelfth Annual IEEE Semiconductor Thermal Measurement and Management Symposium. Proceedings*, 1994, pp. 169–182.

[16]http://www.matweb.com/search/DataSheet.aspx?MatGUID=fce23f90005d4fbe8e12a1bce53ebdc8

[17] http://resindesigns.com/2016/04/19/thermally-conductive-epoxies

Technical and Economic Benefits of Integrating a Smart Electronic Star-Delta Commutator inside the Terminal Box of "Ex d" Line-Operated Three-Phase Induction Motors

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Abstract

The dominant solution for soft-starting line-operated, three-phase, squirrel-cage induction motors (SCIMs) is still the electromechanical star-delta starter. This solution requires three contactors, a timer, a cabinet, and six cables from the starter to the motor. In this paper, a novel, low-cost, ultra-compact, self-powered, smart, electronic device for soft-starting and performance improvement of SCIMs is described. This device can be installed inside the motor terminal box, which is a unique feature. The major benefits associated with this solution in the scope of areas with risk of explosion are pointed out, including motor telemonitoring, protection, fault diagnosis, soft-starting and input power reduction at light loads by means of an automatic load-based star-delta/delta-star commutation strategy that optimizes operating condition. This capability is an important benefit in variable-load, fixed-speed applications, such as conveyors, mixers, presses, pumps, etc., and may lead to 5-15% energy savings and to a significant increase in the power factor. Experimental results for two 7.5-kW SCIMs are presented, demonstrating the efficiency and power factor improvement potential at light loads. Another innovative characteristic of this device is the fact that it can be installed inside the "Ex d" motor terminal box, therefore, halving the number of conductors from the switchboard to the motor and eliminating the need for a dedicated space in the cabinet for the motor starter or, in some cases, eliminating the need for the "Ex" cabinet. The cost of an "Ex" cabinet/enclosure exceeds significantly that of the proposed device, leading to a virtually zero payback time.

Introduction

World industrial electric motor market is moving toward IE4 and IE5 efficiency classes. New three-phase motor technologies are being developed and introduced in the market, such as line-start synchronous motors. Nevertheless, the three-phase squirrel-cage induction motor (SCIM) still dominates the line-operated motor market for fixed-speed applications, being available from IE1 to IE4 classes [1-7].

The dominant solution for soft-starting line-operated SCIMs is still the electromechanical star-delta starter, which requires three contactors, a timer, a cabinet/switchboard, and six cables from the starter to the motor. The use of electronic soft-starters is also increasing, but they are more expensive than the electromechanical star-delta soft-starters. Both solutions are only to be used during the starting period and do not offer any energy saving possibility during the steady-state operation of the motor. Actually, the electronic soft-starter is by-passed after the starting period to avoid the respective losses and the associated harmonic distortion. Modern electronic soft-starters also offer advanced motor protection and have several communication interfaces.

In this paper, a novel electronic device, named InSwitch[64], for starting and performance improvement of SCIMs is presented, and its technical and economic advantages and application in environments with risk of explosion are discussed.

InSwitch

InSwitch is a low-cost, ultra-compact, self-powered, smart, electronic device (Fig. 1) for soft-starting and performance improvement of line-operated SCIMs. This device can be installed inside the motor terminal box, as it can be seen in Fig. 2, which is a unique feature.

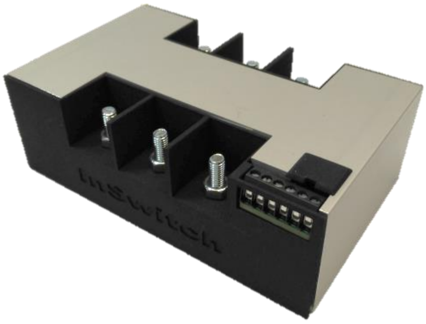

Fig. 1. 24-kVA model of InSwitch.

Fig. 2. InSwitch installed inside the terminal box of a 7.5-kW, 4-pole SCIM.

A detailed description of the device can be found in [8]. The basic topology of InSwitch is presented in Fig. 3. To perform the star/delta connection mode change, 5 or 6 bidirectional switches (S1-S6) are needed, depending if 2 or 3 switches are used for the star connection mode. To operate the motor in star mode, the switches S1, S2, and S3 are in ON state, and the switches S4, S5, and S6 are in OFF state. To operate the motor in delta mode, the switches S1, S2, and S3 are in OFF state, and the switches S4, S5, and S6 are in ON state. The use of 3 bidirectional switches (instead of 2) in the star connection mode reduces the voltage stress over/across them, increasing the reliability of the device, which is an advantage, but produces more conduction losses and increase the cost of the device. If the rotating direction is to be reversed, 4 additional switches are needed. In order to suppress transients and protect the power switches, filters, snubbers and varistors are used.

In the InSwitch, similarly to the commercial low-voltage solid-state contactors/relays, TRIACs are used as bidirectional switches. Alternatively, twin antiparallel thyristors or combined bidirectional IGBT-diode sets can also be used. The motor magnetizing flux adjustment is made on the basis of the winding connection-mode change and not on the phase-angle firing control (used in the electronic soft-starters). Hence, in practice, it can be considered a sinusoidal technology (negligible current and/or voltage harmonic

[64] "InSwitch" is a trademark. This device has been developed and is being commercialized by OptiSigma – Energia & Ambiente, Lda. (www.optisigma.pt).

distortion at the input and output) and used in motor steady-state operation, not requiring an electromechanical by-pass relay/contactor.

Presently, the InSwitch is available for three rated powers, namely, 12 kVA, 24 kVA and 48 kVA (Fig. 4), and customized solutions can be produced for higher power levels. The respective indicative/list prices are 300 €, 600 € and 900 €. The all-in-one multi-feature concept (Fig. 5), offers motor telemonitoring/telemetering, protection, fault diagnosis, soft-starting, and input power reduction and power factor improvement at light loads by means of an automatic load-based delta-star commutation strategy that optimizes the motor operating condition, as it can be seen in Fig. 6 [9-11].

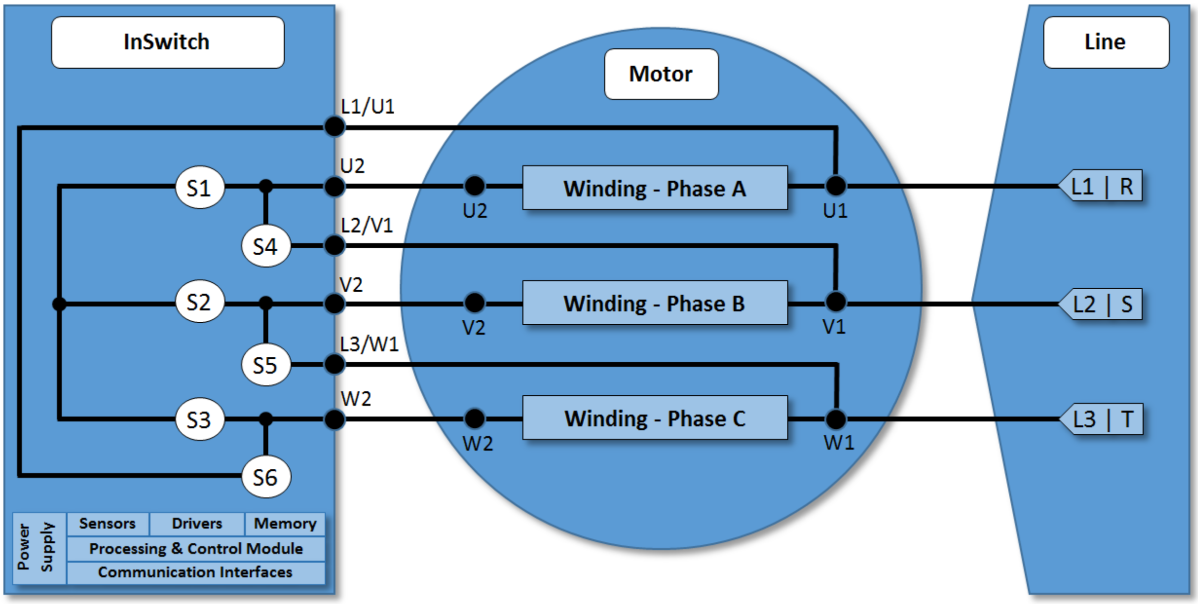

Fig. 3. Basic topology of InSwitch (S1-S6 represent bidirectional power switches).

With InSwitch, the energy savings are only possible in variable-load, fixed-speed SCIMs. For low load levels (lower than 40-50%), the device changes the connection mode to star, reducing the motor phase voltage 1.73 times and, consequently, improving the respective efficiency and power factor (Fig. 6). The efficiency improvement is mainly due to the core losses and saturation level reduction [9-11]. The power factor improvement leads to a reduction of the line current and, consequently, of the Joule losses in the upstream power cables and transformers, ultimately contributing to an additional reduction of the active energy consumption. Therefore, the longer the light-load operating periods are, the higher the energy savings will be.

Furthermore, having wireless (Bluetooth; optional external Wi-Fi and ZigBee modules) and by-wire (RS-485/Modbus) communication capability, the described device also fits into the Industry 4.0 concept, which is the current trend of automation and data exchange in manufacturing technologies, including cyber-physical systems, the Internet of things and cloud computing. In Figs. 7 and 8, the InSwitch as a technology for Industry 4.0 concept and its possible integration in industrial communication/data networks is illustrated. The major advantages associated with InSwitch are summarized in Fig. 9.

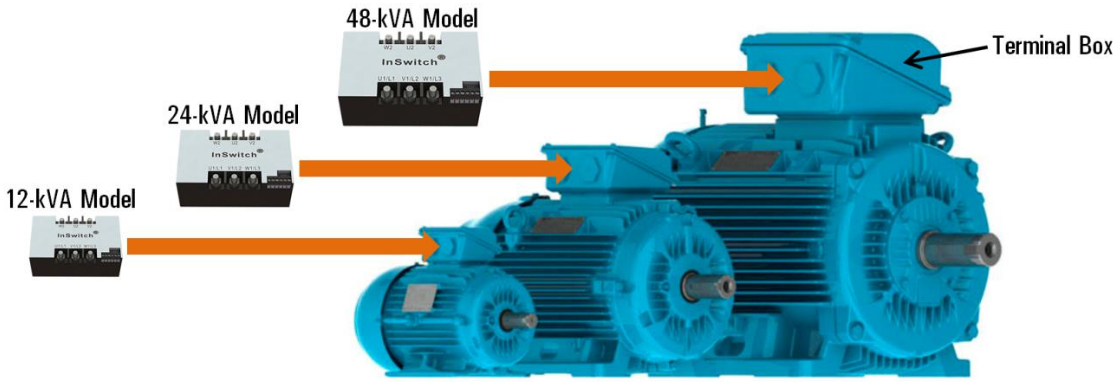

Fig. 4. Commercial models of InSwitch.

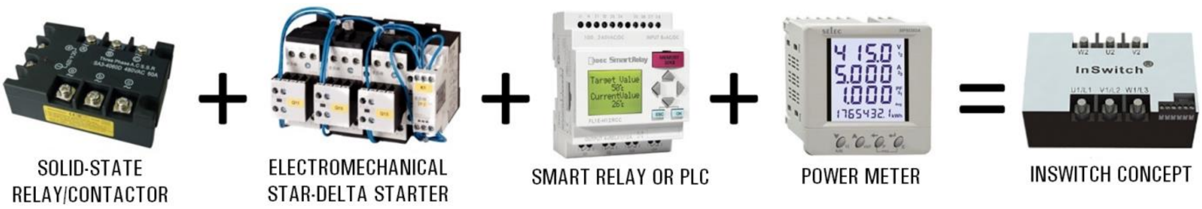

Fig. 5. InSwitch concept.

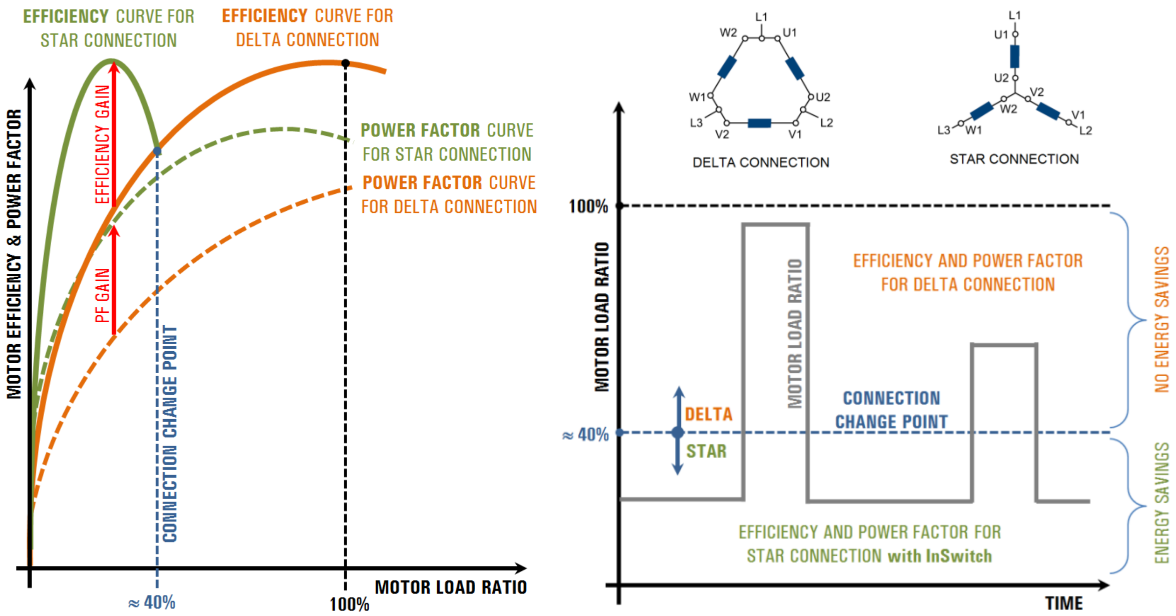

Fig. 6. Principle of efficiency and power factor improvement by means of automatic load-based star-delta commutation strategy.

Fig. 7. InSwitch as a device to integrate SCIMs in the Industry 4.0 concept.

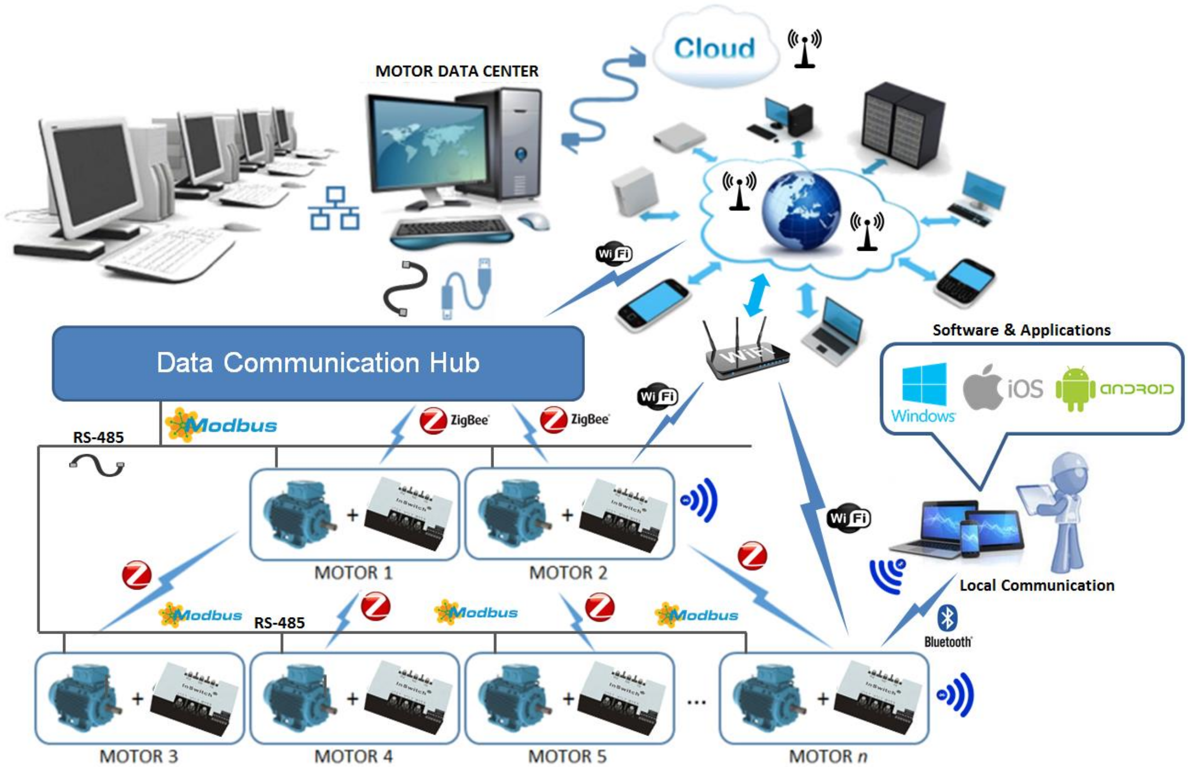

Fig. 8. InSwitch integration in new r existing industrial communication/data networks.

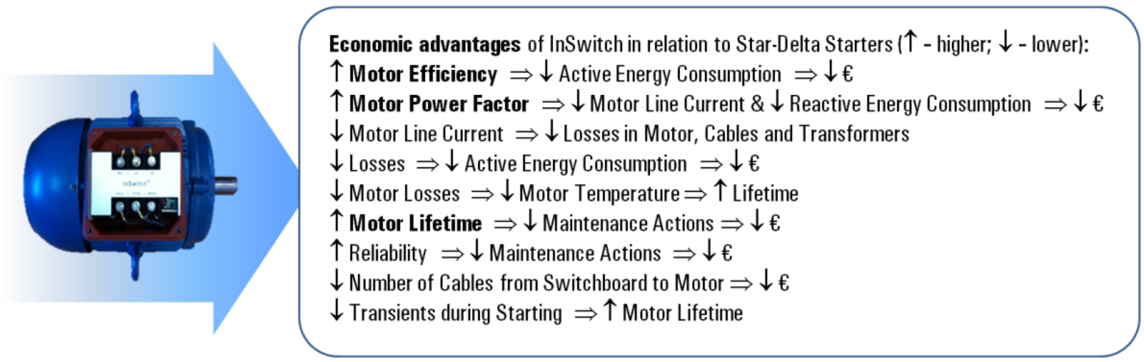

Fig. 9. Summary of the main economic advantages associated with InSwitch.

Experimental Results

The 24-kVA InSwitch model has been experimentally tested with two 7.5-kW, 4-pole SCIMs. In Fig. 10, the experimental efficiency of InSwitch is shown. In delta mode, the efficiency exceeds 99.5%. In Figs. 11 and 12, the efficiency and power factor gains that can be obtained with InSwitch at light loads for the tested motors are shown. The motor active and reactive power reduction is presented in Fig. 13. For the studied cases, the motor active power reduction is maximized at circa 20% load, and it is higher for the IE2-class SCIM.

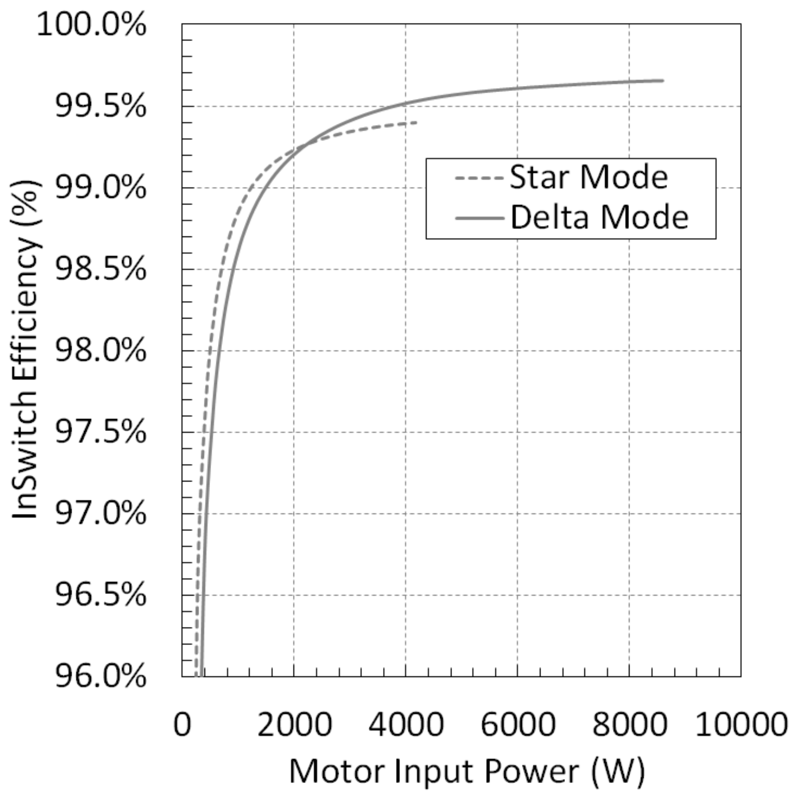

Fig. 10. InSwitch efficiency [12].

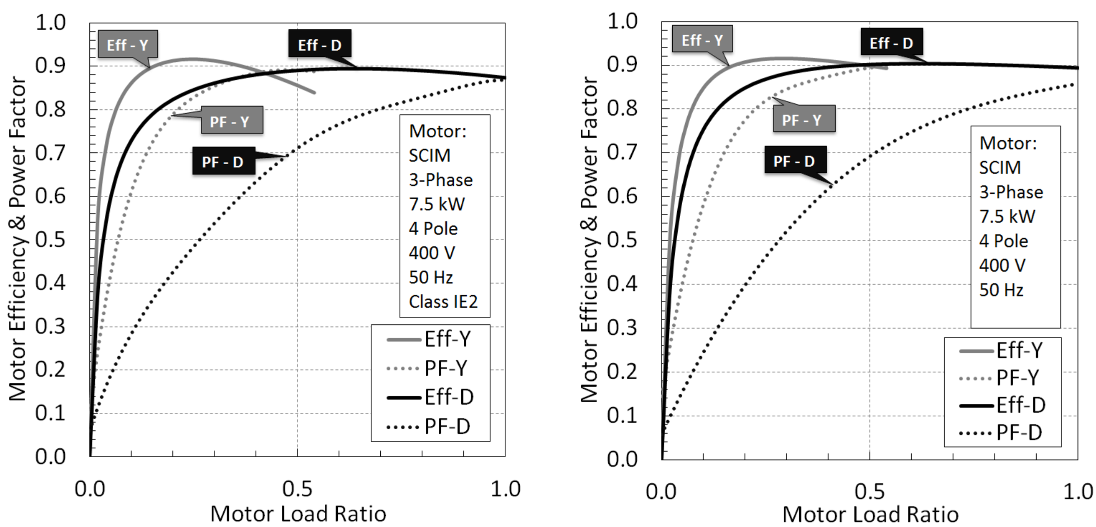

Fig. 11. Motor efficiency and power factor of 7.5-kW, 4-pole SCIMs: (left) Class IE2; (right) Class IE3 [12].

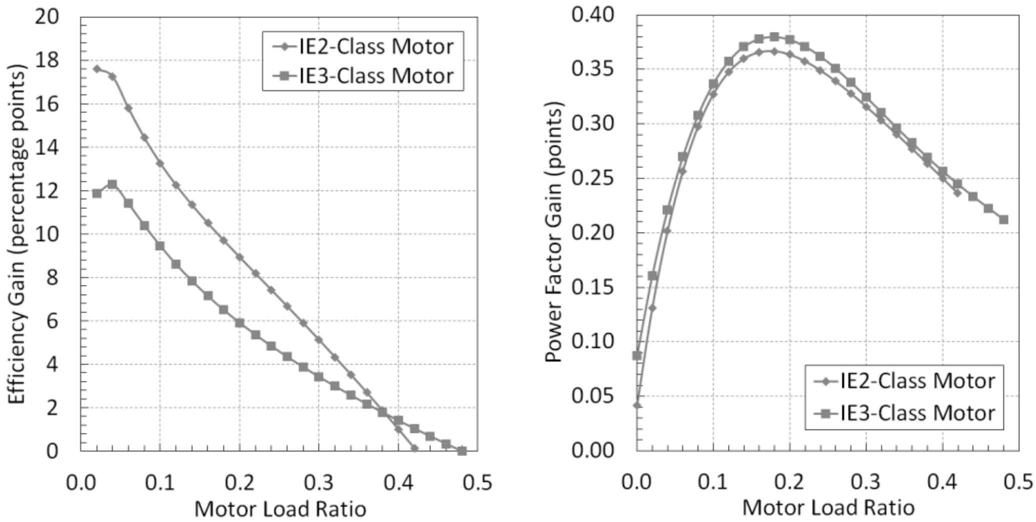

Fig. 12. Motor efficiency and power factor gains of 7.5-kW, 4-pole SCIMs: (left) Efficiency; (right) Power Factor.

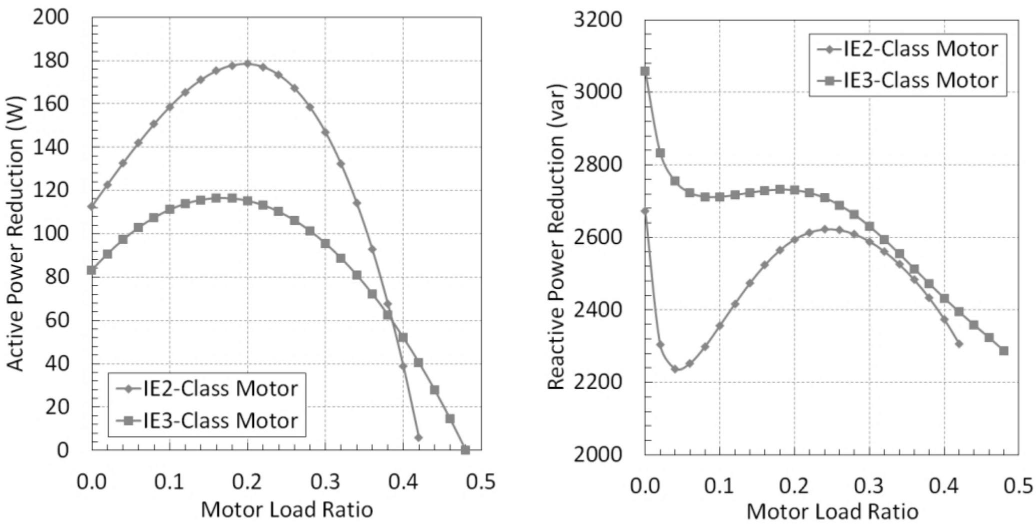

Fig. 13. Motor input active power and reactive power reduction of 7.5-kW, 4-pole SCIMs: (left) Active power; (right) Reactive power.

Application of InSwitch in Facilities with Potentially Explosive Atmospheres

An interesting application of InSwitch is in SCIMs operating in facilities with potentially explosive atmospheres, since it may lead to a reduction in the overall installation cost, including power cables, enclosures/cabinets, and protection and control devices.

The risk of explosion of gases and dust exists in many situations and industries, from sugar refineries and grain mills to offshore oil platforms. The use of incorrect components and installations inside hazardous areas will cause a potential harm in both personal and machinery, thus reducing the quantity of equipment inside such area is reducing the latent risk associated with the installation.

The ATEX (*ATmosphères EXplosibles*, in French) term/mark (Fig. 14) is commonly used to describe potentially explosive atmospheres and standard for protection systems and equipment. Two European directives, ATEX 137 - 99/92/CE (*Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres*) and ATEX 95 - 94/9/CE (*Equipment and protective systems intended for use in potentially explosive atmospheres*), and international standards IEC60079 and

IEC61241, harmonized with EN European standards, apply to this field, providing the essential "safety Ex" requirements for the classified hazardous areas.

According to ATEX, a potentially explosive atmosphere is defined as a mix of flammable substances in the form of gas, vapour or dust (cloud deposit) which, in the presence of an oxidizer (for example air), under normal atmospheric conditions, can completely or partially catch fire in the form of an explosion when exposed to a source of ignition.

Since July 1st, 2003, the European directive ATEX 94/9/CE makes compulsory the use of certified component, equipment or assembly when intended for use in potentially explosive zones/areas, gaseous or dusty atmospheres, ultimately intended to protect employees from explosion risk in those areas.

Fig. 14. Mark for ATEX certified electrical equipment for explosive atmospheres (Ex d – Explosion proof multivoltage motors; Ex de – Explosion proof multivoltage motors with increased safety terminal box).

Regarding ATEX 99/92/EC directive, the requirement is that Employers must classify areas where hazardous explosive atmospheres may occur into zones. The classification given to a particular zone, and its size and location, depends on the likelihood of an explosive atmosphere occurring and its persistence if it does. Areas classified into zones (0, 1, 2 for gas-vapor-mist and 20, 21, 22 for dust) must be protected from effective sources of ignition. Equipment and protective systems intended to be used in zoned areas must meet the requirements of the directive. Zone 0 and 20 require Category 1 marked equipment, zone 1 and 21 require Category 2 marked equipment and zone 2 and 22 require Category 3 marked equipment. Zone 0 and 20 are the zones with the highest risk of an explosive atmosphere being present. The aim of directive 94/9/EC is to allow the free trade of 'ATEX' equipment and protective systems within the EU by removing the need for separate testing and documentation for each member state. The regulations apply to all equipment intended for use in explosive atmospheres, whether electrical or mechanical, including protective systems. There are two categories of equipment 'I' for mining and 'II' for surface industries. Manufacturers who apply its provisions and affix the CE marking and the Ex marking are able to sell their equipment anywhere within the European Union without any further requirements with respect to the risks covered being applied. The directive covers a large range of equipment, potentially including equipment used on fixed offshore platforms, in petrochemical plants, mines, flourmills and other areas where a potentially explosive atmosphere may be present.

In very broad terms, there are three preconditions for the directive to apply: the equipment (i) must have its own effective source of ignition; (ii) be intended for use in a potentially explosive atmosphere (air mixtures); and (iii) be under normal atmospheric conditions.

Once certified, the equipment is marked by the 'CE' (meaning it complies with ATEX and all other relevant directives) and 'Ex' symbol to identify it as approved under the ATEX directive. The technical dossier must be kept for a period of 10 years. Certification ensures that the equipment or protective system is fit for its intended purpose and that adequate information is supplied with it to ensure that it can be used safely.

There are four ATEX classification factors to ensure that a specific piece of equipment or protective system is appropriate and can be safely used in a particular application: (1) Type of unit: mines (group I), surface industry (group II); (2) Zone classification: 0, 1, 2 (which are suitable components of category 1, 2, 3); (3) Characteristics of flammable materials present, such as gas, steam or fogs; (4) Application Group: IIA, IIB, IIC; (5) Temperature classes: T1, T2, T3, T4, T5, T6 (according to the highest allowable surface temperature of the machinery and according to the ignition temperature of the combustible materials).

The ATEX, as an EU directive, has its equivalent in the USA and Canada under the UL and CSA standards, respectively. This standard given by the Occupational Safety and Health Administration defines and classifies hazardous locations such as explosive atmospheres.

Different types of protection are defined in EN 60079 standard. They consist of different approaches to eliminate the risk of equipment explosion. These approaches include the removal of one of the corners of the fire triangle (combustible, oxidizer, and ignition) or the protection of the electrical parts by enclosure. The first approach includes protections like "Ex e" or "Ex i", where the electrical equipment is designed/dimensioned in order to eliminate any ignition source. The second approach includes protections like "Ex d", where electrical parts with no specific protection are placed inside a mechanical reinforced enclosure that guarantee that the occurrence of an explosion inside of it is contained and not transmitted to outside atmosphere, as illustrated in Fig. 15.

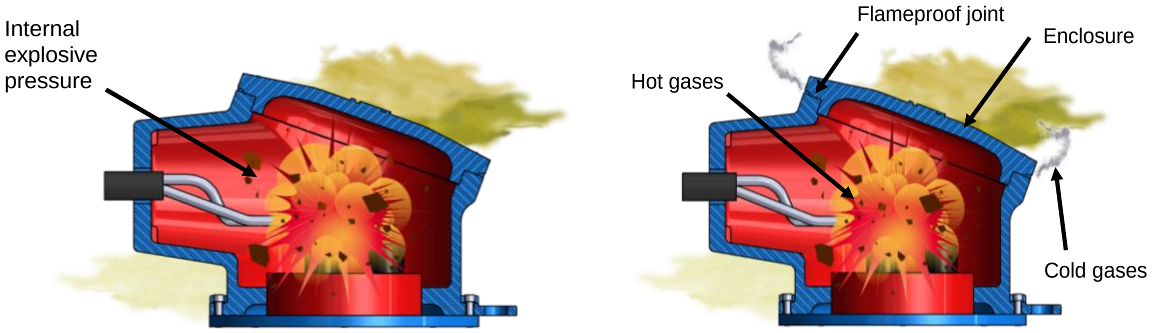

Fig. 15. The two dimensioning criteria for flameproof enclosures "Ex d": (left) enclosure integrity; (right) non-transmission of the flame.

The "Ex" motor compliance is related to zone classification and to flammable material characteristics at the installation site. Besides all classification factors, the nameplate of "Ex" motors must include: (i) the information for a correct choice of the proper motor and for its correct installation; (ii) the reference to the official authority involved on the certification. Technical requirements of the electric motor installation, in the classified areas, are reported by EN 60079-14 standard. The standards for type of protection are: (i) EN 60079-0 and EN 60079-1 for "Ex d"; (ii) EN 60079-0, EN 60079-1 and EN 60079-7 for "Ex de". Hazardous area motors are specially designed to comply with official regulations concerning the risk of explosion. If incorrectly used, poorly connected or if other minimal facts occur, their reliability could be damaged. Standards related to connection and use of electric apparatus in hazardous areas must be taken into consideration. The installation of electric motors where flammable products are continuously handled, processed or storage, must comply with the most demanded safety standards in order to guarantee protection of life, machines and environment. In Fig. 16, a commercial explosion-proof SCIM is shown.

There is also an ATEX-certified range of wall-mounting enclosures/cabinets, including steel, stainless steel and polyester, ensuring safety for every application. Enclosures are certified as components. They will be assembled with other ATEX electrical, pneumatic and hydraulic components, among others to form a final solution, which, in turn, must be ATEX-certified and subjected to a declaration of conformity. In general, wall-mounting enclosures comply with standards for protection against the increased risk of explosion in atmospheres charged with gas and/or dust. ATEX-certified enclosures are in most cases much more expensive than the normal enclosures (up to 5 times more). In Fig. 17, an example of commercial normal and ATEX-certified enclosures is presented.

In Fig. 18, three different possible scenarios for the installation of a line-operated SCIM with a start-delta starter in an ATEX zone.

In the first case (Fig. 18, top), the motor switchgear cabinet is installed in the ATEX space. Therefore, the motor, the 9 cables and the cabined have to be "Ex" marked, being potentially the most expensive solution.

In the second case (Fig. 18, middle), the cabined is outside of the ATEX space, leading to a reduction in the installation cost, but 6 "Ex" cables are still needed from the cabinet to the motor.

Fig. 16. Example of an explosion proof (Ex d / Ex de) IE2-class SCIM.

Fig. 17. Enclosures for electric or electronic systems: (left) steel, 400x300x150 mm, regular environments, list price of 321 €; (right) stainless steel, 380x260x160 mm, ATEX certification[65], list price of 1485 €.

In the third case (Fig. 18, bottom), the InSwitch is embedded in the motor and, therefore, there is no need for a start-delta starter cabinet, and, additionally, only 3 cables are needed from the main electric cabinet to the motor. Since the InSwitch is potentially cheaper than the star-delta starter set plus basic protections (phase loss, voltage/current unbalance, over/undervoltage, overload), the "Ex" cabinet is avoided and

[65] It should be noted that the presented ATEX-certified enclosure is not "Ex d" (explosion protection). Such "Ex d" enclosures allow the use of electronic/electrical/electromechanical parts/devices/components not designed for dangerous environments in gas or dust explosion hazardous areas as well as in harsh or corrosive atmospheres. The list price of "Ex d" enclosures is significantly higher than that of the general ATEX-certified enclosures (as the one presented in Fig. 17).

the number of "Ex" cables is halved, the cost of the system may be reduced to less than half in relation to the first scenario. It should be noted that, since the "Ex" motor terminal box is properly certified and the InSwitch is installed inside it, there is no need for "Ex" certification of InSwitch, which is an advantage.

Even if the cabinet is maintained in the ATEX space, when using InSwitch, its size can be significantly reduced (and thus its cost) because there is no need to use external motor protection devices, soft-starters or contactors. The short-circuit protection (magnetic circuit breaker), which is mandatory in most of the electrical installation regulations (and cannot be replaced by InSwitch), is the only device that has to be installed inside the motor control cabinet.

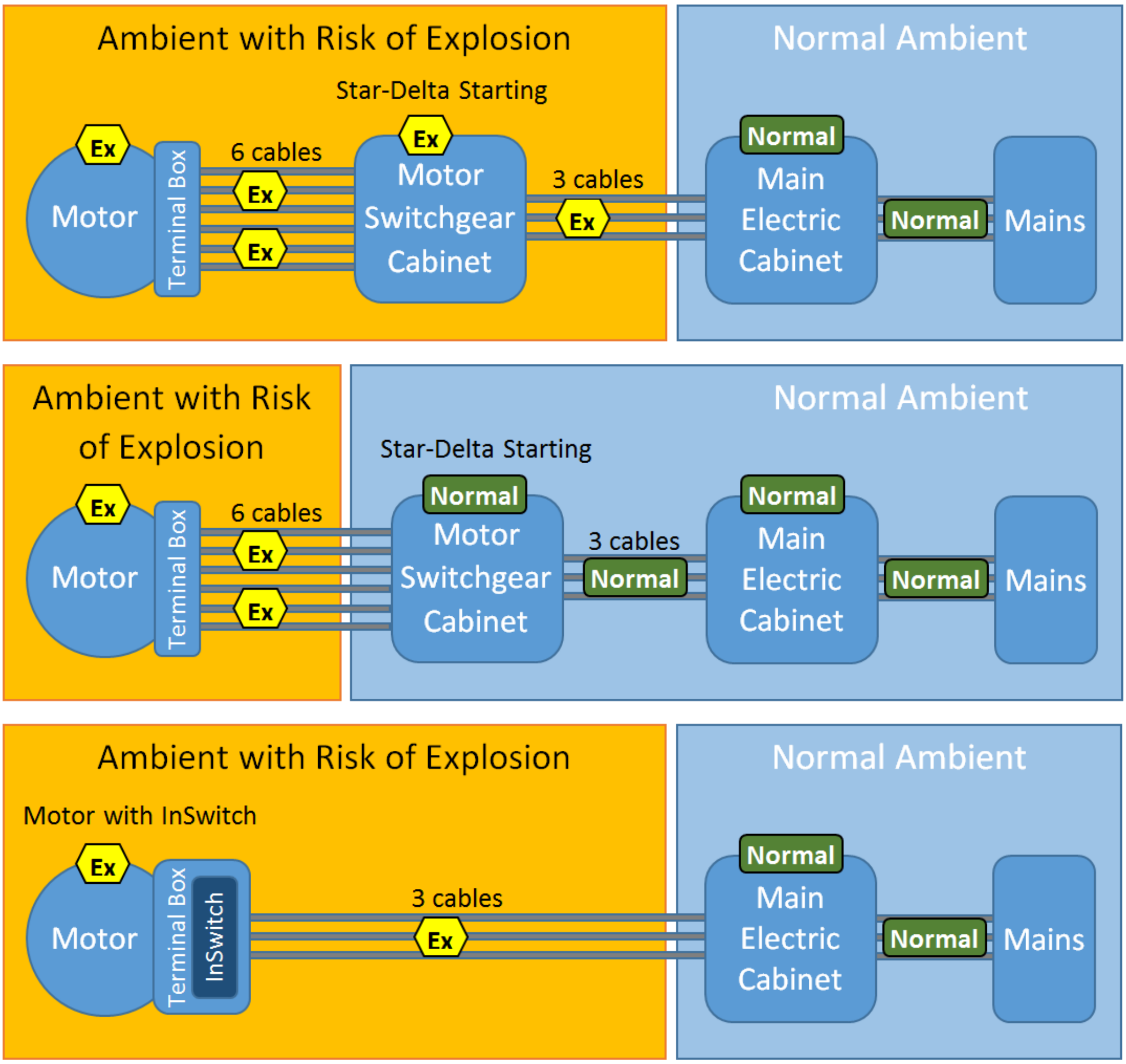

Fig. 18. Three different possible installations for explosion proof SCIMs: (top) motor switchgear cabinet inside the ATEX area; (middle) motor switchgear cabinet outside the ATEX area; (bottom) InSwitch integration into the motor, eliminating the motor switchgear cabinet.

On the top of it, InSwitch may lead to significant energy savings and power factor improvement if the driven application has a load torque as low as 20-30% the motor rated torque during a significant part of the operating cycle (as it can be seen in Fig. 6 and Figs. 11-13).

The InSwitch-based solution is therefore cheaper and potentially more efficient, leading to a virtually zero payback time. Moreover, it also offers the possibility of being integrated on a RS-485 and/or Wi-Fi/ZigBee data network or SCADA system, which is an important feature in the scope of the Industry 4.0 concept.

Conclusions

In this paper, a novel, low-cost, ultra-compact, self-powered, smart, electronic device for soft-starting and performance improvement of line-operated SCIMs has been presented. It was experimentally demonstrated that this device can reduce the motor input power at light loads by means of an automatic load-based connection-mode change strategy that improves the motor operating condition. When used in motors driving variable-load, fixed-speed applications, such as conveyors, mixers, presses, pumps, etc., this device may lead to 5-15% energy savings and to a dramatic increase in the power factor.

This device also offer other important features, such as motor telemonitoring, protection and fault diagnosis, and can be easily integrated in new or existing data network or SCADA systems, fitting into the "Industry 4.0" concept, which is the current trend of automation and data exchange in manufacturing technologies, including cyber-physical systems, the Internet of things and cloud computing

Since the presented device may be installed inside the motor terminal box, the number of conductors from the switchboard to the motor is halved and the need for a dedicated space in the cabinet for the motor starter is eliminated.

In the scope of facilities with risk of explosion, that unique characteristic opens the possibility of, in some cases, eliminating the need of the "Ex" motor cabinet/enclosure, since the device is installed inside the "Ex d" motor terminal box. At the same time, the installation results significantly simplified, reducing significantly the number of "Ex" power cables. The cost of an "Ex" cabinet exceeds significantly that of the proposed power electronic device (e.g. 1485 € for the "Ex" cabinet versus 600 € for the InSwitch device), leading to a virtually zero payback time. Besides that, the user will also benefit from the several useful features offered by the device.

It can be concluded that the proposed multi-feature device offers clear technical and economic advantages over the conventional star-delta starters and electronic soft-starters. These advantages become ever more relevant for industrial facilities with potentially explosive atmospheres, in which the user can reduce significantly the cost of the motor installation.

References

[1] A. T. de Almeida, F. J. Ferreira, A. Duarte, "Technical and economic considerations on super high-efficiency three-phase motors", IEEE Transactions on Industry Applications, Vol. 50, No. 2, March/April 2014, pp. 1274-1285.

[2] A. T. de Almeida, F. J. Ferreira, G. Baoming, "Beyond induction motors technology trends to move up efficiency", IEEE Transactions on Industry Applications, Vol. 50, no. 3, pp. 2103-2114, 2014.

[3] A. T. de Almeida, et al., "Ecodesign Assessment of Energy-Using Products - EuP Lot 11 Motors", Final Report for the EC, Inst. of Syst. and Robotics, Univ. of Coimbra, April 2008.

[4] Alex Chausovsky, "Motor Market Update", Presentation Slides, Motor Summit 2014, Oct. 2014, Zurich.

[5] Conrad Brunner, "Efficient Electric Motor Systems", Presentation Slides, Motor Summit 2014, Oct. 2014, Zurich.

[6] Rita Werle, "Swiss audit program Easy", Presentation Slides, Motor Summit 2014, Oct. 2014, Zurich.

[7] Fernando J. T. E. Ferreira, Aníbal T. de Almeida, "Overview on Energy Saving Opportunities in Electric Motor Driven Systems – Part 1: System Efficiency Improvement", IEEE Industrial & Commercial Power Systems Technical Conf. (ICPS'16), Conf. Rec., May 2016.

[8] Fernando J. T. E. Ferreira; José G. Simões; José M. Oliveira: "Novel Electronic Device to Improve the Performance of Variable-Torque Fixed-Speed Induction Motors", 9th International Conference on Compatibility and Power Electronics, June 2015, Caparica, Lisbon.

[9] Ferreira, F.; de Almeida, A.: "Method for In-Field Evaluation of the Stator Winding Connection of Three-Phase Induction Motors to Maximize Efficiency and Power Factor", IEEE Trans. on Energy Conv., Vol. 21, No. 2, pp. 370-379, June 2006.

[10] Ferreira, F.; de Almeida, A.: "Novel Multi-Flux Level, Three-Phase, Squirrel-Cage Induction Motor for Efficiency and Power Factor Maximization", IEEE Trans. on Energy Conversion, Vol. 23, No. 1, pp. 101-109, March 2008.

[11] Fernando J. T. E. Ferreira, Aníbal T. de Almeida: "Energy Savings Potential Associated with Stator Winding Connection Mode Change in Induction Motors", ICEM 2016, Conf. Rec., Sept. 2016.

[12] InSwitch datasheet (available at www.optisigma.pt).

High efficiency Spoke-type PM Brushless motor for helicopter tail rotor

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Abstract

Electric propulsion in aircraft application seems to promise a better system optimization in terms of weight and size with respect to traditional propulsion systems. In this context, one challenge is the development of an electrical tail rotor drive system for helicopter. "Fenestron®" or "fan-in-tail" is essentially an enclosed version of a classical tail rotor.

The paper proposes to replace the current architecture and mechanical shaft with a high performance and high efficiency electric motor coupled directly to the blades compliant to the safety requirements.

For this application, the PM motor represents the more attractive solutions and an air-cooled BLAC 6-phase PM motor with independent phases is proposed.

The paper presents the motor design highlighting the key tradeoffs in terms of power density, efficiency and weight: then, the motor performance have been investigated by accurate 2D and 3D finite element models.

Introduction

In the last decades lot of efforts were prefunded in the vehicle electrification, such trend involved initially the aside systems but nowadays is involving propulsion and drivetrain. Cutting-edge applications for electric propulsion in aircrafts and helicopters are promising a better system optimization in terms of weight, efficiency and size. In this context, one challenge is the development of the electrical tail rotor drive system for a helicopter. The paper proposes replacement of current architecture and mechanical shaft with a high performance and high efficient electric motor coupled directly to the blades and compliant to the safety requirements.

For this application the permanent magnet (PM) motors represent the more attractive solutions [1, 2] and exhibit well known features such as high efficiency, good operating performance, high power density and high reliability. The higher torque density, simplification, and maintenance are some of the most advantages leading PM machines to be considered as an appealing option for aerospace applications.

Moreover, to satisfy the severe fault tolerant requirements, a multi-phase solution is chosen in which each phase may be regarded as a single module: this choice gives rise to many advantages respect to the traditional three-phase motor drives.

As results of the proposed architecture the rotating blades will be directly driven by a fault tolerant electric motor and its converter, while the main rotor continues to have the standard configuration waiting for increasing in confidence with reliability of converter system in safety critical application. With this prospective the prototype of the proposed high efficiency Spoke-type PM Brushless motor and its convert will be an enabling experiment for the complete electrification of the helicopter.

Motor requirements

The helicopter used for the requirements is an EC-160 with "Fenestron®" (Fig. 1).

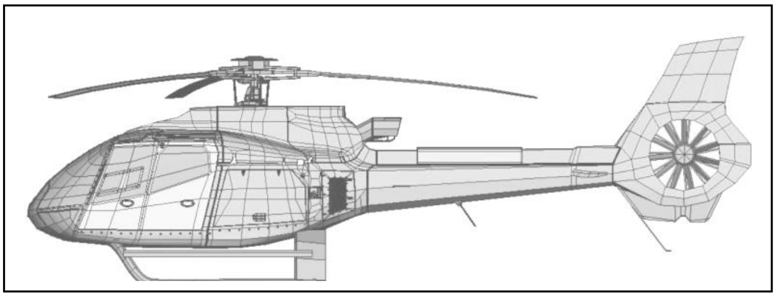

Fig.1 Helicopter with tail rotor Fenestron® type

In order to replace the mechanical solution, the motor should be compatible with the available volume inside the Fenestron where at the moment the 90° gear is accommodate. Moreover, the motor shall be able to work in two main working points that we can call "low power" (5 kW) and "high power" (120 kW). The two working points are the equivalent power of standard and worst flight conditions, the large difference in tail rotor power comes from hover operation vs. forward flight (where the tail fin compensates the main rotor torque).

Required performance and dimensions are listed in Table I: the efficiency should be higher than 95%. Moreover, it is important that the machine is able to operate in respect to the safety conditions.

One of the main goal of the design should be the weight requirement due to the aim to replace the complete mechanical drive train with a lighter solution. Fulfilling this requirement involved mechanical competences in order to evaluate the appropriate mechanical configuration and an optimization process to reduce the weights and guarantee safety and feasibility as well.

Table 1 – Motor Requirements

		Low power 5 kW	High power 120 kW
Torque	Nm	23	320
Speed	rpm	2100	3600
DC Voltage	V	540	
Motor weight	kg	< 25	
Outer diameter	mm	380	
Axial length	mm	< 100	
Efficiency	%	> 95	
Cooling		air cooled	

The motor should satisfy all these conflicting requirements:

- high power;
- high efficiency;

- faulty-mode operations;
- low weight;
- low temperatures;
- air-cooled.

All these constraints on the encumbrance and performance require an accurate motor design by specific sizing procedures

Motor design

The PM motors represent the more attractive solutions and exhibits well known features such as high efficiency, good operating performance, high power density and high reliability. The higher torque density and simplification and maintenance are some of the most advantages leading PM machines to be considered as an appealing option for aerospace applications.

Moreover, to satisfy the severe fault tolerant requirements, a multi-phase solution is chosen [3] in which each phase may be regarded as a single module: this choice gives rise to many advantages respect to the traditional three-phase motor drives. The winding configuration adopted for the PM motors is the non-overlapping single layer as concentrates the most benefits of the investigated winding topologies [4] and the "alternate" teeth wound winding is considered a more favorable choice. With the proposed arrangement, coils belonging to different phases are never in touch and the mutual inductances are effectively minimized: this avoids a possible failure to affect the healthy phase. Moreover, the concentrated winding is very easy to manufacture using automatic winding machinery that can wind one, or more phases at a time to minimize the cost.

An air-cooled BLAC 6-phase PM motor with independent phases is proposed. Moreover, in order to obtain high torque while maintaining small overall dimensions of the motor and simplify the motor assembly inside the helicopter, a solution with interior PMs has been chosen and particularly the spoke-type typology with inner-rotor.

Starting from the specification and the encumbrance, the PM motor has been designed by using a sizing procedure [5, 6] and a spreadsheet software. Then, the preliminary design has been refined by an optimization algorithm [7, 8] that has been linked with a Finite Element software (FE). The optimization procedure uses the information obtained by the FE program to iteratively update the set of motor parameters and try to identify an "optimal" motor by making a trade-off between the different parameters of the machine. The motor has been designed with reference to the high power operation that represents the extreme loading condition.

Fig. 2 shows a 3D view of the final design and the winding distribution, while in Table 2 are listed the main dimension. A priority of the design step was to reduce the motor weight without affecting the performance. This aim has been reached by removing the unused material that affects the overall weight. For this the rotor structure has been accurately lightened by using the support in aluminum (Fig. 2) achieving also additional channel for cooling air along the axial length. The PMs are placed directly on the structure in aluminum and this allows to avoid leakage fluxes.

About the electrical steels and the permanent magnet, high performance materials have been chosen and particularly:

- Electrical steel VacoFlux_50 (0.10 mm thickness) for both the stator and rotor core;
- PM Sm-Co Recoma 33E (Br = 1.16 T, Hc = 865 kA/m @ 20°C).

The choice of the VacoFlux 50 for the iron core is mainly driven by the hard requirements in terms of torque density and efficiency. In fact this Fe-Co soft magnetic alloy, specifically developed for high performance applications, is characterized by a saturation level considerably above than conventional materials (up to 2.3 T) and reduced specific losses at relatively high frequency (less than 15 W/kg at 1.5 T – 400 Hz). Moreover, due to the lamination thickness of 0.10 mm, it is possible to approach a core stacking factor of 0.98. These characteristics make this material particularly suitable for the aerospace applications, even if it has higher density values respect to the typical electrical steel.

The magnets have been axially and radially segmented in order to reduce the losses. The segmentation not only keeps the individual blocks of magnets small, for obvious manufacturing reasons, but also divides the eddy-current paths into smaller loops increasing the effective resistance.

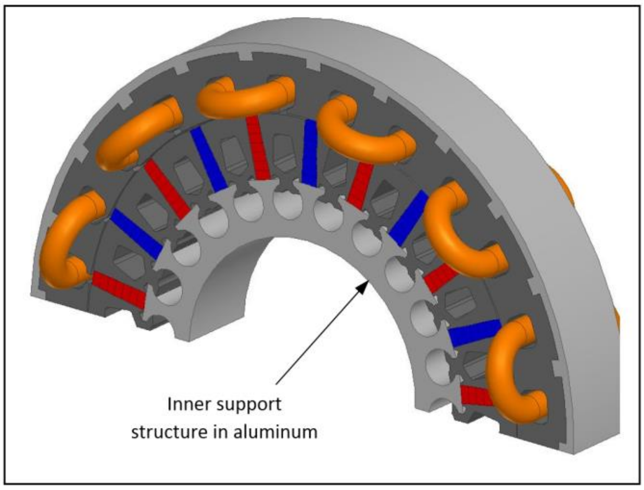

Fig.2 3D view of the 6-phase spoke-type PM motor (half machine)

Table 2 – Main data of the PM motor

N.phase	6
N.pole - N.stator slots	22 - 24
Stack length [mm]	50
Outer stator diameter [mm]	350
Inner stator diameter [mm]	285
Airgap length [mm]	0.60
N.turns per phase [mm]	25
Wire size [mm^2]	6.75
Motor weight [kg]	25

Results and comments

In Table 3 are listed the motor performance. A temperature of 130°C has been imposed for the stator winding and an operating temperature of 120°C for the magnets.The inner stator surface and the outer rotor surface have been accurately shaped to create a variable airgap: this choice has allowed to make sinusoidal BEMF (Fig.3).

The average torques at high power is 320 Nm with a phase current of 100 Amax and an efficiency higher than 97%: these performance satisfy the requirements. The total losses include also the eddy-currents losses in the PM that have been drastically reduced thanks to the segmentation along the radial and axial directions. The losses in the segmented permanent magnets are about 100 W at rated speed and 250 W at the maximum speed of 4600 rpm (which is also the maximum speed required for this application).

At low power the Joule losses drop to few Watts and the main source of losses become the core and the friction losses.

The constraints on the volume and weight have affected the stator core dimensions and then the flux density values that are in the range 2.1-2.2 T (Fig.3), higher respect to the typical values: these values can be accepted in the magnetic structure thanks to the use of the premium steel Vacoflux characterized by high saturation magnetization values and reduced specific losses.

The "Torque per unit of rotor volume" (TRV) is 100 kNm/m^3 and points out that the proposed motor represents a very high torque density solution: this value exceeds the typical values for the aerospace machines [6] that are in the range 60÷90 kNm/m^3 .

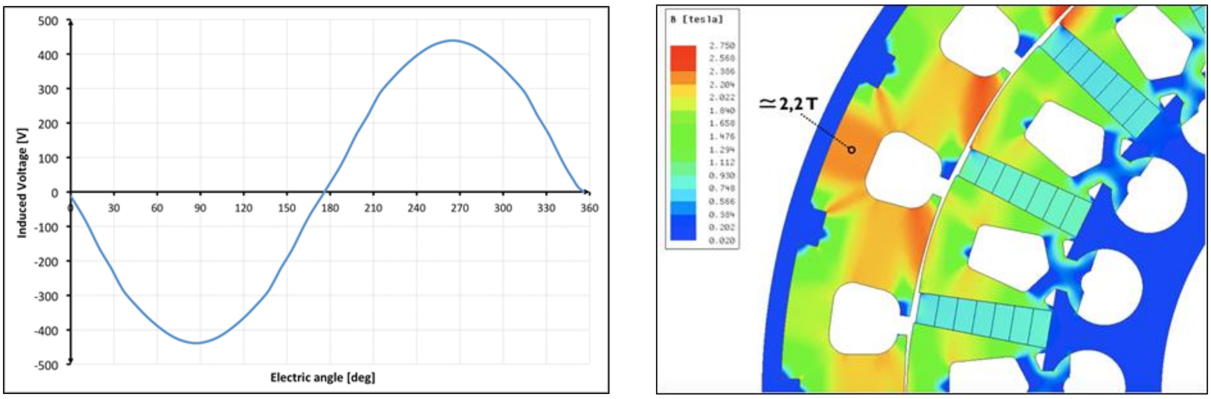

Fig.3 BEMF behavior (left) and flux density at high power (right)

Table 3 – Performance of the 6-phase PM motor

		High power	Low power
Phase current	Amax	100	7.0
Average torque	Nm	320	25
Speed	rpm	3600	2100
Output power	kW	120.6	5.5
Phase resistance @ 130°C	mΩ	41.0	41.0
Joule losses	W	1230	6
Core losses	W	769	109
Total losses	W	3534	295
Efficiency	%	97.1	94.9

The analysis of the torque ripple (without skewing) has been performed by a FE transient analysis and the behavior is shown on the left side of Fig. 4. The ripple is very low (1.1%) and this is due not only to the adoption of the concentrated winding but also to a right choice of the n. of slots and n. of pole.

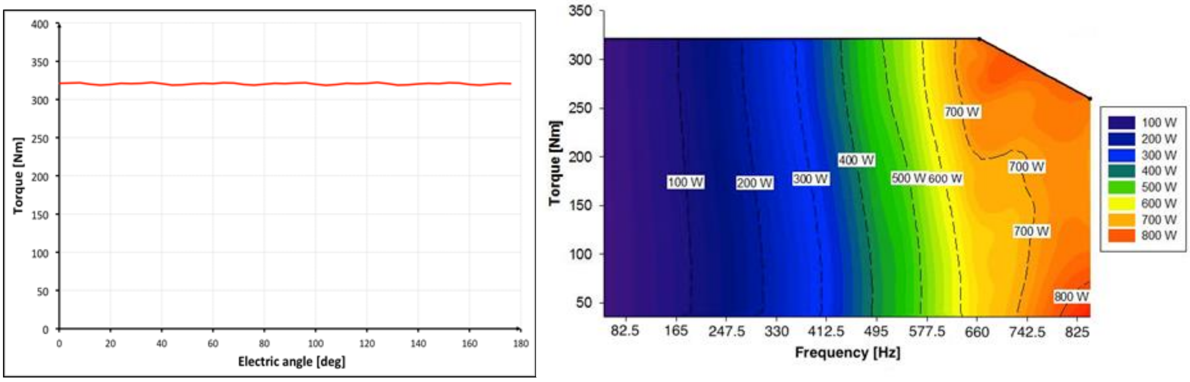

Fig.4 Torque ripple at high power (left) and trend of the core losses (right)

Moreover, on the right side of Fig. 4 the trend of the core losses is introduced as a function of torque and operational frequency. As you can notice also from the previous Table 3, the overall core losses at high power are actually lower than 800 W, which can be considered as a good result considering that the machine is operating at 660 Hz with a working flux density higher than 2 T.

The efficiency map of the motor in the Torque-speed domain is shown in Fig.5: more in the detail, the torque is in the range 30÷320 Nm and the speed between 225 and 4600 rpm. It is interesting to notice how the area with efficiency higher than 97% is wide, coving the most of the domain. On the other hand, the efficiency drops down when high torque at low speed is required and vice versa.

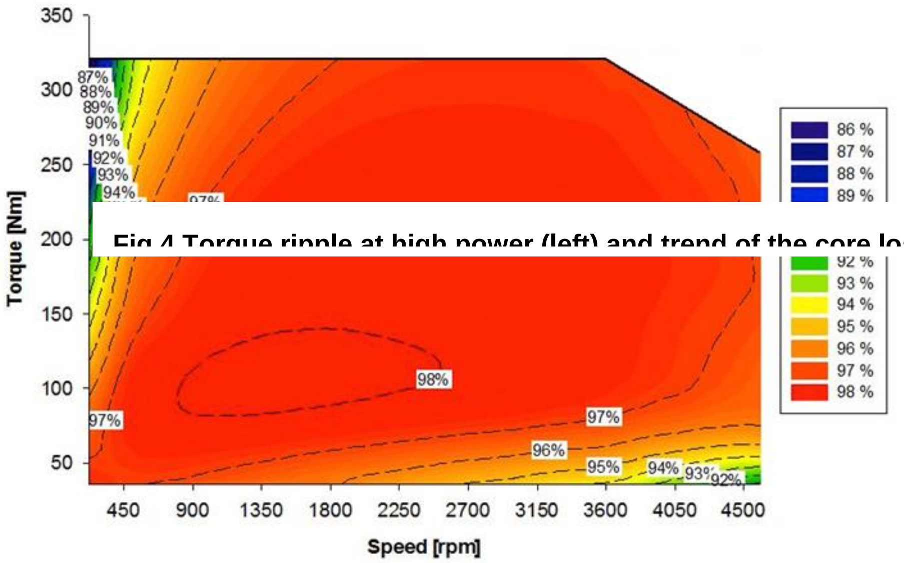

Fig.5 Efficiency map

A static 3D model has been realized mainly to take into account the edge-effects along the axial length. In fact, considering the high power density of the machine, and its reduced stack length, it has been proved that the reduction of the electromagnetic torque introduced by this effect is not negligible.

More in the detail, the investigation of this undesired phenomenon shows the presence of a considerable leakage flux both in the area of the airgap and in proximity of the permanent magnet’s exterior surface.

Fig.6 shows a 3D map of the flux density at high power and the leakage flux in the rotor core. The torque reduction due to this edge effect is about 8% for the high power and decreases almost completely for the low power operation.

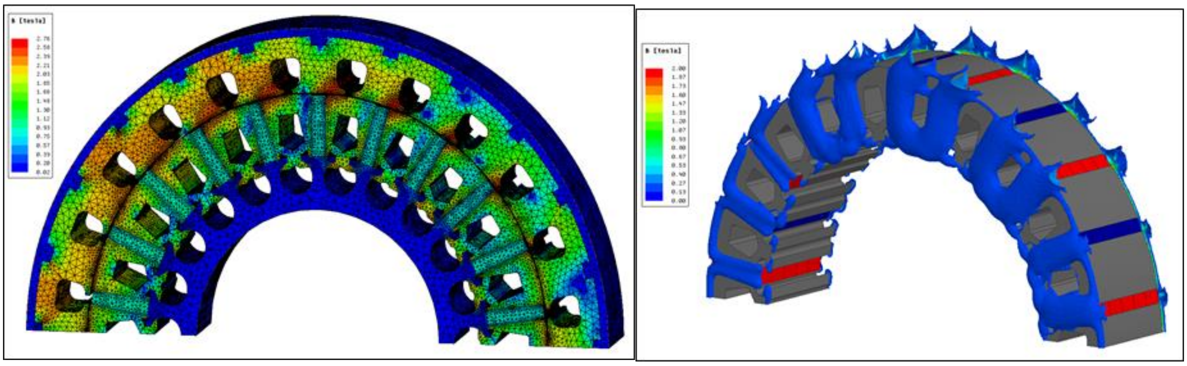

Fig.6 3D FE analysis: flux density (left) and leakage flux in the rotor core (right)

Conclusions

A 6-phase PM motor has been designed for helicopter tail rotor Fenestron® type. A spoke-type solution with interior PMs has been chosen in order to obtain high torque while maintaining small overall dimensions of the motor. Moreover, a multi-phase solution has been adopted in which each phase may be regarded as a single module. The performance of the proposed design fully satisfy the severe requirements at low and high power. The PM motor has a weight of the active part of about 25 kg and satisfactory efficiencies at low and high power operations: this allows a substitution of the actual mechanisms in tail rotor system matching envelope, expected mass and performances. A prototype will be realized and tested.

Acknowledgement

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References

[1] L.Castellini, M.Santececca, M.Tursini, M. Villani "Comparison of PM Brushless motors for helicopter tail rotor Fenestron type", Recent Advances in Aerospace Actuation Systems and Components, March 16-17, 2016, Toulouse, France.

[2] M. Villani, M. Tursini, G. Fabri, L. Castellini "High Reliability Permanent Magnet Brushless Motor Drive for Aircraft Application", IEEE Transactions on Industrial Electronics, vol. 59, p. 2073-2081, ISSN: 0278-0046, DOI: 10.1109/TIE.2011.2160514.

[3] M. Villani, M. Tursini, G. Fabri, L. Castellini, "Multi-phase permanent magnet motor drives for fault-tolerant applications", IEEE International Electric Machines and Drives (IEMDC), 2011, pp.1351-1356.

[4] A.M.EL-Refaie, "Fractional-slot concentrated-windings synchronous permanent magnet machines: opportunities and challenges", IEEE Trans. on Industrial Electronics, vol. 57, n. 1, January 2010.

[5] J. F. Gieras and M. Wing, Permanent Magnet Motor Technology, New York, Marcel Dekker Inc., 2002.

[6] J.R. Hendershot and T.J. E. Miller, Design of Brushless Permanent-Magnet machines, Motor Design Books LLC, 2010.

[7] L. Cirio, S. Lucidi, F. Parasiliti, M. Villani, "A global optimization approach for the synchronous motors design by finite element analysis", International Journal of Applied Electromagnetics and Mechanics, IOS Press, n. 16 (2002), ISSN 1383-5416, pp. 13-27.

[8] S. Lucidi, F. Parasiliti, F. Rinaldi, M. Villani, "Finite Element Based Multi-Objective Design Optimization Procedure of Interior Permanent Magnet Synchronous Motors for Wide Constant-Power Region Operation", IEEE Trans. on Industrial Electronics, vol. 59, p. 2503-2514, ISSN: 0278-0046.

4 TEST METHODS

Power Drive Systems are Changing Efficiency Metrics

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Service Manager

Standards for Electrical/Drives & Motors

SEW-EURODRIVE

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Abstract

The basic premise of CEMEP/NEMA [CNP] has evolved over the last several years as technologies have advanced and the availability, quality, features and reduced cost of the power converters have converged. These advancements have achieved a level of energy savings that CNP believes will provide the means for reaching the necessary 322 TWh estimate annual savings of the OEDC/IEA 2011 report [1]. The paper compares how energy saving is achievable by two routes. Past analysis' has been completed that confirms recent methods included in US regulations covering the system related approach [SrA] and its driven equipment [motor, control and load]. These methods will "move the bar" with a new energy savings [kWh] metric expressed as an EI [energy index] as opposed to relying on a component related approach [CrA] level efficiency metric as has been done in the past. The holistic approach described in an OECD/IEA report suggests a far greater savings can be achieved than with a limited CrA. In addition, a move from a single component [motor] to the system related approach introduces the potential of system communications taking the motor and the system into the scope of the IIoT [Industrial Internet of Things] and Smart Factory automation.

General:

Energy savings [kWh] is a key topic in the long term economic growth of both USA and Europe. It is a necessary responsibility of the current generation to provide future generations a clean and appropriate environment.

There is a connection between natural hazards like thunderstorms, flooding and dramatic change of weather conditions and the influence on this coming from CO_2 emission of all the mankind.

The world community accounts emit about 7 to 7,5 Billion of tons of CO_2 per year. Worldwide industrial facilities alone accounts for emitting about 1,6 to 2 Billion tons of CO_2 per year

It is estimated that between 65% to 70% of the consumed industrial electrical energy is transferred to mechanical energy through motor systems. This leads us to focus on these technologies to successfully take advantage of the energy saving potential as shown in blue on figure [1] rather than attempting to further reduce the small amount of losses remaining of the motor [and control] shown in orange] in figure [1]

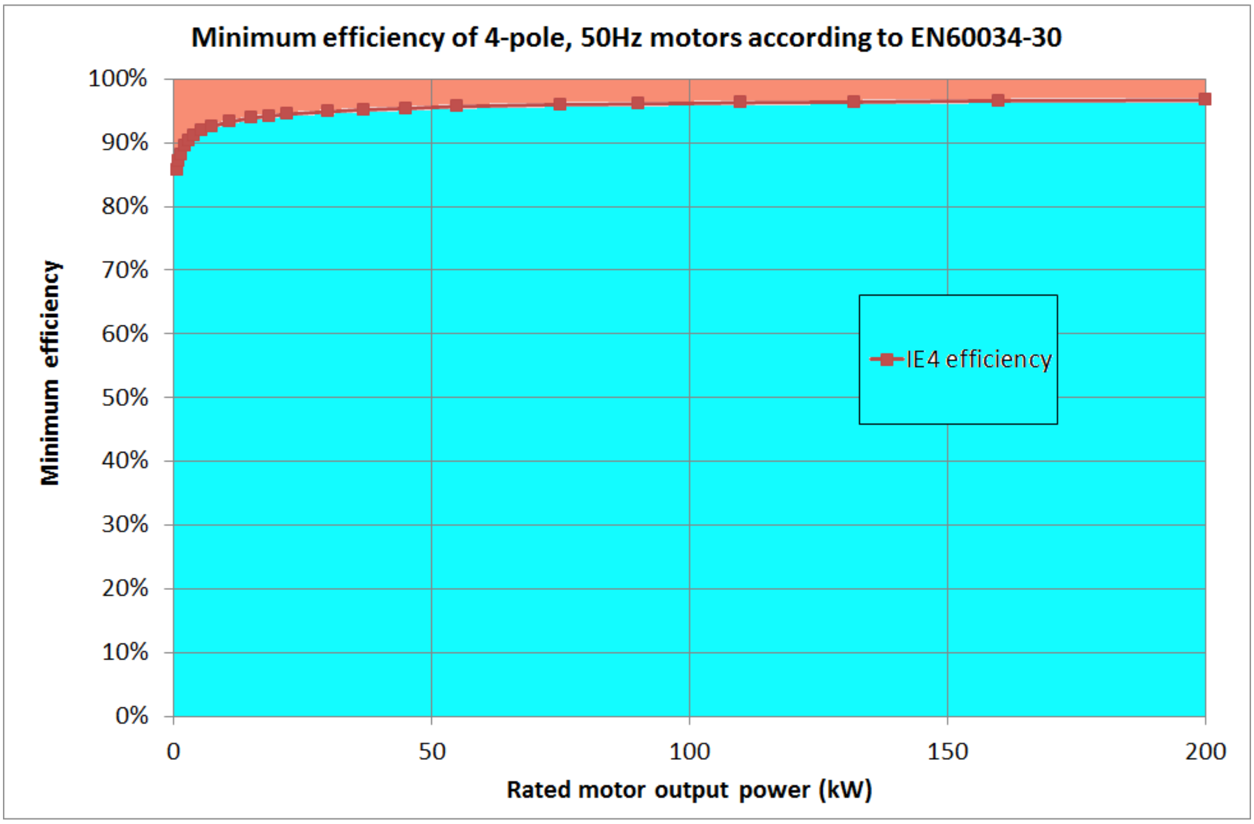


Figure [1]

The following text explains and emphasizes that it should be carefully taken into consideration what kind of market regulation shall be avoided to avoid erroneous regulation or low value regulation and what could be a more effective way to achieving the energy saving potentials without confusing the markets or creating conflicting situations.

1) Energy Savings are much more a function within the application and are process driven and less component driven

Motor systems can be just motors which are line fed or motors which are converter fed. The way to drive an electric motor can be fixed speed or variable speed. If it is fixed speed, the driven machine can deliver the maximum rated power at any time as long it is switched on and no power when it is switched off.

In many motor applications, it is advantageous to provide a demanded fraction of the maximum rated output power (e.g. when the driven process is in idle mode or just does not need to deliver the full power for process reasons).

Circulating pump systems are a good example to show that during normal procedures most of the operating time just about 30% of the installed power is used. Only when there is a clogged filter or a scavenging necessary is the full power of the pump applied for a short time. In this case, it is not energy efficient in normal operation to throttle the flow mechanically down to 30% and waste the remaining 70% of the full mechanical power provided for the heating of the fluid and the throttle itself and for damaging the pump. It is much better to slow down the speed of the pump electronically (variable speed), that during the requested time only 30% would be the maximum provided output power.

The variable speed technology uses a power electronic called "power converter" which produces very low losses during this slow down mode of the pump.

However this could be widely misunderstood in a way that if one purely calculates the resulting electrical efficiency of the converter (about 97%) plus the motor (about 92%) it would be worse (97%*92% = 89 %) compared to the motor efficiency alone (92%), as the combined efficiency lowers by adding the converter losses. This seems to be contradictory to the former statement, that converter driven motors improve the energy efficiency of driven equipment!

This will be better understood as one considers to the motor driven equipment (in our example the pump systems) where all the mechanical losses appear (efficiency less about 60%). In case of electronically reduced speed the energy savings will come from there (efficiency while reducing the flow will increase to more than 90%). Means the losses in the adapted driven process are decisive for calculating the savings measured e.g. in kW and not the losses of an effective motor control improving the energy efficiency in industry it is generally of advantage for the market regulation to be consider first, how the electrical driven equipment is adjusted while working for the customer (customer driven needs summed up in a **S**ystem **r**elated **A**pproach, **SrA**), instead of continuing the confusion with additional component driven market regulation on the electrical components like the electronic converters or increasing motor efficiencies alone (IE-Classes on the **C**omponent **r**elated **A**pproach, **CrA**)!

The SrA in practice is an example of an established energy management system of the demand side and the promotion of energy saving targets by the production site management. They would be more likely to use the best available drive technologies under economic review of the OPEX (Operational Expenditure that is the cost for running the factory) and in conjunction to their energy price contracts.

The energy saving potential in industry using the electronic speed control (SrA) is about three up to ten times higher (overall global energy savings about 250 TWh to 300 TWh) compared to a (CrA) method regulation for IE-classes of motors (about 50TWh up to 70TWh).

We can see that the business-to-business (B2B) of drive technology has different mechanisms and interaction with business partners (OEM, system integrators) and works with other fundamental values than the business-to-customer (B2C), where only the end customer would purchase a stand-alone commodity, means ready to use product (just plug and play).

In the B2B business case the component manufacturer would not know, where motors are sent and used in applicative processes or embedded in a machine which also may be exported. Often the motors are sold to distributors or OEMs and the responsibility for saving energy sticks together with the motor. Means any misapplication of a high efficient motor may lead to higher energy consumption than was intended while taken the decision to apply it. Those effects are well known as so called "Rebound effects".

The manufacturer of the misapplied high efficient motor in B2B will have no control and therefore no possibility to address a CO_2- abatement coming from his product or avoiding Rebound effects.

With a CrA it is of high probability that Rebound effects may happen and the CO_2-abatement effects are not achieved because the application requirements are not considered.

The following table summarizes the comparison between the CrA and the SrA for different aspects concerning the component manufacturers and the industrial market for B2Bses in general.

Note that the SrA is sometimes also mentioned with the term "extended product approach, EPA" when the SrA is limited to the technical description of components losses and machine losses are mentioned together.

SrA in the table includes the demand side energy management as well. The demand side energy management decides also on CAPEX (Capital Expenditure that is the investment for new equipment) and for this uses the LCCA (Life Cycle Cost Analysis).

Component related Approach (CrA)i.e. the motor, …	**System related Approach (SrA)**	**Comments**
Addresses of Regulation Measures		
Motor, pump, fans, compressors, power electronic converter manufacturers, also the market regulating and surveillance authorities or trading companies are addressed	System users and OEM users are addressed. The provision that market competitive energy efficient components are available is state of the art since long time.	Disadvantage of the **CrA:** in a free trade market, actual energy savings are limited. Applications influence the energy saving success and rarely any detailed feedback of dedicated installed results is taken into account.
Energy saving potentials		
Energy saving potential only on the component side delivers only 1-2 % for potential energy saving potential subject to application and power quality variations.	Energy saving potential of the system delivers as much as 30% for motors with VSD (Variable Speed Drives) and 60% with appropriate application of energy saving potentials	Disadvantage of the **CrA:** the achievable energy saving amount in practice is mainly determined from the right application of the components but might be negligible compared to expected potentials based on mechanical speed control and kW demand.
Only new installations could be covered by any market regulation. Old installed, somehow inefficient motors may run the following decades in brownfield installations	Brownfield installations improvement could be included in the Motor System Analysis as well as in new installations	Advantage of the **SrA:** a substantial CO_2-reduction potential in new factories as well as in brownfield installations could be achieved by increasing the awareness
Power range of motors during regulative measures are typically limited between0, 75 kW to 375 kW today in Europe.	No limitation of power is valid. SrA is technology neutral allowing all kinds of motor driven equipment be analyzed and can save	Disadvantage of the CrA**:** the entire energy saving potential of motor driven systems is limited to only one specific power range of a component by exclusion of all customer demanded exceptions.

	different amount of energy from very small to very high kW	
Practical relevant applications for regulative measures need to be limited for the sake of simplicity to mainly duty type S1 or NEMA design A/B/C (according to standard IEC 60034-1 or MG1).	Practical relevant applications could be focused to select optimum industrial energy saving potentials regardless of duty cycles (i.e. for upstream, downstream and main processes).	For the sake of simplification of the market regulation which comes as an advantage for the CrA**,** just one single service condition and load operating point is included for assessment.
Controllability (monitoring) and presumed success in practice		
Misapplication or mismatch of high efficient motors (e.g. for highly dynamic needs or replacement in HVAC systems) are out of control or monitoring	Misapplication can be identified by demand side energy management. Methodology how to analyze would be supported by standardization. Rebound effects might be avoided	Disadvantage of the **CrA:** the expectations on energy saving success are frequently not fulfilled and the failure is not recognized ("Rebound Effect"). The disadvantage of the CrA is significantly described by any misapplication and wrong matching (i.e. a leaking pump system might be compensated by an oversized high efficiency motor or controlled by a hand throttle or not compensating for addition speed of more efficient motors designs
Ongoing regulation is not effective for components can exasperate unintended consequences like "Rebound Effects".	Extended market regulation or control for high efficient motors would no longer be effective. The requirement of a demand side energy management does not touch the mechanism of a free trade market.	Advantage of the SrA**:** a market overregulation and inappropriate burden to manufacturers, customers or market surveillance could be avoided. The loop hole arguing for any component based regulation can be managed.
	Requirements for an approved and independent Motor System Energy Analysis and tracking procedure of energy saving measures on-site are necessary. Measures	Advantage of the **SrA:** the system users and the community can achieve a win-win situation with selected measures by increasing profitability of the installation and by reduction of CO_2-emissions.

	(Investment) only with LCCA-accounted payback time of less than two years might be mandatory.	
Authorities and power utilities could include incentive measures promotion to reduce the price of high efficient motors	Authority may include financial promotion to increase number of LCCA-accounting production sites.	Disadvantage of the **CrA:** the financial promotion is independent of the CO_2 reduction while motors might be mismatched or wrongly applied and used. This would cause higher energy demands than intended ("Rebound effects")
Market population of regulated components can be easily checked via labeling.	Uncontrollable via labeling of the components. A control of qualified Motor System Energy Analysis and promotion of energy management success targets is necessary.	Disadvantage of the **CrA**: market regulation can be easily controlled on one hand but the energy saving success cannot be monitored nor guaranteed sufficiently
Limitation of Todays and Future Technology		
state of the art is the lowest cost upfront technology fulfilling the market regulation. Development of evolving component technology is no more attractive when its more cost effective and delivers much less energy saving to the market	Development of multiple SrA technologies remains unlimited and extendable through Motor System Energy Analysis at any time. "Best available technology" today is the variable speed drive plus technology neutral motor application	Disadvantage of the **CrA**: it has a very limited effect on the development of future technologies. Moreover, new technology development might be limited as manufacturers just focus on the less expensive way to comply with regulations based on 100% load.
	Regeneration of energy through active electronic braking of rotating loads is available today and could also contribute to additional energy savings	Disadvantage of the **CrA**: as it does not include novel solutions and already available emerging technologies for greater energy saving

Market Regulation Measures		
Currently the savings calculation of individual accounted component individually put on the market (motors, pumps and fans) happens by individual product regulations. No follow-up to determine the actual saving achieved from a pump system driven powered by a high efficiency motor?	Seamless common definition and understanding of relevant LCCA system data is identified as: - operation time - intermittent duty - end of life - system efficiency - input/output power - payback of invested money - cost of components - cost of systems - cost of energy - partial load - optimum speed - optimal load operating point…	Disadvantage of the **CrA:** as it is, regulates not the system effect for LCCA assumptions. Best saving duties or speeds for motors and/or driven equipment may differ from the application. With **CrA** they cannot be identified. It is critical how **CrA** can provide a practical relevance as in reality the duty cycle of a motor driven equipment is decisive for energy savings

2) Education is necessary, how to understand the drive system and apply the right standards that save the greatest possible amount of energy

Manufacturers, Standards Development Organizations and other Associations shall take the opportunity to do continue the education for the customers (end users but also system integrators or OEMs) to demonstrate to them the cost saving advantages and other improvements for optimizing the processes while using a SrA

Moreover, it is necessary to explain the latest relevant product standards to motor users to be used in practice and how demand side energy management benefits their use of the motor driven system. Both CEMEP and NEMA recognize this need and are committed to adding application guides such as NEMA MG10 to available documentation explaining the energy savings potential of the SrA or IEC 61800-9 for the system related analysis.

3) Test methods harmonization

OEMs need SrA performance standards to compare component manufacturers. We are selling drive system losses in kW and not energy savings as it will result – the latter will be the result of running the correct application.

For variable speed drives and for fixed speed driven motors the test methods for efficiency related parameters of the components are well described in the standards.

The standardization of such tests leads to a result which is for the sake of simplicity somehow "artificially simplified" compared to the real application. A specific customer driven application cannot be standardized in advance – each is special and unique in practice.

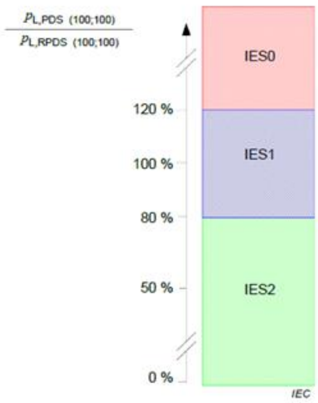
For example, the duty cycle of the application of the equipment (how much power do I really use for a certain timespan at a certain operating point of load demand) will differ from factory to factory.

Therefore, the harmonized test methods in general do not allow offering results as such which may directly lead to cost saving numbers or a dedicated energy efficiency performance values (e.g. how many kWh per year one could save in the factory).

Harmonized test methods for components allow comparing different designs and their rough tendency to increase or decrease efficiency under laboratory conditions in percentages. Therefore, it would not be the interest of component manufacturers to spend much money for such tests when they need to think in terms of SrA.

To provide the global markets with tools to achieve a standardized methodology for determination of the losses of a power drive system and classification of the converter and extended products (e.g. for pumps), IEC/SC 22G/WG 18 has developed and published the standards IEC 61800-9-1 (Extended Product Approach) and IEC 61800-9-2 (Loss Determination of a PDS). These standards explain how to calculate, test and measure the losses of a CDM (Complete drive module including power electronic converter), the PDS (Power Drive System) and how to apply these results to the extended product approach (e.g. a pump system). The 61800-9-2 standard defines the system classification (IES) for the PDS

The movement to determining system losses over a range of load points and managing kwh has led to this IEC standards IEC 61800-9-1 and 61800-9-2 newly issued, where system classes are now defined (IES). [Figure 2]



[Figure 2] **equipment, products and device incorporating the same component)**

If a component has been regulated already together with its applicative equipment where it is embedded (e.g. a small motor in a household appliance, where the efficiency of the appliance has been already regulated), this component is preferably not to be regulated a second time as a single component. Equipment builders must rely on their expertise of the entire system to select and integrate components that achieve the best results [energy savings]. Overlapping or double regulation brings unintended consequences placing restraints on product design and development that can defeat the higher-level savings goals.

The mechanism could work in such a way that the manufacturer of the appliance will purchase only those motors with which he can deliver the required efficiency of the appliance. This will be always done under the best economical advantage, so the lowest cost motor to achieve the appliance efficiency will be the first choice.

If a second regulation just for the motor would require the efficiency to be of a higher value in S1 duty cycle, it may conflict with use, because the lifetime of the appliance driven by this motor does not reach the cost payback time while saving electrical energy and the duty cycle of the appliance might not be according S1 of the motor. In practice, the application works in an operating point not as S1, consequently, consuming possibly more energy.

In this case, additional raw material (copper, aluminum, rare earth magnets and magnetic steel) will be wasted in the motor (to increase its efficiency) without any benefit for the community (battle of materials).

It will be also unclear that with consuming more raw materials the more additional energy needed during production could be saved in a limited duty cycle or lifetime of the appliance.

4) Summary

It has been shown that electrical drives technologies can contribute to a great extend to the energy saving goals worldwide that support improving our future environment.

To achieve this, the industrial market mechanisms in B2B business cases and the differences between theoretically technical efficiency and practically needs in a driven application shall be taken into account to prevent the community from reverse effects.

Appropriate standards can help to fix minimum requirements for needed analyses all of which need to have a system related approach and not a component related approach, limited scope. Collaborative projects are necessary between component (motor and converter) manufacturers and machine or equipment builders.

The system related approach (demand side energy management plus extended product approach) recognizes energy savings as the metric replacing the previous efficiency metric in use today within the component related approach. This change will provide the user with more accurate energy saving measures for comparative analysis than in the past which also may help to solve market surveillance obstacles or loop hole arguing, avoid double regulation and will stimulate the growth of developing more applications using emerging technologies.

Further collaboration between NEMA and CEMEP is strongly supported by all market players to draft improved technical standards and to reduce the necessity for additional regulations while providing OEM's and end users with SrA options that save energy and reduce operating costs.

References

[1] P. Waide, C.U. Brunner, et al.: Energy- efficiency policy opportunities for electric motor-driven systems", OECD/IEA, Paris, France, 2011

Application on-site and comparison of efficiency estimation methods for induction motors

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Abstract

Taking into consideration the increased cost of electric energy, the improvement of the induction motor efficiency in the industrial sector is very important. This improvement is possible and successful only with the correct measure of the efficiency. Measurement methods of efficiency in laboratory are accurate and reliable, but require decoupling and moving the electric motor from site to laboratory, for this purpose, new methods relevant to field efficiency evaluation are appearing every year. These methods were developed with the aim of being applied in situ to minimize the efficiency evaluation period. But the scientific literature is lacking of results that take into consideration real operation conditions of the motors, the effect of the imbalance of the power supply, the presence of harmonics or variation of the voltage around its nominal value. These effects can lead to important errors of measures, the application in situ of efficiency estimation methods is crucial for industrial managers and scientific researchers to have the experience feedback. In this paper, more than 10 of the most generally used methods are described, seven categories of these methods are more related to in-service testing are applied and compared. These efficiency estimation methods have been applied on 46 induction motors directly supplied by the grid, under real conditions and the field results are compared with those obtained by separate loss method. The required measures, the difficulty, the required hardware, the intrusion level and the accuracy of each method are discussed.

Introduction

Asynchronous motor represents the most energy-intensive equipment in the industry; it consumes about 75% of industrial energy consumption. However, providers who produce and distribute electricity are well aware that the amount of electrical energy consumed by electric motors continued to grow. The demand for electricity increases continuously; accordingly, it must consider the efficiency of these motors as a significant reduction in the cost of this consumption factor, since it allows to determine the energy consumption of an associated motor process determined, while assessing the possibility of replacing the motors by new and more efficient ones.

The efficiency measurement is based on the measure of the power input and the useful power delivered to the load. The measure can be done indirectly by evaluating the various losses of the motor. Because of the need to save energy resources, it is important that motor users understand the selection, application, and maintenance of electric motors in order to improve the management of electrical energy consumption. Energy management, as related to electric motors, is the consideration of the factors that contribute to reducing the energy consumption of a total electric motor drive system. Among the factors to be considered are the motor design and application.

The majority of motors in the field are induction motors for which IEEE-Std 112 test procedure for polyphase induction motors and generators [1] would be applicable. However, field evaluation of operating efficiency introduces an environment for which IEEE-Std 112 is not applicable. Thus, when evaluating motor efficiency in the field, it is important to use a technique that can accommodate field conditions.

Influential factors on the efficiency of electric motors

There are eight parameters of concern when referring to use conditions and power quality. These factors are speed of motor, motor load, motor maintenance, oversizing of motor, voltage, current, power actor and harmonics. For each of these areas there are certain negative events and side effects that influence and have a negatively impact on equipment as well as energy wastage. Voltage variation and fluctuation flicker, under voltage conditions like brown outs, dips and blackouts and over voltage, spike and transients are just some of the many damaging voltage conditions a customer can experienced in his facility. Add to this current imbalance, harmonic distortions and low internal facility power factor you have a mixed basket of power quality conditions that significantly affect equipment and thus facility efficiencies and energy usage.

Voltage

Electric motors and in particular induction motors are designed to operate under optimum conditions, once powered by symmetrical three-phase sinusoidal waveforms with the nominal voltage value. Deviation from these ideal conditions can cause a significant deterioration in the efficiency and a reduction in motor lifetime; example of power supplies through converters or waveforms are rich in harmonics.

Induction motors are intended to operate satisfactorily under voltage variations of ± 10%. Unbalanced voltages on induction motors produce large unbalanced currents, overheating of the motor, shorter insulation lifetime, excessive losses and wasted electrical energy. Also, significantly unbalanced line currents make the problem of providing adequate overload protection more difficult.

Table 1 characteristics of a motor based on the voltage supply [2]

Characteristic	**Voltage**	
	110%	90%
Slip	-17%	+23%
Efficiency	+1%	-2%
Power factor	-3%	+1%
Current	-7%	+11%
Starting Torque	+21%	-19%
Starting current	+10%	-10%

Motor load

In the industry today, based on the requirements of production and process, there are number of equipment and machinery suppliers with products of various characteristics, functions and requirements. Variations of the same product by different vendors are often so unique to that product in magnitude that in most cases, its characteristics from no-load to full load cannot be perfectly matched by another provider. The motor load can also have a significant effect on its performance. A motor loaded to more than 50% has a relatively stable efficiency. At lower load, efficiency decreases. Low efficiencies are due to inappropriate loads (overload) or operation at no-load conditions; such situations must be considered for matching with the best efficient motor system [3].

Motor maintenance

It is important to understand that equipment usually fails over time, reliability decreases, losses increase and efficiency decreases over time prior to most catastrophic failures.

Although some equipment faults are instantaneous, the larger majority of catastrophic faults that impact production are the result of a failure in the implementation of a maintenance program. This failure is primarily due to management not fully understanding that maintenance is an investment in the business and not an expense of doing business.

Proper implementation of a maintenance program can reduce energy consumption in plants by as much as 10-14%. Motors run more efficiently, last longer and require less attention if they are cleaned correctly, cooled, dried and lubricated properly. Motors installed in a harsh environment and exposed to a high humidity and frequent cleaned have a life-cycle largely below average [4].

Power factor

In inductive loads, such as motors and transformers, current is used to create magnetic forces, which produces the required torque in motors and the transformed voltage in transformers. These magnetic forces oppose changes in current levels. In an AC system, where the supply voltage is constantly being varied due to magnetic load requirements, the current lags the voltage. The phase angle between current and voltage is referred to as the Power Factor. Ultimate system power factor is unity (100%). The lower the power factor, from the unity, the further current will lag behind the voltage; which results from magnetic current increase. Most common and economical solution to remedy low power factor adopted by most engineers used to be static capacitors [5].

Motor sizing

Oversizing generally leads to overconsumption. If the motor is oversized, it consumes more than necessary, this is the first source of energy loss in the industrial sector. The motors are oversized from the source, resulting in swelling of the operating and investment costs. Indeed, oversized motors increase economic loss. The additional cost of electricity consumed unnecessarily during operation and the initial purchase of the motor, which is more expensive because it is more powerful.

Oversizing of the machines is explained through three causes: the successive addition of safety margins from manufacturers and suppliers, the extra power needed for starting and braking of the motors, the anticipation of a future increase in production. Generally, efficiency of electric motors takes a maximum value for: $0.6I_n \leq I \leq 1I_n$, because in this range, the report of losses to the power consumed is considered minimum. Outside this range, losses becoming much more predominantly, lead to the growth of this report so we have reduction in efficiency [6].

Harmonics

Non-linear loads, such as wave - chopping the DC loads, carry the current signals which are not purely sinusoidal. While the traditional linear loads allow voltage and currents of the fundamental frequency (50 Hz) appear in power systems with little or no harmonic currents, non-linear loads can introduce significant levels of harmonics in the system. A harmonic is simply an integer multiple of the fundamental frequency. The amount of distortion is determined by the frequency and amplitude of the harmonic currents. A non-linear load draws current in abrupt pulses rather than in a smooth sinusoidal fashion. These pulses cause harmonic currents that turn result in voltage distortion and harmonics, causing even more current harmonics in various parts in the power system [7].

Motor speed

High speed motors usually offer a better performance. However, this does not mean that it is always preferable to use a high speed motor and lower its speed by using the mechanisms designed to accommodate to the load. Power losses occurring at speed-lowering mechanisms could reduce the system's performance to a lower value than that obtained with a low speed motor and direct-control.

Generally, Incidents of problems and damage to customer-owned equipment resulting from abnormal voltage conditions, surge and transients, harmonic distortions, current imbalance, system and line losses, poor power factor, short duration dips and associated expenses results in increase inefficiencies and increased electric bills.

Efficiency Measurement Standards

IEEE 112 standard:

The Institute of Electrical and Electronic Engineers (IEEE 112), used in the United States, has five main methods (A, B, C, E, F) for determining efficiency. The efficiency of each method depends on the accuracy, cost and ease of performance measurement for each class of electric motor [8].

Methods A, B, C determine the performance directly by the measurement of electrical input power and the mechanical output power under the operating conditions (direct measurements). The performance is calculated by the output ratio of the input power.

Methods E, F, IEC 34-2 standards (International Electro technical Commission) and standards JEC 37 (Japanese Electro technical Committee) use different techniques to determine input and/or output if direct measurements are not suitable [9].

The main difference between these different methods is in the determination of the losses of dispersion in load (or determination of additional load losses). E and F methods require a separate test to estimate these losses. As the IEC standard, estimate them. The JEC standard uses the diagram from the circle as a primary method for the calculation of the performance and the measure of loss of dispersion is not included, losses are estimated between 8 and 15% of the total loss of the motor.

Table 2 Induction motor efficiency evaluated by different standards [10]

Methods	**4 kW**	**7.5 Kw**	**11 kW**	**15 kW**
IEEE 112 Method B	82.9	85.9	86.1	84.9
IEC 34-2	84.6	86.5	86.4	85.5
JEC 37	85.6	87.1	87.1	85.5

The tested induction motors are of the same series (380 V, 50 Hz, four poles) with rated power of 4kW, 7.5kW, 11kW, and 15 kW.

The appropriate method of measuring the efficiency of a motor can be chosen according to the criteria of the production process in which the motor is part. These criteria are linked: accuracy, the degree of intrusion tolerated, downtime and the cost of the measure. To resolve this problem of intrusion, several oriented themselves to measure in-situ performance of the induction motor taking into account imperfections related to the actual conditions (imbalances, harmonic, balance of voltage, etc.).

Method of estimating the efficiency of the induction motor in-situ

In this section, the available methods in literature for an in-situ efficiency assessment of induction machines are briefly described. The section starts with the simplest and least accurate techniques, and it concludes with the most accurate method. In this section the physical basis of each basic method is described in terms of how the efficiency is obtained and for more details each method has been referenced. Over the years, many motor-efficiency-estimation methods have been proposed. Generally, the measurements needed for each method are different, but most of them require the following common data: input line voltages and line currents. Some methods require the nameplate data (rated voltage, current, rated power, speed, etc.), stator resistance R_s or rotor speed ω_r. Among these, the measurements or estimates of stator resistance and speed have been regarded as the stumbling blocks of various efficiency estimation methods for years. Most of these estimators utilize the terminal voltage and current, which are already available in condition monitoring systems SCADA.

Name plate method

The least intrusive field estimation method is to obtain motor efficiency from the nameplate [11]-[12]-[13].

Slip method

For standard slip method, the percentage of the load is presumed to be proportional to the ratio of the measured slip to the full-load slip. The motor efficiency is, thus, approximated using (1). However, the error comes from the fact that the slip ratio represents the percentage of load, and the efficiency is not equal to the percentage of load. The slip methods rely on the motor speed measurement [11]–[12]-[14]. The main advantage is their simplicity.

$$\eta = \frac{P_{out\ Rated}}{P_{in\ Meas}} \cdot \left(\frac{N_{Sync} - N_{Meas}}{N_{Sync} - N_{Reted}} \right) \tag{1}$$

Where $P_{OutRated}$ is the rated mechanical output power, $P_{In\ Meas}$ is the measured input power, N_{Sync} is the mechanical synchronous speed, N_{Rated} is the mechanical rated speed and N_{Meas} is the mechanical measured speed.

Slip Method with Voltage Compensation

To compensate for the effects of voltage variation on the estimated efficiency, the modified version of the slip method was proposed in [15] and as shown in (2).

$$\eta = \frac{P_{out\ Rated}}{P_{in\ Meas}} \cdot \left(\frac{N_{Sync} - N_{Meas}}{N_{Sync} - N_{Rated}} \right) \cdot \left(\frac{V_{Meas}}{V_{Rated}} \right)^2 \tag{2}$$

Where V_{Meas} is the measured voltage and V_{Rated} is the rated voltage of the machine.

The more accurate version of this equation was proposed in [16], as shown in (3), which is claimed to better reflect the relationship between the slip and load of the induction motor.

$$\eta = \frac{P_{out\ Rated}}{P_{in\ Meas}} \cdot \left(\frac{S_{Meas} - {S_{Meas}}^2}{S_{Rated} - {S_{Rated}}^2} \right) \cdot \left(\frac{V_{Meas}}{V_{Rated}} \right)^2 \tag{3}$$

Where S_{Meas} is the measured slip and S_{Rated} is the rated slip.

Current method

Like the slip methods, the current methods use minimum measurements and manufacturer’s data to estimate the efficiency [11]–[12]-[16]-[17]. Their main advantage is simplicity.

Standard Current Method:

In this method, it is assumed that the input current of the machine changes linearly with the load. Thus, the efficiency can be estimated by (4).

$$\eta = \frac{P_{out\ rated}}{P_{in\ \ Meas}} \cdot \left(\frac{I_{in\ Meas}}{I_{in\ Rated}} \right) \tag{4}$$

Where $I_{in\ Meas}$ is the measured input current and $I_{in\ Rated}$ is the motor rated current.

Modified Current Method

It is possible to improve the accuracy of this relationship by considering the no-load current as shown in (5), [11]-[12]-[16]-[17]-[18].

$$\eta = \frac{P_{out\ Rated}}{P_{in\ Meas}} \cdot \left(\frac{2I_{in\ Meas} - I_{in\ Noload}}{2I_{in\ Rated} - I_{in\ Noload}}\right) \quad (5)$$

Where $I_{inNoload}$ is the no-load current.

Equivalent-Circuit Methods

The efficiency of an induction motor can be calculated from its equivalent electric circuit. These methods can provide an efficiency estimated for a motor operating under load conditions other than those at which measurements are made [1]-[11]-[19].

Statistical method

Usually, application of this method is restricted to the group of motors for which empirical equations were derived. If the statistical results are not used for the group of motors that the empirical equations are based on, significant errors in the efficiency estimation are likely [1]-[12]-[19].

Segregated Loss Methods

These methods are most straightforward because they simply estimate (segregate) each loss component (W_s, W_r, W_{core}, W_{fw}, and W_{SLL}). These methods are generally very accurate [12], although some of them are also quite complex and intrusive, while others rely on empirical values to estimate some of the losses, [1]-[11]-[20].

Conventional and Non-Intrusive Air-Gap Torque Methods

The conventional air-gap torque method works based on the estimation of the air-gap torque value with use of the measured current and voltage signals, as shown in (6) [21]-[22].

$$T_{AG} = \frac{P}{2.\sqrt{3}} \cdot \left[(i_a - i_b) \cdot \int [v_{ca} - R_1(i_c - i_a)]dt - (i_c - i_a) \int [v_{ab} - R_1(i_a - i_b)]dt\right] \quad (6)$$

Where T_{AG} is the air-gap torque, P is the number of the poles, R_1 is the stator resistance $i_{a,b,c}$ is the instantaneous value of the current signal, v_{ab} and v_{ca} is the instantaneous value of the line-to-line voltage signal.

The measurement method, measurement devices

Electrical measurements

For the purpose of that story, the measurements in electric motor, the motor supply voltage, current drawn from the network, apparent power, active power, reactive power and motor power factor have been measured. By using the measured data, the electric motor loadings, operation efficiencies and the power value that has been transmitted to the load have been calculated.

The form of the measurement

We will briefly provide the procedure that we have adopted to transcript the maximum possible induction motors data in order to calculate their actual efficiency and we provide also few remarks.

An electric energy analyser device marked Chauvin Arnoux has been used; the measurements have been made from the current and voltage transformers for the motors that are fed from the medium voltage 10KV. In the motors that are fed from the low voltage 660V level, the voltage has been measured by voltage sensors that are directly connected to the supply point in the main panel of the motor, and the motor current has been measured by clamp ammeter. All measurements have been made in normal operating condition of the motors while driving the pump or the load.

We have consulted the rewinding and revision service of the motors which communicated the data of the no load test after rewinding of motor, stator resistance, the no-load power, the no-load current, voltage and vibration. We visited the various units of the plant and we found the state of the motors and recoded data of the different currents indicated by the located ammeter of each motor. There was also the opportunity to record data from control room in real-time. To measure the currents of low power motors, it is possible to use the power meter clamp Chauvin Arnoux F 407 (in order to use the two wattmeter method), this power meter delivers the value of current, voltage , power factor and absorbed power.

The site where the measurements were carried out utilized power transformers that are equipped with On Load Tap Changer in order to maintain the voltage at an optimal level, for this reason the problems related to disturbance and the variation of the voltage are well reduced. However, the accuracy of speed measurement of motors coupled to their loads had a very high degree of difficulty. Indeed, we have not found a way to measure the speed of the motor in load, which pushed us to wait for the moment of maintenance a motor so as to be able to place a mark or object communicating with non-contact Laser Tachometer in order to measure the speed on load condition.

It is worth noting that during our surveys, the motors are not all on load, some are stopped, since several motors of the production sites are used in redundancy, one operates and the other is in standby mode, in order to ensure continuity of service. In addition, some motors operate only for very limited periods of time, such as those used for the lubrication of generators in the start-up phase.

Application and field results

The characteristic points and the nominal label values of the electric motors on which measurements have been made are given in Table 3.

The results of the electric motors in the area of the measurements are given in Table 4 and 5. By using different efficiency estimation methods; the existing electric motor efficiencies have been calculated.

Table 3 nameplate characteristic and useful information

Sr.N°	Rated voltage (V)	Measured voltage (V)	Rated Power (kW)	Current (A)	Slip (%)	Speed (rpm)	Nameplate Efficiency (%)
1	660	674	22	26.5	3.33	1450	88
7	660	674	45	50	2.00	1470	92
11	660	674	46	50.5	2.00	1470	92
12	660	674	46	50.5	2.00	1470	92
13	660	674	46	50.5	2.00	1470	92
14	660	674	46	50.5	2.00	1470	92
15	660	674	46	50.5	2.00	1470	92
16	660	674	46	50.5	2.00	1470	92
17	660	674	55	60.6	1.67	2950	90
18	660	674	55	60.6	1.67	2950	90

19	660	674	110	117.7	1.33	1480	93
20	660	674	110	117.7	1.33	1480	93
21	660	674	110	118	1.33	1480	93
22	660	674	110	116.5	1.00	1485	94
23	660	674	110	116.5	1.00	1485	94
24	660	674	110	116.5	1.00	1485	94
25	660	674	110	116.5	1.00	1485	94
30	660	674	132	137	1.00	2970	94
31	660	674	132	137	1.00	2970	94
32	660	674	132	137	1.00	2970	94
33	660	674	160	168	1.00	1485	94
34	660	674	160	168	1.00	1485	94
35	660	674	160	168	1.00	1485	94
37	660	674	300	307	6.67	1400	95
40	660	674	300	307	6.67	1400	95
41	660	674	300	307	6.67	1400	95
42	10000	10000	1315	87.2	0.83	2975	95
46	660	674	47.5	53.2	2.00	1470	91

Table 4 Field results of nameplate method, simple current method and modified current method

Sr. N°	P_{In} (kW)	No-load current (A)	Nameplate Efficiency (η_n)	η simple current method (%)	η modified current method (%)	η_n-η_{SCM} (%)	η_n-η_{MCM} (%)
1	16.8	10	88	59.2	40.1	28.8	47.9
2	16.8	10	88	59.2	40.1	28.8	47.9
7	44.2	19	92	79.7	73.0	12.3	19.0
10	44.2	19	92	79.7	73.0	12.3	19.0
11	44.3	19,7	92	79.8	73.1	12.2	18.9

15	40.7	19,6	92	79.8	68.1	12.2	23.9
16	40.7	20	92	79.8	67.7	12.2	24.3
17	46.4	22	89.5	76.2	60.8	13.3	28.7
18	45.7	22	89.5	76.2	59.8	13.3	29.7
19	109.2	54	93	75.3	70.9	17.7	22.1
21	108.2	54	93	75.5	70.5	17.5	22.5
22	102.2	40	94	73.5	67.0	20.5	27.0
23	101.9	40	94	73.5	66.8	20.5	27.2
24	102.7	40	94	73.5	67.2	20.5	26.8
25	98.9	47	94	73.5	63.1	20.5	30.9
26	98.2	47	94	73.5	62.7	20.5	31.3
27	100.1	47	94	73.5	63.8	20.5	30.2
28	77.7	40	94	73.5	52.7	20.5	41.3
30	136.6	45	93.5	78.5	76.4	15.0	17.1
31	136.6	45	93.5	78.5	76.4	15.0	17.1
32	136.6	45	93.5	78.5	76.4	15.0	17.1
33	131.5	43	94	74.2	66.2	19.8	27.8
34	133.6	43	94	74.2	66.7	19.8	27.3
35	137.7	43	94	74.2	67.7	19.8	26.3
37	259.7	74	95	78.4	72.7	16.6	22.3
38	259.7	74	95	78.4	72.7	16.6	22.3
39	259.7	70	95	78.4	73.1	16.6	21.9
41	270.1	75	95	78.4	73.8	16.6	21.2
42	1188.6	40	95	86.3	74.4	8.7	20.6
43	1172.8	40	95	86.3	73.3	8.7	21.7
44	1220.3	30	95	86.3	80.3	8.7	14.7

45	41.2	21	90.5	78.6	63.4	11.9	27.1
46	41.2	21	90.5	78.6	63.4	11.9	27.1

Table 5 Field results of separate losses method, slip method, Slip Method with Voltage Compensation and statistical method

Sr.N°	η Separate losses method (%)	η Slip method (%)	η Slip method with voltage compensation (%)	η Statistical method (%)	η_n-η_{SpLM} (%)	η_n-η_{SlM} (%)	η_n-η_{SMVC} (%)	η_n-η_{StM} (%)
1	74.58	64.82	67.60	72.57	13.42	23.18	20.40	15.43
3	76.84	64.82	67.60	74.83	11.16	23.18	20.40	13.17
6	75.99	62.97	65.67	73.98	12.01	25.03	22.33	14.02
7	74.92	73.98	77.15	73.36	17.08	18.02	14.85	18.64
8	74.92	73.98	77.15	73.36	17.08	18.02	14.85	18.64
9	78.45	73.98	77.15	76.89	13.55	18.02	14.85	15.11
10	78.97	73.98	77.15	77.41	13.03	18.02	14.85	14.59
11	76.93	67.69	70.59	75.33	15.07	24.31	21.41	16.67
12	76.17	67.69	70.59	74.58	15.83	24.31	21.41	17.42
13	76.55	67.69	70.59	74.96	15.45	24.31	21.41	17.04
14	77.11	67.69	70.59	75.51	14.89	24.31	21.41	16.49
17	77.65	76.36	79.64	75.78	11.85	13.14	9.86	13.72
18	74.32	74.67	77.87	72.48	15.18	14.83	11.63	17.02
19	63.45	66.00	68.83	61.80	29.55	27.00	24.17	31.20
20	61.57	74.16	77.34	59.71	31.43	18.84	15.66	33.29
21	83.73	71.24	74.29	82.16	9.27	21.76	18.71	10.84
24	68.29	69.98	72.98	66.65	25.71	24.02	21.02	27.35
26	65.91	67.10	69.98	64.20	28.09	26.90	24.02	29.80
27	65.87	71.85	74.93	64.19	28.13	22.15	19.07	29.81
30	67.77	76.04	79.30	66.29	25.73	17.46	14.20	27.21

31	67.80	73.22	76.36	66.32	25.70	20.28	17.14	27.18
33	71.50	74.33	77.52	69.60	22.50	19.67	16.48	24.40
34	72.03	72.21	75.30	70.19	21.97	21.79	18.70	23.81
35	70.77	70.22	73.23	68.98	23.23	23.78	20.77	25.02
36	66.01	72.73	75.85	64.24	28.99	22.27	19.15	30.76
39	69.09	73.72	76.88	67.32	25.91	21.28	18.12	27.68
40	68.37	70.88	73.92	66.67	26.63	24.12	21.08	28.33
41	68.11	70.88	73.92	66.41	26.89	24.12	21.08	28.59
42	78.59	76.28	76.28	77.27	16.41	18.72	18.72	17.73
43	78.33	77.31	77.31	76.98	16.67	17.69	17.69	18.02
44	84.06	74.30	74.30	82.77	10.94	20.70	20.70	12.23
45	67.56	72.94	76.07	65.79	22.94	17.56	14.43	24.71
46	67.56	72.94	76.07	65.79	22.94	17.56	14.43	24.71

Discussions and comparison of different methods

The no-load current corresponds to the current measured during the no-load test, taking for example the motor number 22, its no-load current is 54 A, while the empirical no-load current value of this motor is equal to I_0=39.23A, which is well below than 54A, which shows that the losses have risen enormously due to rewinding, refurbishment and the quality of the induction motor insulation, that explains the decrease in the efficiency of motor. For high power motors, efficiencies calculated by simple current method and modified current method are close, for example motors number 22, 23 and 24. However, there is a large difference between those efficiencies for low-power motors, which is the case for motors number 1and3.

Table 6 Comparison advantages and inconvenient

Method	Advantages	Inconvenient
Slip method	-Simple in its use -The data to be overcome are accessible -Is completely non-intrusive	-The assumed assumption is not verified in reality -External environmental disturbances (temperature, tension) influence the accuracy of this method -Do not provide accurate estimation of efficiency
Slip Method with Voltage Compensation	-Easy to use -Data are available	-The supposed assumption is not verified in reality

		-The method is still incorrect
Nameplate method	-Least intrusive method	-This method has poor accuracy
Simple current method	-Potentially simple in usage -Data to meet are available	-The assumed assumption on the current is not always true because of the existence of the disturbances -Good validity for high power motors
Modified current method	-Improves the accuracy of the simple current method -Data to be used are accessible	-Each motor must be tested at load test
Equivalent-Circuit Methods	-The equivalent circuit parameters are known -Estimate motor efficiency under several conditions is possible	-Very heavy and difficult method
Separate losses method	-Accurate method	-It is not a good method for an in-situ -Estimation because it is complicated
Air gap Torque method	-Less error in efficiency estimation	-Several tests are required -Complexity of calculation

If we want to be more precise, the no-load current should not be ignored, because its value is important, as well, which promotes the simple current method, is the fact that it does not require a no load test, in our case, we have the no-load current measures for motors in the subject. Therefore, and preferably, it is the modified current method that must be applied because it is more precise and takes account of the no-load current.

For motors of lower power, it is clear that there is efficiency reduction that sometimes reaches 40%, due to the fact that the load is 60% of the full load, the absorbed current is well below the nominal current, as well as the no-load current is not negligible.

The different efficiency measurement methods have given values that vary from one method to another. This depends on the accuracy of each method, however, it can generally be concluded that the efficiency of induction motors in this plant varies from 50% to 80%, although some motors have an efficiency that can be less than 40% in a few operating points.

Conclusion

This paper has presented field results of testing forty six induction motors under real conditions by using different methods of estimating efficiency in-situ. This application of the estimation efficiency methods of induction motors has been performed in a big industrial manufacturing facility. More than 10 efficiency-estimation methods are described. Among them, the following seven methods: 1)Nameplate method, 2)Simple current method, 3)Modified current method, 4)Separate losses method, 5)Slip method, 6)Slip method with voltage compensation and 7)Statistical method, has been applied and experimental results are presented. Another major contribution of this paper is the sharing of field result of these traditional methods with researchers for further interpretation and use to become nonintrusive. Some remarks and practical points are reported briefly for industrial manager to inspire from this study that can assist to make effective cost decisions in replacing the inefficient motors with more efficient ones by using the assessment of overconsumption.

References

[1] IEEE Standard Test Procedure for Polyphase Induction Motors and Generators, IEEE Std112, IEEE Power Engineering Society, New York. 2004.

[2] http://www.nrcan.gc.ca/energy/products/reference/15297.

[3] M. Thirugnanasambandam, M. Hasanuzzaman, R. Saidur, M.B. Ali and S. Rajakarunakaran, D. Devaraj, N.A. Rahim ''Analysis of electrical motors load factors and energy savings in an Indian cement industry'', Vol. 36, Iss. 7, pp. 4307–4314, Energy, July 2011.

[4] R. Saidur, ''A review on electrical motors energy use and energy savings'', Renewable and Sustainable Energy Reviews, Vol. 14, pp. 877–898, 2010.

[5] Fernando J. T. E. Ferreira and Aníbal T. de Almeida ''Method for in-field evaluation of the stator winding connection of three-phase induction motors to maximize efficiency and power factor'' IEEE Transaction on Energy Conversion, July 2006.

[6] Fernando J.T.E. Ferreiraa and Aníbal T. de Almeidaa ''Induction motor downsizing as a low-cost strategy to save energy European Commission. Vol. 24, pp 117–131 Journal of Cleaner Production, March 2012.

[7] R. Rajalakshmi and V. Rajasekaran ''Improvement of energy efficiency through power quality by the compensation of harmonics with shunt active power filter'', International Conference on Recent Advancements in Electrical, Electronics and Control Engineering, 2011.

[8] IEC Std 61972, "Method for Determining Losses and Efficiency of Three-Phase Cage Induction Motors", First edition 2002-11, IEEE.

[9] A. Boglietti; A. Cavagnino, M. Lazzari and M. Pastorelli, "Induction Motor Efficiency Measurements in accordance to IEEE 112-B, IEC 34-2 and JEC 37 International Standards", IEEE, pp. 1599-1605, 2003.

[10] A Boglietti, A Cavagnino, M. Lazzari and M. Pastorelli, "International Standards for the Induction Motor Efficiency Evaluation: a Critical Analysis of the Stray-Load Loss Determination", IEEE, pp. 841-848, 2003.

[11] Bin Lu, Thomas G. Habetler and Ronald G. Harley, ''A survey of efficiency-estimation methods for in-service induction motors'', IEEE Transaction on Industry Applications, Vol. 42, No. 4, July/August 2006.

[12] J. Hsu, J. Kueck, M. Olszewski, D. Casada, P. Otaduy and L. Tolbert, "Comparison of induction motor field efficiency estimation methods", IEEE Trans. Ind. Appl. Vol. 34, no. 1, pp. 117–125. Jan/Feb 1998.

[13] A. Wallance, A. Von Jouanne, E. Wiedenbrug,E. Matheson and J. Douglass "A laboratory assessment of in-service and non-intrusive motor efficiency testing methods" Electr. Power Compon. Syst, Vol. 29, no. 6, pp. 517–529, Jun 2001.

[14] V.P. Sakthivel and S. Subramanian ''On-site efficiency evaluation of three-phase induction motor based on particle swarm optimization Energy'', Energy, Vol. 36, pp.1713-1720, 2011.

[15] J. R. Holmquist, J. A. Rooks, M. E. Richter "Practical approach for determining motor efficiency in the field using calculated and measured values "IEEE Trans. Ind. Appl. Vol. 40, no. 1, pp. 242- 248, Feb 2004.

[16] F. Ferreira and A. T. de Almeida "Considerations on in-field induction motor load estimation methods", in Proc. IEEE Int. Conf. Electrical Machines, pp. 1-8, 2008.

[17] N. El Khattabi ''Identification Parameters of Induction Motor for Measuring efficiency in Situ'' Thesis in University of Quebec Three Rivers Feb 2009.

[18] Arbi Gharakhani Siraki ‘’Efficiency Estimation of Induction Machines with Limited Measurements’’ Thesis in the Department of Electrical and Computer Engineering. Concordia University Montreal. Quebec. Canada. August 2012.

[19] Motors and Generators. NEMA MG1-2003 Standard, 2003.

[20] J. D. Kueck “Development of a method for estimating motor efficiency and analysing motor condition” in Proc. IEEE Pulp and Paper Ind. Tech. Conf, pp. 67–72, Jun 1998.

[21] Bin Lu, Cao Wenping, I. French, K. J. Bradley and T. G. Habetler"Non-intrusive efficiency determination of in-service induction motors using genetic algorithm and air-gap torque methods" in Conf. Rec. IEEE 42nd IAS Annual Meeting, pp. 1186-1192, 2007.

[22] J. S. Hsu, P. L. Sorenson, "Field assessment of induction motor efficiency through air-gap torque" IEEE Trans. Energy Convers., Vol. 11, no. 3, pp. 489-494, Sep 1996.

Towards automatic determination of power drive system losses on the basis of EN50598-2

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Abstract

According to Ecodesign Directive (Directive 2009/125/EC) electric drives as energy-using/related products will be mandatorily assessed in terms of energy efficiency. Especially, procedures regarding power losses determination as well as efficiency classification of complete drive module (CDM) and power drive system (PDS) are defined by the European Standard EN 50598-2. The standard defines three methods for PDS loss determination: a) calorimetric b) input-output power measuring and c) calculation. However, the development of a unified automatic method of determining efficiency classes of PDSs is a challenging issue due to the plethora of optimization techniques adopted for system efficiency enhancement.

This paper focuses on automatic determination of PDSs losses via calculation over a wide range of systems nominal power and highlights the key factors influencing on PDS efficiency. The calculated losses of twelve commercial drive systems are compared with the corresponding results derived from input-output method. The Euclidean metric is introduced as a mean to compare the PDS losses by the two methods referring to the same operating point. In that way, results can be evaluated in terms of similarity. The average Euclidean distance is also exploited for methods assessment for partial load operation. The adopted sophisticated calculation tool decisively facilitates towards automatic PDS losses data generation. Finally, a framework for PDS losses data management is proposed, which couples the generated IES data with further application oriented webtools designed for dimensioning, energy saving, investment progress, documentation provision

Introduction

European Union (EU) enlists energy efficiency as a key factor for improving environmental performance of energy related products and strengthening the energy security by reducing its dependence on fossil energy. In 2008, the announcement of European Energy and Climate Plan serve this purpose. A legislation package is established that determines the goals and the means of implementing the 20-20-20 strategy by 2020. The strategy identifies headline targets for boosting growth in EU and refers to:

- a) at least 20% reduction of greenhouse gas emissions, compared to 1990 level or by 30% if the conditions are right,
- b) increase the renewable energy ratio in final energy consumption to 20%, and
- c) achieve 20% increase in energy efficiency.

Aiming on energy efficiency improvement of products, Ecodesign and Energy Labelling Directives were established in 2009 and 2010 accordingly. This framework along with associated implementing measures (e.g. regulation 640/2009/EC for electric motors) and Standards constitute an effective tool that facilitates the elimination of the least performing products from the market and contributes on EU 2020 objectives. Compliance to the Standards enables manufacturers to confirm that their products satisfy the laws by self-declaration, while supports industrial competitiveness and innovation for more energy efficient products; this is also applied to electric drives.

Within that context, the requirements for drive systems used in electrically powered machines as well as their evaluation in terms of efficiency levels or power losses are defined in the EN 50598 standard series. Hence, energy efficiency improvement is supported through a systematic selection of the most efficient drive technology. Especially, that standard series comprises three parts. Part 1 specifies the methodology to determine the energy efficiency index of an application based on the extended product approach (EPA) and semi analytical models (SAMs). These methods are required for analysis of every applicative electrical system analysis and refer to the powered drive system (PDS) and the installed driven equipment (the extended product). Part 2 provides indicators for assessing energy efficiency performance and classification of drive systems with rated power from 0.12 kW up to 1 MW and rated voltage lower than 1 kV. Finally, part 3 of the standard specifies requirements regarding essential basic environmental conscious design of products and declaration of the drive systems. Such an approach indicates a system design that has to reach an efficiency level rather than a design based on choosing components at best efficiency point [1, 2].

Regarding motor losses determination, there is different group of international standards and technical specifications to be used (IEC 60034-30-1, IEC TS 60034-30-2, IEC TS 60034-2-3). Especially, the standard 60034-30-1 determines efficiency classes for grid connected motors. In parallel, the technical specification 60034-30-2 focuses on efficiency classification of converter supplied motors, while the IEC 60034-2-3 will specify test methods for determining losses and efficiencies for the same type of AC motors.

This paper focuses on power losses determination of drive systems referred as PDS in the standard EN50598-2, with emphasis on calculation approach challenges. An overview of the definitions related to the system components along with power losses determination methods is described. Additionally, the power losses distribution of a low voltage high power PDS is demonstrated exploiting standard mathematical equations. In this example, distinct parameters affecting power losses of a drive system as well as their correlation are addressed. The contribution degree of different system components on PDS power losses can indicate the optimization possibilities for a system supplier. Additionally, a comparative study concerning losses determination of twelve commercial drive systems with rated power from 4 kW up to 535 kW and different efficiency levels is presented. The PDS losses of the aforementioned drive system are determined by both input-output method and a sophisticated calculation tool. Both methods inherit uncertainty which is rather difficult to be precisely determined for the whole range of systems rated power. For that reason, both methods results referring to the same operating point are considered to be of the same significance. Therefore, the Euclidean metric is introduced for assessing the determined PDS losses in an operating point expressing results convergence. Additionally, the average Euclidean metric is adopted for accessing results convergence for all 8 operating points. In that way, the effectiveness of the sophisticated calculation tool in terms of accuracy is evaluated. It is important to notice that the development of such a tool significantly contributes towards automated PDS losses data generation, which can decisively reduce time delivery and costs. Finally, a framework for PDS losses data management exploiting this tool is proposed. The introduced framework couples the generated IES data with further application oriented Webtools designed for dimensioning, energy saving, investment progress, documentation provision, etc …

System overview and PDS losses determination methods according to EN 50598

In the EN 50598-2 standard the complete electric drive system referred as PDS is considered to be consisted by the power electronics converter (the BDM) plus the feeding section and auxiliaries referred as Complete Drive Module (CDM) and the motor, as depicted in Fig.1. Additionally, the standard defines energy efficiency classes (IE classes for CDM and IES classes for PDS) by providing limits for power loss and test procedures for the classification. To maintain assessable data and complexity in reasonable limits the loss determination procedure is carried out at eight predefined torque producing current-frequency operational points for the CDM and eight speed-torque points for the PDS, as shown in Fig. 2a and Fig. 2b. The determined losses must be compared with the losses of a reference CDM (RCDM) and a reference PDS (RPDS) accordingly. The percentage of converter or drive system losses in respect to the losses of a corresponding RCDM or RPDS is utilized for the efficiency class determination.

Concerning RCDMs, the standard provides the reference losses that are exploited for benchmarking the power electronic converters of different suppliers. For every source contributing to CDM losses (inverter conduction and switching losses, rectifier conduction losses, input choke, DC link, current rail, control, standby and cooling losses) a model is described. For assessing the losses of an industrial CDM a test load is considered, since the torque producing current does not fully reflect to the CDM output current. Essentially, the test load must fulfill the current ratio and displacement factor requirements in every operating point for different rated powers as described in [3]. It should be noticed that the classification point of a CDM correspond to the 90 percent of its rated frequency. The reason is for avoiding overmodulation region of the converter.

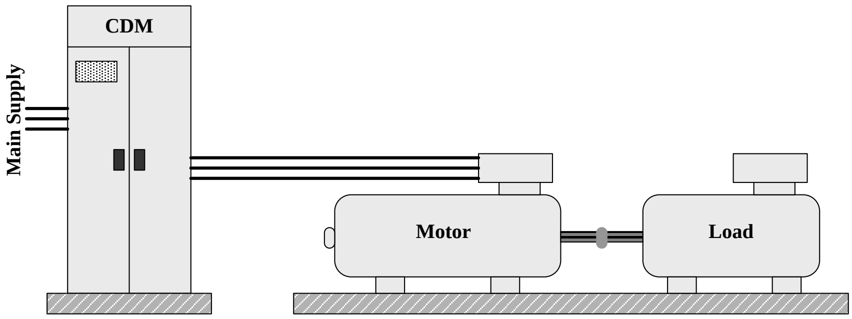


Figure 1: Basic diagram of PDS as described by the EN50598-2.

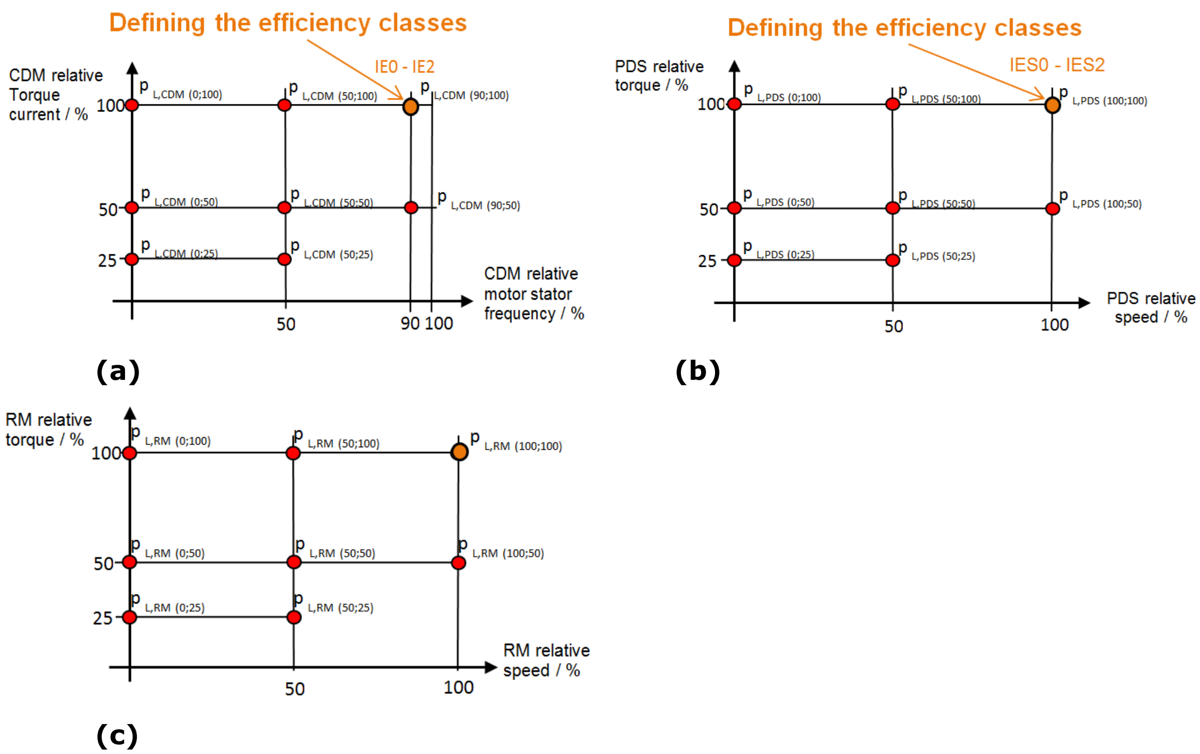


Figure 2: Operating points to determine the relative power loss for (a) the CDM, (b) the PDS and (c) the reference motor [3].

The definition of the RPDS poses the losses of the reference motor (RM) to be computed in the eight torque-speed operating points, as depicted in Fig. 2c. The motor losses as described in the standard consist of stator winding, rotor winding, iron, additional load (stray), friction, windage and additional harmonic losses. Especially, the additional harmonic losses of the RM in converter operation are computed as the 15 percent of the motor losses in the nominal operating point with sinusoidal supply for motors with rated power up to 90 kW. In parallel, additional harmonic losses for motors with rated power above 90 kW are considered to be the 25 percent of the corresponding losses. The outcome of such computation should be added for every operating point. It should be noticed that the RM losses cannot be utilized for motor efficiency class determination. This purpose is served by the standard 60034-30-1 and the technical specification 60034-30-2 for sinusoidal supply and converter fed motors respectively. In parallel, the technical specification 60034-2-3 defines converter fed motor losses exploiting a test converter. However, the motor losses defined by the 60034-2-3 should not be utilized for PDS efficiency classification due to the restrictions of the test converter. This originates from PDS definition where optimization techniques are allowed to be applied in drive system design and operation. In other words, an optimization scheme can contribute to system efficiency irrespectively to motor efficiency class by limiting the side effects of the specific converter-motor interconnection [1-2, 4].

The losses of the RPDS are computed based on the RCDM and RM losses in the eight operating points as described above. Especially, the PDS losses in the operating point (100,100) are based on the (90,100) RCDM losses and (100,100) RM losses. This is assumed since the increased motor losses in the operation area near nominal torque and speed of the drive will be compensated by the decreased CDM switching losses. Converters with Space Vector Modulation (SVM) without overmodulation as the RCDM described in the standard, face the issue of limited output voltage. Thus, the motor losses will be increased for the nominal mechanical power operating point due to the lack of overmodulation. Considering this fact, a weighting factor x (according to EN50598-2), which is the ratio of the rated motor voltage to maximum CDM output voltage, is introduced for computing RPDS losses in the (100, 100) point as follows:

$$P_{L,RPDS(100,100)} = P_{L,RCM(90,100)} + x.P_{L,RM(100,100)} \quad \text{Eq.(1)}$$

Both CDM and PDS classification is based on power losses rather than on efficiency, in contrast to motors classes. This originates from the fact that an energy effective (in terms of energy saving) process cannot be directly correlated with PDS efficiency. As an example the comparison between a Direct On Line (DOL) pump versus a pump incorporating a variable frequency drive can be adopted. Even though the efficiency for a given operating point can be lower in the second case, the whole process is more efficient i.e. the energy saving potential is incomparably greater.

The EN 50598-2 standard defines the following three methods for the losses determination of the CDM and the PDS:

a) calorimetric method; the power losses are established on the basis of the coolant flow rate and the temperature differences measurement. The exact testing conditions are described in detail in the standard.

b) input-output method; The input and output power of the CDM/PDS are directly measured via power analyzers and power losses are computed by the difference. Particularly, for the CDM losses the electrical power in the input and output of the power electronic converter have to be measured. Accordingly, for the PDS losses the electrical power in the input of the converter and the mechanical power at the motor shaft are required.

c) calculation; the CDM and PDS losses are calculated according to the mathematical models provided in the standard. However, manufacturers are free to use their own theoretical models or simulations to determine the power losses at their own discretion.

All three methods are applicable for power losses determination of electric drives and their implementation differs in terms of uncertainty and effort. According to [5], the accuracy of the input-output power measurement method depends on the efficiency level and the introduced error is increased in partial load in comparison to full load operation. The decisive factor in the input-output measurement is the accuracy of the measurement equipment depending on power factor, frequency spectrum and fundamental frequency. The accuracy issue might also affect classification process for very high efficiency systems. On the other hand, calorimetric measurement and calculation approaches preserve a relatively low inaccuracy for a broad efficiency band irrespectively to nominal power of the system. The highest accuracy can be obtained by a high performance calorimetric method while influenced by heat dissipated via hosing and slots. In both calorimetric and input-output measurement methods the investigated drive system must reach a thermal steady state. Additionally, the duration of the measurement also depends on the volume and the thermal constant of the drive. As the volume of drives increases, duration of experiments extends. Especially, the implementation of the calorimetric method is usually limited to PDS with relatively low nominal power. Moreover, the aforementioned experimentally based methods require the investigated converter and motor to be available for tests. However, such a requirement further raises time delivery and costs. In parallel, testing procedure of every converter – motor possible combination might not be feasible for a manufacturer with a large portfolio. As regards calculation method, the loss components can be segregated and reveal the potential for further and targeted improvement of products. The required information of power loss determination of system components is often available. In case of insufficient or inadequate accuracy of the provided information measurements can be made to identify the parameters exploited by the experience based mathematical equations for describing system part losses. The accuracy of the calculation method is strongly affected by parameter value selection. Relatively limited effort characterizes both calculation and input-output method. However, providing flexibility on product selection strongly facilitates customers to meet their needs and preferences. Such a capability can be offered effectively only by the calculation approach.

System optimization challenges – PDS losses determination through measurement and calculation

The power loss distribution of a reference PDS with rated power of 400 kW is analyzed as an example in this section in order the contribution degree of each loss source on total losses to be quantitatively determined. The investigated RPDS consists of a RCDM and RM, where all parameter values are provided in the standard. The RCDM is a conventional three phase 2-level converter for speed and torque control of electric motors. The basic parts of the converter are an input choke, a diode rectifier, DC link capacitors, a three phase IGBT inverter along with control and cooling subsystems. It is assumed that SVM is utilized for the whole operating area of the converter without overmodulation. As regards the RM, a three phase asynchronous motor is utilized. The analysis along with the power loss distribution presented in Fig.3 is based on the mathematical expressions provided by the standard. The equations concerning the motor are only valid for asynchronous machines. Systems with other motor types will be considered in future editions of the standard.

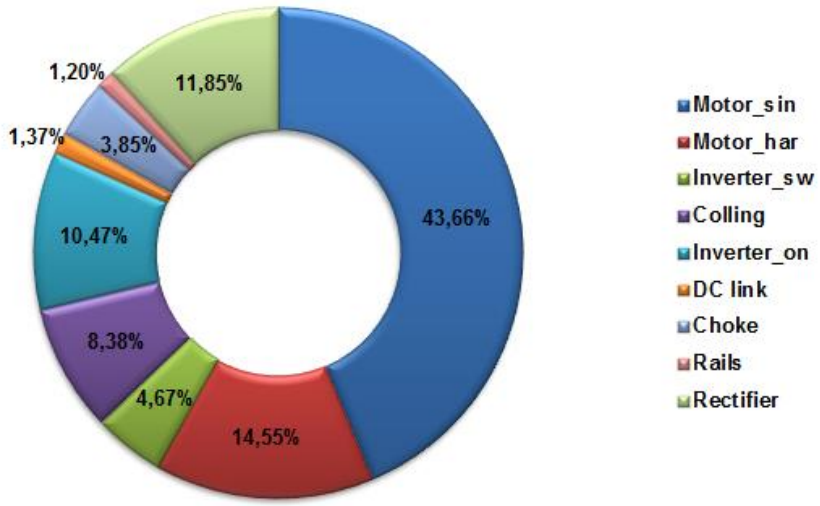


Figure 3: Losses distribution for a 400 kW reference PDS (sw: switching losses, on: conduction losses, sin: losses of the fundamental motor frequency, har: losses of the higher harmonics).

In Fig.3 the power losses distribution of the investigated PDS is presented. Results indicate that the motor losses in the fundamental frequency (referring to sinusoidal supply of a motor) make the largest contribution to the total PDS losses (43,66%). However, significant is the contribution of the additional harmonic losses of the motor and conduction losses (both for rectifier and inverter) while the cooling and inverter switching losses follow.

The dominant fundamental frequency motor losses mainly depend on fundamental voltage and current amplitude for a given motor design. Considering a relatively common case of commercial converters that utilize SVM without overmodulation, the maximum output voltage of the converter for the fundamental frequency lies at the range of 370 V. When this converter is combined with a motor of 400 V rated voltage, a substantial increase in motor losses occurs under nominal load operation. The raise in motor losses can be calculated with the help of factor x defined in standard and leads to approximately 8 percent increase of the losses for the aforementioned example. Therefore, a challenge for optimizing PDS performance is raised for the manufacturers. Possible considerations for the manufacturers could be the increase of maximum output voltage of the converter for the fundamental frequency exploiting special modulation techniques such as optimized pulse patterns in the overmodulation area. In the same direction, an alternative solution could be a specific motor design concerning geometrical characteristics or special motor windings in order the nominal motor voltage to be reduced matching converter output voltage at nominal load.

An important system-related part of the PDS power loss is the additional harmonic losses for the motor. This kind of losses can be strongly influenced by the utilized modulation technique and especially in the high modulation index (MI) area (MI is defined as the ratio of peak magnitudes of the modulating waveform and the carrier waveform). Furthermore, the converter switching losses are also influenced by the modulation technique apart for the semiconductor characteristics. Therefore, a system manufacturer, since more detailed information about every part of the system are available, can minimize PDS losses by optimizing modulation types.

System related losses could be considered also by the conduction losses of the converter and the CDM cooling losses. They consist the 11,85%+10,47%+8,38%=30,7% of the PDS losses. Especially, conduction losses depend on the rms values of the converter output current, which also includes higher harmonic component of current. By minimizing the harmonic spectrum of current, reduced conduction losses can be achieved. A converter cooling system that can be adjustable to converter load can also contribute on PDS losses decrease.

Calorimetric or input-output measurement methods for PDS losses determination do not require deep knowledge of the internal processes over drive operation, since there are black box procedures. However, the investigated converters and motors have to be available for tests. Considering that these PDS losses determination methods pose a time consuming experiment the time delivery as well as the costs are raised. Additionally, accuracy dependency on efficiency level of the input-output method might raise classification issues for the very high efficiency systems.

On the other hand, the development of sophisticated calculation tools for system losses determination demands a clear interpretation of the parameters and phenomena affecting drive system efficiency as well as the way these are correlated. The design of an effective calculation tool efficiency mapping on existing products is ameliorated in terms of accuracy. In that way, the development of new products with enhanced efficiency is enabled. It should be also mentioned that the adoption of an accurate and time effective calculation method can decisively facilitate configuration phase of a customer project. During this phase multiple combinations of motors converters and settings can be compared in terms of efficiency in order to meets application restrictions as well as customer needs.

In sequence, PDS losses determination of twelve commercial drive systems via a sophisticated calculation tool is presented. The effectiveness of the exploited calculation tool is validated by a comparative study in respect to experimental input-output method. In Table 1, distinct technical characteristics of the investigated drive systems are presented. The set of these drive systems refers to a wide range of nominal power (4 kW – 535 kW) and different efficiency motor levels.

The relative PDS losses of the twelve investigated drive systems i.e. the power losses related to the nominal power of each drive system are presented in Table 2. The $p_{L,PDS}$ data are determined for the classification operating point, namely for 100% of the nominal motor speed and for the 100% of the nominal motor torque both via the adopted sophisticated calculation tool and via input output method. In parallel, the relative losses of the RPDS are given for every case.

The experimentally determined PDS losses require the utilization of different measurement devices in terms of current transducers and torque meters concerning the rated power range of the investigated drive systems in order to be accurately defined [6]. In parallel, the uncertainties of the calculation method lay on the utilized parameters and models in different drive system parts. These facts constitute rather impractically to precisely determine inherited uncertainty of both methods. It is assumed that both method results referring to the same operating point are considered to be of the same significance and thus none of the results can be considered as the comparison basis.

Table 1: Technical characteristics of the investigated drive systems

Drive System	Rated Power[kW]	Rated Motor Voltage [V]	Number of Motor poles	Rated Motor Speed [rpm]	Corresponding Motor Efficiency Class referring to IEC64000-30-1
1	4	400	4	1500	IE1
2	15	400	4	1500	IE1
3	30	400	4	1500	IE2
4	45	400	4	1500	IE2
5	55	400	4	1500	IE2
6	90	400	4	1500	IE2
7	300	380	6	750	IE2
8	320	380	6	750	IE2
9	335	380	4	1500	IE3
10	390	380	6	1000	IE2
11	450	380	4	1500	IE2
12	535	380	4	1500	IE2

Table 2: Relative PDS losses of the investigated drive systems in the nominal operating point [100,100] as defined through input-output and calculation methods along with the corresponding RPDS losses

Drive System	Rated Power [kW]	Relative PDS losses in the efficiency classification operating point [100,100] determined by:		Relative losses of the corresponding RPDS in the [100,100] point
		Measurement $p_{L,PDSmeas}$ (%)	Calculation $p_{L,PDScal}$ (%)	$p_{L,RPDS}$ (%)
1	4	22.75	23.25	29.11
2	15	15.38	15.49	19.88
3	30	11.84	11.97	16.84
4	45	10.89	10.67	15.46
5	55	11.09	10.73	14.76

6	90	9.22	9.27	13.60
7	300	7.63	8.17	12.10
8	320	8.92	9.11	12.09
9	335	6.89	7.11	12.09
10	390	7.16	7.56	12.09
11	450	7.41	7.28	12.08
12	535	6.72	6.29	12.08

Such a declaration is also indirectly supported by the standard EN50598-2 since it is considered that when the calculation method is adopted the losses should be increased by 10%, while lower permissible uncertainty limits (0,2%) for the measurement equipment is determined for the input-output method. On the contrary, a metric should be exploited for comparing pairs of variables across cases which can evaluate their similarity. Therefore, the Euclidean metric is introduced for assessing the determined PDS losses in an operating point expressing results convergence.

The Euclidean metric is the function d: $\mathbf{R}^n \times \mathbf{R}^n \rightarrow \mathbf{R}$ that assigns to any two vectors in Euclidean **n**-space **x** =(x_1,...,x_n) and **y**=(y_1,...,y_n) the number:

$$d(x,y) = \sqrt{(x_1 - y_1)^2 + \cdots + (x_n - y_n)^2}$$
Eq.(2)

and gives the "standard" distance between any two vectors in $\mathbf{R}^n$.

For the given case, the Euclidean metric for results assessment of every PDS in an operating point is defined as follows:

$$d(p_{\mathrm{L,PDScal}}, p_{\mathrm{L,PDSmeas}}) = |p_{\mathrm{L,PDScal}} - p_{\mathrm{L,PDSmeas}}|$$
Eq.(3)

In Fig.4 the comparative results expressed by Euclidean metric concerning calculation and input-output methods are presented. Results indicate that the relative PDS losses deviation between two methods is limited up to only 0.5% approximately. It should be noticed that the investigated drive systems consist of motors with different configurations (e.g. geometrical characteristics and cooling types) and converters with optimal system settings. The resulted deviation proves that the adopted tool calculates precisely PDS losses over a wide range of drive systems rated power and under different configurations. Such a small deviation practically does not have any impact on correct efficiency class determination of the twelve commercial drive systems. This claim is confirmed by Table 3.

Apart from the nominal operating point, it is critical to know precisely the amount of power losses of a PDS to partial load operation and especially for applications that have a particular load profile. According to EN 50598-2, the PDS losses should be determined in the 8 operating points. In that way, the losses for the intermediate points, if necessary, can be estimated. Therefore, the PDS losses determined via the adopted calculation and the input-output method in the 8 operating points are compared. Three drive systems with nominal mechanical power of the motor 30 kW, 320 kW and 335 kW (drive systems 3, 8 and 9 according to Table.1) are selected to indicate results convergence of the two methods in partial load operation. Essentially, the drive systems 3 and 8 are arbitrary selected corresponding to small (≤90 kW) and large (>90 kW) drives as categorized by EN 50598-2. Even though drive system 9 has similar nominal power with system 8, its utilized motor has a higher efficiency level due to special structural design. This drive system is selected to highlight the importance of a calculation tool to take into consideration efficiency optimization setups.

The average Euclidean distance is exploited for evaluating of the PDS losses in 8 operating points between calculation and measurement for a given drive system. This metric is defined as average distance between all pairs of variables, as follows:

$$d_{avg}(p_{L,PDScal}, p_{L,PDSmeas}) = \frac{1}{8}\sum_{i=1}^{8} d_i(p_{L,PDScal}, p_{L,PDSmeas})$$
Eq.(4)

where $d_i(p_{L,PDScal},p_{L,PDSmeas})$ is the Euclidean metric at the operating point i, as defined by Eq.3. Essentially, this metric expresses results similarity of the two methods for the whole operational area of a given drive system.

The power losses data for the three PDSs are depicted in Fig.5 as derived from both methods. The average Euclidean distance for the three drive systems with 30 kW, 320 kW and 335 kW rated power is 0.16%, 0.20% and 0.21%, respectively. These small deviations prove calculation tool accuracy also for partial load operation of the drive systems. It should be noticed that the maximum deviation i.e. the maximum value of the Euclidean metric is only 0.36% and occurs at 50% of nominal motor speed and 25% of nominal motor torque of the 300 kW drive system. In general, accuracy issues might be raised especially for the input-output measurement method in the low frequency operating area, i.e. the (0%,25%), (0%,50%) and (0%,100%) operating points. However, the presented results concerning Euclidean metric ($d_i(p_{L,PDScal},p_{L,PDSmeas})$) in these points indicate a high similarity degree for both losses determination methods.

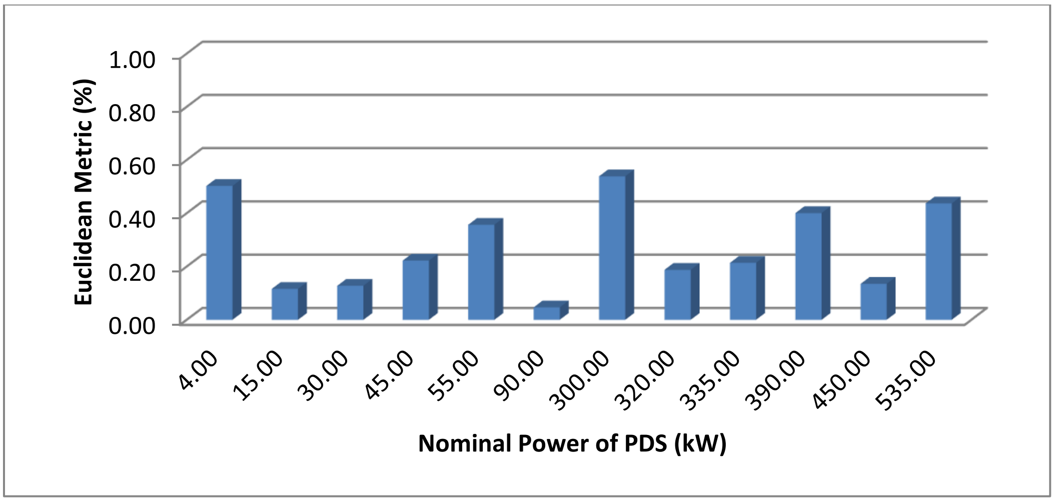


Figure 4: Euclidean metric as a mean to assess results convergence between the adopted calculation tool and the input-output method for the twelve investigated drive systems in [100,100] operating point.

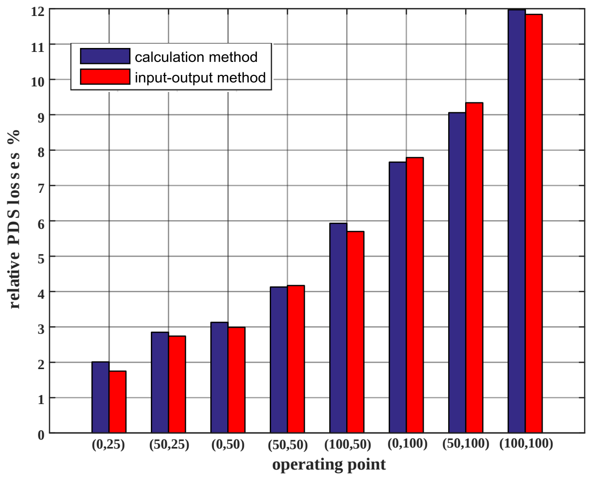
Table 3: Efficiency classes of the investigated drive systems as defined through input-output and calculation methods

Drive System	Rated Power [kW]	Efficiency class according to EN50598-2 determined by:	
		Measurement	Calculation
1	4	IES1	IES1
2	15	IES2	IES2
3	30	IES2	IES2
4	45	IES2	IES2
5	55	IES2	IES2
6	90	IES2	IES2
7	300	IES2	IES2
8	320	IES2	IES2
9	335	IES2	IES2
10	390	IES2	IES2
11	450	IES2	IES2
12	535	IES2	IES2

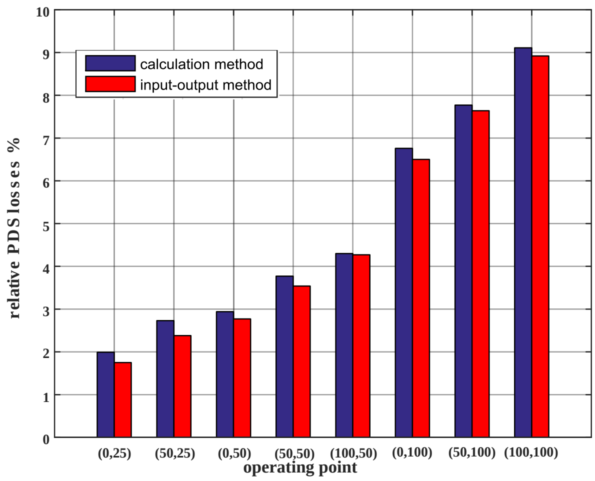
PDS losses data management framework

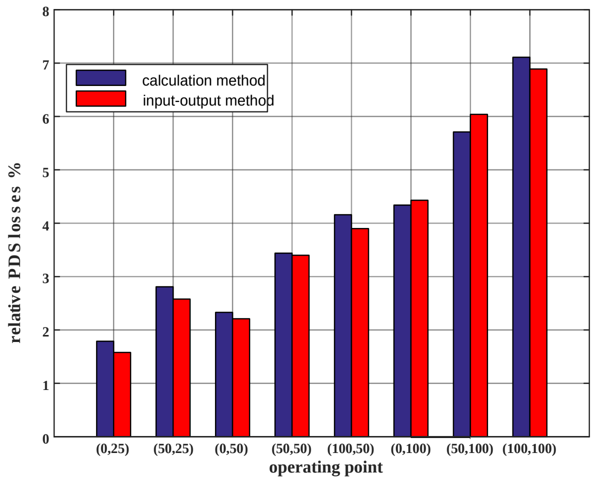
The EN50598-2 requires from the manufacturer to provide both the IES rating and the losses values in all eight operating points of a PDS in product documentation. As it is mentioned above, optimized setups are allowed to be exploited for minimizing drive system losses for PDS rating. In this case, the huge amount of the possible combinations between motor, converter and system settings constitute rather infeasible to determine the 8 operating point losses in the laboratory for a supplier with large portfolio. Within that context, three possible paths are recommended for generating and organizing data concerning PDS losses:

- PDS losses data are calculated in advance for predetermined motor, converter combinations along with essential system settings – parameters as acquired after market analysis,
- PDS losses data are calculated on demand when special configurations are required in motor/converter design or in settings as posed by application restrictions,



(a)





(b) (c)

Figure 5: PDS losses for the 8 operating points of drive system 3 (a), 8 (b) and 9 (c) as determined via the adopted calculation tool and input-output method.

- PDS losses data are defined via measurement on demand in case of critical applications, complex configurations or for data verification by customer inquiry.

The first and second path require the development of a sophisticated calculation tool while the third products availability, accurate measurement equipment and increased time and cost. Concerning the first path a PDS losses data management framework is presented in this work, shown in Fig.6.

Initially, data concerning different motors and converters are stored in a database which also contains products combinations. However, calculation of PDS losses for a given drive depends on system settings. For that purpose parameters such as voltage supply, converter switching frequency, control scheme etc., have to be predefined and taken into consideration for PDS losses calculation. The generated data are stored into an internal database which also enables version management. An integrated verification process serves the purpose of data supervision. The generated data are stored into a central database which is exploited by tools for further calculations or representations and company webpages, directly available to customers. It is important to notice that two different databases are utilized in order to avoid the release of data of products which are under development. The aforementioned tools provide webservices such as:

- datasheet compilation,

- product or technology assessment concerning energy saving,
- power consumption analysis
- investment evaluation for specific applications (e.g. pumps and fans) and
- product recommendation

under dimensioning and application restrictions combined with special installation services.

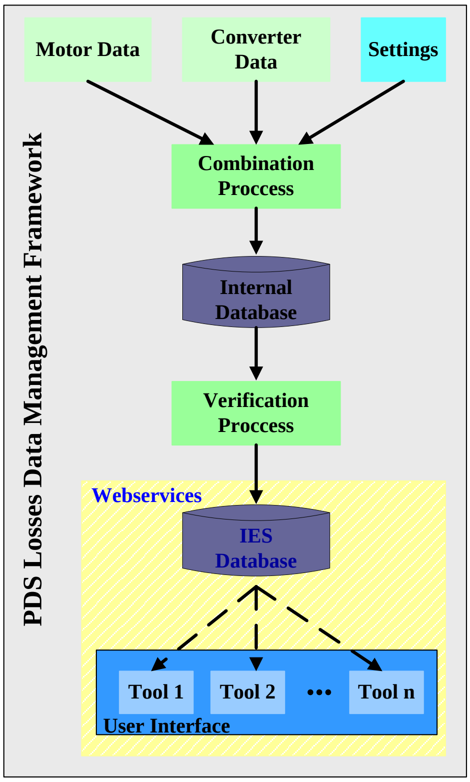


Figure 6: Proposed PDS losses data management framework.

Conclusion

This paper provides an overview of the standard EN 50598-2 and focuses on PDS losses determination processes. Losses distribution of a given low voltage high power drive is presented, while the optimization possibilities for such a system are analyzed. In addition, 12 drive systems with rated power from 4 kW up to 535 kW are investigated where their relative losses are determined via input-output and calculation method. The Euclidean metric is proposed for results comparison, since both methods are of the same significance. This comparative study verifies the adopted calculation tool effectiveness and indicates the influence of optimal design versus power losses consideration. Finally, a framework of PDS losses data flow for managing the huge amount of possible combinations between motor and converter type as well as system settings that a system manufacturer can offer is demonstrated.

References

[1] J. Malinowski, W. Hoyt, P. Zwanziger and B. Finley, "Motor and Drive-System Efficiency Regulations: Review of Regulations in the United States and Europe," in IEEE Industry Applications Magazine, vol. 23, no. 1, pp. 34-41, Jan.-Feb. 2017.

[2] B. Weis, “Calculation of losses for frequency converters and drives for a technical standard” (in German), SPS Drives, Nuremberg, November 2013.

[3] Ecodesign for power drive systems, motor starters, power electronics and their driven applications – Part 2: Energy efficiency indicators for power drive systems and motor starters, EN50598-2.

[4] I. P. Tsoumas, H. Tischmacher and P. Köllensperger, "The European Standard EN 50598-2: Efficiency classes of converters and drive systems," 2014 International Conference on Electrical Machines (ICEM), Berlin, 2014, pp. 929-935.

[5] F.W. Fuchs, J. Schröder, B. Wittig, "State of the technology of power loss determination in power converters," presented at the EPE-ECCE Conference, Lille, France, September 2013.

[6] M. Doppelbauer, ‘Measurement uncertainty of direct and indirect efficiency testing of induction machines, International Conference on Energy Efficiency in Motor Driven Systems, 2015.

Novel method for evaluating the iron losses in SMC materials

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Abstract

Industrial systems comprehending reduced losses components are always more and more requested: the Standards push towards the improvement of the efficiency, and this forces to find new solutions to fulfill the constraints. For laminated steels appropriate methods to measure or estimate the iron losses are applied: Epstein frame or Single Sheet Tester (SST) for measurements, FEM simulation and analytical approach to estimate the penetration of the losses due to mechanical processing. In the case of the Soft Magnetic Composites (SMC) the test method normally adopted is the one with toroidal samples, which cannot give information about the losses distribution and the contribution due to processing. For this reason a new method based on a thermographic analysis is proposed: a contactless and non-destructive technique to evaluate the core losses and their distribution has been developed. The principle is based on the observation of the temperature changes distribution on the device surface; a deep elaboration of the temperature information allows to deduce the specific iron losses distribution. In this way it is possible to analyze in details the energetic behavior of the SMC and also to evaluate the impact of some process parameters (molding pressure, orientation etc.) on the losses; moreover the method could be applied to devices of every shape and dimension and adopted also outside the laboratories facilities.

Introduction

In many energy applications the reduction of the losses and the improvement of the efficiency is becoming mandatory. This aspect regards also electromagnetic and electromechanical devices containing components realized with soft magnetic materials [1], [2], where iron losses are located.

Recently, in the field of the electrical machines, new magnetic materials have been proposed and developed [3], [4]; the research has involved on the one hand the use of soft magnetic composites (SMC), to substitute the traditional ferromagnetic sheets [5], and on the other, the adoption of NdFeB bonded magnets in substitution of ferrites. Owing to the development of the powder metallurgy, it is possible to use magnetic powders in substitution of the laminations sheets [6]; though the mechanical processing, and defects or damaged areas, are critical points, affecting the performance of the devices. For such a reason it would be opportune to have the possibility to carefully evaluate the iron losses distribution in such devices [7].

The Soft Magnetic Composites (SMC), used in substitution of ferromagnetic laminations [8]-[10], allow new design criteria and offer several advantages in many applications: "3D" isotropic ferromagnetic behavior, very low eddy current losses, relatively low total core loss at medium and high frequencies, flexible machine design and assembly (with new geometries) [11]-[13]. Under these points of view SMCs represent a good solution, but on the other hand this opens new questions regarding a detailed evaluation of the iron losses. For laminated sheets, processes and machining affect the performances [14], but in a similar way it happens for SMC cores; however some aspects are not easily comprehensible and evaluable with the classic methods [15]-[17].

From the decision to explore new methodologies; different appropriate methods are adopted to measure or to estimate the iron losses: some of them present an innovative approach while others are more traditional [18]-[22]; the Authors propose a contactless and non-destructive techniques.

At that purpose the methods normally adopted in the applications are substantially two, and are based on the measurement of the temperature distribution due to the magnetic material losses [23]: the first is based on the adoption of thermocouples stuck on the surface to be observed, the second on a thermographic method [24]-[27]. The first is not suitable at the scope, as doesn't allow to reach the required definition and resolution, the second is based on a sophisticated thermographic analysis of the device surface. In some experiments, according to the method based on thermographic analysis, the device is placed in a vacuum chamber and observed from a special glass window [24], [25]; the glass of the vacuum chamber could cause also the alteration of the measurement and such particular arrangements is not easily adoptable in common cases; it requires for instance specific dimensions for the apparatus. The Authors propose a method that could be applied to devices of every shape and dimension and adoptable also outside the laboratories facilities avoiding the use of the complicate vacuum chamber [28].

The method consist in the observation of the initial part of the thermal transient, which is linear: with the device operating in rated magnetic conditions, every point of the surface is monitored for intervals of short duration compared to the thermal time constant. The experimental phase is then followed by a complex elaboration of the large amount of data; necessary to obtain the iron losses distribution [28].

The aim of the work consists in the adoptability of the method to investigate the energetic behavior of Soft Magnetic Composites (SMC). Recently the Authors have studied and adopted new magnetic materials, both for the case of hard bonded magnets [29]-[31], and with the adoption of new soft SMC [8], [32]. Owing to the experience in the field of the realization of SMC materials different considerations have been adopted and particular cases have been examined; for instance the effects of molding pressure, the application of the magnetize field during the process, etc. However it is necessary, at first, to explain the methodology to obtain the data necessary to deduce the iron losses distribution on the device surface.

The evident need of "observing" the active parts makes possible to apply the methodology only on components of electric devices or in particular cases *ad hoc* realized or where, like the case of the transformer, the magnetic material is mostly visible.

Methodology description

Recently the method has been tested with the application of a particular case: a small shell-type transformer [28]. The guidelines have been identified, but for a better comprehension some points are also reported in this work.

Different samples of SMC materials have been analyzed with a thermometric camera placed in front to them with the scope to store the temperature variations. The surface to be examined has been carefully cleaned and painted with matt black to avoid possible contributions due to reflection phenomena (Fig. 1). Moreover, under the excitation winding, insulating rubber sheets are placed to limit the heating due to conduction heat effect during the test (**Fig. 2**); the temperature increment should only depend on the iron losses in the magnetic core.

Fig. 1– Surface of the SMC toroid under exam indicated with the red line and matt black painted to avoid reflections

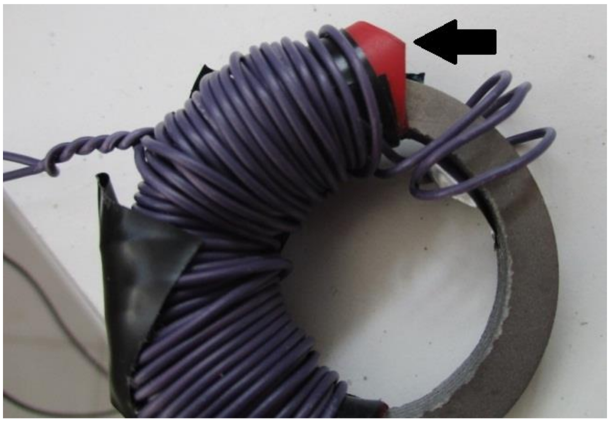


Fig. 2 – Heat exchange protection with insulating rubber

First of all the thermal camera must be set with the introduction of the following parameters: emissivity [33], apparent reflected temperature, ambient temperature, relative humidity, distance from the surface to be observed and measured. During the test the collected data will constitute a map of the temperatures for every element in which the observed surface is subdivided; the adopted thermal camera presents a resolution of 240×180 pixels (Fig. 3). The proposed methodology provides that every discrete element of the SMC's surface will be characterized by its own thermal evolution.

Fig. 3 – Setting of thermal camera parameters

If no time duration limits would be introduced, the rate of rise of the temperatures tend to decrase and reach a limit due to the thermal conductivity of magnetic material; the linear trend could not be obtained because of the convective heat evacuation towards the external ambient.

In order to get, for every observed point of the surface, the temperature increment proportional to the iron losses in that point, the experimental measurements must be limited in time. For the duration of each measurement has been fixed in function of the excitation frequency; for example for tests under 100Hz the time is 20 seconds, for medium frequency (100Hz ÷ 250Hz) is 16 seconds while for values over 250Hz is 10 seconds. Also the cooling time after a test must be chosen in opportune mode, with the certainty of the exhaustion of every other phenomena with the return to the initial conditions.

Due to the sensitivity of the thermal camera, a dispersion of the measured temperatures around the linear trend may be present. To remedy this problem the same measurement has to be repeated a large number of times in order to have a good reliability of the interpolating line; this one is obtained through the average value of all the tests results. Each single elements is defined from two coordinates (i, j).

The linear trend of the temperature is measured during the test:

$$\vartheta = \vartheta_a + K_{i,j} \cdot t \qquad (1)$$

where:

ϑ_a = ambient temperature

ϑ = temperature of the element identified with coordinates (i, j)

$K_{i,j}$ = angular coefficient of the straight line temperature increment associated to the element (i, j)

The results of each experimental test can be elaborated and organized in a matrix of the coefficients $K_{i,j}$ which correspond to the slope of the temperature arise in time for the element (i,j); the test is repeated N times, obtaining N matrixes. The average value of the slope coefficients is calculated and considered representative of what really happens in (i, j). The surface of the machine is observed while it is supplied with sinusoidal voltage, recording the temperatures of the 240×180 surface portions with a sample rate of 1 sample/second. This means that every experimental test gives origin to a 3D matrix of data: 240×180×td samples (**Fig. 4**).

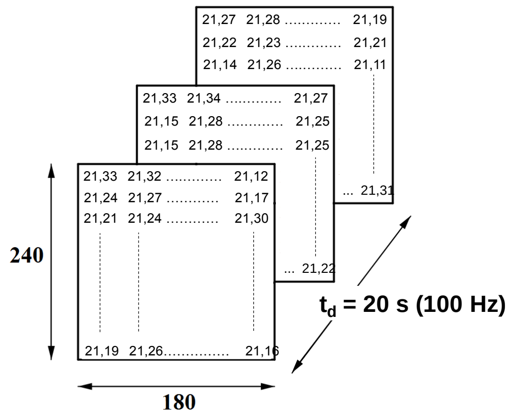


Fig. 4 – Example of matrix performed for every element of surface of the device under exam

It has to be remembered that the increment of temperature in a generic element, measured by means of the radiated energy E_r, is correlated to the relation:

$$E_r = W \cdot t_d = c_s \cdot \Delta\vartheta = c_s \cdot (\vartheta_{td} - \vartheta_a) = c_s \cdot K_{i,j} \cdot t_d \quad (2)$$

and then:

$$W = c_s \cdot K_{i,j} \quad (3)$$

where:

W = specific power losses in the considered element

c_s = specific heat of the iron powders; taking into account of resin presence its value may present a value around 600 J/kg°C.

t_d = time duration of the test

ϑ_{td} = element temperature at the end of the test.

Experimental tests and results

Different tests have been performed with the aim to investigate the energetic behavior of SMC materials. Such materials have been prepared in the laboratory and are concerning some research activities conducted by the authors [8], [32]. The realized SMC starts from a common ferromagnetic powder, without the presence of any insulating layer on each individual grain; the addition of an organic binder (epoxy or phenolic resins) makes it possible to keep together the grain structure, and to provide electrical insulation. The typical toroid which is used to measure the magnetic characteristic of the ferromagnetic material (Fig. 5) [34], [35], has been adopted to carry out our thermographic test with the addition of the excitation winding (Fig. 1 and **Fig. 2**).

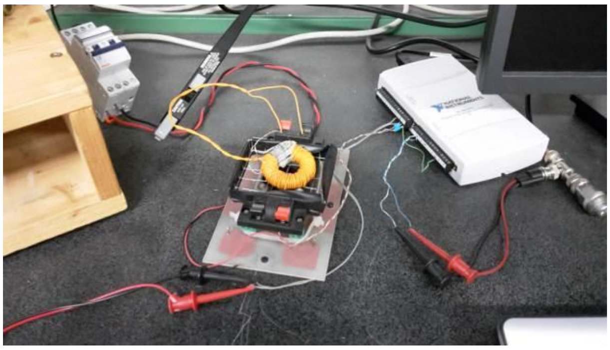


Fig. 5 – Classic method to measure the magnetic characteristic

The thermographic method has been tested supplying the samples at different frequencies, but carefully maintaining the same flux density in the magnetic core. For each supply frequency the tests have been repeated "N" times in order to reduce the possible errors of the measurements. Each of the N conducted tests, as already mentioned, must be short enough to avoid phenomena of heat conduction. To identify the actual iron losses due to the sinusoidal magnetization [36], harmonic contributions [37] in the voltage waveform must be cancelled, and it is necessary to have at disposal a good and stable supply source. The adopted supply system for the measurement setup is represented in Fig. 6, and has been realized at the scope: a signal generator in cascade with a linear amplifier allows to obtain a sinusoidal voltage waveform having a THD (total harmonic distortion) lower than 0.5% for every frequency value.

In the following several cases of measurements through the thermographic method described previously will be considered.

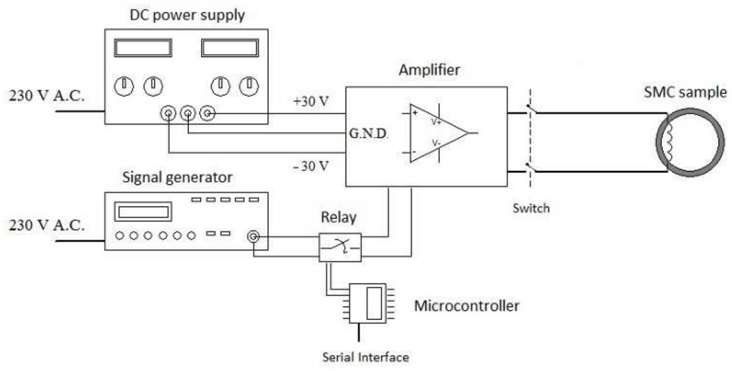


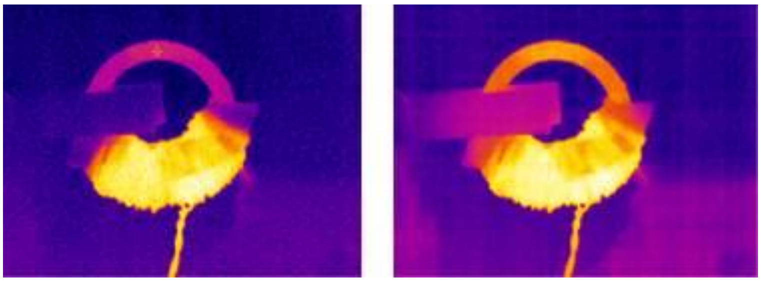
Fig. 6 – Supply system for adopted methods

A. Thermographic method compared with toroid "magnetic tests" - Its reliability

First of all a good validation of the proposed method is needed; this is possible through the comparison with the results of the magnetic test. Usually such results present a good accuracy and this procedure requires a long time. In the following the data obtained through the "magnetic test" will be use to obtain the reliability of the thermographic measurements. The mixture which is then used to realize the discoidal samples for the characterization has been prepared in our laboratories; for all these experiments the same percentage of the binder (0.2%) and identical pressures on the cylindrical mold (700 MPa) have been adopted. The disks are then subjected to reticulation process, and finally, by mechanical milling, the toroid samples [38], ready to be wounded for the electromagnetic tests (Fig. 7) are obtained.

Fig. 7 – Realization of the discoidal samples

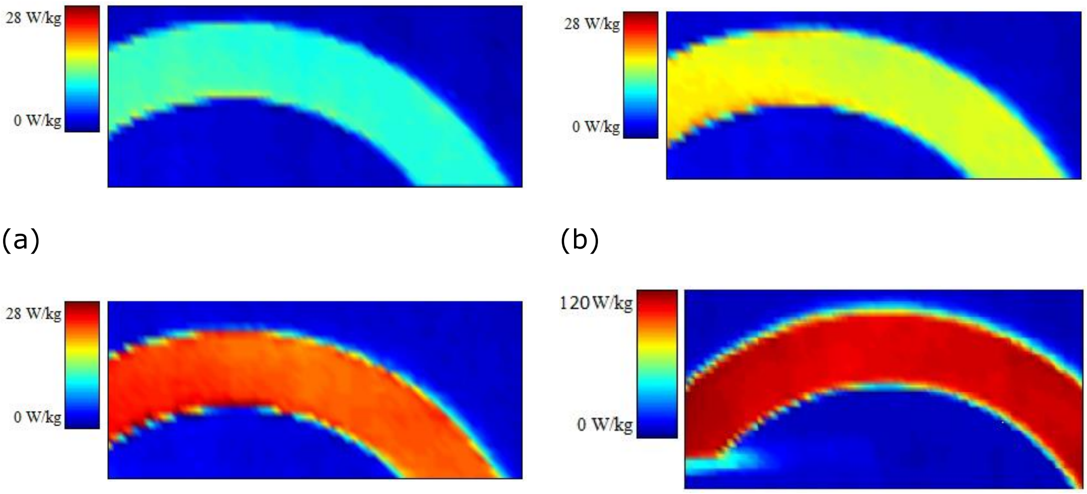
For both methods the same supply system has been adopted; as previously mentioned it is necessary to have a sinusoidal waveform in order to guarantee a low harmonic content. In our case the sinusoidal supply has been realized with the adoption of a linear amplifier; a data acquisition board is driven by a devoted LabView code to automatically acquire the "magnetic test" data and to process them for deducing the magnetic proprieties. The tests have been performed in order to obtain the values of the specific iron losses to compare them with the measurements obtained with our thermographic method. While the values of specific iron losses serve for the comparison and calibration of the thermographic analysis, on the other hand the obtained data concerning the magnetic field are used to determine the necessary magneto motive force in order to supply the samples with the appropriate current. The comparison for two methods has been carried out at the magnetic induction level of 1 T (**Table 44**). Hence there are all data to start the measurements with the thermographic method (**Fig. 8**).



(a) (b)

Fig. 8 – Thermal camera vision: at the beginning (a) and the end (b) of the thermographic test

The reliability of our thermographic method may be retained good enough. Different tests have been performed for various frequencies (up to 500Hz); in order to deduce the specific iron losses for every point of the magnetic core surface, as reported in **Fig. 9**. The losses increase with the increment of the frequency; besides the results have been compared with those obtained with the "magnetic test" (**Table 44**). In particular the average values of the specific iron losses are used for the comparison and the two methods present a good matching of the results. In this way the thermographic method has been validated and can be used for other type of investigations.



(a) (b) (c) (d)

Fig. 9 - Specific iron losses for different frequencies: (a) 50Hz, (b) 75 Hz, (c) 100Hz and (d) 500Hz

Table 44 – The specific losses: comparison of the two methods at 1T

Frequency [Hz]	Specific Losses Magnetic test [W/kg]	Specific Losses Thermographic method [W/kg]
50	8,65	9,0
75	13,31	11,0
100	18,13	18,1
250	51,3	47,6
500	119,2	119,6

B. Thermographic method: detection of damaged zone

A possible, and useful, application of the proposed method is the analysis and the detection of the damaged areas of a magnetic core (**Fig. 10**), due to mechanical processes or defects present in the materials. The typical machining leads to damages on the edges, not visible to the human eye; for instance, along the inner circumference (**Fig. 12** B), the losses result higher than the other parts of the magnetic core and greater of about 20% with respect to the average value. In the case of more evident and visible damages (**Fig. 10**) the losses reach values also 25% greater than the average one (**Fig. 11**). In some cases it can happen that the magnetic core presents defects caused by an incorrect handling of the material. Areas with lower flux density may be present losses about 10% lower of the average (**Fig. 12** A), but presenting on the other hand a weaker magnetic performance.

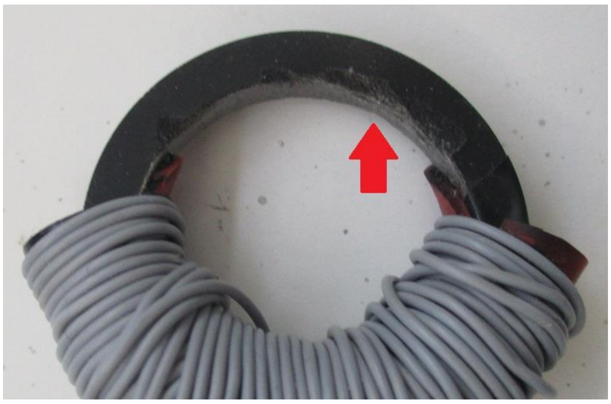


Fig. 10 – Damaged areas of SMC materials

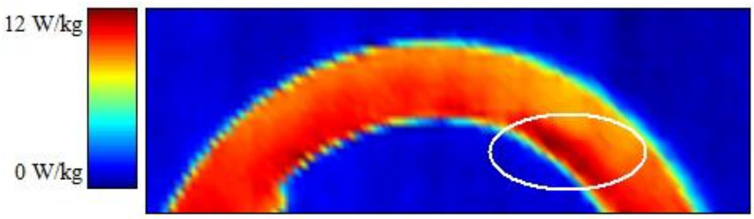


Fig. 11 – Presence of damaged parts of the magnetic core; higher losses in the encircled area

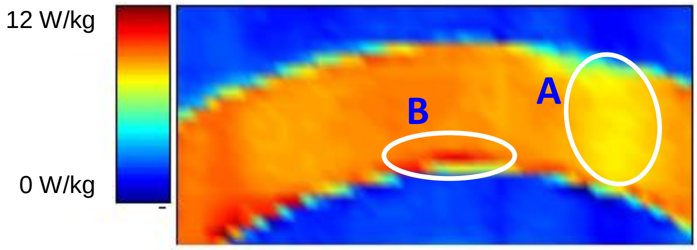


Fig. 12 - Detection of damaged zone: A defects in the magnetic structure and B losses due to machining

C. Thermographic method: effect of the molding process on the SMC

An important property regarding the SMC materials is the magnetic isotropic behavior; they have the possibility to carry the flux in all directions with the same properties. In this way it is possible to change the design approach, from a 2D vision to a 3D design of the magnetic pattern. Therefore it should be interesting to consider the effects of the molding process for each directions on a SMC sample. In order to verify such a property it is necessary to adopt another shape; some samples having rectangular shape have been realized (Fig. 13), which present yokes and columns corresponding to the pressure direction and its orthogonal; the internal windows allows also to host the excitation winding. Also in this case the specimen has been painted with matt black and the insulation protection in rubber has been adopted. The considered surface is the one delimited by the red line as shown in Fig. 13; from Fig. 14 it can be deduced that the specific losses have the same values in both the column and the yoke. In conclusion the SMC materials losses don’t depend on the direction of the molding pressure, which is opposite to what happens with electrical sheets, which are affected by the direction of lamination [1], [15]. Hence SMC materials are magnetically isotropic and permit the design of complex shapes, not achievable adopting traditional ferromagnetic sheets.

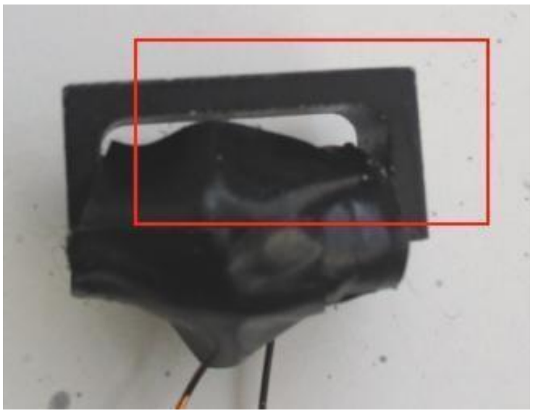
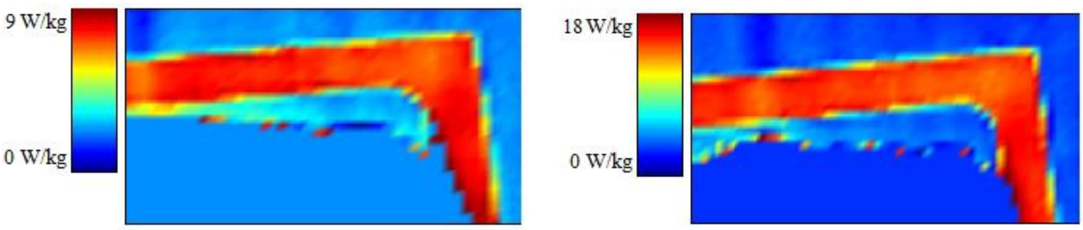


Fig. 13 – Rectangular shape for SMC samples: surface under exam



(a) (b)

Fig. 14 – Same specific losses in each direction: (a) for 50Hz and (b) for 100Hz

D. Thermographic method: effect of magnetic orientation during the process

In order to obtain anisotropic characteristics for some magnetic materials it is possible to apply an external magnetic field during the molding process; better magnetic and energetic performances may be obtained. Usually such property is associated with the use of permanent magnets; anyway the Authors decided to proceed with the same process during the molding of SMC. Therefore an external magnetic field has been applied in the same direction supplying the windings placed on the press punches (**Fig. 15**). The SMC samples have been realized with yokes (short side) in the direction of the magnetic field, while columns (long side) in orthogonal direction with respect to the magnetic field (**Fig. 16**). Matt black painting and insulation protection in rubber is applied. From the results it can be deduced that the specific losses in the columns are increased of about 40% with respect to the average value of the whole sample, while in the yokes the losses are lower and even better with respect to all the cases examined in the work (about 6,8 W/kg), as reported in **Fig. 17**.

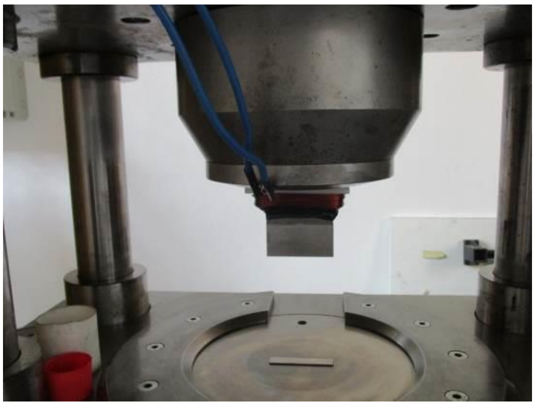
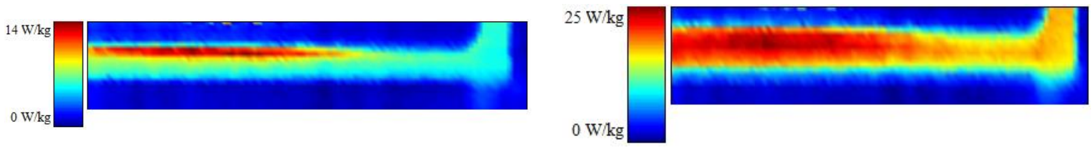


Fig. 15 - Magnetic orientation during the process: the punch wound

Fig. 16 – SMC sample used to study the effect of magnetic orientation



(a) (b)

Fig. 17 – Distribution of the specific losses in the function of magnetic orientation: (a) for 50Hz and (b) for 100Hz

Final considerations

Different evaluations of iron losses in the SMC materials, obtained with the new thermographic method have been proposed. At first the method is described and compared to the classic "magnetic method", obtaining very good matching for several tests at different frequencies.

Some aspects regarding SMC materials cannot be analyzed with traditional method, as such as for example: evaluation of the damaged areas, presence of defects and effect of machining. Furthermore the verification of the isotropy of SMC materials is easily possible with the new thermographic method.

The other important consideration is concerning the ability to steer magnetically the SMC materials in the desired direction, obtaining anisotropic properties; that constitutes an interesting characteristic of the thermographic method.

As the magnetic performance for SMC materials are usually detected with toroidal technique the new proposed method based on the thermographic analysis appears to be an important alternative to evaluate the energetic behavior of components of electric devices, in particular those obtained with innovative materials.

References

[1] P. Beckley, "Modern steels for transformers and machines", *IEE J. Engineering Science and Education*, 8, August 1999, pp. 149–159.

[2] Y. Oda, M. Kohno, A. Honda, (2008). "Recent development of non-oriented electrical steel sheet for automobile electrical devices" *J. Magnetism and Magnetic Materials*, 320, 2008, pp. 2430–2435.

[3] A. Krings, M. Cossale, A. Tenconi, J. Soulard, A. Cavagnino, A. Boglietti, "Characteristics comparison and selection guide for magnetic materials used in electrical machines", *IEEE IEMDC Conf.*, Coeur d'Alene (USA), 10÷13 May 2015, Conf. Proc. pp. 1152-1157.

[4] M. Peter, J. Fleischer, F. S. L. Blanc, J. P. Jastrzembski, "New conceptual lightweight design approaches for integrated manufacturing processes: Influence of alternative materials on the process chain of electric motor manufacturing", *IEEE EDPC Conf.*, Nuremberg (Germany), 29÷30 October 2013, Conf. Proc..

[5] A. Boehm, I. Hahn, "Comparison of soft magnetic composites (SMCs) and electrical steel", *IEEE EDPC Conf*., Nuremberg (Germany), 15÷18 October 2012, Conf. Proc..

[6] A. Schoppa, P. Delarbre, E. Holzmann, M. Sigl, "Magnetic properties of soft magnetic powder composites at higher frequencies in comparison with electrical steels", *IEEE EDPC Conf*., Nuremberg (Germany), 29÷30 October 2013, Conf. Proc.

[7] L. Ferraris, F. Franchini, E. Pošković, A. Tenconi, "Impact of a bonded-magnet adoption on a specific fractional motor power and efficiency", *IEEE Trans. On Ind. Appl*., 50, pp. 3249-3257, September/October 2014.

[8] L. Ferraris, E. Pošković, F. Franchini, "New soft magnetic composites for electromagnetic applications with improved mechanical properties", *AIP Advances* 6 (2016).

[9] L. Hultman, O. Andersson, "Advances in SMC Technology – Materials and Applications", *EPMA EURO PM2009*, Copenhagen (Denmark), 13 October 2009, Conf. Proc..

[10] Y. Dou, Y. Guo, J. Zhu, "Investigation of motor topologies for SMC application", *IEEE ICEMS Conf.*, Seoul (South Korea), 8÷11 October 2007, Conf. Proc. pp. 695 - 698.

[11] R. P. Deodhar, A. Pride, J. J. Bremner, "Design method and experimental verification of a novel technique for torque ripple reduction in stator claw-pole PM machines", *IEEE Trans. on Ind. Appl.*, 51, pp. 3743-3750, September/October 2015.

[12] C. Liu, J. Zhu, Y. Wang, Y. Guo, G. Lei, "Comparison of claw-pole machines with different rotor structures", *IEEE Trans. On Magn.*, 51, November 2015.

[13] M. A. Khan, P. Pillay, N. R. Batane, D. J. Morrison, "Prototyping a composite SMC/steel axial-flux PM wind generator", *IEEE IAS Annual Meeting*, Tampa (USA),8÷12 October 2006, Conf. Proc. pp. 2374–2381.

[14] A. Schoppa, J. Schneider, C. D. Wuppermann, "Influence of the manufacturing process on the magnetic properties of non-oriented electrical steels", *J. Magnetism and Magnetic Materials*, 215-216, 2000, pp.74–78.

[15] J. Sievert, "The measurement of magnetic properties of electrical sheet steel – survey on methods and situation of standards", *J. Magnetism and Magnetic Materials*, 215–216, 2000, pp. 647–651.

[16] E. Antonelli, E. Cardelli, A. Faba, "Epstein frame: How and when it can be really representative about the magnetic behavior of laminated magnetic steels", *IEEE Trans. On Magn.*, 41, pp. 1516–1519, May 2005.

[17] C. Freitag, C. Joost, T. Leibfried,. "Modified Epstein frame for measuring electrical steel under transformer like conditions", *IEEE ICHVE Conf.*, Poznan (Poland), 8÷11 September 2014, Conf. Proc. pp..

[18] Y. Zhang, N. Alatawneh, M. C. Cheng, P. Pillay, "Magnetic core losses measurement instrumentations and a dynamic hysteresis loss model", *IEEE EPEC Conf*., Montreal (Canada), 22÷23 October 2009, Conf. Proc. pp..

[19] M. Ibrahim, P. Pillay, "Novel equipment for the measurement of core losses in laminations for advanced machines", *IEEE IEMDC Conf*., Niagara Falls (USA), 15÷18 May 2011, Conf. Proc. pp. 1231 - 1236.

[20] M. J. Manyage, P. Pillay, "New Epstein frame for core loss measurements at high frequencies and high flux densities", *IEEE IAS Annual Meeting*, Edmonton (Canada), 5÷9 October 2008, Conf. Proc..

[21] Z. Gmyrek, A. Boglietti, A. Cavagnino, "Estimation of iron losses in induction motors: calculation method, results, and analysis", *IEEE Trans. On Ind. Electron*., 57, pp. 161-171, January 2010.

[22] A. Boglietti, A. Cavagnino, D. M. Ionel, M. Popescu, D. A. Staton, S. Vaschetto, "A General Model to predict the iron losses in PWM inverter-fed induction motors", *IEEE Trans. On Ind. Appl.*, 46, pp. 1882-1890, September/October 2010.

[23] F. Marignetti, V. Delli Colli "Thermal analysis of an axial flux permanent-magnet synchronous machine", *IEEE Trans. On Magn*., 45, pp. 2970-2974, July 2009.

[24] H. Shimoji, B E. Borkowski, T. Todak, M. Enokizono, "Measurement of core-loss distribution using thermography", *IEEE Trans. On Magn*., 47, pp. 4372-4375, October 2011.

[25] H. Shimoji, B E. Borkowski, T. Todak, M. Enokizono, "Visualizing iron loss distribution in permanent magnet motors" *IEEE ICEMS Conf.*, Sapporo (Japan), 21÷24 October 2012, Conf. Proc..

[26] B. Gao, A. Yin, Y. Wang, G. Tian, W. L. Woo, H. Liu, "Thermography spatial-transient-stage tensor model and materal property characterization", *IEEE Nondestructive Evaluation/Testing (FENDT) Forum*., Chengdu (China), 20÷23 June 2014, Conf. Proc. pp. 199 - 203.

[27] Z. Gmyrek, M. Strąkowska, B. Więcek, "A method of local magnetic loss determination in punched ferromagnetic strips", *J. Magnetism and Magnetic Materials* 355, 2014, pp. 282-288.

[28] L. Ferraris, F. Franchini, E. Pošković, "A thermographic method for the evaluation of the iron losses distribution in electromagnetic devices", *IEEE IECON Conf.*, Florence (Italy), 23÷26 October 2016, Conf. Proc. pp. 1584–1589.

[29] L. Ferraris, P. Ferraris, E. Pošković, A. Tenconi, "Theoretic and experimental approach to the adoption of bonded magnets in fractional machines for automotive applications*", IEEE Trans. On Ind. Electron.*, 59, pp. 2309-2318, May 2012.

[30] L. Ferraris, F. Franchini, D. La Cascia, E. Pošković, "Adoption of bonded magnets in place of sintered NdFeB: performance and economic considerations on a small power generator", *IEEE EPE ECCE Europe Conf*., Geneva (Switzerland), 8÷10 September 2015, Conf. Proc..

[31] L. Ferraris, F. Franchini, E. Pošković, "Design optimization of bonded PM BLDC motors with reference to the cogging torque amplitude", *IEEE IECON Conf.*, Yokohama (Japan), 9÷12 November 2015, Conf. Proc. pp. 001264 – 001269.

[32] M. Actis Grande, L. Ferraris, F. Franchini, E. Pošković, "A new material for small electrical machine with very good mechanical properties", *IEEE ICEM Conf.*, Lausanne (Switzerland), 4÷7 September 2016, Conf. Proc. pp. 1244-1250.

[33] T. Suesut, N. Nunak, T. Nunak, A. Rotrugsa, Y. Tuppadung, "Emissivity measurements on material and equipment in electrical distribution system", *IEEE ICCAS Conf.*, Gyeonggi-do (South Korea), 26÷29 October 2011, Conf. Proc. pp. 1259 - 1263.

[34] M. Actis Grande, R. Bidulský, A. Cavagnino, L. Ferraris, P. Ferraris, "Investigations on different processing conditions on soft magnetic composite material behavior al low frequency", *IEEE Trans. On Ind. Appl.*, 48, pp. 1335-1343, July/August 2012.

[35] O. de la Barrie`re, C. Appino, F. Fiorillo, C. Ragusa, H. Ben Ahmed, M. Gabsi, F. Mazaleyrat, M. LoBue, "Loss separation in soft magnetic composites", *AIP Journal of Applied Physics* 109, 2011.

[36] M. S. Lancarotte, A. de A. Penteado Jr, "Estimation of core losses under sinusoidal or non-sinusoidal induction by analysis of magnetization rate", *IEEE Trans. On Energy Convers.*, 16, pp. 174-179, June 2001.

[37] Z. Gmyrek, A. Boglietti, A. Cavagnino, "Iron loss prediction with PWM supply using low- and high-frequency measurements: analysis and results comparison", *IEEE Trans. On Ind. Electron.*, 55, pp. 1722-1728, April 2008.

[38] M. Actis Grande, A. Boglietti, A. Cavagnino, L. Ferraris, P. Ferraris, "Experimental analysis of materials for electromagnetic converters obtainable by powder pressing", *IEEE IECON Conf.*, Porto (Portugal), 2÷5 November 2009, Conf. Proc. pp. 1130-1135.

“Efficiency Islands”: A new approach to meet EN50598 (EN61800-9)

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Abstract

Traditionally, pump speeds have been selected to match the motor 50Hz speed. This restriction prevents the best opportunity to place a pump operating point (speed) within the best ‘Efficiency Island’ of the controlling VSD/motor package.

The concept of ‘Efficiency Islands’ arises from design requirements imposed by the Ecodesign Directive. The variation of motor losses: copper loss and iron loss, which vary in sympathy with speed and load, means there is always an ‘Efficiency Island’ where these losses are equal. This yields an efficiency that is at its’ best possible value when the copper and iron loss are balanced, and can be up to 2 percentage points HIGHER than that for the nominal design.

Operating a VSD controlled motor in the Constant Power region, means an “Efficiency Island” can be achieved with the best efficiency value and by using suitable VSD control, an 'Island' can be flexibly positioned around an equipment's duty point : different to the nominal design point of the controlled motor.

The ability to 'position' the "Efficiency Island" allows greater freedom of selection, for instance, a pump/fan design based solely on Specific Speed. The net result is the best/most feasible VSD/Motor/Pump string efficiency to meet the Energy Efficiency Index values of EN 50598-3

To the author’s knowledge this is the first time that this efficiency pattern has been recognised and used to determine, and illustrate, the best combined efficiency point from the interaction between a motor and VSD choice, and an associated process, according to the ‘Extended Product Approach’.

Advisory

Since submitting this paper for peer review, EN 50598-1 & EN 50598-2 have become the harmonised standards EN 61800-9-1 & EN 61800-9-2. For consistency with the paper title, reference to EN 50598 has been retained with the corresponding reference to EN 61800 appended.

Introduction

The European Ecodesign directives are maturing to look at energy usage and its’ environmental impact; throughout a product’s conceptualization, manufacture, and use - the directives being part of the EU’s plan to meet energy efficiency and CO emission goals.

Existing Energy Related Products (ErP) standards have focused on products like motors, pumps and fans, with Energy efficiency indicators (IEs) for these products defined to help identify a product’s overall energy efficiency level. Variable speed/variable frequency drives have not, until now, had similar IE classifications. The standard EN 50598 (now EN 61800-9) series addresses this, in three parts;

EN 50598-1 (released December, 2014), now EN 61800-9-1 (released March 2017) [10] ”General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi-analytic model (SAM).”

EN 50598-2, (released in December, 2014), now EN 61800-9-2 (released March 2017) [9] “Energy efficiency indicators for power drive systems and motor starters.”

EN 50598-3, (released in March, 2015) – Part 3 of EN 61800-3 has not yet released “Quantitative ecodesign approach through life cycle assessment including product category rules and the content of environmental declarations.”

The author first became aware of the EN 50598 standards when preparing VSD heat loss contour graphs; heat loss for power & current, of ventilation fans for a large tunnel project. These graphs were prepared from VSD/motor loss data produced by DRIVESIZE® software.

As an experiment, the loss contours were converted into iso-efficiency contours – at this point the only data available was for operating points below base speed, so the contours showed no particular features.

However, after an Internet search for Iso-efficiency curves – for pumps rather than VSDs, the papers of Stockman, Dereyne, Vanhooydonck, Symens, Lemmens and Deprez [1] and Stockman, Dereyne [2], were found. The results shown in these papers were in the form of iso-efficiency contours – see Figs 1a) – 1c), which all shared a common pattern ; in the Constant Power region of operation there was a contour which surrounded an ‘Island’ the contour having an efficiency value higher than the nominal design efficiency.

The iso-efficiency contour graphs obtained in [1] & [2] used the IN-OUT method of EN 50598-2 (now EN 61800-9-2) [9]. There was no similar data for SynRm operation – the Manufacturer’s Statement for SynRm motor/VSD packages only covering the Constant Torque range; as per EN 50598-2 (EN 61800-9-2) guidelines, and so the author had to use the Semi-Analytical Method (SAM) using DRIVESIZE® software.

The DRIVESIZE®loss figures were calculated for both Constant Power & Constant Torque operating regions. From these loss figures a 3rd order Least Square Fit – Speed and Torque, was used to generate loss equations that could be displayed as iso-efficiency contour graphs in EXCEL. The result is shown in Fig 2. The similarity of the contour pattern to those shown in [1] & [2] was striking.

Due to the restriction of measurement range under EN 50598-2 (EN 61800-9-2) there is no published data for operation in the Constant Power range. This lack of data was resolved when some IN-OUT test data from Lappeenranta University was made available to the author [6].

This data is displayed as iso-efficiency graphs derived from a LSF to the load/speed points of IEC 61800-9-2, in Figs 3 & 4. Again, the similarity of the iso-efficiency pattern to those shown in [1] & [2] is evident.

The U.S. Department of Energy Vehicle Technologies paper [4] showed iso-efficiency graphs for differing base speed (as the available voltage changed), see Figs 5a) – 5c). The ‘Island’ pattern again being evident but, significantly, this ‘Island’ moves with the change in base speed.

The similar results for SAM and IN-OUT methods of EN50598-2 (EN 61800-9-2) [9] and the indicative data from [4], lead the author to the “Efficiency Island” concept described in this paper.

Note : The purpose of the figures in this paper is to emphasise the similarity of iso-efficiency contour patterns across a range of motor/VSD types, when operated in the Constant Power region. All show a characteristic ‘Island’ where efficiency is at its maximum value. The simple theory outlined in the Appendix explains why these ‘Islands’ should exist.

Although “Efficiency Islands” can also exist for Permanent Magnet motors [3] & [5], see Figs 7a) – 7b), the ‘Island’ occurs at different speed/torque points, some below nominal speed some in regions where the thermal design of the motor is exceeded. In any case these ‘Islands’ occupy a more restricted range of useful efficiency improvement than that achievable with an Induction motor or SynRM/VSD package. As such PM motors do not lend themselves easily to the “Efficiency Island” concept.

There are many examples of Iso-efficiency contour graphs available on the Internet. However, it is believed that this paper is the first to identify the ‘Efficiency Island’ concept and that it can be used to establish the most efficient package of motor/VSD, with an associated process, to meet the Extended Product Approach requirements in EN 61800-9-1.

Introduction to “Efficiency Islands”

The Extended Product Approach (EPA) recognises that the overall efficiency of a PDS (Power Drive System) is not, necessarily, an addition of individual component efficiencies, but a unique result of the motor/VSD combination and application.

In [7] the following comments on EPA were made

- Takes account of real life operating conditions – time and power consumption at each load point of typical time: duration curve
- Gives full benefit to better controls
- Where not known, can generate part load component performance by extrapolation (Semi-analytical method)
- Focus on the system controls, not component efficiency

To gain the best measurements, and to have confidence in those measurements, the Electrical IN-OUT method, using a dynamometer, is necessary. This method is the only practical measurement method that allows the full operating range, Constant Torque- below base speed and Constant Power- above base speed, of a motor/VSD package, to be measured.

The “Efficiency Island” concept

From transformer theory, the best efficiency is achieved at an operating point where the resistive (Copper) losses are matched by the magnetic (Iron) losses (see Appendix).

A similar situation occurs with variable speed Induction and Synchronous Reluctance motors, where the copper loss is load dependent, as for a transformer, BUT, the magnetic losses are frequency (speed) dependent as discussed in the Appendix.

Magnetic losses can be divided into three contributory sources, Bertotti [8]

a. Hysteresis Loss proportional to B^{α} and f
b. Eddy Current Loss proportional to B^{2} and f^{2}
c. Excess Loss proportional to $B^{1.5}$ and $f^{1.5}$

Where α is the Steinmetz Coefficient, normal value 1.6

B is peak magnetic flux

f is frequency

In the Constant Power region the magnetic flux, B, is controlled in the ratio of f_0/f,

where f_0 is the base design frequency ;

the frequency at which nominal voltage is applied.

Applying this ratio to the magnetic flux B in losses a) to c), yields the modified losses below

a. Hysteresis Loss proportional to f^ $^{1/(\alpha-1)}$
b. Eddy Current Loss - constant
c. Excess Loss – constant

In the Constant Power region the copper loss; for a particular torque, increases approximately, as the square of f_0/f,

For a particular value of 'Island' efficiency there will be many combinations of torque and speed which yield the balance condition between copper and magnetic losses, this balance region is shown in Figs 1 – 5.

Iso-efficiency Contour Derivation

The derivation of the contours shown in Figs 2 to 4 was based on loss calculation/ measurement, for a range of speed/torque points, using a Least Squares Fit (LSF).

Initially the LSF used 3rd order parametric coefficients of loss for torque and speed, i.e 16 variables- similar to IEC 61800-9-2 [9], but over a different set of torque/speed values, to create a loss interpolation equation. This interpolation equation was then used to calculate the Iso-efficiency contours.

It was found that a good fit could be achieved with different orders of parameters between Constant Torque region and Constant Power region; 2nd order parameters for Speed and 3rd order parameters for the Constant Power region and 3rd order parameters for both Speed and Torque for the Constant Torque region.

The region of maximum efficiency, or "Efficiency Island", commences close to nominal speed and extends downward on a nearly Constant power curve to higher speeds – with lower torque.

'Island' position vs Nominal Speed

The Nominal speed for a motor is determined by the electrical design of the motor and the maximum output voltage of the controlling VSD. The VSDs maximum output voltage is fixed by the internal DC link voltage, or by control. By altering the maximum output voltage, the "Efficiency Island" can be moved in sympathy to a new region, e.g output voltage 75% of maximum achievable leads to a 25% lower in speed.

Figures 5a) – 5c), from Olszewski [4], show the position of the 'Island'; relative to nominal speed ; as this nominal speed changes with maximum output voltage, outlined by the YELLOW, BLUE and GREEN ovals.

These show that, with suitable VSD control of the maximum motor voltage, and the ability to control a motor in the Constant Power range, an "Efficiency Island" can be positioned over a wide range of torque and speed regions to match a driven equipment's optimum efficiency range.

Note: Re-connection of a DELTA winding into STAR can also be used to re-position the nominal speed to a lower speed; the 'Island' moving correspondingly, for the same nominal motor voltage.

Efficiency Improvement: Points to note

a) From Figs 1a) – 1b) indicate a general improvement of about 1% To utilise the 'Island' the motor must be over-sized for the load point.
b) As the IE class improves so the 'Island' encloses the nominal speed/torque point
c) For high efficiency motors Figs 1c) – 4, the 'Island' encloses a large speed/torque region with the same high efficiency value.

d) For high efficiency motors can extend beyond the thermal limit of the winding design, see Figs 3 & 4. This could be a limiting factor in motor selection.

Efficiency Island" Concept applied to Pump selection

The Specific Speed of a pump defines the impellor and volute dimensions AND the required speed to meet the Duty point Head and Flow.

For constant values of flow, head and BEP the shaft power remains the same, only the rotational speed changing as the Specific Speed value alters over a design range.

For a given flow, head and Best Efficiency Point (BEP), there will be a range of pump designs that can meet this Duty point. The range of pump designs available are defined by the Specific Speed within the design range.

From the above it can be shown that a range of available Specific Speeds will follow a Constant Power line on a motor Torque vs Speed graph, see Fig 8

It is clear, from Fig 9 that restricting the motor operating envelope, at or below, nominal speed (sub-synchronous), and below nominal torque, will impose a severe restriction on the available choice of pump designs – GREEN dots in Fig 9

By extending into the super-synchronous speed range the available choice of pump designs is significantly extended – YELLOW dots in Fig 9.

Not only does this ease the pump selection process, but, also allows this pump selection to be matched to the "Efficiency Island" of the motor/VSD package to yield a best overall efficiency. This is shown in Fig 10 where the maximum and minimum points of the 'Static' and 'Friction' torque/speed curves have nearly constant motor/VSD efficiency as they cross the "Efficiency Island".

If these same curves were placed such that the maxima occurred at base speed then the reduction in motor/VSD package efficiency would be at least 5 percentage points worse at minimum, against 1 percentage point when these curves are positioned over the "Efficiency Island".

The ability to position the duty point correctly over an "Efficiency Island" region, the best overall efficiency can be maintained over a reduced flow range, which assists in minimised Life Cycle Costs and to meet the EIs defined in EN 61800-9-2.

Conclusions

"Efficiency Islands" have been shown to be present for all Induction Motor, Synchronous Reluctance Motor and controlling inverter packages. These "Islands" offer improved efficiency in the working range of VSD controlled equipment and widen the choice of suitable duty points where the package efficiency can be maximised.

By suitable control an 'Island' can be "fitted" around the most efficient operating point of the driven equipment enabling the requirements of the EPA concept in EN 50598 (EN 61800-9) to be achieved.

Further work is needed to define the extent of an "Efficiency Island", especially for motors with IE3 or better efficiency class. Indications are that, for these motors, the 'Island' occurs around a speed/torque region which includes the thermal limits of the motor and this could , possibly, be a limiting condition for selection such high efficiency motors.

Simple interpolation rules, similar to those in EN 61800-9-2 have still to be constructed. Without these simple rules it will be difficult to transfer this concept to practical use. To underpin the construction of these rules IN-OUT measurements will have to be made so that Iso-efficiency contours can be plotted. Another, line of investigation could be by means of the SAM using individual values of magnetic loss and copper loss using values obtained by the Separation of Losses method – this data maybe more readily available,

To take advantage of this concept a greater dialogue between pump manufacturers, specifiers and drive/motor suppliers will be required so that the best solutions, from each, can deliver a pump/VSD/motor package which has the best achievable string efficiency to meet the ideals of the Ecodesign Directive.

References

[1} Kurt Stockman, Steve Dereyne, Dirk Vanhooydonck, Wim Symens, JorisLemmens, Wim Deprez Ghent University: Iso Efficiency Contour Measurement Results for Variable Speed Drives: ICEM 2010:

[2] Kurt Stockman, Steve Dereyne, Ghent University: Total drive train optimization of Industrial Fans and pumps considering VFD driven motor, transmission and load: Motor Summit 2014

[3] By authorInternal ABB Report 17/11/2015,

[4] Mitch Olszewski ,EVALUATION OF THE 2010 TOYOTA PRIUS HYBRID SYNERGY DRIVE SYSTEMU.S. Department of Energy Vehicle Technologies, 2011

[5] GKN Evodrive Technical Datasheet, GKN Land Systems

[6] Internal data from Lappeenranta University 03/2016

[7] Hugh Falkner (Atkins), Anibal De Almeida (University of Coimbra), Joao Fong (University of Coimbra), Duncan Josh (Atkins), Market Surveillance Challenges for complex motor systems, EEMODS 2015

[8] G. Bertotti, F. Fiorillo, G. Soardo. THE PREDICTION OF POWER LOSSES IN SOFT MAGNETIC MATERIALS. Journal de Physique Colloques, 1988, 49 (C8), pp.C8-1915-C8-1919.

[9] IEC 61800-9-2, Adjustable speed electrical power drive systems – Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications – Energy efficiency indicators for power drive systems and motor starters

[10] IEC 61800-9-1, Adjustable speed electrical power drive systems – Part 9-1: Ecodesign for power drive systems, motor starters, power electronics and their driven applications – General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi analytic model (SAM)

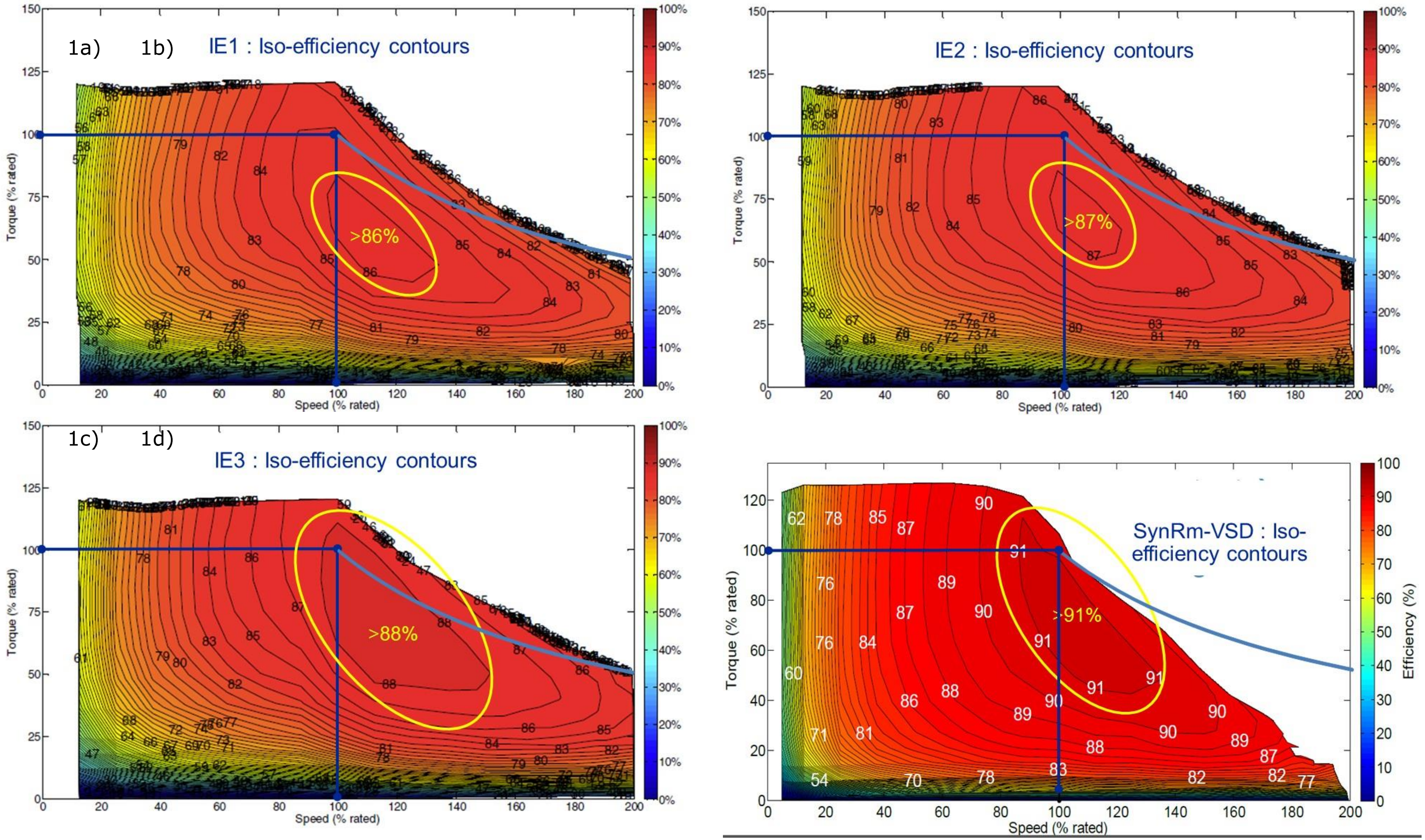


Figure : 1a) - 1c) 11kW Induction Motor Reproduced from [1], 1d) 11kW SynRM Reproduced from [2]

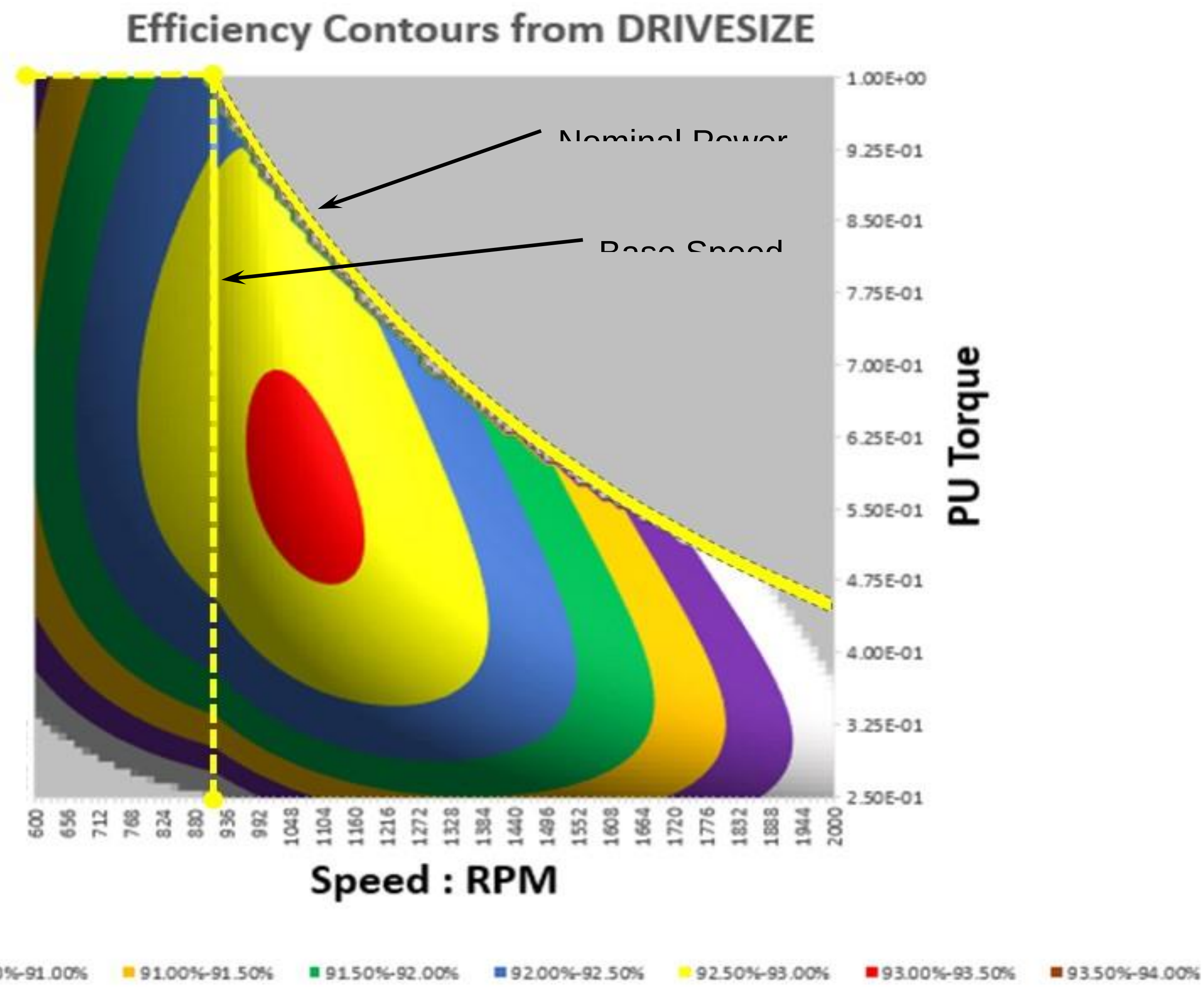


Figure : 2 Picture of Efficiency Contours from DRIVESIZE® loss estimations ; Semi-Analytic Method

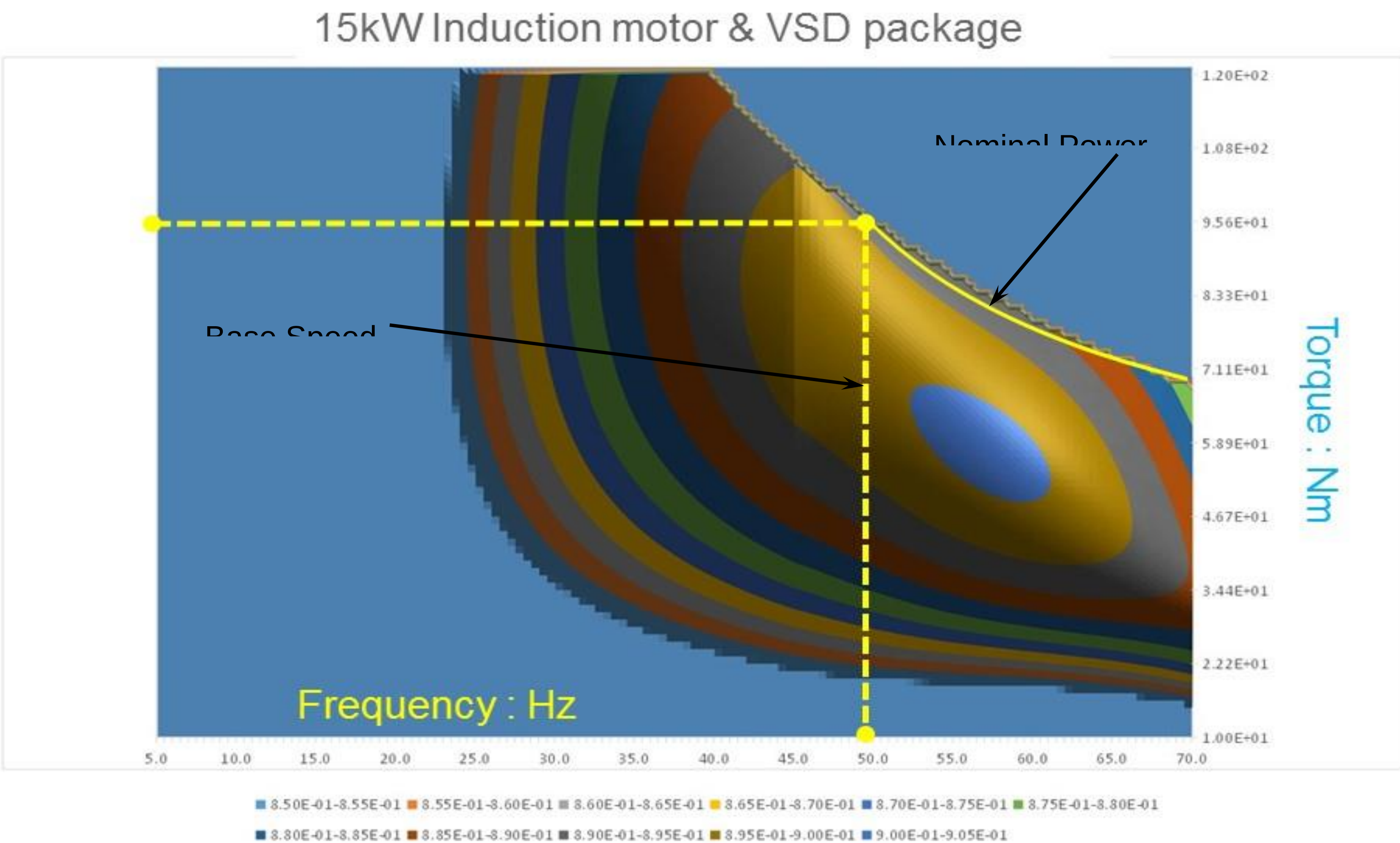


Figure : 3 15kW VSD/motor Efficiency Contours based on data from Lappeenranta data [6] IN-OUT Method

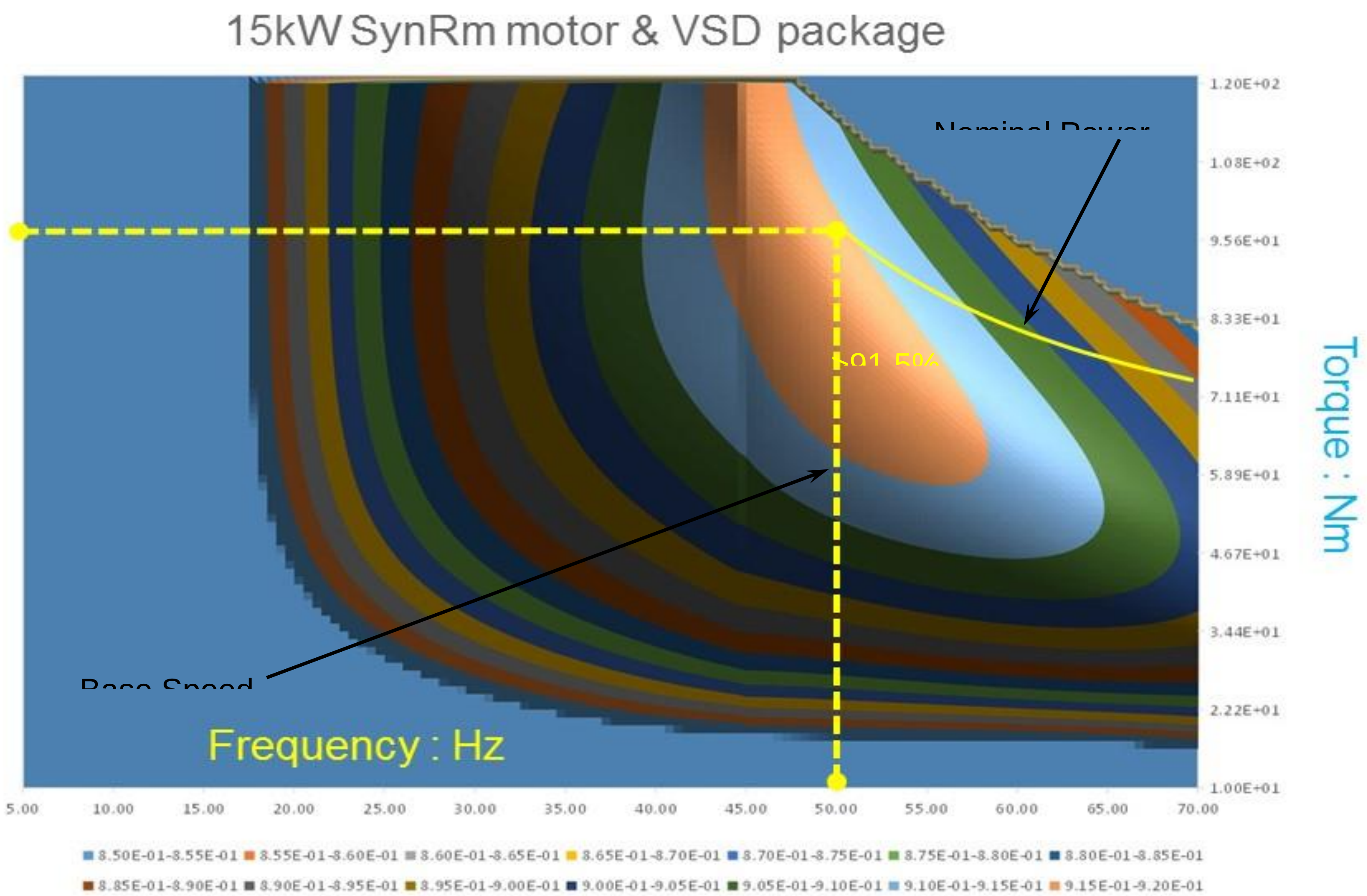


Figure : 4 15kW VSD/motor Efficiency Contours based on data from Lappeenranta data [6] IN-OUT Method

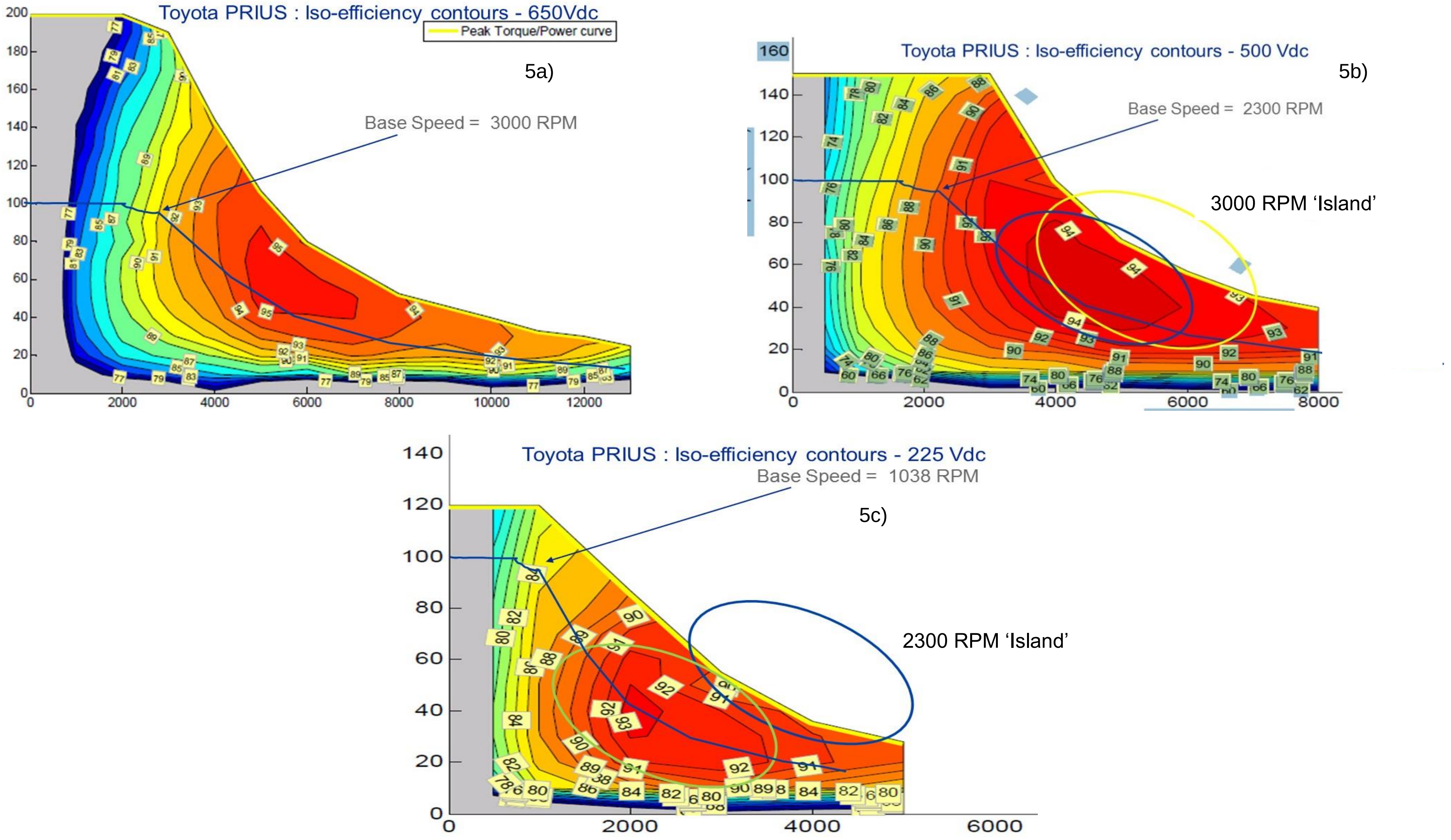


Figure : 5a) – 5c) Efficiency contours TOYOTA PRIUS VSD/motor IN-OUT Method Reproduced from [4]

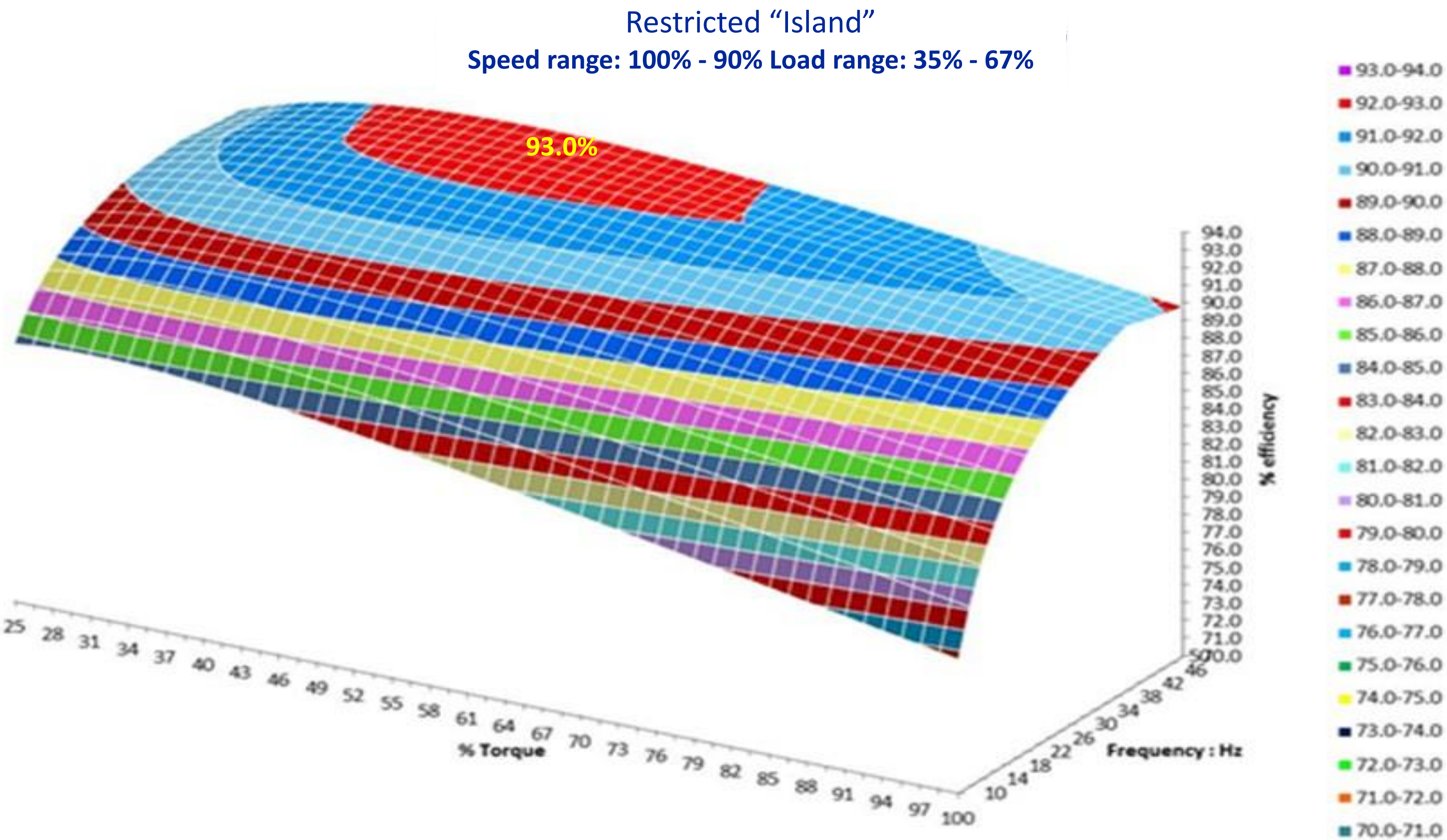
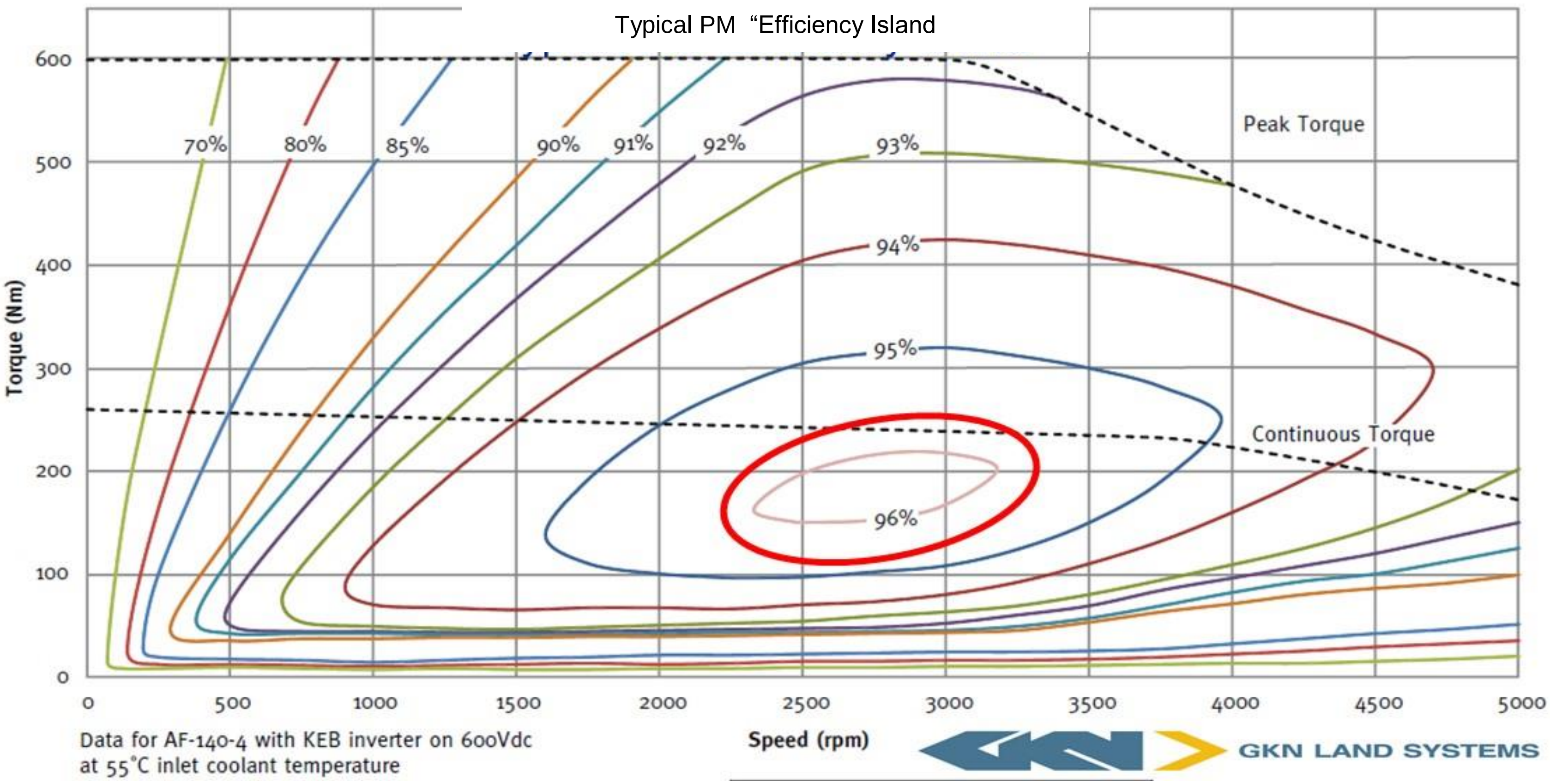
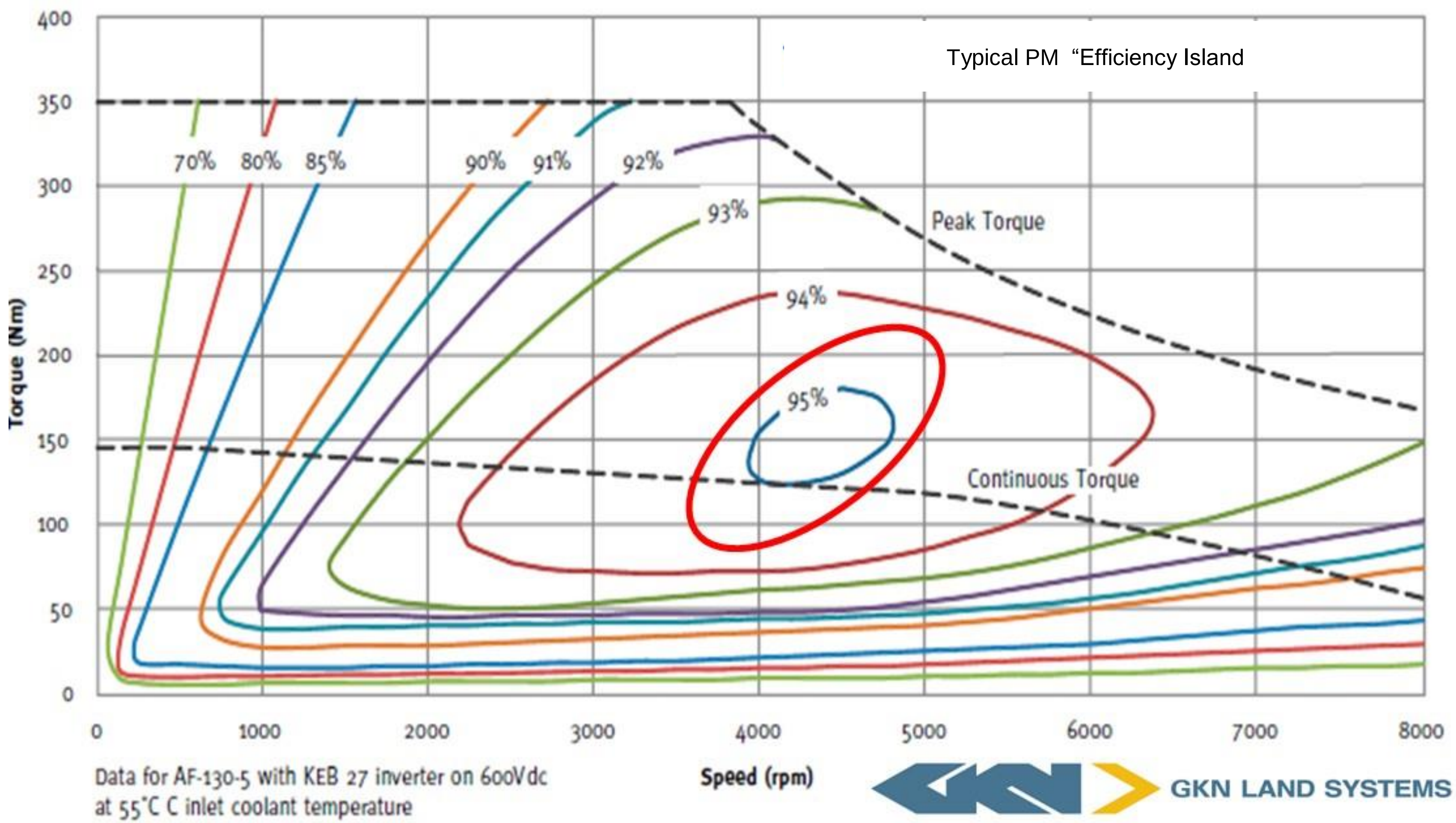


Figure : 6 Permanent magnet VSD/Motor Semi-Analytic Method Reproduced from [3]



Restricted "Island" **Speed range: 130% - 55% Load range: 100% - 67%**

Figure : 7a) Permanent Magnet VSD/motor Reproduced from [5]



Restricted "Island" **Speed range: 86% - 67% Load range: 80% - 60%**

Figure : 7b) Permanent Magnet VSD/motor Reproduced from [5]

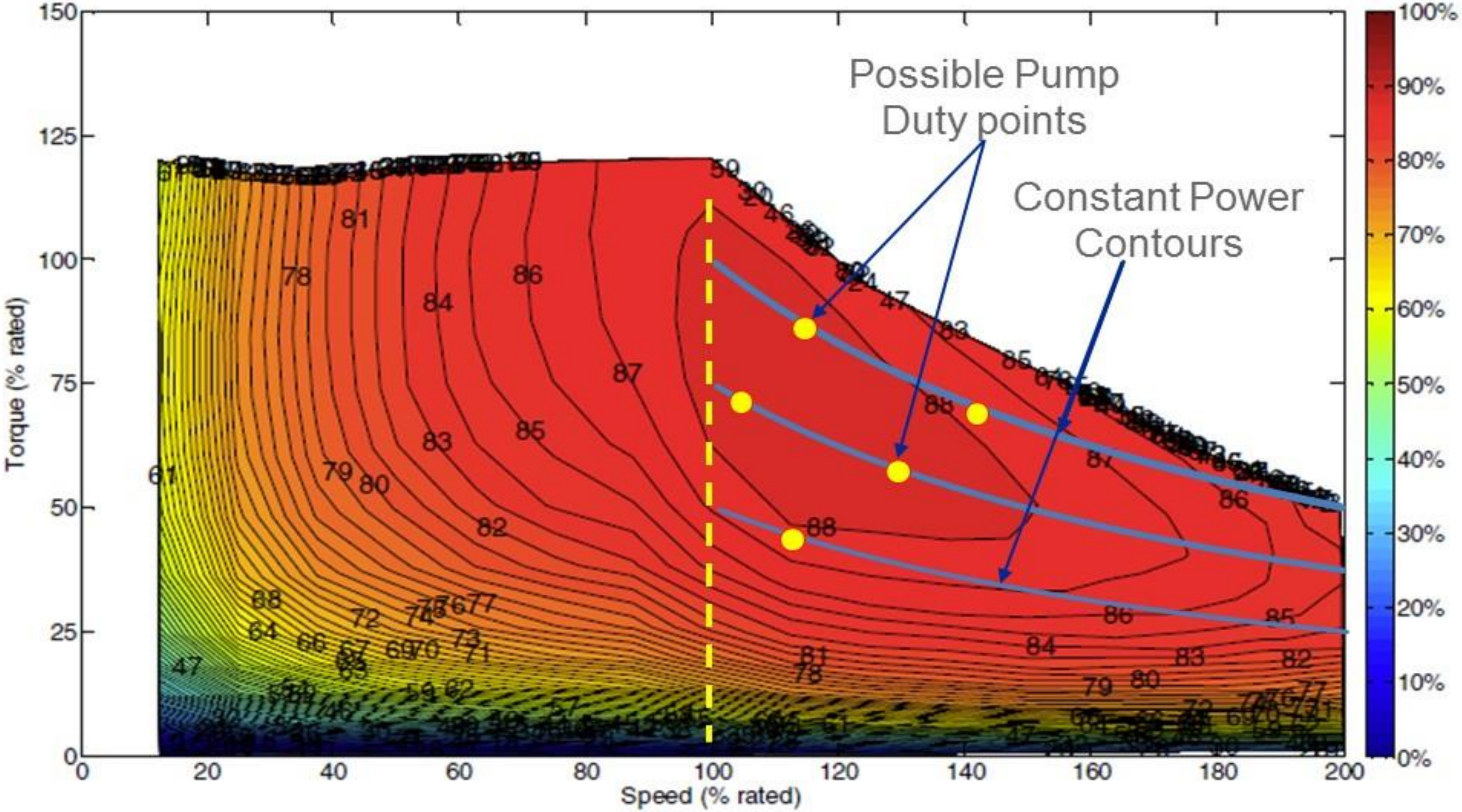


Figure : 8 Picture showing typical pump Torque/Speed points vs Efficiency contours Figure :

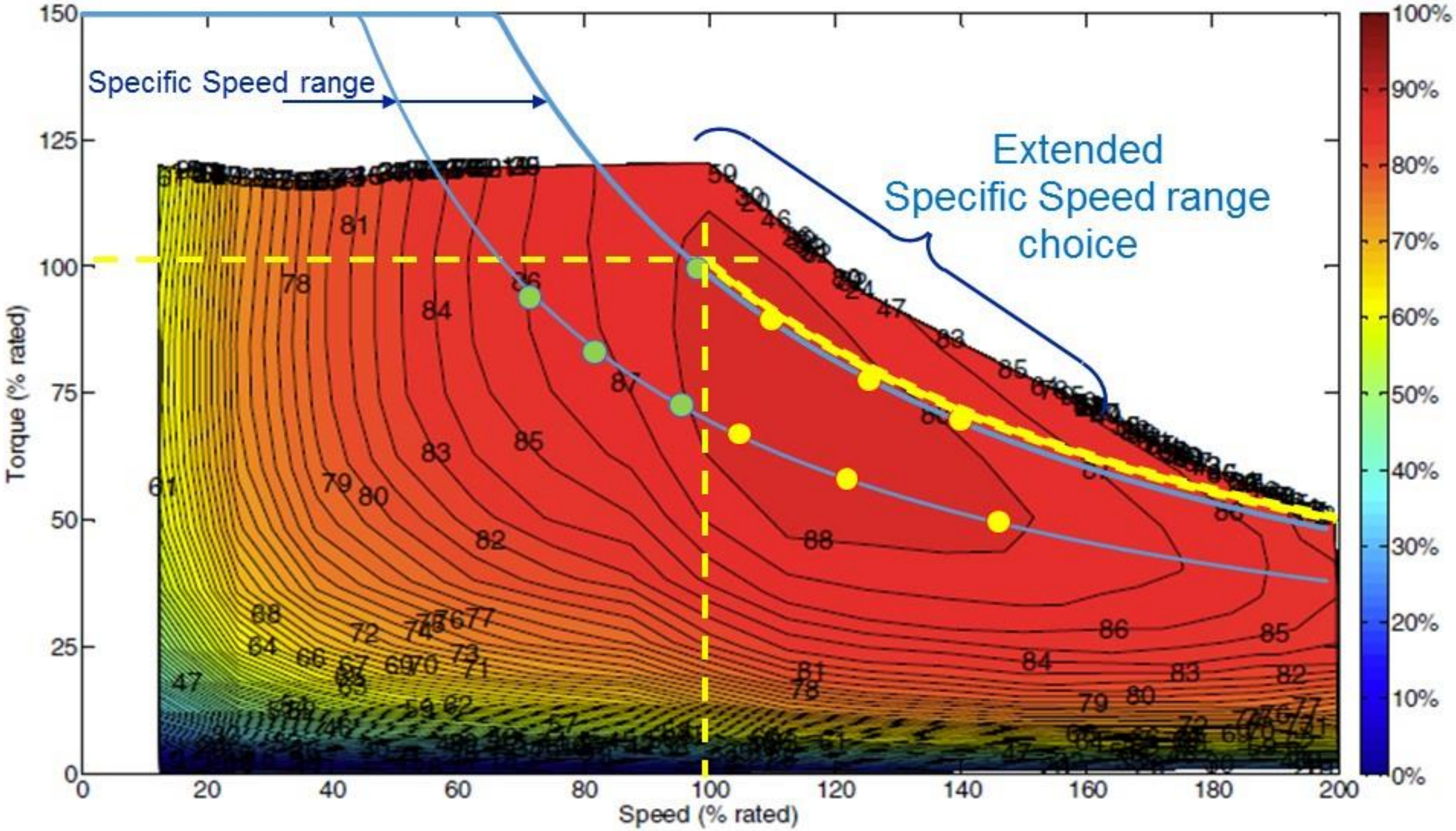


Figure : 9 Picture of Pump Torque/Speed points vs Efficiency contours – Extended Specific Speed range

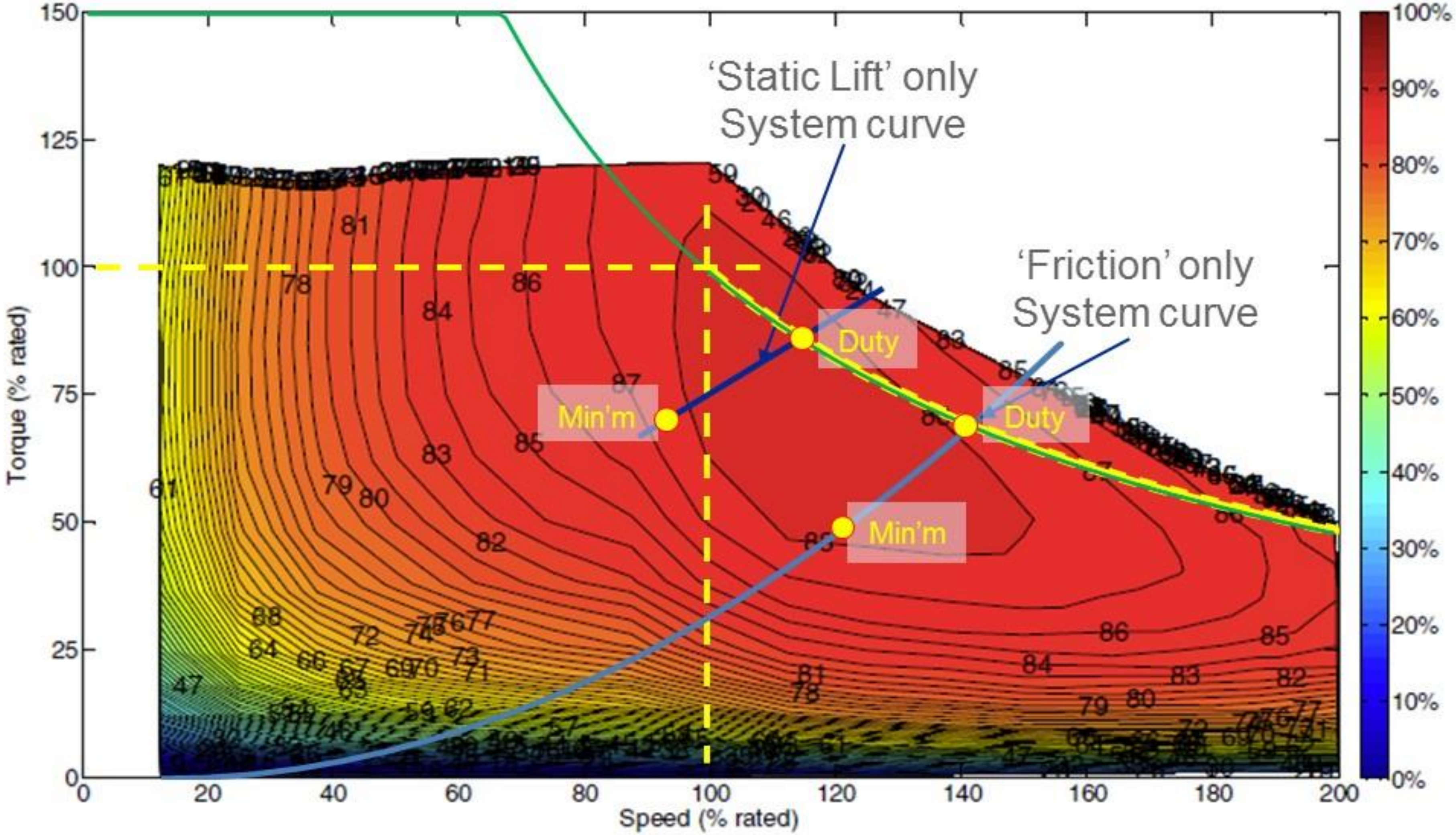


Figure : 10 Picture of Pump Torque/Speed points vs Efficiency contours for typical system curve

Appendix

A variable speed controlled motor operates in two regions defined by the speed vs torque envelope.

1) Constant Torque

   Speed up to base speed

   Magnetic flux is constant

   Torque is proportional to current

2) Constant Power

   Speed greater than base speed

   Magnetic flux reduces as the ratio of base speed to running speed

   Torque is proportional to ratio of running speed to base speed

Constant Torque

Optimum efficiency occurs where the copper and iron losses are equal.

Copper loss is proportional current squared

Iron loss has two components

a) kh - Hysteresis proportional to speed

b) ke - Eddy current proportional to speed squared

Windage - kw proportional to speed cubed

Where;

Isq - Current squared

r - Resistance

V - Motor nominal voltage at base speed

I - Motor current

N - Motor speed ratio – Normally based on a base speed @ 50Hz

Voltage varies with speed N : constant magnetic flux

Eff = 1 - [$I^2 * r + N * kh + N^2 * ke + N^3 * kw$]/(N * V * I *cosphi * 3^0.5)

dEff/dN = ($I^2 * r - N^2 * ke - 2 * N^3 * kw$)

Deff/Dn = 0 at best eff

Hence $I^2 * r = N^2 * ke + 2 * N^3 * kw$

i.e. 'Classic' transformer rule

Best efficiency occurs where the copper loss and eddy current loss are equal (assuming Windage factor kw is small)

Constant Power

Optimum efficiency occurs where the copper and iron losses are equal.

Copper loss is proportional current squared

Current increases as R for a given torque

Iron loss has two components

a) kh - Hysteresis loss at base speed

varies as the ratio 1/R ^1.6 : Steinmetz coefficient

b) ke - Eddy current loss remains constant

Windage kw - proportional to speed cubed

Where;

Isq - Current squared

r - Resistance

V - Motor nominal voltage at base speed

I - Motor current at base speed

R - Motor speed ratio above base speed – Normally based on a base speed @ 50Hz

It is assumed that the magnetic flux is in the inverse ratio (1/R) of operating speed to base speed

Eff = 1 - [$R^2 * I^2 * r$ + R/R^1.6 * kh + ke + $R^3 * kw$]/(R * V * I * cosphi * 3^0.5)

dEff/dR = ($R^2 * I^2 * r$ - 1.6 * kh/R^0.6 - ke + 2 * R^3 * kw)

Deff/Dn = 0 at best eff

Hence $R^2 * I^2 * r = 1.6 * kh/R^{0.6} + ke - 2 * R^3 * kw$

i.e Nearly, 'Classic' transformer rule

Best efficiency occurs where the copper loss and the sum of eddy current and hysteresis losses are equal (assuming Windage factor kw is small)

Review of Energy Efficiency Measurement Standards for Three-Phase Induction Motors – A 2017 Update

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Abstract

The IEC testing standard 60034-2-1 (2014): "Rotating Electrical Machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)" is actually used by many country members for the determination of electric motor efficiency.

Among other standards in use, the Institute of Electrical and Electronic Engineers: "IEEE 112 Standard Test Procedure for Polyphase Induction Motors and Generators", Method B has been revised from the 2004 edition, and is currently in its final steps and most likely be published by the end of 2017 and the Canadian Standards Association, CSA C390 (R2015): "Test methods, marking requirements, and energy efficiency levels for three-phase induction motors" are well recognized and used globally.

In recent years, much effort has been done to harmonize these energy efficiency standards but even with the recent revisions, differences still exist. Some authors in the past have compared these standards mainly based on the contents and procedures but this paper is aimed at making the comparison based on results from data of about five hundred (500) motors tested in the same independent laboratory in the range of 0.75-375 kW.

Introduction

The IEC testing standard 60034-2-1 (2014): "Rotating Electrical Machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)" [1] is actually used by many country members for the determination of electric motor efficiency.

Among other standards in use, the Institute of Electrical and Electronic Engineers: "IEEE 112 Standard Test Procedure for Polyphase Induction Motors and Generators", Method B [2] has been revised from the 2004 edition, and is currently in its final steps and most likely be published by the end of 2017* and the Canadian Standards Association, CSA C390 (R2015): "Test methods, marking requirements, and energy efficiency levels for three-phase induction motors" [3] are well recognized and used globally.

In recent years, much effort has been done to harmonize these energy efficiency standards but even with the recent revisions, differences still exist. Some authors in the past have compared these standards mainly based on the contents and procedures but this paper is aimed at making the comparison based on results from data of about five hundred (500) motors tested in the same independent laboratory in the range of 0.75-375 kW.

Other national standards exist from countries like China, Mexico, India, Australia, South Korea and Brazil but it is agreed that all those standards are in a way subsets of either IEC 60034-2-1, CSA C390 and IEEE 112 standards so the comparison is thus focused on those three. In the following study, these standards will be noted as IEC, CSA and IEEE to simplify the text.

Comparison of tolerances

Due to variations in materials and manufacturing process, it is not possible to build all motors having the same exact efficiency marked (or declared) on the nameplate. Moreover the determination of motor efficiency (or losses) in lab or at the manufacturer location is not without some uncertainty. So when the nameplate efficiency is marked, it should represent the average value of a statistically significant population of motors of the same design[66]. In the IEC world, the performance, safety, construction, and manufacture of motors is based on IEC 60034-1 [4] and NEMA MG 1 [5] is the reference in North America. Depending of the reference used, there is a difference in tolerances on the *actual measured* efficiency. IEC 60034-1 standard has two (2) tolerances based on the following equations:

- motors up to and including 150 kW (or kVA) –15 % of (1 – efficiency)
- motors above 150 kW (or kVA) –10 % of (1 – efficiency)

With NEMA MG 1 Table 12-10, the tolerance is not referenced on efficiency but on total losses difference for:

- All 50/60 Hz motors rated 5000 volts or less + 20% Loss Difference

It should be noted here that the specifications in IEC (-10 and -15 %) do not exactly equal the tolerances of +10 % and + 15 % loss difference and NEMA Table 12-10 (+ 20 %) does not always equal the tolerances of +20 % loss difference in the value presented in the table. However the differences especially for efficiency higher that 80 % are considered marginal.

In all cases, the tolerances can also convert for homogeneity from these numbers to percentage point based on the nameplate efficiency that varies with the rated power. This approach is used in the following graphs for the comparison.

Test conditions

The series of motors including most 4-pole but also some 2-pole and 6-pole from 0.75-375 kW constituted the sample of approximately five hundreds (500) motors that were tested in the same independent laboratory according to CSA standard. The motors were all with very few exceptions classified as high energy efficient 60 Hz TEFC motors or IE2 equivalent, the minimum standard in North America at the time of the testing. Premium or IE3 equivalent is the minimum standard in this area today but considering the small differences in efficiency (or losses) between these two (2) classes, results of this analysis should be expected as similar.

For the need of this study, the motors were not necessarily retested against IEEE that is assumed to be identical in its test procedure to CSA. In case of IEC, among the difference, the measurement of stator winding resistance before and after the load and the no-load test were added to conform to the IEC standard.

It is assumed that the test set-up and the uncertainty in the instrumentation have no impact in the efficiency measurement and calculations. All tests were concluded with a minimum correlation coefficient of 0.99 of the residual losses dedicating the quality and the precision of the tests performed. All comparisons are made at 100 % nominal load of the motor.

Results and analysis

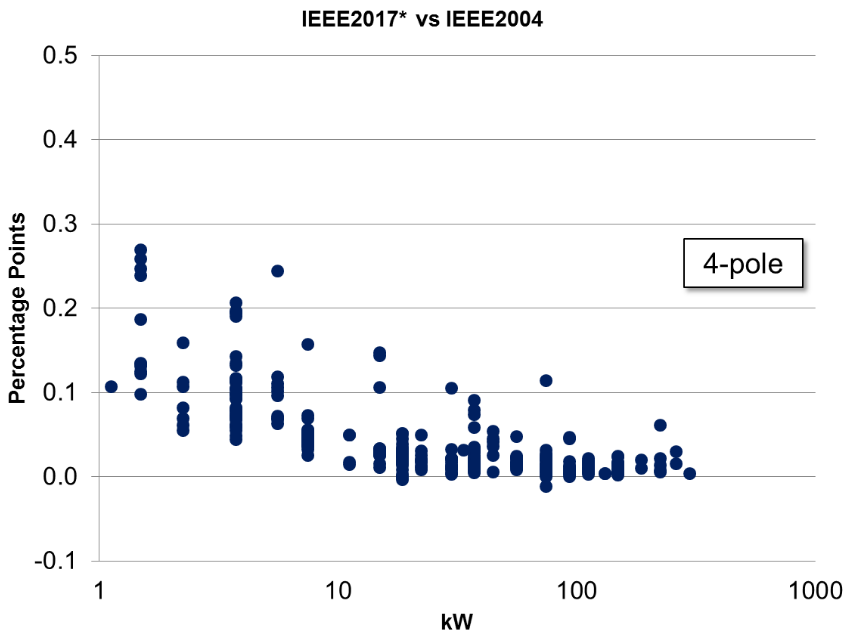
The first comparison is presented in figure 1. It shows the difference in percentage points obtained by the revision of IEEE compared to the actual published version of 2004. The main difference comes from the decision to take into account the voltage drop in the stator winding that reflects more the real situation when the motor is under load. The

[66] Definition from CSA C 390 standard and NEMA MG 1

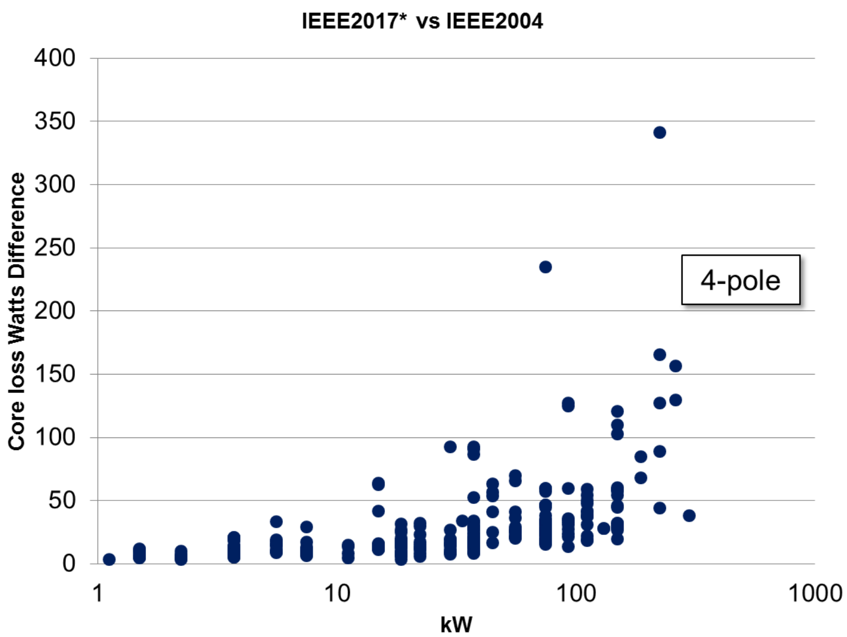
same decision was also taken a few years ago at CSA and IEC improving the evaluation of the losses.

It is clear that this impact more small motors than larger ones due higher resistance ratio. The impact related to motor efficiency is positive from + 0 to + 0.3 percentage points meaning that the new IEEE will give higher efficiencies than its predecessor.

Figure 2 shows over the range of test for 4-pole motors that the main impact is related to the change of the core or iron losses motors showing less value of core losses with IEEE2017 than IEEE2004.



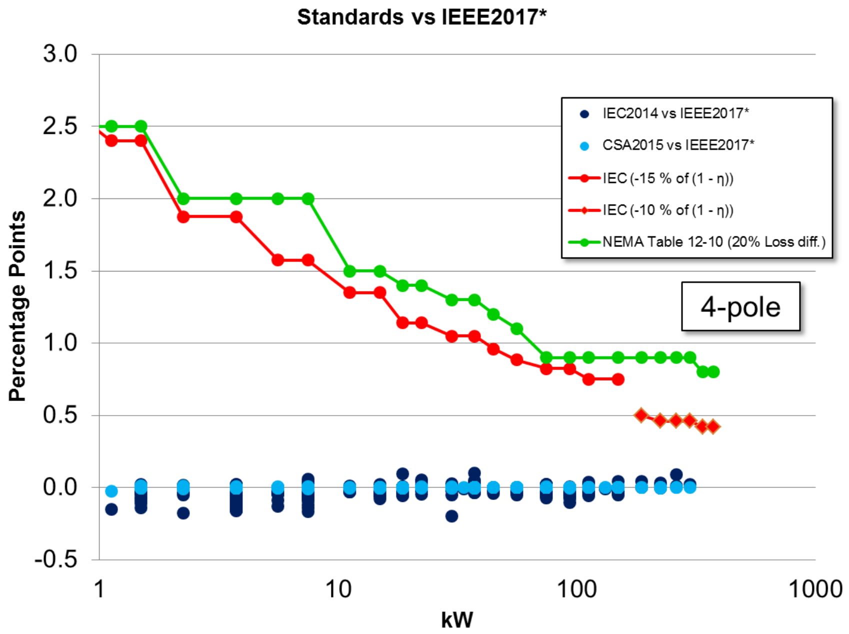
Comparison between IEEE 2004 and IEEE2017*



Core loss difference between IEEE 2004 and IEEE2017*

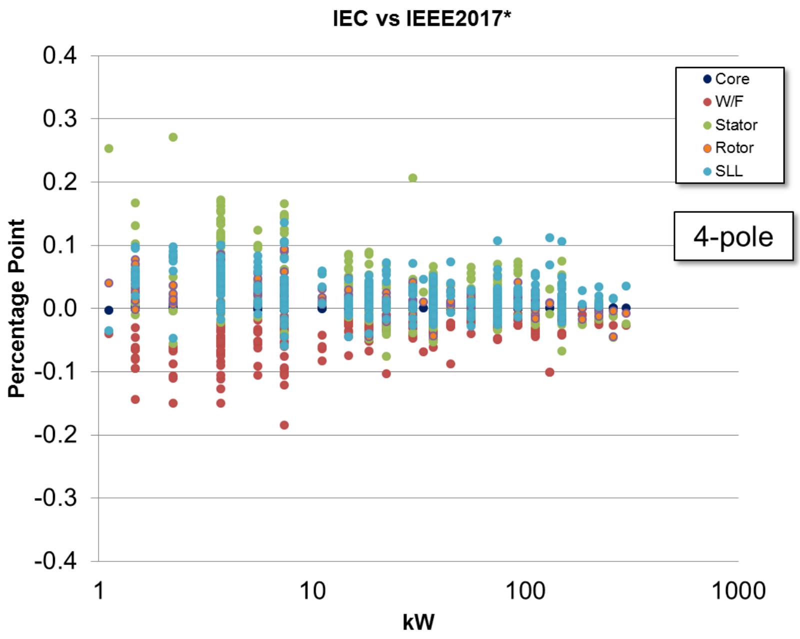
An improved comparison of standards can now be done considering the new revised IEEE2017*. The reference standard to choose can be either one of the three: CSA, IEC or IEEE2017* without affecting the results. In this case, IEEE2017* is selected as the reference.

Figure 3 shows the comparison. It can be seen that when compared, CSA and IEEE2017*have no difference in the results so can be considered almost identical. The comparison between IEC and IEEE2017* gives differences between + 0.1 and -0.2 percentage point mainly for small motors and marginal for larger motors.



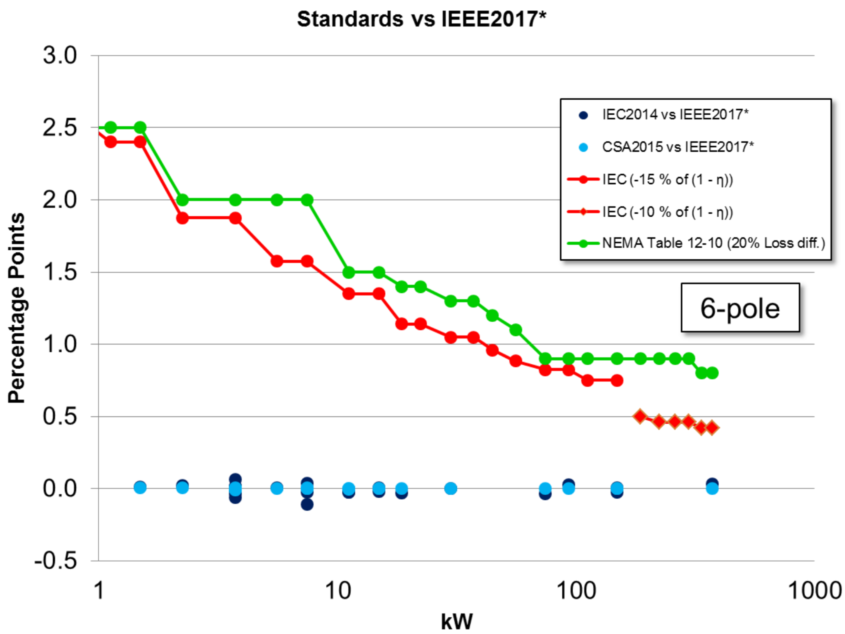
Comparison between standards and IEEE2017* - 4-pole

Also included in figure 3 are the tolerances detailed before i.e. for IEC -15 % and -10 % and 20 % for NEMA (identical for CSA) with all values converted in percentage points. The graph shows that it exist a large margin between the difference between the standards and these tolerances resulting in no significant impact on the classification for IEC or NEMA motors based on the selection of the standard used. Despite the small discrepancies in percentage point between IEC and IEEE2017*, it is still interesting to know what losses are different. Figure 4 specifies the impact of each loss of the motors' efficiency. The visible differences are in the stator winding losses due to the difference in the resulting temperature of the motor by thermocouple / resistance method (IEEE) or by resistance method only (IEC) and the friction / windage losses resulting of the correction of these losses (lower) by IEC (not done by IEEE) that takes into account in the calculation the variation in motor nominal load speed compared to the synchronous one. Despite these, the impact in efficiency is considered very low.



Comparison of each loss difference between IEC and IEEE2017* - 4-pole

Figure 5 presents the results for 6-pole motors with the same conclusion despite the small sample.



Comparison between standards and IEEE2017* - 6-pole

Conclusion

Nevertheless the small differences in the calculations and in the test procedure of the three (3) standards CSA, IEEE and IEC evaluated, the results showed that the three (3) can be used and interchanged without significant discrepancies in the calculated efficiency considering the same test set-up and instrumentation accuracy. The differences were limited to + 0.1 to -0.2 percentage point mainly for small motors (0.75 – 4 kW) and no measurable difference for motors larger than about 18.5 kW. With the upcoming revised IEEE 112 close to be published, we can now say that the three standards are finally harmonized and the resulting computed efficiency is very equivalent. Hopefully these results would influence the authorities to finally accept this equivalence all over the world.

References

[1] IEC 60034-2-1 Rotating Electrical Machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles), International Electrotechnical Commission, 2014

[2] IEEE 112 Standard Test Procedure for Polyphase Induction Motors and Generators, Institute of Electrical and Electronic Engineers, 2004, revision to be published in 2017

[3] CSA C390 Test methods, marking requirements, and energy efficiency levels for three-phase induction motors, Canadian Standards Association, 2015

[4] IEC 60034-1 Rotating electrical machines - Part 1: Rating and performance, International Electrotechnical Commission, 2010

[5] NEMA MG 1 Motors and Generators, National Electrical Manufacturers Association, 2016

The role and traceability of torque measurements in the determination of induction motor losses and efficiency

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Sandie Braendgaard Nielsen Danish Technical Institute, Denmark

Abstract

There is now international consensus that the preferred method for the measurement of induction motor losses and efficiency is by the technique of separation-of-losses, with additional load losses determined by the smoothing of residual losses. The measurement of electrical quantities in this process is straight forward, but measurement of motor torque is less so: The currently published standard requires high torque measurement accuracy (0.2%), but calibration of torque transducers to that level of precision is difficult, as many countries (including the USA and Australia, for example) do not possess national torque standards, and the generation of torque 'in-house' to that accuracy level is very difficult. This paper analyses the role which torque measurements play in the determination of induction motor efficiency, and suggests measurement 'quality indicators' which can draw attention to the existence of errors in the measurement of motor shaft torque. It is shown that the separation-of-losses, with smoothing of additional losses, method for determination of motor efficiency is quite tolerant of torque measurement errors, and that torque transducer accuracy requirements may be relaxed by up to an order of magnitude, compared with IEC requirements.

Introduction

The relatively recent development and availability of high precision 'flange'-type torque measuring instruments has greatly facilitated the determination of the efficiency of rotating electrical machines, and induction motors in particular. Whereas it was previously only possible to estimate additional load losses, these new torque measuring instruments have made it possible to determine the value of additional load losses with high accuracy, using the 'smoothing of residual losses' technique which is now the preferred method for the determination of induction motor efficiency as described in IEC 60034-2-1:2014[1] ('the standard').

Modern flange-type torque meters are highly stable and linear, as demonstrated by 'smoothing of residual losses' processes in which correlation coefficients closely approach unity and 'B-intercept' values are very small.

Torque meter *scale factor* is thus the only parameter which requires verification, by calibration.

The current (2014) edition of IEC 60034-2-1 [1] provides a single figure of 'minimum Class 0.2%' (at Clause 5.5.3) for the accuracy of torque measurement systems, regardless of the particular method employed for the determination of motor efficiency. This single requirement appears to be both ambiguous and inadequate, however, as the various efficiency measurement methods have very different requirements for torque measurement accuracy: In the case of input-output methods, torque measurement accuracy becomes increasingly important as motor efficiency increases, to the point where highly efficient motors and motor systems cannot be accurately characterised even using the best available ('state-of-the-art') transducers.

The question which this paper addresses is the extent to which errors in the measurement of torque affect final induction motor efficiency figures, from which conclusions may be drawn as to the actual accuracy required. This information is useful because of the significant difficulties associated with the calibration of torque measuring systems with small uncertainty.

Study methodology

The aim of this study was to perform a series of 'separation of losses' efficiency measurements on a single cage-rotor induction machine, using high quality electrical and mechanical instrumentation, including a number of 'load curve' measurements additional to those specified in the standard in the range 95-105% of rated motor output power, in order to determine the influence of torque measurement errors within that range on final motor efficiency figures.

Those measurements thus simulated torque meter errors of up to ±5% - more than an order of magnitude greater than those permitted by the current standard.

Also studied were the effects of those 'errors' on what this study has labelled the 'quality indicators', including the correlation factor (gamma) and the 'B-intercept', both produced as part of the smoothing of residual losses process, and a comparison between 'separation-of-losses' efficiency and that determined as the simple ratio of mechanical output power to electrical input power, the 'input-output' method.

The experimental method and measurement conditions

The experimental measurements were made on a single 11 kW, 4 pole IE2 efficiency cage-rotor induction motor at a laboratory ambient air-temperature of 25 °C, so that temperature corrections for stator winding resistance were not required, thus facilitating the direct comparison of the two test methods.

The torque measurement system used in this study was an HBM T12 500 N.m torque-flange type, having an accuracy, as assigned by the manufacturer, of Class 0.03(%). That transducer also incorporated an optical speed measuring device producing 360 pulses per revolution of the motor shaft. Overall torque measurement accuracy was probably as claimed by the manufacturer, but, in any case, and for the purposes of this study, measurements made using that equipment were considered 'true'.

Electrical measurements were made with Yokogawa equipment, with a nominal accuracy of 0.2%.

Slip was measured by the ratio-metric method described in the standard (Annex C).

All measurements, both electrical and mechanical, were averaged over a 10 s period.

Test series 1:

A separation-of-losses procedure was carried out on the above motor, as prescribed in IEC 60034-2-1, but with deviations from that method as follows:

- The machine was not, at any stage, loaded beyond its nameplate rating, in order to preserve the thermal state it attained in the 'rated load test'.
- When temperature stability had been attained at the completion of the rated load test, the 'load curve test' was initially carried out at the following loads:

105%, 102.5%, 100%, 97.5% and 95% of motor rating, repeated three times, providing at total of 20 sets of measurement data at and in the vicinity of rated mechanical load, thus simulating torque measurement errors over a range of ±5%.

- The load curve test was then continued with a single set of measurements made at loads of 75%, 50% and 25%.

All 'load curve' measurements, as above, were made in rapid succession, with stator winding resistance measurements made before and after the near full-load measurements agreeing within less than 0.1%, indicating that no significant winding temperature changes had taken place during that process.

The above procedure thus effectively represented a total 20+3 complete motor efficiency tests, but with focus on the region in the close vicinity of rated load (+5%, +2.5%, +0%, -2.5% and -5%) in order to facilitate examination of the effect on final calculated motor efficiency values of known torque measurement scale errors.

Test series 2:

A second set of separation of losses procedures was carried out on the same motor, but without deviations from the method specified in the standard. A total of three complete sets of separation-of-losses measurements were made in order to simulate torque transducer scale errors of +5%, zero and -5%, in order to show the effect of such errors on the 'B-intercept' value obtained in the 'smoothing of residuals' procedure. Those measurements were made at an ambient air temperature which differed from the 25°C value used in the first test series, as above.

Results (1): Motor efficiency values without deliberate torque measurement errors

The following curves show motor efficiency as a function of load for both separation-of-losses and input-output methods, both of which indicate that maximum efficiency was obtained at approximately 75% of motor rated load. All electrical mechanical and electrical measurements used to produce the charts shown in Figures 1 and 2 were 'as read' at the time the tests were undertaken, and thus represent, as closely as possible, the 'true' behaviour of both motor and instrumentation:

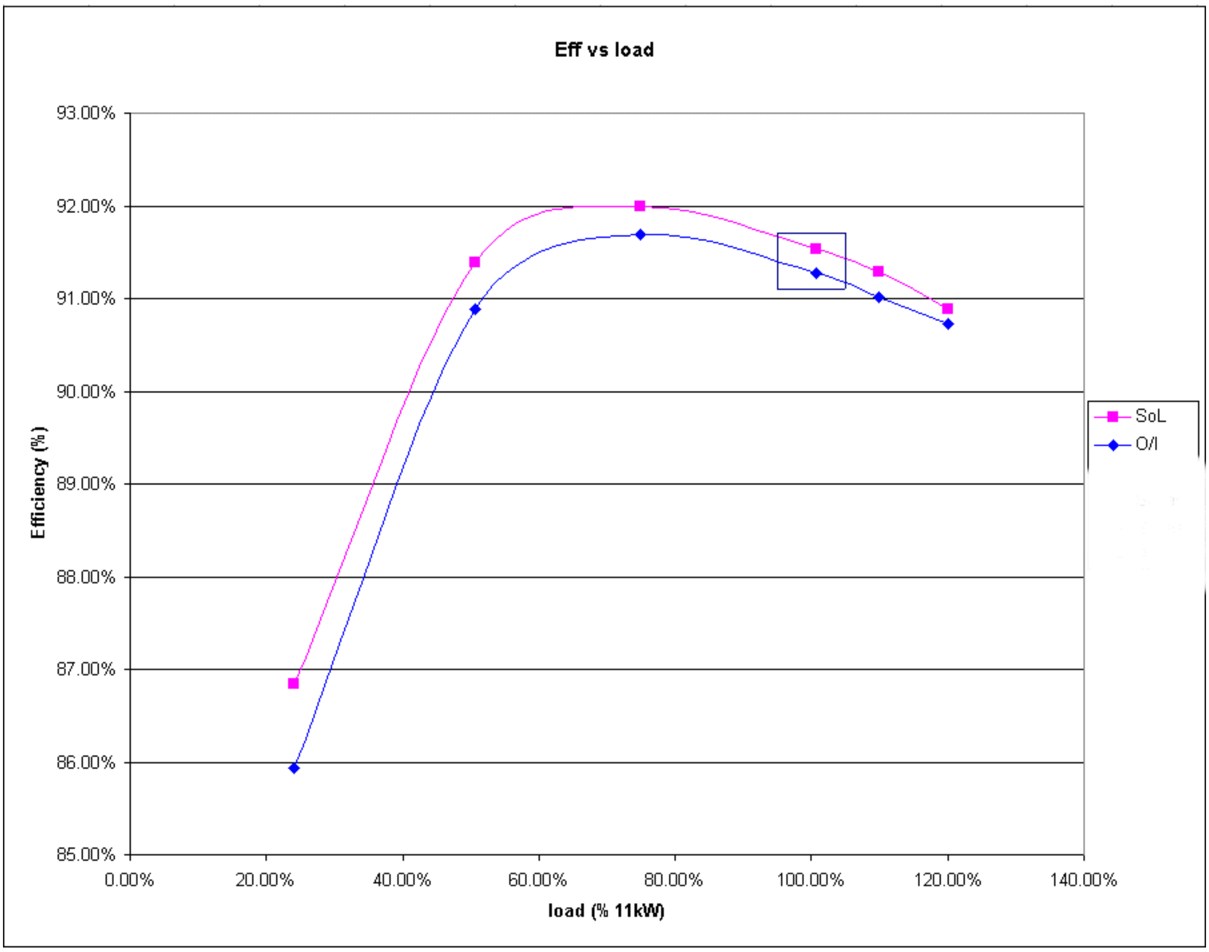

Figure 1: Motor efficiency curves over the load range 25 – 120% of rating (11 kW)

Upper curve: Separation-of-losses method - Lower curve: input-output method

Note: The IEC 60034-30-1: 2014 (50 Hz) IE2 efficiency lower limit for this 11 kW, 4 pole machine is 89.8%, and the IE3 limit is 91.4%, as shown

Motor efficiency behaviour within the rectangle, as above, is shown enlarged in Figure 2

Figure 2, below, shows motor efficiency values obtained from both the separation of losses and input-output methods for motor shaft loads in close proximity to motor rated output power.

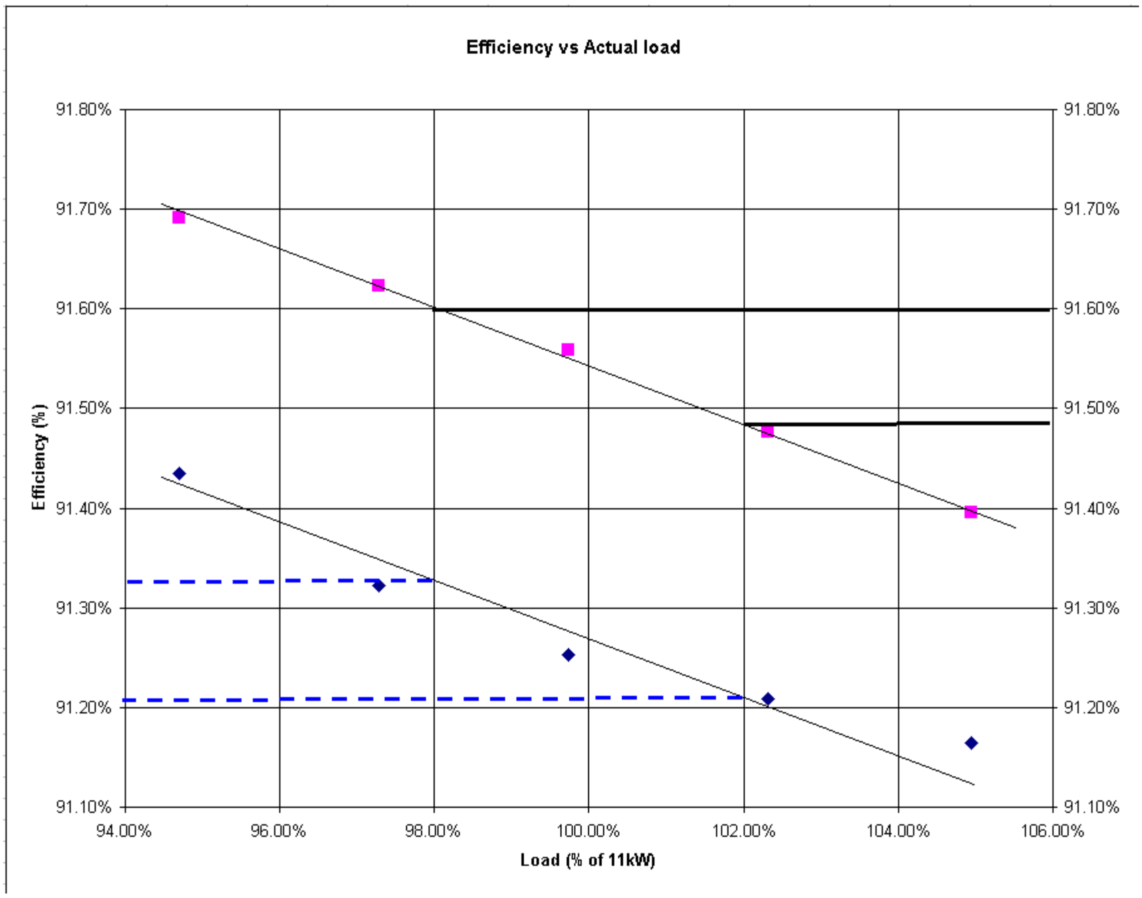

Figure 2: Motor efficiency values, as in Figure 1, but over the load range 95 – 105% of rating (11 kW)

Upper line: Separation-of-losses method - Lower line: input-output method

Straight lines were fitted to both sets of efficiency data, the slope of which is a characteristic of the motor itself, with efficiency falling slowly with rising load, since the maximum efficiency exhibited by that motor occurred at a load of approximately 75%. Thus, with essentially error-free measurements, those two lines are essentially parallel, (i.e. have the same slope), the separation between which (just less than 0.3 percentage points) is an indication of the implicit differences between the two test methods, the most important of which is probably the assumption that loss components determined as a result of a number of discrete and independent measurements, may simply be added together algebraically, without considering any possible interdependence of those quantities. In other words, the principle of superposition applies.

Figure 2 may be interpreted as showing that the least effect which torque measurement errors may have is to determine motor efficiency at the wrong load, and that the actual error in the motor efficiency value so-determined is a characteristic of the motor itself.

Thus for this particular motor, 'errors' of ±2% in torque measurements (i.e. from 98% of rated torque to 102%) result in changes in indicated motor efficiency of about ±0.06 percentage points. This result suggests that if a torque transducer had an uncertainty of ±0.2%, as specified in the standard, the motor efficiency error resulting from an error in the load point would be entirely negligible, at a tenth of the above value, namely ±0.006%.

Results (2): Motor efficiency values with torque measurement errors

A second chart was produced in which it was imagined that the torque meter (only) exhibited scale errors in the range ±5%, and the experimental measurements, made as described above, were, in five separate (sets) of load curve measurements, all treated as if they represented 100% of rated motor mechanical output power (11 kW in this case).

Thus, for example, to simulate the torque meter reading at all times 5% low, the "100% load" measurements were actually made with the torque meter reading 105% of the figure corresponding to rated torque, and all torque measurements associated with the efficiency calculations in both cases (input-output and separation-of-losses methods) were adjusted upwards by 5%. That recalculation process was repeated for all other load points in the vicinity of motor rated load.

The results were as shown in Table 1, below:

Torque meter measurements	**5% low (%)**	**2.5% low (%)**	**'Error-free' (%)**	**2.5% high (%)**	**5% high (%)**	**Average indicated efficiency (%)**	**Efficiency value range (pp)**
Separation of losses efficiency	91.59	91.57	91.55	91.52	91.49	91.54	0.099
Input-output efficiency	96.50	93.88	91.50	89.16	86.87	91.58	9.63

Table 1: Summary of efficiency values obtained by both the separation-of-losses and input-output methods under conditions of torque meter scale errors in the range ±5%

The above results, shown in graphical form below, (Figure 3) show clearly that separation-of-losses efficiency figures are comparatively insensitive to torque meter errors, but that input-output method derived figures, on the other hand, are highly influenced.

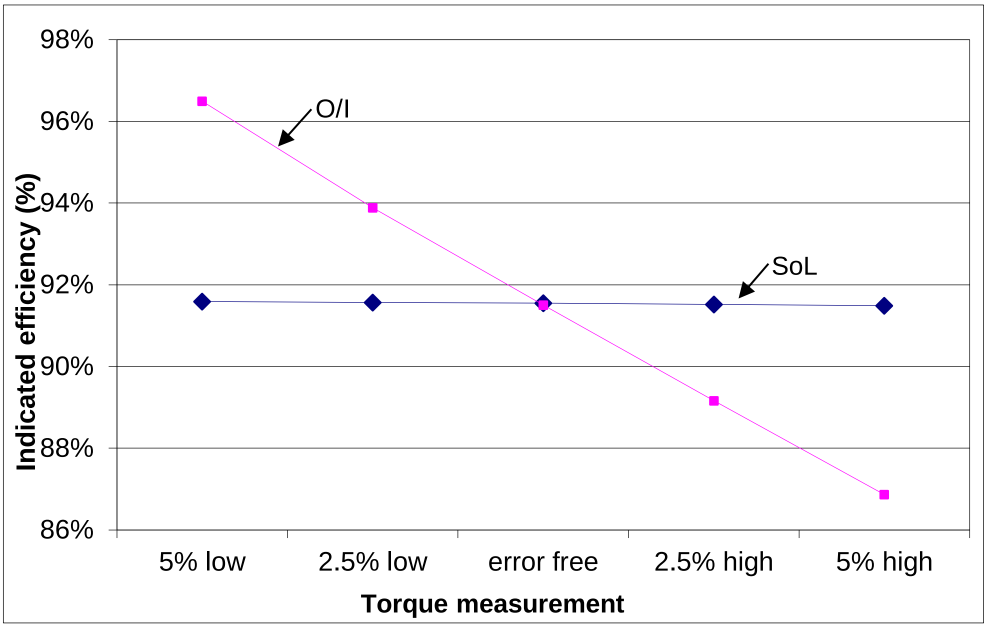

Figure 3: Indicated motor efficiency as affected by torque measurement errors

Results (3): The effect on 'B-intercept' values of torque measurement errors

In the 'Test series 2', as above, attention was directed towards the 'smoothing of residuals' data manipulation process.

Figure 4 shows the three 'smoothing lines' obtained at motor loads assumed to be rated values, but actually in error by +5%, zero and -5%, respectively:

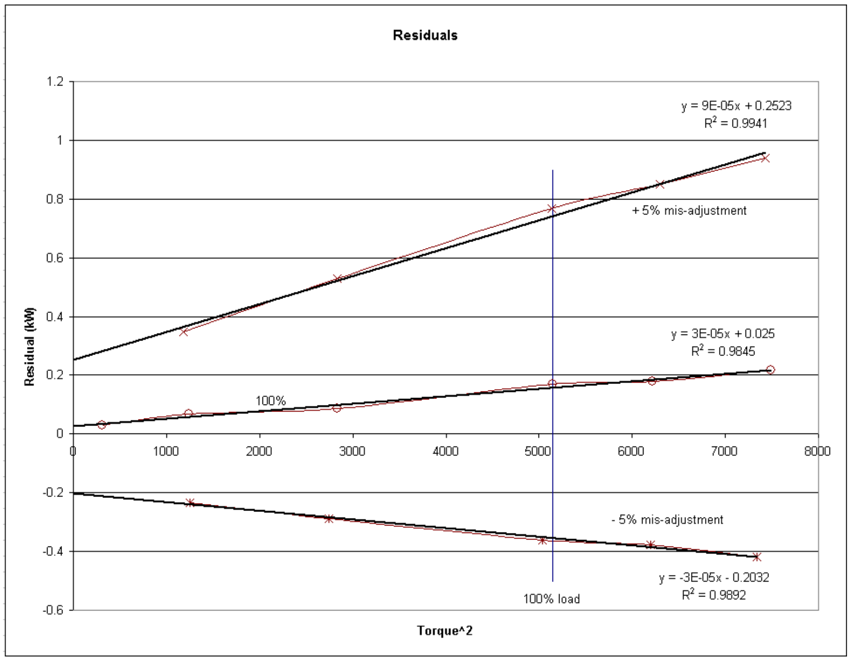

Figure 4: Smoothing of the residual loss data

Top curve: Torque measurements all 5% high: B = 0.25 kW (27% of total motor losses)

Middle curve: Torque measurements 'true': B = 0.025 kW (2.7% of total motor losses)

Bottom curve: Torque measurements all 5% low: B = 0.20 kW (21% of total motor losses)

Table 2, below, shows values of correlation factor, gamma, and B-intercept, both as absolute values and relative to the sum of the losses at rated (100%) load.

Torque measurement	**Correlation factor (gamma)**	**B-intercept value (kW)**	**B-intercept (% of 925 W)**
Reads 5% high (top line)	0.99	0.25	27%
Reads correctly (middle line)	0.98	0.025	2.7%
Reads 5% low (bottom line)	0.99	0.20	22%

Table 2: B-intercept values for different torque measurement scale errors

Note that a 5% error in torque scale value produces an order of magnitude change in the value of the B-intercept.

Finally, Figure 5 shows a scatter diagram for a series of laboratory MEPS induction motor check-tests in which the B-intercept value is plotted versus motor power rating, using a 500 Nm full scale torque measuring system.

From this it can be seen that if a maximum B-intercept value of 5% of total losses is acceptable, then a 500 Nm torque transducer (corresponding to about full-load torque for a 75 kW, 4 pole, 50 Hz induction motor) can be used satisfactorily for measurements on motors with ratings down to below 2.2 kW, i.e. less than 3% of its full dynamic range.

This contrasts with the standard's requirement that (Clause 5.5.3) '*The minimum torque measured shall be at least 10% of the torque meter's nominal torque*'.

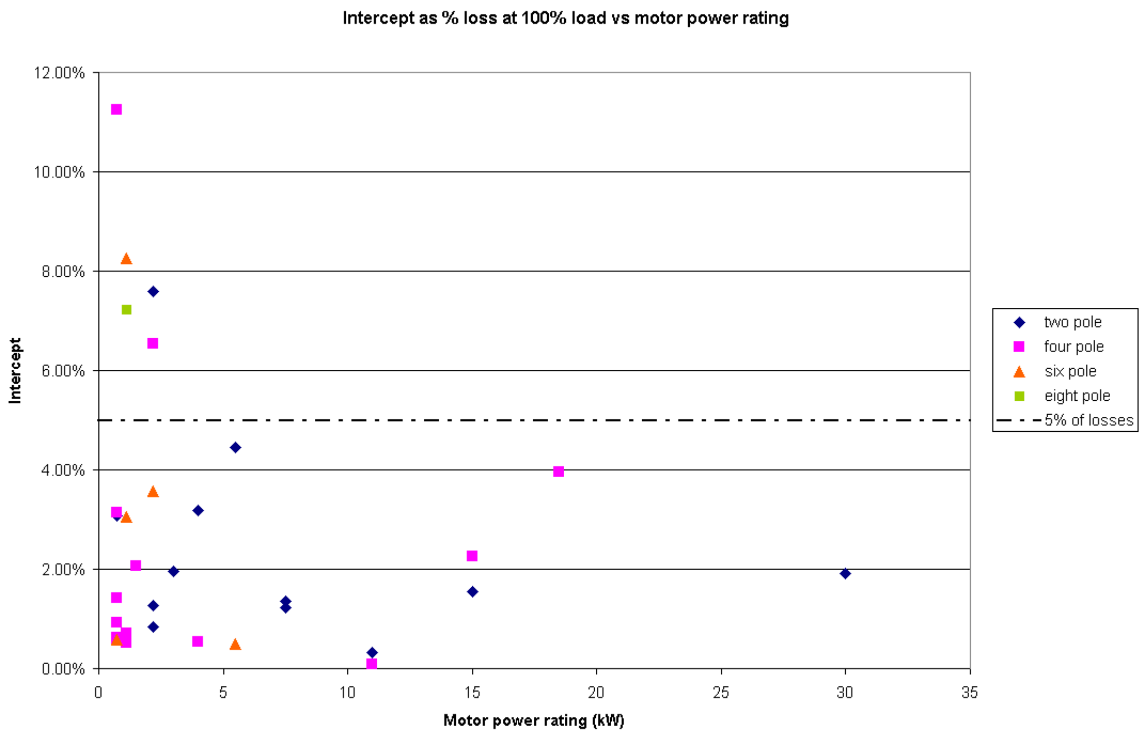

Figure 5: Scatter diagram showing 'B-intercept' values as a fraction of total losses for a range of induction motors which have been MEPS check-tested

The horizontal broken line represents 5% of total motor loss in each case, a possible limit below which the efficiency measurement process might be considered to be of high quality.

Discussion and conclusions

The results of this study suggest that the separation-of-losses method for the determination of induction motor efficiency is quite tolerant of torque measurement errors, to the extent that the standard's present requirement for class 0.2 torque accuracy could be relaxed by an order of magnitude to class 2 (with respect to scale factor), without incurring any significant increase in the uncertainty of final motor efficiency figures.

Note that it is *not* suggested that other than the very best torque measuring systems can or should be used for separation-of-losses induction motor efficiency measurements: the highest possible stability and linearity will always be required. The objective of this study has been rather to demonstrate that it is possible to lessen the requirement for the torque meter *scale factor* to be precisely known, and therefore to ease the requirement for torque calibration facilities which may be difficult, costly and time-consuming to access.

The high degree to which final separation-of-losses efficiency measurements are tolerant of torque measurement scale errors is initially surprising, until it is realised that none of the calculations leading to numerical values of the individual motor loss components, as specified in the standard (Clauses 6.1.3.2.2 to 6.1.3.3), contain terms involving motor torque. Rather, those loss components are the results of electrical, shaft speed and speed ratio measurements, the latter two being essentially error-free.

Loss component	**Effect of torque measurement error on loss component**	**Comment**
Iron loss, P_{FE}	Extremely small	Torque measurement error may influence motor temperature very slightly
Stator winding loss, $(I^2R)_S$	Small	Stator winding current increases with load, but not linearly, due to finite current at no-load, (of the order 30% of rated current).
P_F	Zero	---
$(I^2R)_R$	Direct, since rotor current is proportional to torque	For an efficient motor, slip, and therefore rotor loss, is very small. Torque measurement error thus has very little effect on total motor losses.
P_{LL}, Additional load loss	Proportional to torque squared	Additional load loss is a small fraction of total motor losses, and torque measurement error therefore has only a small impact on total motor losses.

Table 3: Influence of torque measurement errors on the various components of total motor loss

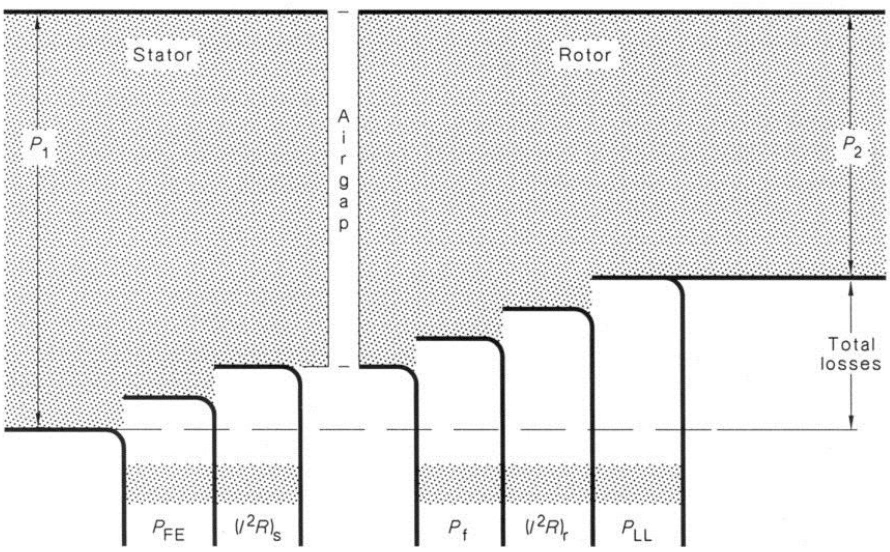

Figure 6: Graphical illustration of motor loss components

A low 'B-intercept' value and/or close agreement between separation-of-losses and input-output efficiency values, represents a reconciliation of electrical and mechanical measurements. If shaft speed is essentially error free (as a result of counting around 100 000 pulses or more during a typical 10 s averaging period), then achievement of the above conditions represents a *de facto*, if not formal, calibration of the torque meter scale factor against the electrical measuring equipment.

Reduction of the degree of torque meter precision as currently specified in the standard would greatly facilitate calibration of torque measuring equipment 'in-house', using simple equipment and a minimum requirement for external calibration in order to maintain traceability of measurements to international standards.

On the other hand, input-output methods, a last resort, when other methods are not applicable, may, depending on the efficiency of the equipment under test, require torque measurement accuracy an order of magnitude (or more) *better* than is required by the current standard.

The standard's requirement for a single accuracy class is inappropriate, therefore, and should be reviewed.

Further, although the standard's 'smoothing of residual losses' process requires that the 'B-intercept' be determined, but it then discards that figure. This study suggests, however, that the B-intercept is very useful as a sensitive indicator (together with the correlation factor, gamma) of the overall quality, not only of the measurement process, but also of the subsequent numerical processing of the measured data.

It is suggested, therefore, that the standard include a requirement that the B-intercept be less than or equal to a fixed percentage of a given motor's losses. A B-intercept of less than or equal to 5% might be an appropriate indicator of the overall acceptability of a given set of induction motor efficiency measurement results.

Finally, another quality indicator which may be worth considering is a comparison between the separation-of-losses efficiency figure and that which is calculated from the simple ratio of output/input power. Note, however, that such a ratio would need to be calculated before any correction for ambient air temperature were applied to the separation-of-losses efficiency figure.

References

[1] IEC 60034-2-1 : 2014 *Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)*

[2] Cummings, P.G., Bowers, W.D. and Martiny, W.J: *Induction motor efficiency test methods*, IEEE Industry Applications Society Conference Record, 1979.

Dedication

John Henry Yelland, one of the authors of this paper, and a significant contributor to the reported experimental work, died earlier this year after a long illness. This paper is dedicated to his memory.

Analytical Power Loss Calculation Method for Gearboxes

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Abstract

Recently, the Extended Product Approach has been gaining interest as a tool to increase the energy efficiency of Power Drive System. High savings can only be achieved by optimizing the efficiency of the entire motor driven system. To apply the EPA, energy efficiency or power loss values of each drive train component in a wide operating range are required. For electric motors and their power electronic control units, this information is gradually becoming available because new standards being accepted. For mechanical transmissions such as gearboxes, this information is lacking. Therefore this paper presents a method to create analytical power loss maps for small and medium sized helical, helical-bevel and helical-worm gearboxes. The analytical expressions contain physics based and non-physics based terms. The coefficients used in the expressions have been derived from a first set of measurement data. Also scaling laws are proposed to enlarge the scope of the method.

Introduction

Over the last years the interest in the energy efficiency of gearboxes has gained interest, especially with respect to applications in the automotive and wind energy industry [1]. In these applications, energy efficiency and energy yield have been main drivers in the innovation. For gearboxes used in traditional industry, the available information on the energy efficiency is very limited. In contrast to electric motors and power electronic converters [2], no standards dealing with the energy efficiency classification or measurement procedures for traditional gearboxes have been developed.

Gearbox manufacturers currently rely on ISO/TR 14179. This ISO standard describes 2 methods to design gearboxes based on the thermal properties of the device. In the first part the American method (American Gear Manufacturers Association, AGMA) is given which is based on a thermal equilibrium at 95°C sump temperature [3]. It uses an analytical heat balance model to calculate the thermal transmittable power for a single of multiple stage gear drive lubricated with mineral oil. The bearing losses are calculated from catalogue information supplied by bearing manufacturers. The gear windage and churning loss formulations originally appeared in work presented by Dudley, and have been modified to account for the effects of changes in lubricant viscosity and amount of gear submergence. The gear load losses are derived from the early investigators of rolling and sliding friction who approximated gear tooth action by means of disk testers. The coefficients in the load loss equation were then developed from a multiple parameter regression analysis of experimental data. The second part of ISO/TR 14179 is based on a German proposal whereby the thermal equilibrium between power loss and dissipated heat is calculated in an iterative way [4]. Both theoretical and experimental investigations are combined to calculate the power loss of cylindrical, bevel, hypoid and worm gears. It includes load dependent power losses but highly relies on experimental data.

The expertise available in ISO/TR 14179 has been integrated in several software packages such as WTplus [5], developed in a research project by the Forschungsvereinigung Antriebstechnik (FVA, Frankfurt) or the KISSsys gear software

[6]. Both tools require knowledge of the internal design of the gearbox under consideration. As such, these tools are very convenient for gearbox manufacturers but extremely unpractical for a gearbox end user because to many design parameters are unknown to the user.

In this paper a simple analytical method is proposed to help the end user to gain better understanding in the power losses of small gearboxes without the need to understand the specific internal design details of the gearbox under consideration. The aim is to be able to create a power loss map or efficiency map with acceptable accuracy in the entire torque and speed range of the gearbox that can be used in the context of the Extended Product Approach to assess the overall efficiency of an electromechanical drive train [7]. Finally, the method is to be publically available by integrating it in the Motor Systems Tool [8].

Gearbox Efficiency measurements

To develop and validate the analytic method presented in this paper a set of 13 gearboxes have been extensively tested. A first test bench and a measurement procedure was designed and reported at EEMODS 2015 [9].

The purpose of the test bench is to measure gearbox efficiency at different loads and speeds within the allowed working area of the gearbox. A lot of industrial gearboxes are used for conveyors and other applications in the lower power range and they come in various types. Currently, two test benches are available. The data used in this paper is based on a 15 kW test bench and allows load torques up to 1000 Nm. Recently a new test bench has been realized with a power limit of 150 kW and load torque up to 45 kNm. For both setups, the direct back to back method is used to determine the overall efficiency. This method requires accurate measurement of the mechanical in- and output power. The torque is measured by means of dedicated sensors with an accuracy of 0.1% full scale. The speed is measured using incremental encoders. The measurement principle is shown in figure 1 and allows to conduct steady state efficiency measurements, i.e. measurements at constant speed and constant load torque. The gearbox under test is driven by means of a speed controlled motor. The loading of the gearbox is realized by means of a reducer gearbox driven by an induction machine which is torque controlled with a regenerative VSD. Both setups are temperature controlled to stabilize the temperature dependent losses.

During the research, 13 gearboxes have been measured resulting in many possible comparisons. The basic properties of each gearbox are summarized in table 1. Only the rated efficiency values are given. An overview of the efficiency contour maps can be found in [9].

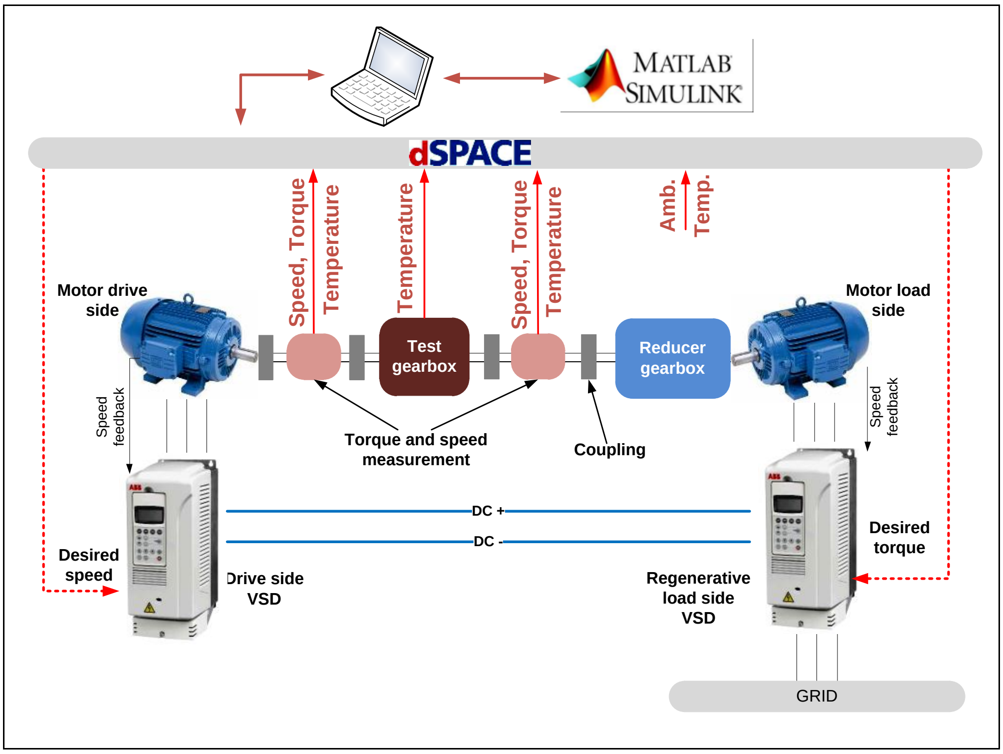


Figure 1: measurement principle gearbox test bench

Table 1: overview gearbox measurements at rated power

	Brand B (I)	Brand A (II)	Brand C (III)	Brand C (IV)	Brand C (V)	Brand D (VI)	Brand D (VII)	Brand E (VIII)	Brand E (IX)	Brand E (X)	Brand F (XI)	Brand F (XII)	Brand F (XIII)
Type	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Straight	Right angled	Right angled	Right angled
Techno-logy	Helical bevel	Worm	Helical bevel	Helical worm	Helical spirod	Helical bevel	Helical worm	Helical bevel	Helical worm	helical	Helical worm	Helical worm	Helical worm
Stages	2	1	3	2	2	3	2	3	2	2	2	2	2
Ratio	77.76	80	72,54	71,75	74,98	72,21	77	11,41	11,67	10,93	87,65	68,44	30,26
Torque (Nm)	505	450	186	167	180	190	180	434	373	390	285	270	260
Power	0,95	0,82	0,37	0,35	0,36	0,39	0,34	5,58	4,7	5,23	0,69	0,82	1,51

(kW)													
Catalog η	95%	62%	96%	62%	±90 %	95%	78%	94%	90%	96%	69%	71%	83%
Measured η	84,5 %	73%	88%	56,5 %	65,5 %	87,5 %	70,5 %	95,5 %	91,5 %	95,5 %	59%	62%	68%

Analytical power loss and efficiency calculation

The modelling process used in this paper includes three major steps. Firstly, scaling laws are developed that express the rated efficiency of the gear. Secondly, equations that model the losses in each working point of the gear are derived based on a combination of physics based equations and curve-fitting techniques. In a third and final step, the efficiency is evaluated in each operation point which results in an efficiency map of the gear. The methodology is applied to Helical-Bevel gears, Helical gears and Helical-Worm gears.

Helical-Bevel Gears

In this section, mathematical expressions that calculate the efficiency of helical-bevel gears as a function of the input speed and output torque are derived. These mathematical expressions cover helical-bevel gears with a gear ratio R between 0 and 100, and a rated output torque T_n between 100Nm and 1000Nm.

Rated Efficiency values

In the first modelling step, scaling laws which estimate the rated efficiency η_n of the gear are derived. Rated efficiency data from different suppliers is combined with scaling laws suggested in literature or by suppliers. This data showed a maximum efficiency for helical-bevel gears which is about 95%. This maximum efficiency is independent of the output torque.

Research of the available data revealed that the rated efficiency decreases more or less linearly with the gear ratio. On the other hand, the slope of these curves varies with the output torque. For the same gear ratio, helical-bevel gears with a high rated output torque generally have a higher efficiency in comparison with gears with a lower rated output torque.

In Fig. 2, the rated efficiency as a function of the gear ratio and rated output torque is shown. Rated efficiencies calculated by the scaling law are in agreement with the measured ones given in Table 1.

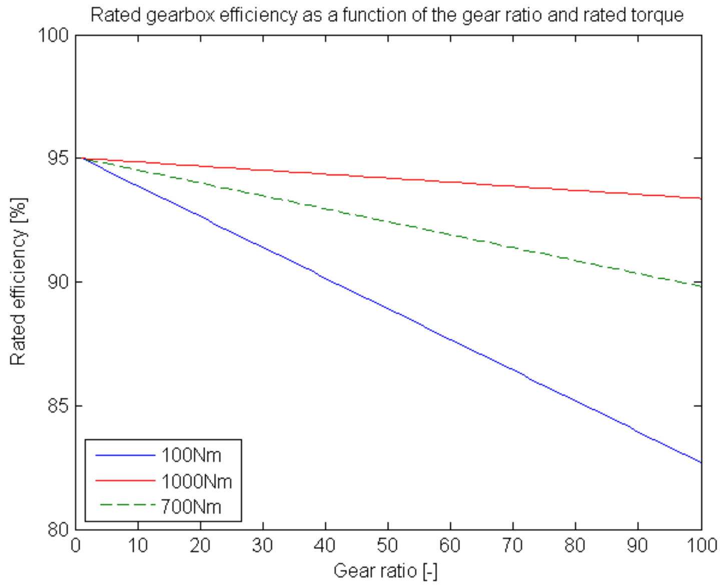


Fig. 2: The rated efficiency of helical-bevel gears as a function of the gear ratio and rated output torque

Loss Modelling

Many research has already been done on the loss modelling of gears [10-13]. These models very often describe different loss mechanism such as churning, bearing losses, tooth friction, etc. in very detail. The aim of the loss modelling in this paper is not to model the individual loss components in gears, but to be able to express the total gear loss. Therefore, the loss modelling suggested in this work uses curve fitting techniques on the data measured on different gears.

For helical-bevel gears, a factor *a*, which expresses the loss dependency on the product of the input speed and output torque *i.e.* power, and a factor *b* which expresses the dependency of input speed are fitted for each available set of measurements. These dependencies on power and speed are physics based and are found in literature.

Notwithstanding, a curve fitting based model including only these two parameters was still inaccurate for many operational points of the gear. Therefore, an additional term which is proportional to the speed to the power 3/2 has been introduced to the loss model:

$$P_{HB} \propto aN_iT_o + bN_i + cN_i^{3/2}$$

A higher accuracy of the loss model is achieved, however, the introduced term is not based on any physical relation. In Fig. 3 the measured and modelled losses in a helical-bevel gear with a gear ratio of 72.54 and a rated torque of 186Nm are presented. A good correspondence between modelled and measured losses is found in all operational regions of the gear.

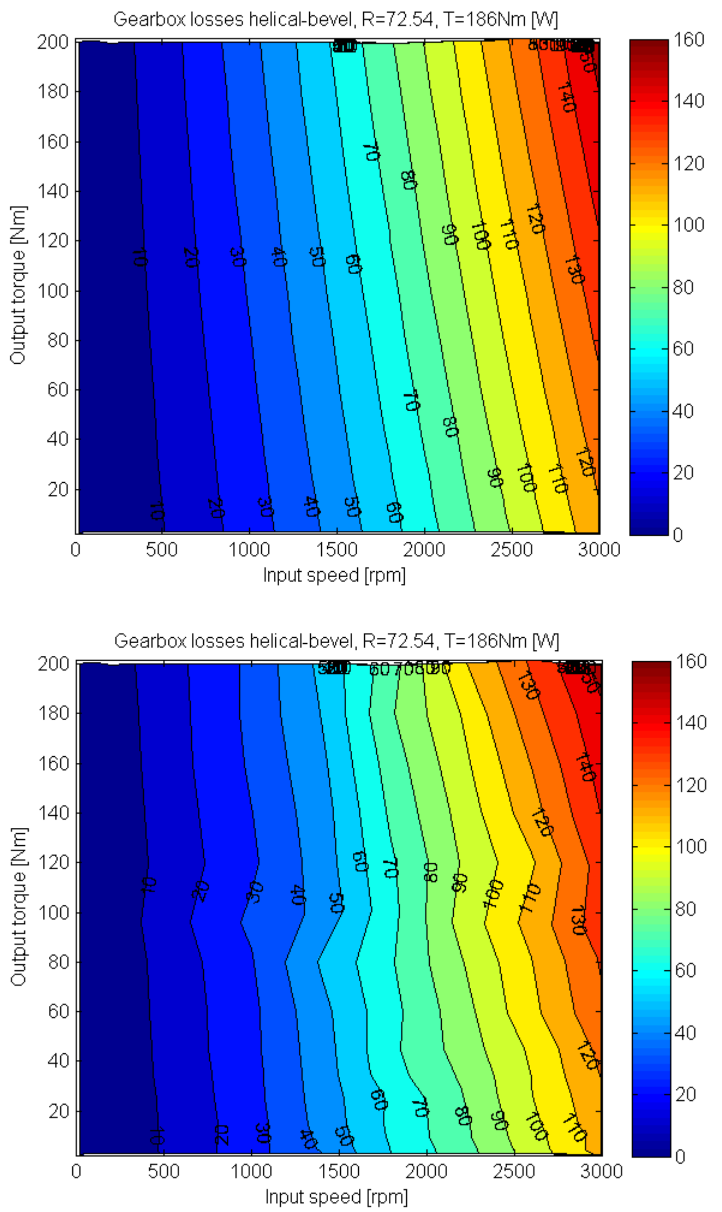


Fig. 3: The modelled and measured losses in a helical-bevel gear with a gear ratio of 72.54 and a rated torque of 186Nm

Subsequently to the curve fitting on the losses of the different measured gears, sizing equations for the parameters a, b and c are derived. These sizing equations are analytical expressions that express these parameters as a function of the gear ratio, the rated output torque, the gear ratio and the rated efficiency.

$$a(N_n, T_n, R, \eta_n)$$

$$b(N_n, T_n, R, \eta_n)$$

$$c(N_n, T_n, R, \eta_n)$$

Efficiency Maps

Given the loss model from previous section, the efficiency map can be built. In Fig. 4, the modelled and measured efficiency map of the helical-bevel gear with a ratio of 72.54 and a rated output torque of 186Nm is illustrated. As for the losses, a good correspondence over the full operational range is found.

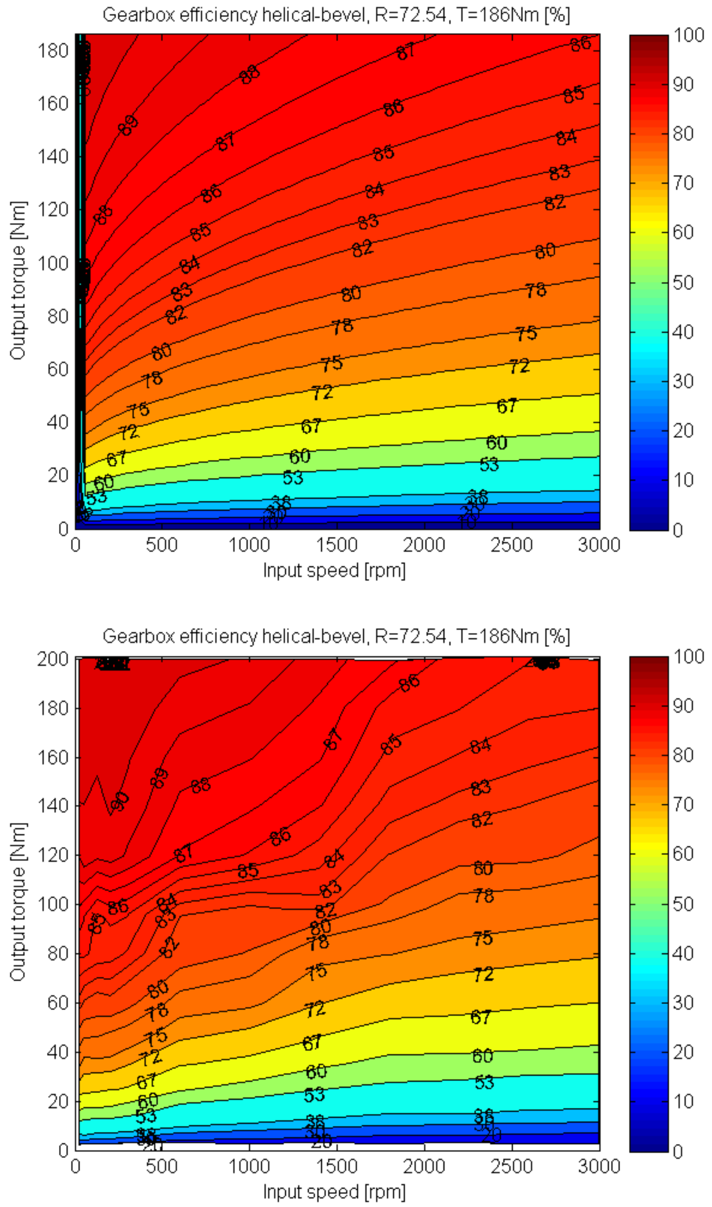


Fig. 4: Modelled and measured efficiency map of the helical-bevel gear with a ratio of 72.54 and a rated output torque of 186Nm

Helical Gears

Due to the very limited number of pure helical gears under test, the models developed for helical-bevel gears are extended to pure helical gears.

For the rated efficiency of helical gears, a literature study has indicated similar relations as for helical-bevel gears. Nevertheless, the maximum rated efficiency of pure helical gear was found to be 97%, which is 2% higher compared to the helical-bevel gears. Therefore, the scaling law derived for pure helical gears is a shifted version of these of the helical-bevel gears. This results in the scaling illustrated in Fig. 5.

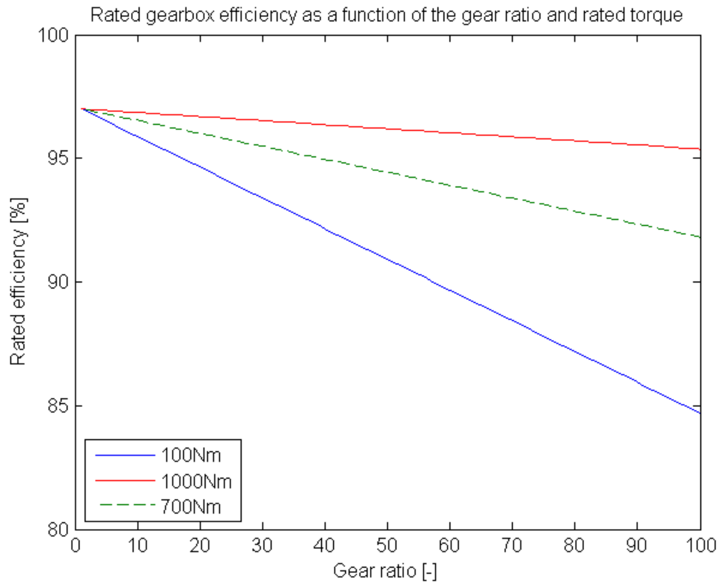
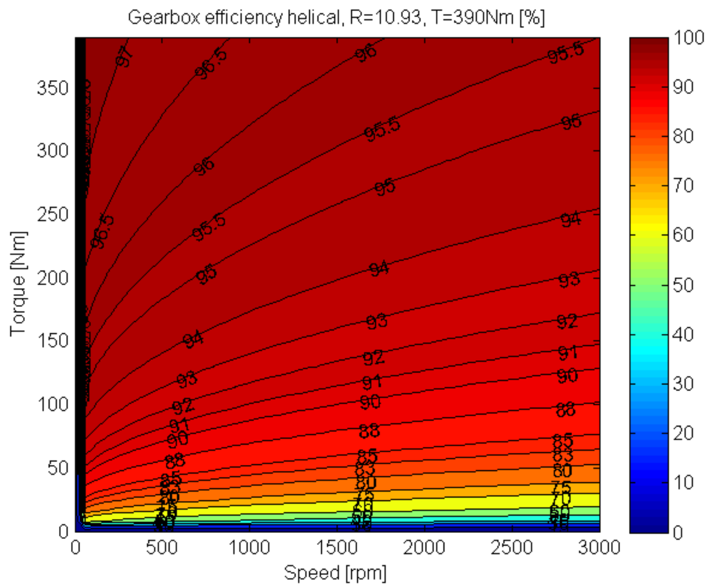


Fig. 5: The rated efficiency of helical gears as a function of the gear ratio and rated output torque

As the number of measurements was too low to apply curve fitting techniques, the loss models that were developed for helical-bevel gears are implemented for pure helical gears without any adaptation.

The accuracy of the modelling is validated on a pure helical gear with ratio of 10.93 and a rated torque of 390Nm. The modelled and measured efficiency maps are presented in Fig. 6.

Despite the loss modelling tools for the helical-bevel gears are used, an overall good correspondence between the modelled and measured efficiency maps is found. Only in the lower torque region, the accuracy of the calculated efficiency is less. Fine-tuning of the loss model through additional measurements on pure helical gears will be required to improve the accuracy over the full operational region.



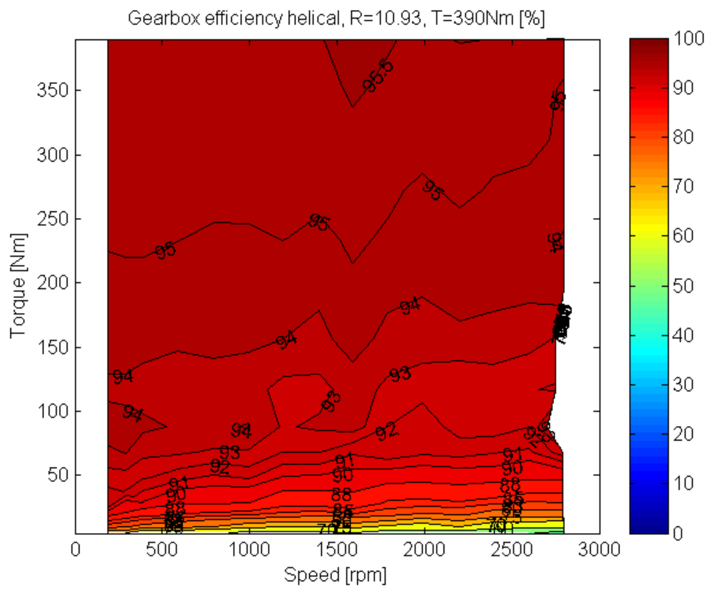


Fig. 6: Modelled and measured efficiency map of the helical gear with a ratio of 10.93 and a rated output torque of 390Nm

Helical-Worm Gears

Rated Efficiency values

As for the helical-bevel and helical gears, rated efficiency data from different suppliers and scaling laws suggested in literature or by suppliers are combined and used to derive a scaling law for helical-worm gears.

In contrast to helical-bevel and helical gears, more spread on the data is found. Nevertheless, comparable trends as for helical-bevel and helical gears are found. The rated efficiency of helical-worm gears as a function of the gear ratio and rated output torque is illustrated in Fig. 7.

It is clear that helical-worm gears have much lower efficiencies compared to helical-bevel and helical gears. Rather poor rated efficiencies are found for higher gear ratios.

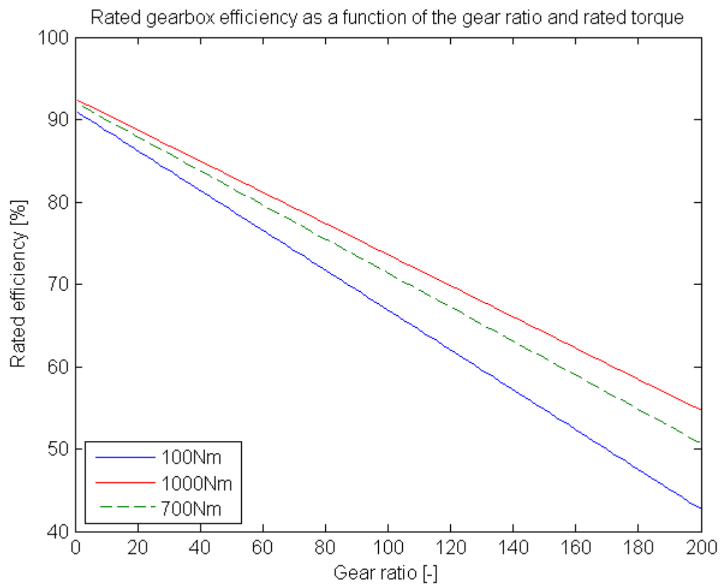


Fig. 7: The rated efficiency of helical-worm gears as a function of the gear ratio and rated output torque

Loss Modelling

During the curve fitting process the power and speed dependent terms were extended with a torque dependent term:

$$P_{HW} \propto aN_iT_o + bN_i + cT_o$$

For the coefficients *a*, *b* and *c* comparable relations as for helical-bevel gears were developed. As for helical-bevel gears, these sizing equations are analytical expressions that express these parameters as a function of the gear ratio, the rated output torque, the gear ratio and the rated efficiency.

In Fig. 8, the measured and modelled losses in a helical-worm gear with a gear ratio of 71.75 and a rated torque of 167Nm. The accuracy of the calculated losses corresponds good with the measured ones.

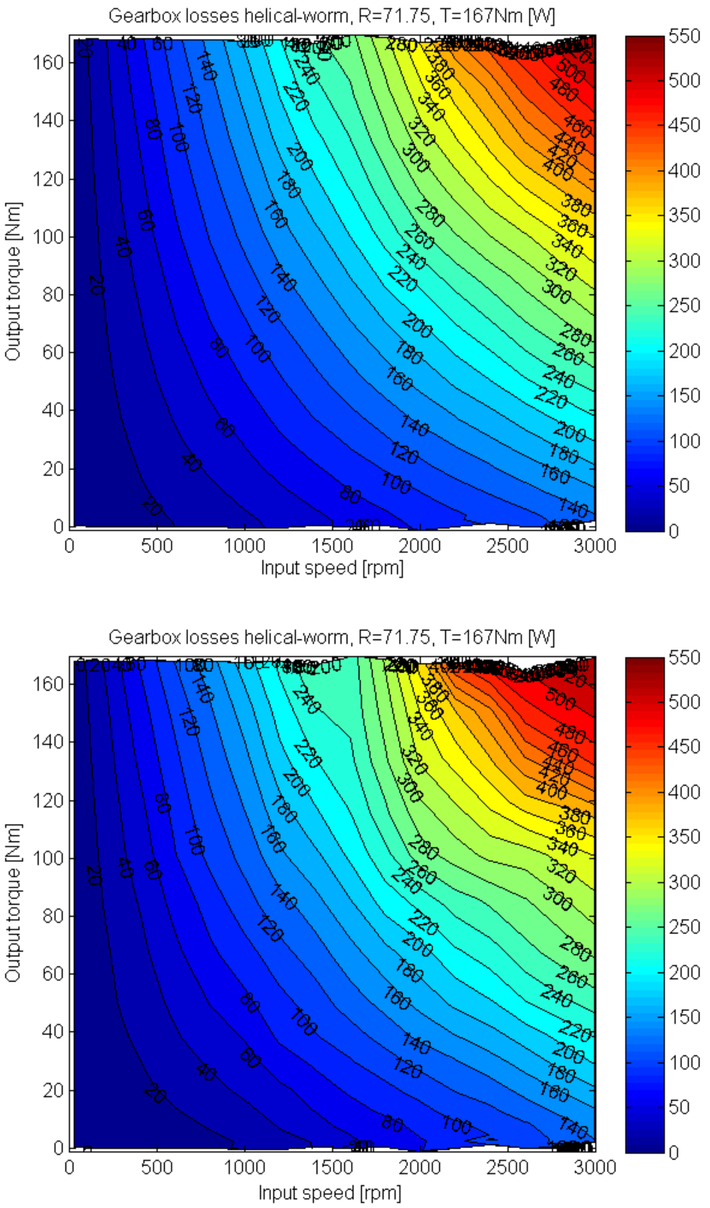


Fig. 8: The modelled and measured losses in a helical-worm gear with a gear ratio of 71.75 and a rated torque of 167Nm

Efficiency Maps

Despite the overall good correspondence between the modelled and measured losses in helical-worm gears, at first look, the modelled and measured efficiency map differ quite a lot. Certainly in low torque and low speed region, the accuracy of the model is not accurate.

This difference can be explained by the dominant impact of the losses in the calculation of the efficiency. On one hand, the efficiency of helical-worm gears is generally poor which results in high losses (Fig. 9). On the other hand, the transferred power in the low torque and low speed region is limited. Therefore, a small error in the calculated losses results in a significantly different efficiency. In this perspective, the accuracy of the power measurements for low transferred powers might also be less accurate, which can explain differences at the measurement side.

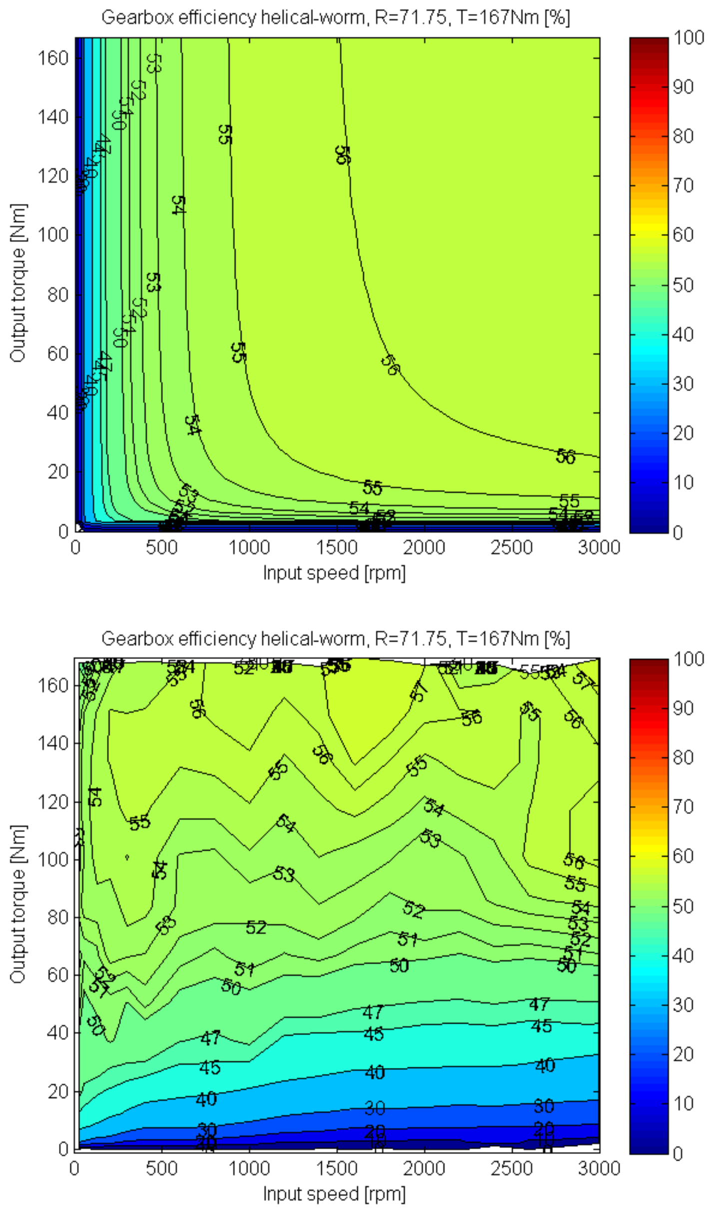


Fig. 9: Modelled and measured efficiency map of the helical-worm gear with a ratio of 71.75 and a rated output torque of 167Nm

Conclusions

An analytical approach is presented to determine power loss maps and efficiency contour maps for helical, helical-bevel and helical-worm gearboxes. Only the rated efficiency and the gear ratio are required as input data. The outcome of the approach are efficiency values in the entire torque speed operation region of the gearbox. The results can be graphically represented by means of contour maps and can easily be integrated in software tools such as the Motor System Tool.

The accuracy of the methods is validated by means of a set of 13 gearboxes in the power range up to 15 kW. The analytically determined values are reliable for the helical-bevel gearboxes. For helical-worm gears, the model is less accurate in the low-torque range. Additional measurement on a larger set of gearboxes and with a larger spread in power are required to fine-tune the presented approach.

The presented approach allows non-experts to use available datasheet information to obtain relevant contour maps that can be used to optimize drive trains from an energetic point of view by means of the Extended Product Approach.

References

[1] Fernandes C., Hammami M. et al. , Power loss prediction: Application to a 2.5 MW wind turbine gearbox, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 2015.

[2] IEC 61800-9-2:2017*, Adjustable speed electrical power drive systems - Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications - Energy efficiency indicators for power drive systems and motor starters.*

[3] ISO/TR 14179-1:2001 Gears -- Thermal capacity -- Part 1: Rating gear drives with thermal equilibrium at 95 °C sump temperature (https://www.iso.org/standard)

[4] ISO/TR 14179-1:2001 Gears -- Thermal capacity -- Part 2: Thermal load-carrying capacity (https://www.iso.org/standard)

[5] Höhn BR., Michaelis K. et al. , WTplus 2.0, Lehrstuhl für Machineelemente der Technischen Universität München, forschungsstelle für Zahnräder und Getriebebau (2008).

[6] Http://www.kisssoft.ch/english/home/index.php

[7] Dereyne S., Defreyne P., Algoet E, K. Stockman (2014). Total drive train optimization of industrial fans and pumps considering VFD driven motor, transmission and load, Motor Summit 2014, Zürich.

[8] Https://www.motorsystems.org/motor-systems-tool

[9] Stockman K., Dereyne S., Defreyne P., K. & Algoet, E. (2015). Efficiency Measurement Campaing on gearboxes, *EEMODS 2015*, Helsinki, Finland.

[10] Höhn B.r., Michaelis K., Wimmer A. (2007) *Low loss gears*, Gear technology magazine, June 2007.

[11] Y. Diab, F. Ville, P. Velex, and C. Changenet, "Windage Losses in High Speed Gears—Preliminary Experimental and Theoretical Results," *Journal of Mechanical Design*, vol. 126, no. 5, p. 903, 2004.

[12] C. Yenti, S. Phongsupasamit, and C. Ratanasumawong, "Analytical and Experimental Investigation of Parameters Affecting Sliding Loss in a Spur Gear Pair," *Engineering Journal*, vol. 17, no. 1, pp. 79–94, Jan. 2013.

[13] C. Changenet and P. Velex, "A Model for the Prediction of Churning Losses in Geared Transmissions—Preliminary Results," *Journal of Mechanical Design*, vol. 129, no. 1, p. 128, 2007.

Alternative Efficiency Determination Method (AEDM): A Reliable Determination Method is Essential to Ensure MEPS Conformance

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Abstract

The number of products covered under global the Minimum Efficiency Performance Standards (MEPS) is expanding every year. As a result of these expanding regulations, conformance testing is becoming extremely costly and unmanageable, but regulation would not be effective without any required method of efficiency verification. With the high number of custom models covered today, it became unrealistic to test every model for regulation—particularly if the manufacturer has many model variations per rating.

Efficiency determination methods can vary widely by geography or background. This may result in different efficiency level that either disqualify or qualify the same motors even though the requirements may seem to be identical. Without a common economical method for efficiency determination, this becomes an inconsistent and costly procedure that is passed on to the customer. It may offset any energy conservation expected. Another extreme would be if every rating or model were not required to follow a specific efficiency determination method. This could result in even greater variations in actual efficiencies between manufacturers.

Regulating authorities typically demand reliable methods to realistically determine motor efficiency. A globally accepted consistent efficiency determination method that is not overly burdensome is therefore needed. This paper will propose one such method based on a procedure established by regulators in the US.

Understanding the Conformance Process

There are at least seven steps in the conformance process. All steps should be performed in the proper order or the process falls apart. The following are the steps as identified in the US, but similar processes are used worldwide.

1. **Establish The Basic Ratings/Model Covered Defined**

Well in advance of any regulation, the basic ratings and models intended to be covered must be identified, and the ratings or models exempted should be clearly documented. Many of the basic models will have identical ratings for example power, speed, voltage and enclosure but have a differing electrical, physical or functional characteristic, which affects their energy consumption thereby making it a new basic model. The characteristics or deviations that make it a unique model should be identified—these can affect the energy efficiency of the motor. This is critical because the efficiency levels of each model must be properly established. Each manufacturer may have many basic models per basic rating.

It is well known that higher starting current allowances will support higher efficiency, but higher starting torque requirements could reduce potential efficiency. There are many other performance characteristics that must also be considered such as voltage during start and run, inertias, acceleration times. Mechanical characteristics such as cooling methods, hazardous duty, shaft seals and brakes can also affect energy consumption and efficiency. This makes the process more complex for higher power ratings—these are not typically a stock commodity motor but are custom designed around very special application requirements. Though more common on the larger machines, these difficult application performance requirements may also be seen on smaller machines.

2. Establish A Consistent Accurate Test Procedure

There are many test procedures defined today for establishing energy efficiency. They all have their place and a particular one may be utilized depending on machine size or orientation. Regretfully, they will not all achieve the same resulting efficiency. Therefore, the test procedure or determination method must first be defined before establishing energy efficiency levels. US tests are defined under IEEE 112. For reference, these different test methods are included in in the last column in Table 1. The **International Electrotechnical Commission (IEC)** standard that covers this is IEC 60034-2 included in Table 1 in the second column.

TABLE 1

IEC & IEEE TEST METHODS COMPARISON

	IEC	**IEEE**
Test Method	**Test Method** **IEC 60034-2 (Clause)**	**Test Method** **IEEE 112 (Clause)**
Input-output	1ϕ Machines Method 1A (6.1.2)	Method A (6.3)
Input-output with segregation of losses and indirect measurement of stray-load loss	≤2 MW 60034-2-1 Method 1B (6.1.3)	≤500 HP Method B (6.4) 60034-2-1 1B B,
Input-output with assumed temp.	N/A	Method B 1 – (6.5)
Duplicate machines with segregation of losses & indirect measurement –stray	Method 1D (6.2.2)	Method C (6.6)
Segregation of losses w/ direct measurement- stray	Method 1C +Method 1F (Rev Rot.)	> 500 HP Method E (6.7)
Segregation of losses & Assigned stray-load loss.	2 MW and greater 60034-2-1 Method 1C (6.2.3)	Method E1 (6.7)
Equivalent circuit w/ direct measurement of stray-load loss	Method 1H & 1F (1H 6.2.6 & 1F 6.2.4)	Method F, (6.8) Stray(5.7.2&.3)
Equivalent circuit with assigned- stray	Method 1H 6.2.6	Method F1 (6.8)
Equivalent circuit calibrated with one load point		Method C/F, E/F, or E1/F1 (6.9)

It was important that one reliable and consistent test procedure be established for motor models that are regulated. Based on years of comparative and round robin testing, we determined that the residual loss test procedure method defined in IEEE 112 method B, CSA 390, or IEC 60034-2-1B be used for the regulation. These procedures are now in harmony and offer a consistent accurate determination of the efficiency while also providing the most repeatable results. This was demonstrated via a round robin test where the same motor was tested in many different labs around the world.

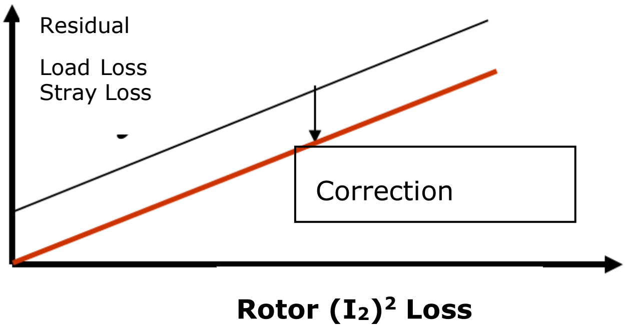

Figure 1: PLOT OF RESIDUAL LOSS

Though this residual loss test procedures is the most reliable there is still some variation in test results. The inconsistency is a result measuring the total power in and power out to identify the losses and establish the efficiency. Current motors often exceed 95% efficiency. Ninety five percent of the electrical power entering the motors leaves as mechanical power out the shaft. Due to instrument accuracy, there can be a high level of uncertainty in separating this small amount of power loss (<5%) from the total power entering the motor.

The residual loss method helps to correct this error by determining the stator loss, rotor loss, core loss and windage loss and then subtracting this from the total loss at each load point—the reminder is the residual load-related loss. The procedure then plots the load-related losses at each load point. The load loss curve is adjusted to accurately pass through zero (zero load loss at zero load) thereby reducing the level of uncertainty and increasing repeatability. In addition, when testing the same motor in different labs, the level of uncertainty increases substantially. This was proven through round robin testing. The residual method today is used up to 1000 kW. This will later have to be evaluated for higher power ratings and testing capabilities. The graphical representation of the load loss correction is shown in Figure 1.

3. Establish Test Lab Requirements

Next, the test lab accuracy and procedure requirements are defined. The consistency and accuracy of the tests is critical for repeatable results and controlling the measurement uncertainties. The motors may already have a manufacturing uncertainty of around 10% based on material and manufacturing variation (dependent on size and processes). The uncertainty of the test procedure could also be as much 10 percent even when all labs followed the exact same procedure; this has also been previously demonstrated in round robin tests. Considerable work has gone into reducing the uncertainty, and tests are presently ongoing to verify the improvements. The results are not in as this paper is being written but are expected sometime this year. Of course, the global test variation could be much greater if measurement accuracy and procedures were not global harmonized.

US Standards such as NEMA MG 1 (National Electrical Manufacturers Association) (Motor and Generator Section 1) [5] and the international standard IEC 60034-1 [1] establish the maximum tolerance allowed from the nominal efficiency taking into account both testing and manufacturing uncertainty. Total tolerance per NEMA may be as high as 20% but this is not necessarily in global harmony.

It would be difficult to define the test lab requirements if the test procedure and ratings/models covered had not been previously defined. Again, the order in which the steps are performed is critical. A global test lab requirement is possible because the global test procedures are defined and in harmony.

Table 2

Specifications of the instrumentation

2. **Parameter**	3. **IEC 2014**	4. **IEEE 2004**	5. **IEEE 2017 Draft**
6. Instrument transformer (%)	7. ± 0.3	8. ± 0.3	9. ± 0.3
10. Power (%)	11. ± 0.2 FS	12. ± 0.2 FS	13. ± 0.2 FS ± 1.0 R
14. Voltage (%)	15. ± 0.2 FS	16. ± 0.2 FS	17. ± 0.2 FS ± .05 R
18. Current (%)	19. ± 0.2 FS	20. ± 0.2 FS	21. ± 0.2 FS ± .05 R
22. Torque (%)	23. ± 0.2 FS	24. ± 0.2 FS	25. ± 0.2 FS ± .07 R
26. Speed (rpm)	27. ± 1	28. ± 1	29.
30. ≤ 1800 rpm	31.	32.	33. ± 1
34. > 1800 rpm	35.	36.	37. ± 0.1 + .05 R
38. Frequency (%)	39. ± 0.1 FS	40. ± 0.1 FS	41. ± 0.1 FS ± .05 R
42. Resistance (%)	43. ± 0.2 FS	44. ± 0.2 FS	45. ± 0.2 FS
46. Temperature (°C)	47. ± 1	48. ± 1	49. ± 1

Typically, the global testing lab requirements are in Accordance ISO 17025. This not only helps drive the accuracy, reliability, repeatability and traceability of the measurement equipment to the standards, but it also verifies the use of the proper procedures for testing. The procedure typically relies on other test procedures to define the accuracy requirements of the test equipment. Whether the manufacturer is self-certified or certified by third party they are testing to the same defined requirements. A summary of instrument accuracy is shown in Table 2. It included the pending changes proposed for IEEE 112.

4. Method for Efficiency Determination Defined

Efficiency can be determined by either testing or by a method referred to as an alternate efficiency determination method. As stated before, there are many different models for each rating that will make the quantity of the base models quite large. It is normally not possible to test every basic model in a way that is not excessively burdensome however some level of confidence in the efficiency determination method is still needed. When testing to verify conformance a sampling size and pass fail criteria must be established.

In the US a sampling size of 5 which represents a small population was chosen. The justification and pass fail criteria is discussed later in this paper,

With this excessive testing burden the regulator will need an alternate method to assure adherence to the regulations. An alternate efficiency determination method should then be considered. The details of a proposal that is regulated in the US will be discussed later in the paper.

5. **Minimum Efficiency Performance Standards Must be Defined (Based on Steps 1-4)**

After the first four steps above are complete, it is now possible to establish the minimum energy efficiency requirements. The levels would then have to be reconsidered if any the steps are modified in a way that would change the efficiency results. Efficiency levels are based on the determination method, test equipment and testing lab accuracy etc. They are not independent and cannot be separated. In the US NEMA MG 1 and the Department of Energy (DOE) establish the efficiency levels. IEC 60034-30-1 establishes the energy efficiency levels along with local regulators. Table 3 shows the efficiency levels for the most popular presently regulated four pole machines.

Over the past years there has been an extensive effort to harmonize the various global motor performances and efficiency standards. This is complicated by the fact that all global performance standard requirements are not identical. Some performance requirements that might affect efficiency for example include locked rotor current, locked rotor torque and even running vibration levels. However, even with this, the international groups were able to harmonize efficiencies for most of the ratings. They were able to establish common energy efficiency levels based on common testing procedures. It may be possible to meet all the global performance requirements and have a motor that meets the global efficiency levels, but the motors may have to be over-built to meet these global requirements, which may add unneeded cost. Manufacturers would have to make a decision whether to have multiple different designs for the different global requirements or have one design that meets them all.

The regulated levels shown in TABLE 3 are very similar with some variations in the lower power ratings. Regretfully, motors in the US below 3 horsepower (HP) are included to two different US regulations where they have regulated two different levels. The efficiencies which differ are highlighted in grey in the table. One regulation covers small motors and second rating covers medium or integral horsepower motors. Some of the ratings 3 HP and below are identical. This made it impossible for 100 percent of the ratings to be harmonized. There are also a few ratings in the higher power range where equivalent ratings do not exist. These are marked as not applicable (NA). In addition, the harmonization effort focused on the Totally Enclosed Fan-Cooled (TEFC) ratings because they are the more popular for the for integral HP motors. NEMA established different levels for Open Drip Proof (ODP) and TEFC motors. Therefore not all ODP levels are in harmony with IEC levels and these levels are highlighted in grey. A similar result would be seen when tabulating the other speed/pole motors.

TABLE 3

IE2 and IE3 Vs. NEMA premium and NEma High Efficiency 4 pole motors

KW	HP	IE3 60 HZ	NEMA PREM TEFC	NEMA PREM ODP	IE2 60 HZ	NEMA & DoE High Eff.	IE3 50 HZ	IE3 & NEMA PREM 50 HZ
0.75	1	83.5	85.5	85.5	78.0	82.5	82,5	82,5
1.1	1.5	86.5	86.5	86.5	84.0	84.0	84,1	84,1
1.5	2.0	86.5	86.5	86.5	84.0	84.0	85,3	85,3
2.2	3.0	89.5	89.5	89.5	87.5	87.5	86,7	86,7
3.7	5.0	89.5	89.5	89.5	87.5	87.5	NA	88.4
5.5	7.5	91.7	91.7	91.0	89.5	89.5	89,6	89,6
7.5	10.0	91.7	91.7	91.7	89.5	89.5	90,4	90,4
11	15	92.4	92.4	93.0	91.0	91.0	91,4	91,4
15	20	93.0	93.0	93.0	91.0	91.0	92,1	92,1
18.5	25	93.6	93.6	93.6	92.4	92.4	92,6	92,6
22	30	93.6	93.6	94.1	92.4	92.4	93,0	93,0
30	40	94.1	94.1	94.1	93.0	93.0	93,6	93,6
37	50	94.5	94.5	94.5	93.0	93.0	93,9	93,9
45	60	95.0	95.0	95.0	93.6	93.6	94,2	94,2
55	75	95.4	95.4	95.0	94.1	94.1	94,6	94,6
75	100	95.4	95.4	95.4	94.5	94.5	95,0	95,0
90	125	95.4	95.4	95.4	94.5	94.5	95,2	95,2
110	150	95.8	95.8	95.8	95.0	95.0	95,4	95,4
150	200	96.2	96.2	95.8	95.0	95.0	NA	95,8
185	250	96.2	96.2	95.8	95.0	95.0	NA	95.9
220	300	96.2	96.2	95.8	95.4	95.4	96.0	96.0
250	350	96.2	96.2	95.8	95.4	95.4	96.0	96.0
300	400	96.2	96.2	95.8	95.4	95.4	96.0	96.0
335	450	96.2	96.2	96.2	95.4	95.8	96.0	96.0

TABLE 3

IE2 and IE3 Vs. NEMA premium and NEma High Efficiency 4 pole motors

KW	HP	IE3 60 HZ	NEMA PREM TEFC	NEMA PREM ODP	IE2 60 HZ	NEMA & DoE High Eff.	IE3 50 HZ	IE3 & NEMA PREM 50 HZ
373	500	96.2	96.2	96.2	95.8	95.8	96.0	96.0

6. **Registration Process Available for Products Defined**

To ensure that all motors meet the minimum efficiency level, some method of documentation needs to be available for review by the regulators and custom agents. One procedure actively being pursued today is an establishment of clear documentation on the motors entering the country as to what local MEPS the product meets or is required to meet. In the past, if the requirements were not documented, then the border custom agents would not know any regulation existed, and they would just pass into the country unobstructed. To correct this, the motor will need to be listed with the DOE with additional information documented in the literature or nameplate if and why the motor entering the country is exempt from the MEPS or what level it is required to meet.

7. **Enforcement Policy Defined (In line with1-5)**

It is also important that the enforcement procedure and penalty for not complying be clearly identified. The enforcement testing method may be slightly different than the qualification testing but the procedure must be defined so there are no surprises. This will be discussed in a later section.

Alternative Efficiency Determination Method (AEDM): A Reliable Determination Method is Essential to Ensure MEPS Conformance

It was determined in the US that a reasonable sample size was required in order to test for the nominal efficiency. Testing only one motor to ensure that the minimum nominal level was exceeded was not considered adequate. However, testing a large population of every model manufactured is unrealistic and costly. Even when the sampling procedure utilizes all the manufacturers' certified labs and the few existing third party certified labs, testing would be not only overly burdensome but probably impossible. The alternate extreme would be that no efficiency determination method is defined or required. This could result in a greater risk of non-conformance. This statistically-based verified AEDM proposed here was developed by US regulators in conjunction with NEMA and could result a common global efficiency determination method.

Excessive Testing Burden

For example consider that performing a type test for each motor of a base rating could take more than 12 hours. If we then consider a sample of five motors tested for each base rating, it could take as much as eight working days to complete the process for each rating. The original 113 ratings identified in the 1990s covered all the power ratings, speeds, voltages and enclosures. Thus, this testing would require over 900 working days for each manufacturer if each rating had only one base model. Since each base model must be essentially identical, and may not have any differing physical or functional characteristics that affect energy consumption or efficiency, each manufacturer could have multiple models for each base rating. Today, the number of potential base models has grown to well over 100,000 and continues to grow with higher voltages, power ratings and custom variations. There would not be enough test facilities (Figure 2) in the world to test a sample of one manufacturer's base models. In addition if the cost is excessive, then the end users may find it more economical to repair lower efficient products than to buy new more efficient products. This would negate any potential energy savings. Sample testing of each model of a covered product is only practical if the number of models is limited. This may exist for some serial production products.

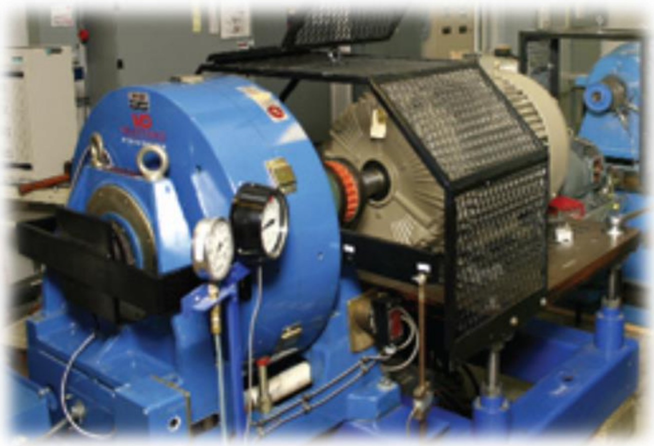

Figure 2: Coupled Load test

When the US Department of Energy (DOE) evaluated the testing demand in the late 1990s, it became clear that an alternate approach, as was previously used in other DOE regulations for other products, were required. The need to establish a reasonable alternative that is not overly burdensome resulted in the development of the Alternate Efficiency Determination Method (AEDM).

Minimum Efficiency Performance Standard

A few terms need to be defined before the ADEM discussion. Even though the definition of nominal and minimum efficiency seems simple, it has proven to be somewhat challenging and has resulted in various interpretations. A clear definition is critical when certifying a model. The **nominal efficiency** is the average efficiency of a large population of any one base model, and **minimum efficiency** is the minimum allowed efficiency of the same large population.

Round robin tests showed variations of +/- 10% in loss. In addition to testing variability, motor manufacturing variations further increase uncertainty. Therefore, NEMA and the DOE established 20% as the maximum allowed increase in loss for any one motor from the nominal level to account for both manufacturing and testing variations and uncertainties.

To determine the nominal efficiency, a statistical sampling of each rating would have to be tested. In the US a sampling of five units is required and is considered to be a small population. It is statistically possible that the average efficiency of this small population is less than the nominal efficiency, but for the same reason, the greatest loss among the five units would probably have less than a 20% increase in loss. In order to minimize testing, and also based on a statistical analysis for a small population, the legislation in the US for model certification established an allowance for a plus 5% increase in loss for the nominal efficiency of the small population, but it limits the worst case to a 15% increase in loss. Figure 1 illustrates the range of efficiencies possible for both large and small populations.

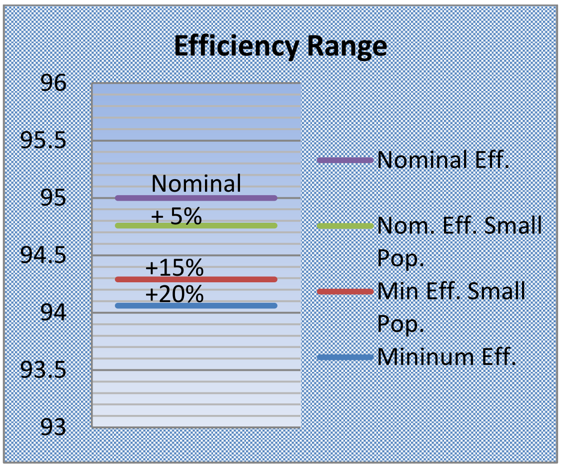

Figure 3: Range of Efficiency for 95% Nominal.

The US Alternate Efficiency Determination Method (AEDM)

An AEDM is an analytical certified calculation method to determine energy efficiency. Manufacturers do not utilize a common calculation tool and manufacturing process variations must be considered. Thus, each manufacturer's AEDM must be qualified through a series of tests that are to be conducted in either the manufacturer's or a third party certified test lab.

To substantiate the AEDM tool, regulators required that the AEDM be based on statistics, and the AEDM results must be correlated with the test results of a sample (five units) of at least five basic models. The guidelines for the selection of these basic models include the following: 1) they are among the highest unit volumes for the manufacturer; 2) of different horse-powers; 3) of different frame number series; and 4) should cover the range of ratings for which the AEDM is to be applied.

The AEDM qualification process first requires that the predicted power loss must be determined to be within ± 10% of the mean tested power loss of each basic model being sampled. And second, the mean tested loss for each model must not be 5% greater than the listed nominal loss, and thirdly, the maximum loss must not be 15 % greater than the listed nominal loss.

As an example, consider the following where a manufacturer determines that it is not practical to run a complete test for efficiency on every model they manufacturer. It is therefore decided to qualify an AEDM. The manufacturer must choose 5 models from across their product portfolio to test that meets all the rules listed previously. Once the AEDM is qualified this would allow this AEDM to be used for all their ratings for the product portfolio for which it was qualified. Note that a manufacturer may have thousands of models that would now have to be qualified by this AEDM method. Also it should be noted that once the AEDM is certified the determined Efficiency from the AEDM must exceed the regulated value.

Now as an example, consider that one of the 5 models chosen is a 60 horsepower NEMA Premium TEFC motor that is regulated at 95% nominal efficiency. The manufacturer would then establish the efficiency with his AEDM. For this example let's assume a 95.1% efficiency is determined. As stated before the AEDM determined level must exceed the regulated value as here it clearly does. The losses calculated for this 95.1% efficient design are= $(\frac{60\times746}{.951}) - (60\times746) = (47066 - 44760) = 2306\text{W}$. The resulting average tested losses of a sampling of five 60 HP units must be within the range ±10% of the AEDM determined losses$(2306W \pm 230W)$. Therefore the losses must be within the range of (2076-2536).

The second criterion that must be satisfied is that the average efficiency of these five motors tested must be $\geq \frac{100}{1+1.05\left(\frac{100}{95-1}-1\right)} = 94.76\%$ and the third criterion establishes that the minimum efficiency of any motor tested must be $\geq \frac{100}{1+1.15\left(\frac{100}{95}-1\right)} = 94.29\%$. So now we will apply these three criteria rules in three different sampling examples:

Sampling 1: 95.2%, 94.2%, 95.6%, 95.0%, and 94.9%:

The average of the five motors tested in sampling 1 is 94.98% (2366 W Loss) which is in the range of losses required (2076-2536W) as established above and also meets the average efficiency criteria of 94.76% but the minimum tested efficiency of 94.2% is less than the 94.29 requirement, so the AEDM fails the test.

Sampling 2: 95.0%, 94.3%, 94.7%, 95.0%, and 94.6%:

The average of the 5 motors tested in sampling 2 is 94.72% (2496 W Loss) which is in the range of losses required (2076-2536W), but fails to meet the average efficiency criteria of 94.76%. It does meet minimum tested efficiency requirement of 94.29% but fails based on not meeting the average efficiency level and therefore the AEDM fails the test.

Sampling 3: 95.2%, 94.3%, 95.1%, 95.0%, and 94.8%:

The average of the 5 motors tested in sampling 3 is 94.88% (2415 W Loss) which is in the range of losses required (2076-2536W) and also meets the average efficiency criterion of 94.76% and the lowest efficiency tested is 94.3% exceeding the minimum tested efficiency requirement of 94.29% so the AEDM in this case passes all the test criteria.

The above example is for just one of the five models that must pass the tests in order to qualify the AEDM. For the AEDM to be qualified all five models must follow the same process and pass all criteria.

After the AEDM is verified, the manufacturer must have records showing the methods, the mathematical model, the statistical analysis, the computer simulations, and any other analytics used to determine the average full load efficiency of each basic model for which the AEDM was applied.

Conclusion

The AEDM is a valuable method to ensure that nominal efficiencies are consistently determined and applied when large numbers of basic models are being evaluated. An AEDM program verified in accordance with DOE regulations mitigates excessive and unreasonable testing burden while minimizing the risk of non-conforming motors. As a result, excessive costs do not need to be passed along to the end user, and they can benefit from the energy savings and have confidence in the motor performance.

Any changes in the steps identified above that affect the efficiency determination should result in a change in the efficiency level or be established by going through all the steps of the regulation process.

If a certified AEDM is not used and it is not practical or even possible to test a population of every design or model with a qualified test procedure the risk of having non-conforming product could be high. Keep in mind that some custom designs may only be produced in quantities of one or two and the cost of running an efficiency test will approach the motor cost. This certainly would not be cost effective. By making sure through this process that a certain level of verification is complete as laid out in this process, the risk of non-conforming motors in the market place is greatly reduced.

References:

[1] IEC 60034-1:2016 *Rotating electrical machines – Part 1: Rating and performance - Edition 12.0,* International Electrotechnical Committee Central Office, 3, rue de Varembé, CH-1211 Geneva 20, Switzerland

[2] IEC 60034-2-1 Rotating electrical machines - Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)

[3] IEC 60034-30 Rotating electrical machines - Part 1: Efficiency classes of single speed, three-phase, cage-induction motors (IE-code), International Electrotechnical Committee Central Office, 3, rue de Varembé, CH-1211 Geneva 20, Switzerland

[4] IEC 60034-30 Rotating electrical machines - Part 30-2: Efficiency classes of variable speed AC motors (IE-code)

[5] NEMA Standards Publication No. MG 1-206, National Electrical Manufacturers Association, 1300 N 17th Street, Suite 1752, Roslyn, VA.

[6] IEEE 112 2004, Standard Test Procedure for Poly-phase Induction Motors and Generators, Institute of Electrical and Electronics Engineers, Piscataway, New Jersey.

[7] CSA 390-93 2015 Energy Efficiency Test Methods for Three-Phase Induction Motors, Canadian Standards Association

On Efficiency Measurement of Motor-Drive Systems

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Abstract

The growing focus on motor-drive systems require reliable test methods to characterize efficiency. There are standards in place and new standards are being developed but the test methods are not at consensus level. Some factors that influence system efficiency measurement of motor-drive systems are discussed in this paper. In particular, the dependence of measurement quantities on power meter setting was demonstrated in the paper. Also, several motor-drive systems were tested with voltage unbalance and voltage magnitude deviation and the impact on system efficiency is quantified. The influence of intrinsic motor performance to these voltage abnormalities is highlighted.

Introduction

Within the past few years, the efficiency of motor-drive systems has become more important due to proliferation of variable frequency drives. There is an increase in development of motor-drive standardization and standards such as [1]-[5] are evidence of importance of the subject in industry. More recently, [6] has proposed mostly analytically based calculation methods for losses in drives for the main purpose of categorizing drives into efficiency classes. There are concerns that methods that are fully based on actual testing would provide more acceptable results than calculation based methods. However, a reliable and acceptable test method for motor-drive systems is currently not at consensus level. This is partly due to several factors, including multiple operating conditions of drives, influence of drives on motor operation and vice versa, and challenges in measuring non-sinusoidal power. It is clear that more work is needed in order to achieve the consensus that is critical for the acceptance of any developed standard.

In this paper, some of the factors outlined above are investigated with a goal to assessing their impact on motor-drive system efficiency. In support of this goal, measurements were carried out on several motor-drive systems from different manufacturers under different power meter settings and under various operating conditions of voltage magnitude deviation and unbalance.

Efficiency Measurement

A. General Measurement Approach

Unlike line-powered motors, test methods are now under development or in early stages of use for motor-drive systems. For these systems, efficiency has to be more clearly specified in terms of either system efficiency, or component efficiency (motor or drive). The most convenient way to measure motor-drive system efficiency is the direct input-output method in (1).

$$\eta_{dir} = \frac{P_{out}}{P_{in}} \qquad (1)$$

where P_{out} is power output, P_{in} is power input and η_{dir} is efficiency.

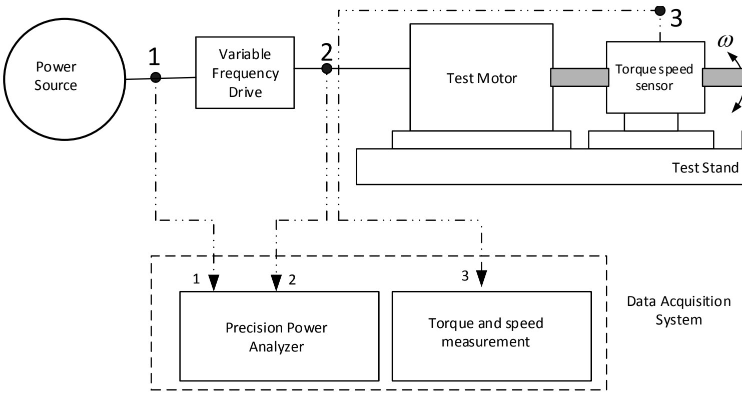


Fig 1: General test schematic for motor-drive system

The power output measurement data (torque and speed) is taken at point 3 and electrical power data is taken at point 1 of Fig 1. The test data is taken after the motor has attained a thermal equilibrium. Measurements are taken at a combination of various torques and speeds, regularly spaced in a matrix format. In general, contour plots such as Fig 2 can be developed from the test data. In order to calculate the test motor or drive efficiency separately, an additional data measurement is taken at point 2.

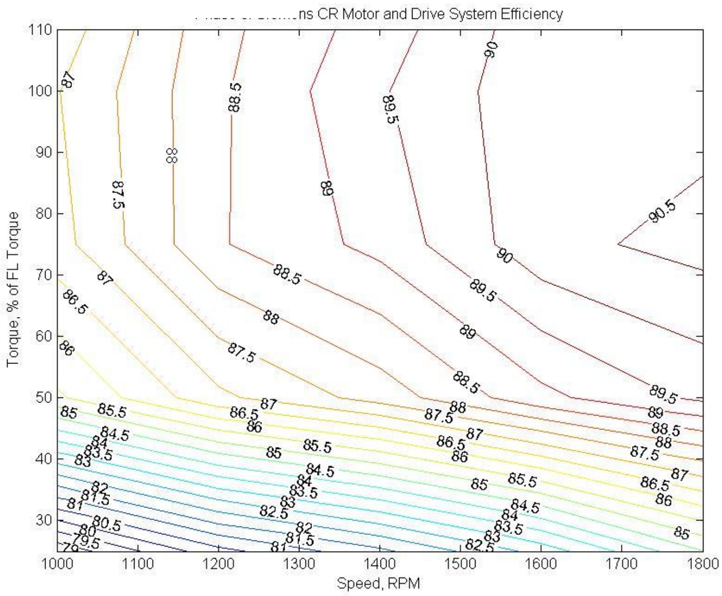


Fig 2: Efficiency contour plot of motor-VFD system

The search for improved methods of efficiency determination in motor-drive systems is ongoing. There have been attempts to quantify losses in system components as a way of determining the total losses in motor-drive systems in order to determine efficiency. It is often suggested that harmonic losses generated in the motor as a result of operating on a drive are independent of load and could be determined at no-load using equation (2), where P_{harm} is the harmonic loss, P_{PWM_NL} is the measured no-load power with the motor operating on VFD and P_o is the no-load power with the motor operating on a sinusoidal power source.

$$P_{harm} = P_{PWM\_NL} - P_o \quad (2)$$

With the harmonic loss determined and assumed constant with load, it is possible then to estimate the total loss of the motor operating on the drive at any load. Nevertheless the issue of harmonic loss and as to whether it is constant on load is still debated and it is not that straightforward whether all or part of the loss truly applies to load or no-load condition. In addition, the approach of determining harmonic loss requires operation of the motor under sinusoidal power. This added step may cost significant effort but with limited added benefits.

B. Factors Affecting System Efficiency Measurement

One significant factor that affects motor-drive system efficiency measurement is the measurement of electrical power. The electrical power measurement at points 1 and 2 is challenging due to the PWM output waveform of the drive and the non-linear input current. The outcome of efficiency measurement is therefore affected by how well these quantities are measured. Secondly, the input characteristics of the power source, such as voltage unbalance and voltage magnitude deviation may affect the efficiency result and need to be considered. In the following sections, the influence of these factors on motor-drive system efficiency is discussed.

Power Measurement

In order to demonstrate some of the challenges of power measurement in a motor-drive system, a 20hp 4-pole motor operating on a drive was tested. A standard no-load test at various no-load voltages was performed on the 20hp motor, using a variable frequency drive source and a sinusoidal power supply for comparison. The 20hp motor was tested under different settings of the power meter with the goal to determining the effect of power meter "filtering" and "no filtering" settings on the measurement results. The motor was first run until bearing loss had stabilized. At the first target voltage test point, the power instrument was set with no line filtering and data was taken. The power meter filter setting was changed to the next setting and the measurement was repeated while the motor was still running. The process was repeated until all the filter settings were exhausted before moving to the next target voltage. At all target voltages, the fundamental frequency was maintained at 60Hz to run the motor at 1800 rpm. All measurements were taken as quickly as possible at a given target voltage level so that the state of the motor did not change to affect the readings.

The test results are presented in Tables I-II for the no filter and 500Hz filter settings and harmonic loss is compared for all the filter settings in Table III. The first observation is that the rms current measurements were consistent for all the power analyzer settings while the rms voltages and power measurements varied with the setting. Secondly, the rms voltage magnitude of the unfiltered signal gradually reduced as filtering is applied from 50kHz to 500Hz. It is important to note that the fundamental and the total voltages are very close in value, apparently due to the harmonic measurement mode of the power analyzer being a band limited mode.

TABLE I

Voltage, Current and Power Measurement (no filter)

Target Voltage, V	Voltage, V			Current, A			Power, W		
	total	fund.	numeric	total	fund.	numeric	total	fund.	numeric
500	485.0	484.8	539.3	9.4	9.4	9.5	342.7	341.3	399.3
483	478.1	477.9	535.4	9.1	9.1	9.2	327.8	327.1	389.8
460	463.5	463.2	527.2	8.6	8.6	8.6	308.8	308.5	370.2
437	442.6	442.3	515.6	7.9	7.9	7.9	280.6	280.3	348.6
184	190.6	190.3	338.1	2.9	2.9	2.9	102.4	102.2	169.6
138	145.4	144.7	294.4	2.2	2.2	2.2	86.0	85.7	141.0
115	122.5	121.8	270.2	1.9	1.9	1.9	78.5	78.3	126.9

TABLE II

Voltage, Current and Power Measurement (filter 500Hz)

Target Voltage	Voltage, V			Current, A			Power, W		
	total	fund.	numeric	total	fund.	numeric	total	fund.	numeric
500	484.9	484.8	484.9	9.4	9.4	9.4	345.4	344.5	352.0
483	478.0	478.0	478.0	9.1	9.1	9.1	332.0	331.6	337.7
460	463.5	463.5	463.5	8.6	8.6	8.6	312.4	312.4	317.1
437	442.2	442.2	442.2	7.9	7.9	7.9	285.0	285.0	289.1
184	190.4	190.4	190.4	2.9	2.9	2.9	103.0	103.0	103.8
138	144.8	144.8	144.8	2.2	2.2	2.2	86.0	86.0	86.5
115	122.1	122.1	122.1	1.9	1.9	1.9	78.5	78.4	78.6

TABLE III

Harmonic Loss Comparison (500Hz to 50kHz)

Parameter	Sinusoidal Supply	PWM Source				
		No Filter	Frequency Filter	50kHz	5.5kHz	500Hz
Average Current, A	8.2	8.6	8.6	8.6	8.6	8.6
Average Voltage, V	459.7	527.6	527.2	521.0	476.4	463.5
No Load Power, W	323.3	370.4	370.2	361.2	316.8	317.1
Harmonic Loss, W	0.0	47.2	46.9	37.9	-6.4	-6.2

Fig 3 shows the measured voltage plotted against the target voltage. Ideally, such a plot will result in a straight line with slope of one if the target and measured voltages correspond. The different rms values recorded for the different filter settings is evident. In Fig 3, no filter and frequency filter setting are coincident as they are virtually the same condition. According to the power analyzer manual, the frequency filter is used to detect the zero crossing of the signal (for proper fundamental frequency read-out). Therefore essentially, the frequency filter is on for all the cases and consequently, the frequency filter curve and no filter curve are coincident. As expected, the 50kHz setting values are closer to the values for no filter setting while the setting corresponding to 500Hz should be close to the fundamental.

Comparing the current measured at any given target voltage it is seen that the rms currents are consistent, as shown in Fig 4. This can also be seen by comparing the current values in Tables I and II. The consistency in the current values is important and can be utilized as a reference quantity. While the measurement methods for voltage may differ from PWM and sinusoidal waveforms the measurement techniques for current are the same regardless of the waveform, hence the consistency.

The harmonic loss calculated by (2) and shown in Table III is interesting and shows why filter settings on the power analyzer may present a distorted picture of actual loss measurement in the motor during PWM excitation. While the no filter and frequency filter values are close, as filter is applied the value deviates and assumes unreasonable levels. For example, the harmonic loss value during the 500Hz and 5.5 kHz filter settings are negative, meaning that the motor consumed less power than in the sinusoidal case, which is questionable. The negative values also point to the inconsistency of non-sinusoidal power measurement.

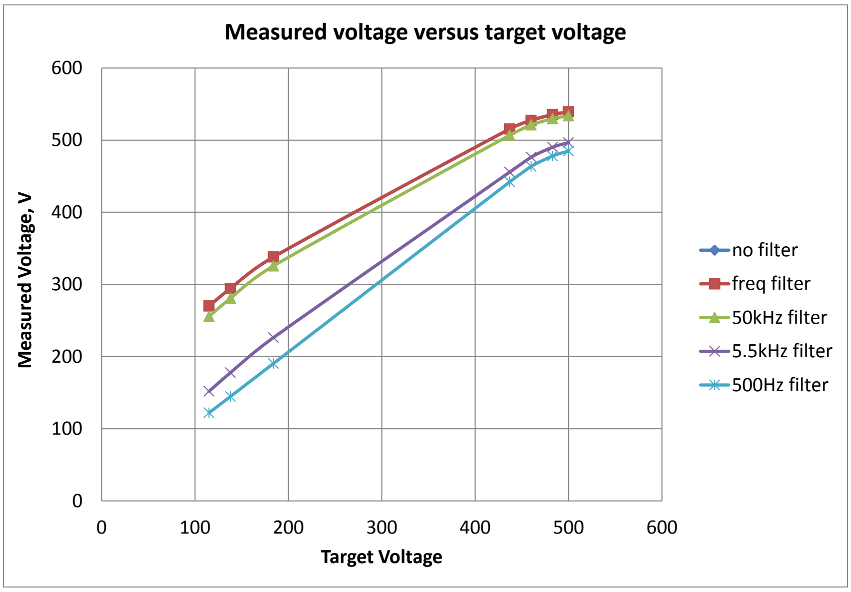


Fig 3: Measured voltage at output of drive

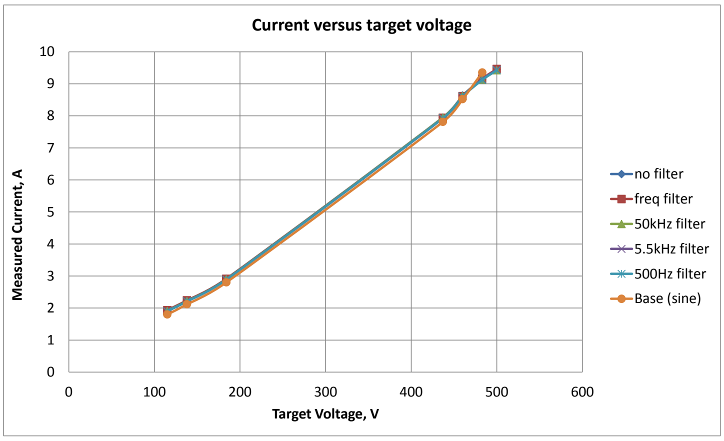


Fig 4: Measured motor no-load current

In Fig 5 the voltage current characteristic (V-I) is presented matching the measured voltage to the measured current. Even though the currents are identical in all the cases of different power meter settings, because of the differences in measured voltage, the V-I characteristics are different. The same applies to the power measurement plot in Fig 6. Again, because of the differences in voltages, the representation in Fig 6 presents a distorted picture, which seems to indicate that all voltages the sinusoidal power is higher, which is not the case. Therefore, for graphical representations, it is recommended to plot the measurements of electrical quantities with respect to the reference fundamental voltages.

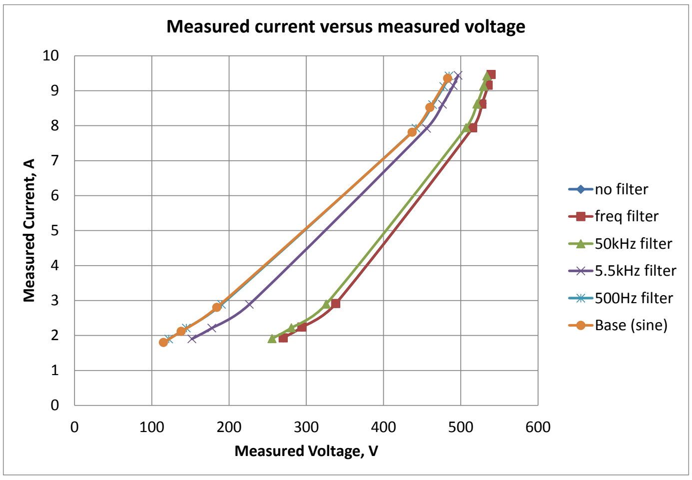


Figure 5: Voltage-current characteristics

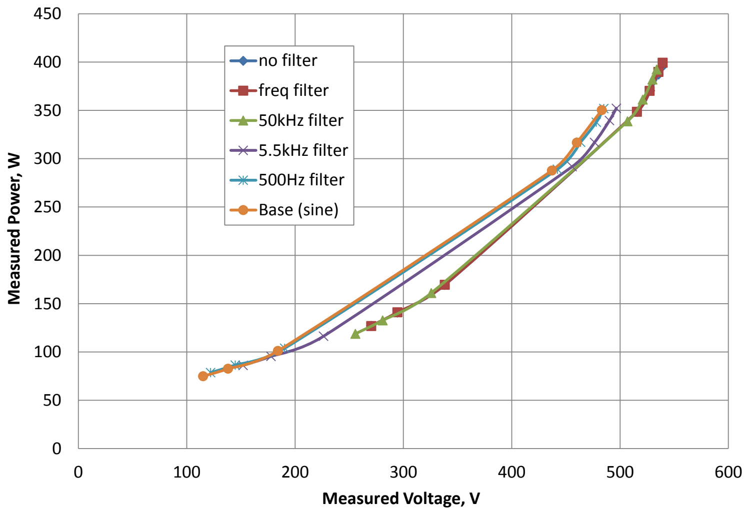


Figure 6: Measured no-load power versus voltage

Input Voltage Characteristics

The magnitude and characteristics of the ac input voltage into the drive has a functional relationship with the dc bus voltage and other performance features of the drive. In the US, the national standard that regulates service and utilization voltages is the ANSI C84.1-2011 [7]. The standard defines ranges for service voltage and utilization voltage of electrical equipment and the tolerances applied to these voltages. The ranges are defined for both normal operation and acceptable but abnormal conditions (short-time duration). Thus, magnitude of the input voltage into a drive can vary within acceptable range and deviate from the nominal, due to the allowances on the service voltage. In addition to voltage magnitude deviation there is also voltage unbalance occasioned by factors inherent in power supply and plant distribution system. The above factors can potentially affect the performance of the drive system efficiency. Voltage magnitude deviation and unbalance are also known to affect intrinsic motor performance [8]. Therefore input power quality has to be considered in efficiency measurement and comparison of motor-drive systems.

A. Voltage Unbalance

Voltage unbalance is often defined as the maximum line voltage deviation from the average, expressed as a percentage of the average line voltage (3):

$$V_{un} = \frac{max\ \left(\left|V_{ab} - V_{avg}\right|, \left|V_{bc} - V_{avg}\right|, \left|V_{ca} - V_{avg}\right|\right)}{V_{avg}} \times 100 \qquad (3)$$

where V_{un} is the percentage voltage unbalance, V_{ab}, V_{bc}, V_{ca} are line voltages *and* V_{avg} is the average of the three line voltages. Another definition of voltage unbalance is expressed as the ratio of the negative and positive sequence voltages:

$$V_{unf} = \frac{V_2}{V_1} \times 100 \qquad (4)$$

where V_{unf} is the voltage unbalance factor, V_1 is positive sequence voltage, V_2, is the negative sequence voltage. As is well known, induction motors respond to positive and negative sequence voltages, generating corresponding torques that may interact in an opposing manner, leading to torque pulsations, overcurrent, overheating, etc. In general, voltage unbalance negatively impacts the performance of induction motors as stated in various literature. The general observed trend is that motor efficiency reduced with increasing voltage unbalance.

In the case of a motor-drive system, the VFD topology acts to isolate the motor from most abnormal voltage conditions at the expense of increased losses in the drive and detrimental effects on drive components. The most common general-purpose industrial VFDs are six-pulse voltage source drives with diode bridge rectifier front end. The input current waveform of such drives is non-linear with the well-known double-pulse profile. With a balanced source voltage the current is symmetrical and the harmonic content in the VFD is generally defined by the characteristic harmonics of a q-pulse rectifier [9]:

$$h = kq \pm 1 \qquad (5)$$

where h is the harmonic order, q is the number of pulses of the rectifier (in this case q=6) and k is an integer (k=*1, 2, 3, …)*. The characteristic harmonics of the input current is therefore mostly odd of the order 5, 7, 11, 13, etc. As source voltage unbalance is introduced, conduction of the diodes become asymmetrical and variations of the current waveform can be seen with the pulses exhibiting unequal peaks and one pulse may totally disappear at increased levels of voltage unbalance. The input current waveform variations also reflect changes in the harmonic content of the current, and other non-characteristic harmonics such as triplens appear in the current harmonic profile. The effects of voltage unbalance include the increase in the rms current through the diodes, the dc bus voltage ripple, possible stresses on capacitors. Other characteristics of the power source, such as stiffness and presence or addition of line reactors and dc chokes, affect the waveform shape characteristic. All the above factors affect losses within the drive and therefore, the characteristics of the input source supply profoundly impacts drive performance and affects system efficiency.

B. Voltage Magnitude Deviation

The motor is a critical component of the motor-drive system and its intrinsic performance has been found to heavily influence the overall performance of the motor-drive system. In this section, we review some results of induction motor performance under voltage magnitude deviation and unbalance, to underscore motor-drive system performance.

From results presented in [8], we note that, as the voltage magnitude is increased above the nominal, slip is reduced and efficiency varies. Two efficiency profiles can be observed - in some motor designs, higher efficiency resulted from elevated voltages above nominal and lower efficiency resulted from voltages below nominal; other motors showed an opposite trend (see Fig 7). At reduced voltage and full load, current tend to increase in the motor, thus increasing joule losses. At elevated voltages, core loss may increase significantly. Therefore the efficiency trends are directly related to variation of losses within the motor and on the specific loss that increases more rapidly; core loss (strong voltage dependence) or joule loss (strong current dependence) and to a lesser extent stray losses. Saturation may play a part but that is ultimately reflected in the distribution of losses within the motor. Figure 7 depicts the two typical trends in efficiency variation that was observed during voltage magnitude deviation on sinusoidal power for two 1hp, 4-pole motors. The motor "prem", was fairly constant at voltages up to about the nominal voltage and efficiency sharply reduced at higher voltages. Motor "epact" exhibited a different performance characteristic (opposite). With respect to motor efficiency, lower voltages are favorable for motor "prem" and unfavorable to motor "epact".

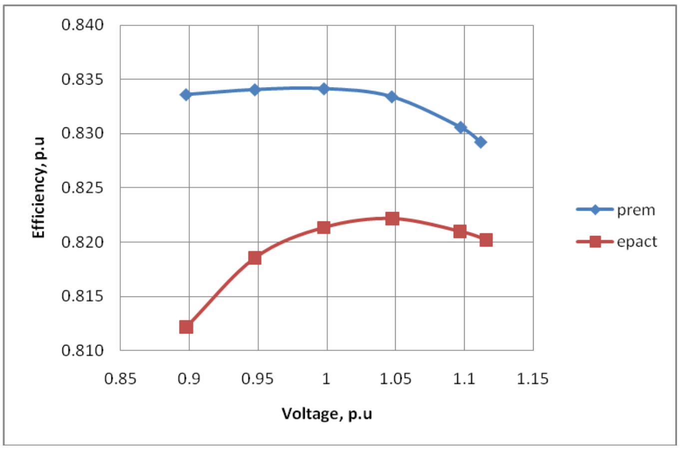


Figure 7: Typical motor efficiency profiles during voltage magnitude deviation on sinusoidal power for two 1hp, 4-pole motors

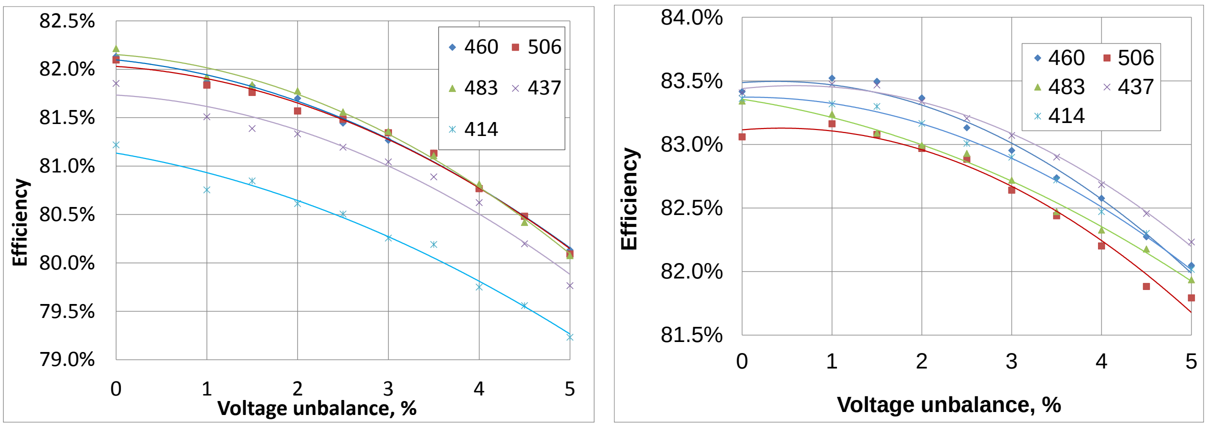
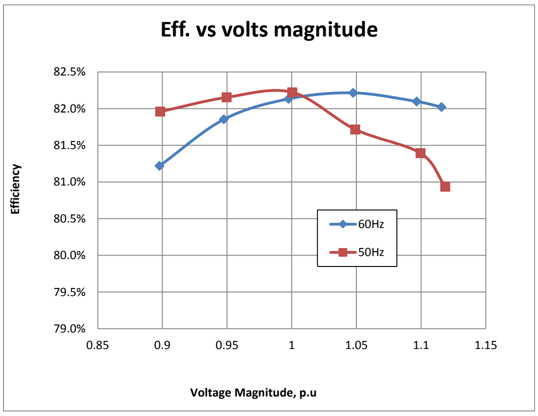


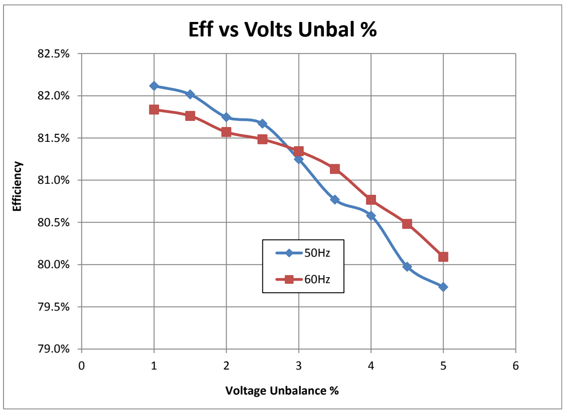
Figure 8: motor efficiency 1hp under voltage magnitude deviation and unbalance with sinusoidal power

Figure 8 show the motor efficiency under combined voltage magnitude deviation and voltage unbalance under sinusoidal power for the 1hp motors. As voltage unbalance increased, efficiency reduced in both cases. However, we note that the lowest efficiency curve in Fig 8 (a) corresponds to the 414V case while that of Fig 8(b) corresponds to the 506V case. The motors' efficiency performance at the different voltages followed closely and is consistent with the characteristic in Fig 7. As we shall see in subsequent sections, the motor-drive system efficiency mimics the intrinsic motor performance, as a result of a strong influence of the component motor on the drive system.

Another important consideration is the fundamental frequency. This is particularly important because motor-drive efficiency regulations are on-going in both 50Hz and 60Hz frequency regions and dual frequency motors rated for 50/60Hz are quite common. The efficiency characteristics presented in Fig 9, show relative performance differences of a 1hp, 4-pole, 50/60Hz motor tested under voltage magnitude deviation and unbalance at the two frequencies. Note that the performance curves presented in Fig 9 have interesting features that could influence selection of motor-drive applications. As the drive system was not tested at different frequencies, we reserve the conclusions until further work is carried out. However, it is clear that for motors designed for dual frequency, there could be efficiency implications, depending on which frequency the motor is certified, in relation to the variations in voltage. For discussions on the 50/60Hz considerations in motor testing and applications, the reader is referred to [10].



(a)



(b)

Figure 9: A 1hp 50/60Hz motor efficiency from sinusoidal power under (a) voltage magnitude deviation and (b) voltage unbalance

System Efficiency Measurement Comparisons

In order to further explore the voltage magnitude and unbalance factors, system efficiency measurements were carried out on a number of motor-drives. Tests were done with 1 hp, 7.5 hp, 20 hp and 50 hp VFDs from different manufacturers. All drives were rated for an AC input voltage of 380-480 Vac, 3-phase, 50/60Hz; each was tested on the same matching motors of similar rating. For the 1-hp system, one drive was used to test two different motors. For the 7.5hp and 20hp systems, the same motor was tested with three different drives. The tests were performed with the VFDs mostly in the basic V/f mode and at default configurations. Fig. 10 shows a 7.5 hp motor-drive system under test.

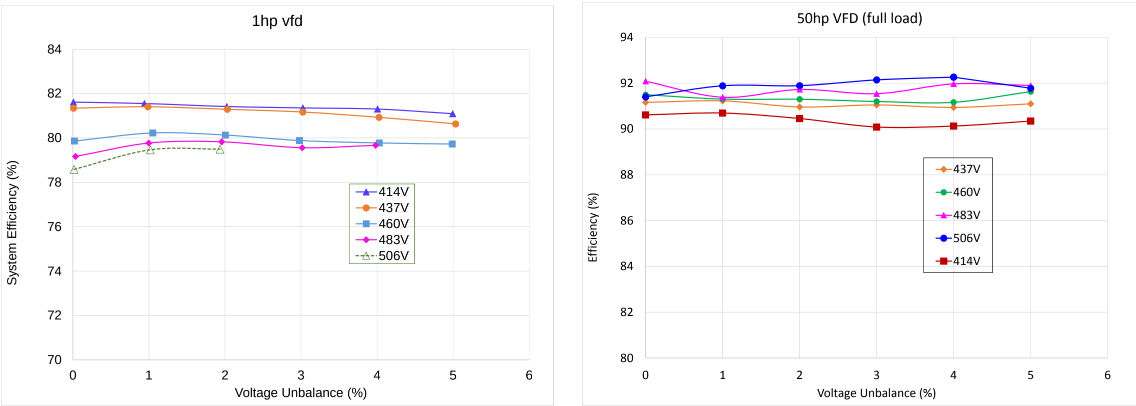
The load test measurement data is typically taken after the motor has attained a steady state thermal equilibrium and this was pursued for some of the tests. However, the impact of thermal stability was determined to have minimal impact for the purpose of the investigations in this paper and most of the tests were performed without strictly adhering to thermal stability.

The motor-drives were tested at full load and part load (50% and 75%) under combination of voltage magnitude deviations within the range of ±10% of the nominal and voltage unbalance from 1% up to 5%. The motors were also separately tested on a sinusoidal supply for comparison. The test procedure is as follows: the target output torque corresponding to each load (100%, 75%, and 50%) was first established with a balanced rated nominal of 460 Vac at the drive terminal and was not further adjusted as voltage unbalance and deviations was applied. This approach of not adjusting the torque when a voltage unbalance is introduced is fairly consistent with a typical field operation, where equipment is subjected to voltage abnormalities while in operation and the load is not necessarily adjusted under those conditions. After the torque was set on the dynamometer, the input voltage to the VFD was adjusted as desired, to create various combinations of over/under voltage and unbalance at which data was taken. Because the shaft torque was not further adjusted, there is a possibility of drift in output torque that could lead to slight change in horsepower. Since voltage is strongly correlated with motor slip, the speed could also change slightly with voltage, leading to variation in horsepower that could potentially affect the comparisons reported. However, observations showed that the speed and torque variation was minimal.

Fig 10: A 7.5hp motor-drive system under test

A. Impact of the Motor Characteristic on System Efficiency

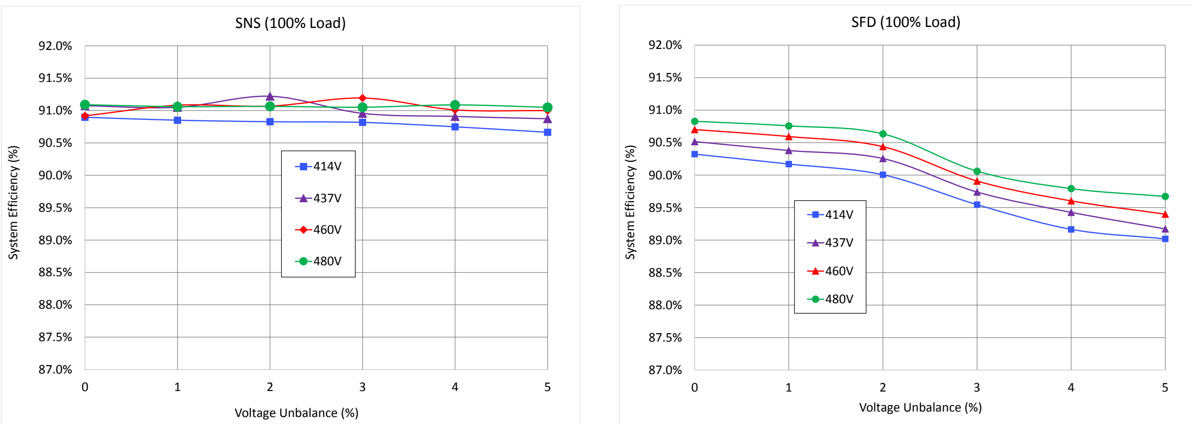
It was observed that, the system efficiency of the motor-drive system generally followed trends similar to that of the intrinsic motor characteristic. This is probably due to a stronger effect of the motor efficiency on the combined system efficiency. Figure 11 presents system efficiency plots for 1 hp and 50 hp motor-drive systems at various levels of voltage magnitude deviation and unbalance. Both systems maintained a fairly flat profile with minimal dependence on unbalance. However, the influence of voltage magnitude deviation is more visible. The lowest system efficiency was recorded at the highest voltage for the 1 hp system while that of the 50hp system corresponded to the lowest voltage. These trends also reflect the performance of the respective motors on sinusoidal power, under voltage magnitude deviation.



(a) (b)

Figure 11: Motor-drive system efficiency (a) 1hp motor-VFD and (b) 50hp motor-VFD

Another comparison is made for different drives tested on an identical 20 hp motor. Each drive is described with a three-letter code. As shown in Fig. 12, for example, the test of the SNS 20 hp drive maintained a fairly flat system efficiency profile at full load. Also, the various levels of over/under voltage did not appear to have any distinct impact on the overall system efficiency, except the 414 Vac that was consistently lower than the other input voltage levels. Comparing Figures 12 (a) and 12 (b), it is seen that system efficiency dropped significantly at voltage unbalance above 2% for the SFD drive. Furthermore, the efficiency at various over/under voltage conditions is more distinct for SFD than in the case of SNS.

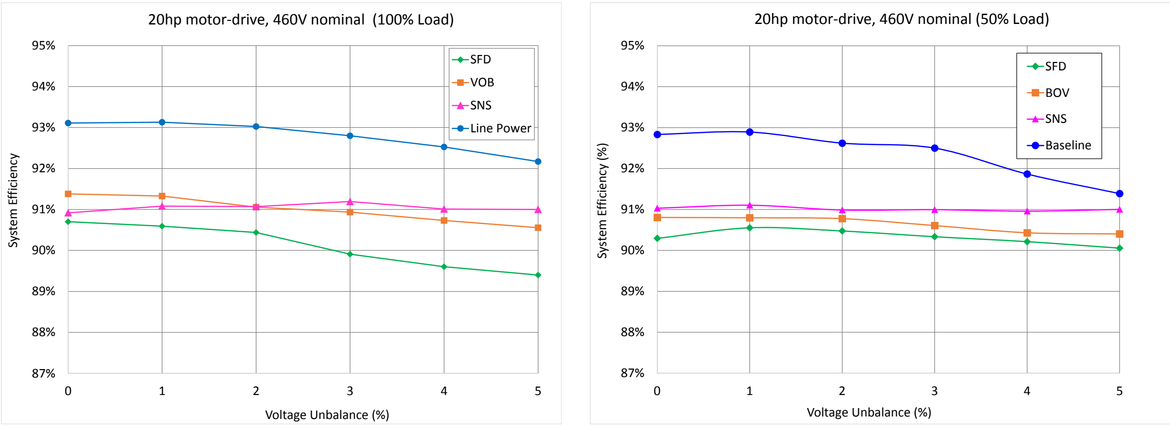


(a) (b)

Figure 12: System efficiency of 20hp motor-drive system (SNS – left, SFD – right)

B. Impact of Loading on System Efficiency

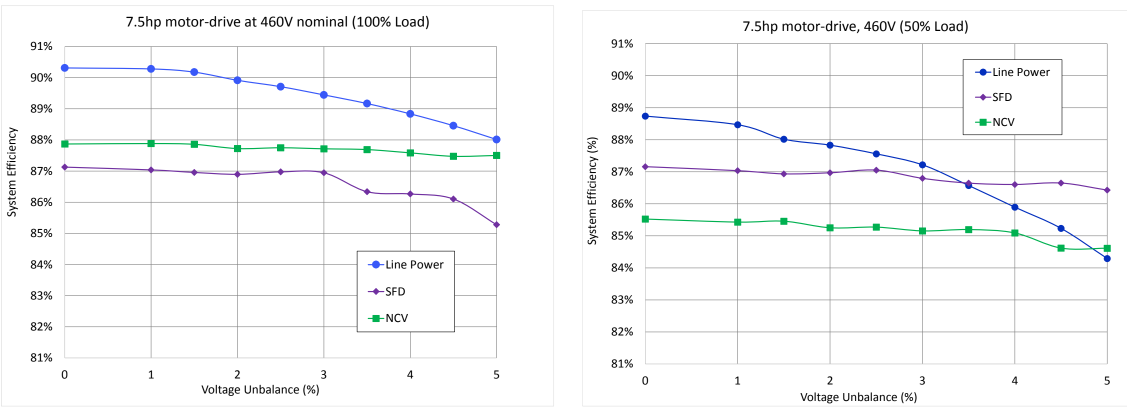
Figure 13 compares the performance of three drives tested at the 460 Vac nominal voltage using an identical motor. On the same plot, the test with sinusoidal line power (motor only) is plotted as the baseline. The differences between the drives is clearly evident and so is the drop in efficiency when a drive is used with this 20hp motor compared to a sinusoidal power supply. For example, it is seen that there is more than 2% points reduction in efficiency as a result of using the VFD on this motor compared to sinusoidal excitation. Two of the drives (VOB and SNS) could be considered to have comparable performance, while the third drive had lower system efficiency performance than the other two. The 50% load characteristics shown in Figure 13(b) are similar to the test at full load, except that the three VFDs did not have overlapping performance at any voltage unbalance. Also, note that the SFD drive did not experience the large reduction in system efficiency that was observed at full load.



(a) (b)

Fig 13: System efficiency of 20 hp motor-drive system at full load (left) and half load (right)

Figure 14 presents 7.5hp drives tested on an identical motor. The 7.5 hp VFD test results showed a similar trend to the 20hp tests. In this case the disparities between VFDs are more pronounced than in the 20 hp case. Another interesting point is that at 50% load - the SFD is more efficient than NCV while the opposite is true at full load. Also, above voltage unbalance of 3.5%, SFD motor-drive system has higher efficiency than the motor operating at half load but with that level of high voltage unbalance.



(a) (b)

Fig 14: System efficiency 7.5hp motor-drive system at full load (left) and half load (right)

Figure 15 shows the calculated motor efficiency of the 20hp system at full load and 50% load. A look at the calculated motor efficiency could provide a good indication of the drive's impact on system efficiency. First of all, it is that the motor efficiency on the drive is only slightly lower than that of sinusoidal power, the difference being accounted for by harmonic losses in the motor as a result of the pulse width modulation excitation. Comparing Figs. 13 and 15 indicates that there is more than 2% points drop in efficiency as a result of using the VFD on this motor over the sinusoidal case. Given the harmonic losses are low (as indicated by Fig. 15), the bulk of the efficiency drop can be attributed to losses in the VFD.

It is interesting to note in Fig. 15 (b) that at 50% load, the motor efficiency on sinusoidal power was lower than the motor efficiency with a drive at unbalance values above 2%. Given that the overall system efficiency in Fig. 13 was still lower for the test with drive, it is evident that the drives contributed in large part to the reduction in system efficiency.

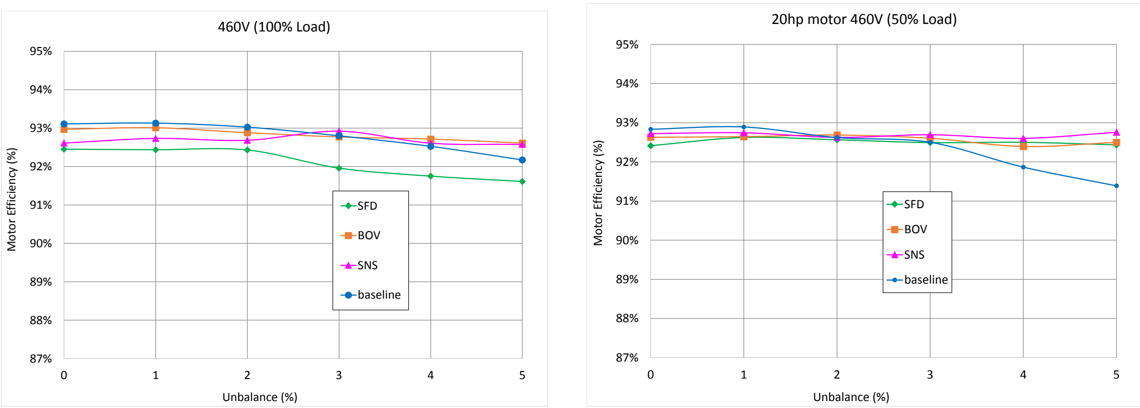


Fig 15: Motor efficiency of 20 hp motor-drive system with identical motor and three different drives at full load (left) and half load (right)

Discussion

From the above findings, it is obvious that power meter settings have significant impact on measurements. Even though recently developed power analyzers claim high accuracies, their performance on non-sinusoidal power is still an area that requires careful evaluation due to the different functional algorithms of these new meters. The findings support a view that, for motor-drives testing it is incorrect to apply filter settings on the power meter as the power measurement values obtained do not reflect the true state of the signal being measured. Although this observation may be obvious for experienced test personnel, it is important to expressly specify this in test standards to avoid ambiguity. In the same vein, graphically presenting electrical quantities with respect to measured voltages, for comparison purposes, creates a distorted picture because of the disparities between the rms values of PWM voltage and sinusoidal (or fundamental). Such comparisons must be graphically displayed with respect to the reference fundamental voltage.

The second factor examined, which relates to power quality also appeared to have an important impact on system efficiency. In particular, both voltage magnitude deviation and voltage unbalance affect system efficiency measurement. However, the voltage magnitude deviation was found to have a more significant impact than the voltage unbalance. Furthermore, the voltage magnitude deviation closely followed the intrinsic behavior of the motor under this same voltage anomaly. This finding is important for selection of motor-drive systems.

In general, the motor-drive system efficiency decreased with increased voltage unbalance. However, the efficiency reduction is more modest for drive system than it was for the motors operated on sinusoidal power. There was some variation in performance between different drives, indicating that some are more energy efficient than others. The susceptibility of the drives to voltage unbalance, with regard to their impact on system efficiency also varied; some drives exhibited a flatter profile as voltage unbalance increased while others experienced a sharp reduction in system efficiency at voltage unbalance above 2 to 3%. Many industrial distribution systems can easily experience a voltage unbalance of about 2%, thus this finding is also important for selection of motor-drive systems.

As mentioned previously, the system efficiency profile of the motor-drive under voltage magnitude deviation typically followed the intrinsic motor performance (motor alone), under those same conditions, indicating that the motor performance is a strong factor and contributor to overall system performance. During the design of motor-drive systems, it is therefore important to consider the motor efficiency profile with respect to voltage magnitude deviation, as the system efficiency profile will follow a similar trend. This finding could also be of benefit in comparison of drives for regulatory purposes, as the motor performance profile should be a critical consideration. In this regard, all drives intended for comparison should be tested with the exact same motor.

The loading on the motor also seemed to have some impact. In general, the disparity in system efficiency is smaller at reduced loads for all the VFDs tested, which suggests that motor-VFD systems could be relatively more energy efficient at reduced loads under unbalanced voltage operation. This makes sense because the low load corresponds to relatively lower losses in the drive, while it isolates the motor from negative effects of the unbalance.

Conclusion

The increasing application of motor-drive systems and impending regulations have triggered ongoing efforts to develop suitable test standard. The existing standard are currently not at consensus level and more discussions are required to highlight the factors that affect efficiency measurement of motor-drive systems. This paper discussed the impact of power meter settings on measurements of the output of the drive. The paper also compared system efficiency performance of different commercially available drives operated with imposed voltage magnitude deviation and voltage unbalance.

Findings indicate that the factors investigated have profound impact on the measured system efficiency. When a comparison is desired, voltage input characteristic need to be specified stringently and more correctly, as opposed to terms such as nominal voltage or rated voltage. It is also important to note that the motor-drive system is relatively more susceptible to voltage magnitude deviation than voltage unbalance, with the intrinsic motor performance and system load being strong factors. It is therefore important to consider the motor efficiency profile with respect to voltage magnitude deviation in motor-drive system design. The motor-drive system appeared to be relatively more energy efficient under unbalanced voltage operation if the motor is operated at reduced loads.

In general, the variations in performance among different drives is expected, as these are products of different designs from different manufacturers. It is therefore important for users to carefully evaluate products prior to selection, considering the application and the motor to be applied.

References

[1] CSA C838-13, Energy efficiency test methods for three-phase variable frequency drives systems, 2013

[2] IEC 60034-2-3, Rotating electrical machines part 2-3: specific test methods for determining the losses of converter-fed AC machines, 2013.

[3] AHRI 1210, Performance rating of variable frequency drives, 2011

[4] IEEE 1566-2015 "IEEE Standard for Perfromance of Adjustable Speed AC Drives Rated 375 kW and Larger"

[5] IEEE 499-1997 "IEEE Recommended Practices and Requirements for Cement Plant Electric Drives and Related Equipment"

[6] IEC 61800-9-2, Adjustable speed electrical power drive systems - Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications - Energy efficiency indicators for power drive systems and motor starters, 2017.

[7] ANSI C84.1-2011, American National Standards for Electric Power Systems and Equipment, voltage Rating (60Hz).

[8] E. B. Agamloh, S. Peele, J. Grappe, "A comparative analysis of voltage magnitude deviation and unbalance on standard and premium efficient induction motors," IEEE Pulp and Paper Industry Conference, Portland, June 2012.

[9] A. von Jouanne, B. Banerjee, "Assessmentof Voltage Unbalance on Induction Machines", IEEE Transactions on Power Delivery, vol 16., no. 4, pp. 782-790, October 2001.

[10] E. B. Agamloh, A. Boglietti, A. Cavagnino, "Interchanging induction motors for 50Hz and 60Hz operation," IEEE IECON Conference, Nov. 10-13, 2013, Vienna, Austria.

[11] E. B. Agamloh, S. Peele, J. Grappe, "Operation of VFDs with source voltage unbalance," IEEE Pulp, Paper and Forest Products Industry Conference, Tacoma, Wa, June 2017.

[12] European Commission, Commission Regulation No. 640/2009 of July 22, 2009: Implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to Ecodesign Requirements for Electric Motors, Official Journal of the European Union, July 23, 2009.

[13] Emmanuel Agamloh, "Power and efficiency measurement of motor-variable frequency drive systems", IEEE Transactions on Industry Applications, vol 53., no. 1, pp. 766-773, Jan/Feb 2017.

[14] A. K. Singh, G. K. Singh, R. Mitra, "Impact of Source Voltage Unbalance on AC-DC Rectifier Performance," 2nd International Conference on Power Electronics Systems and Applications, 2006

[15] JTE Fernando, AT Almeida, and G Baoming. "Impact of voltage sags and continuous unbalance on variable-speed drives", ICEM Conference Record, 2010, pp 1-6.

[16] K Lee, TM Jahns, TA Lipo, G Venkataramanan, and WE Berkopec. "Impact of Input Voltage Sag and Unbalance on DC-Link Inductor and Capacitor Stress in Adjustable Speed Drives", IEEE Transactions on Industry Applications, vol 44-6, 2008, pp 1825-1833.

[17] K Lee, T Jahns, DW Novotny, TA Lipo, WE Berkopevc, and V Blasko. "Impact of Inductor Placement on the Perfromance of Adjustable-Speed Drives Under Input Voltage Unbalance and Sag Conditions", IEEE Transactions on Industry Applications, vol 42-5, 2006, pp 1230-1240.

[18] Sebastião E. M. de Oliveira, and José Octávio R. P. Guimarães, "Effects of Voltage Supply Unbalance on AC Harmonic Current Components Produced by AC/DC Converters", IEEE Transactions on Power Delivery, vol 22., no. 4, pp. 766-773, Oct 2007.

Real time estimation of measurement uncertainty for Power Drive Systems with respect to EN 50598-2

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Abstract

This paper investigates the impact of the measurement uncertainty on efficiency of motors, drives, and power drive systems. According to European standard EN 50598-2, efficiency class definitions of motor and power drive systems should include the uncertainty of measuring instrumentation. This renders the choice of the uncertainty estimation model crucial, in order to guarantee a reliable class declaration. The proposed methodology follows the guidelines presented in EN 50598-2 for input-output technique, and accounts for the contribution of measurement uncertainty related to the accuracy specifications of the instruments and sensors. A LabVIEW based tool for automated sequencing and efficiency measurement is developed. The tool accounts for configuration of instruments, basic control of the drives for testing at different operating conditions, data acquisition, efficiency class declaration and online uncertainty calculation based on the method proposed in this paper. A series of tests are carried out on an actual motor drive system test bench for the experimental validation of the analysis. The tests allowed for precise evaluation of the feasibility of the test procedures described in the standard, especially in the case of motor drive testing. The analysis highlights the necessity of a well-defined uncertainty calculation methodology to ensure a reliable declaration of the efficiency class of the product (PDS) under test.

Keywords: - *EN 50598-2, IEC60034-30-1, IEC60034-30-2, IEC60034-2-1, IEC 60034-2-3, Direct input-output efficiency measurement, uncertainty of efficiency measurement methods*

Introduction

In the field of industrial sustainability, the European Commission (EC) has demanded the implementation of regulations in terms of Eco-design, in order to meet the requirements of the European plan 2020 and create a competitive market with innovative and qualitative products [1]. This process was initiated in 2005 for general "energy-using" appliances [2] and was improved in 2009 with the commission regulation [3] for electric motors. In line with this direction, the commission's actions can be summarized in the production and harmonization of series of standards. IEC Standards 60634-30 and 60034-2-1 are the main references for efficiency class definition and efficiency testing for line-operated AC motors [5], [7], whereas similar standard is now published for measurement of efficiency of for converter-fed AC motors [6]. IEC 60034-2-1 includes reference values for efficiency, requirements on measurements and efficiency class definitions.

Due to technological innovations in motor materials, design methods and better cooling concepts, it is now possible to reach higher efficiency levels, which also demands for definition of higher efficiency classes for motors, but then the gaps between the newly defined efficiency classes becomes narrower. This puts stringent requirements on the accuracy levels of measurement instruments used for classification of motor efficiency levels. The next logical step was to regulate the overall efficiency of motor drive system together rather than individual component level: in this effect European standard series EN 50598 are published now which describe efficiency requirements regarding converters and converter driven products. In this aspect, the information on energy efficiency classes and test methodologies for Complete Drive Modules (CDM) and Power Drive Systems (PDS) is provided in [8. As per definition, a PDS is the combination of a motor and a CDM.

The major change in [8] as compared to previously defined standards is that now the uncertainty of efficiency is specifically required to determine the efficiency class of the PDS. EN 50598-2 describes mathematical models, power loss calculation, test methods, requirements for user's documentation and general guidelines for uncertainty calculation of CDM and PDS [8]. As basis for PDS classification in terms of efficiency, a reference model, named reference power drive system (RPDS), is defined. Beside the RPDS, a PDS includes all the auxiliaries that are necessary for the ordinary operation of the system. Mathematical models allow the evaluation of the efficiency class in cases where actual measurements cannot be carried out and define the so-called reference losses associated to RPDS. The use of reference values and standardized tests allows for an easy comparison between different products and renders the combination of different parts possible, in order to derive the efficiency of the extended product. According to [8], when losses of a PDS are measured at full load test point, the efficiency class is defined by the following ratio:

$$\frac{p_{L,PDS}}{p_{L,RPDS}} = \frac{\frac{P_{L,\mathrm{PDS},meas} + u(P_{L,\mathrm{PDS},meas})}{P_{r,M}}}{p_{L,RPDS}} \quad \textbf{(1)}$$

where $p_{L,PDS}$ indicate the relative power losses of the PDS under test. $P_{L,PDS,meas}$ is the actual power loss, to be associated to the PDS, and $P_{L,\mathrm{PDS},meas}$ is the measured power loss. The quantity $p_{L,RPDS}$, defined as relative power losses of the RPDS, is stated in [1] and it is associated to the apparent rated power of the motor $P_{r,M}$. $u(P_{L,PDS,meas})$ indicates the uncertainty related to measured power losses PDS. This is the main differences between earlier standards and EN50598-2 [8]. Equation (1) shows how the uncertainty is accounted for in the final definition of the efficiency class, and should be clearly defined in order to enable direct comparisons between different product's efficiencies.

This paper analyses the testing procedure and efficiency class definitions including measurement uncertainty as described in EN50598 and shows that the measurement uncertainty evaluation as described in standard results in suboptimal performance. An improved method, which takes into account the state of the art of the uncertainty theory and the actual accuracies of the motor testing instrumentation, is described afterwards and its performance is compared with the earlier described methods. The impact of individual instrument uncertainty on the overall efficient class declaration of the motor drive systems is also analyzed in the end.

Uncertainty estimation background

The main reference for uncertainty calculation is JCGM 100:2008 [9], which presents definitions, basic concepts of statistical distributions and practical examples of measurements. In general, the measured value can be influenced by different parameters. The most influential parameters of a measurement are: errors by operator, measurement inaccuracies caused by instruments (accuracy from the datasheet), wrong settings of instruments, errors in setup configuration, environmental conditions and inaccurate calculations. According to the definitions of [9], these parameters give information on the available knowledge on the possible variability of the measurand, which defines the type B uncertainty.

Following the guidelines of [9], [8] states that the knowledge of all tolerances of the used measurement method is mandatory and the normal distribution function shall be used for the conversion of the accuracy data of the instrumentation and normal distribution function shall be used for the conversion of the accuracy data of the instrumentation.

Evaluation of uncertainty at randomly occurring errors requires calculation of standard deviation of the power losses of the CDM or PDS, ΔP_L, defined as:

$$\Delta p_L = \frac{\Delta P_L}{P_L} = \frac{s_y}{y} = \frac{\sqrt{\sum_{i=1}^{n}\left(\frac{\partial y}{\partial x_i} s_{x_i}\right)^2}}{y} \tag{2}$$

where s_y is the standard deviation associated to a quantity y. In case, y is function of variables x_i , its derivative with respect to x_i , $\frac{\partial y}{\partial x_i}$ shall be multiplied into the standard deviation s_{x_i} associated to x_i. The main sources of inaccuracy are not specifically defined in the standard, neither are there provided any sample cases of calculation which can be used as guidelines for deriving such procedures by users.

The important influence of uncertainty on efficiency measurements, as utilized in EN50598-2 [8], intensively encouraged the investigation on uncertainties for efficiency evaluation in the last years. Various earlier prior art, such as [10], focuses on the uncertainties for different measurement methods are presented, matching the uncertainty trends indicated EN50598-2 standard, based on Monte-Carlo simulations. The result shows that errors related to the input electrical power and torque measurements are the most critical as they have largest influence of final loss and efficiency variations. Interesting effects of PWM supply are presented in [11], underlining its impact on the efficiency accuracy. However, in the proposed methodology, distribution functions and combined standard uncertainty were not used in [11], and not all the inaccuracy sources were considered. However, the results are useful for a qualitative comparison between line-fed and converter-fed efficiency evaluations.

Proposed method of uncertainty estimation

Uncertainty calculation is subject to the test setup and other factors, so an accurate model is difficult to be defined. A model must take into account all sources that contribute to the final uncertainty value. The impact of some important factors for the uncertainty calculation, pointed out in the prior art, and the extensive theory of [9] can be used as basis to present a step-by-step approach suitable for efficiency and loss uncertainty calculation for PDS testing. According to the datasheets of the instrumentation, the accuracy of the instrument is usually defined as a percentage of measured quantities (ε_{read}), a percentage of ranges (ε_{range}) or constant errors (ε_{cst}). All of these errors should be considered in the calculation of the uncertainty for a certain quantity x_i, as follows:

$$a_{meas.}(x_i) = \varepsilon_{read} * (\mathrm{x}_{i\_rdg}) + \varepsilon_{range} * (\mathrm{x}_{i\_rng}) + \varepsilon_{cst} \tag{3}$$

where x_{i_rdg} is the measured value, as seen on the instrument's display, x_{i_rng} is the range set on the instrument, and $a_{meas.}(x_i)$ is the interval of confidence in which the measurement x_i may occur. Apart from the accuracy which is directly related to the measured quantity, there are errors caused by other influential conditions (i.e. room temperature, parasitic effects), which can alter the accuracy of the measurement. These errors are usually expressed as percentage of the measured quantity, giving a measure of the variation of the basic accuracy when those conditions occur. The combined uncertainty $u_{TOT}(x_i)$ related to the quantity x_i, influenced by other parameters q_i, is defined by:

$$u_{TOT}(x_i) = \sqrt{u(x_i)^2 + \sum_{j=1}^{n}\left(\frac{\partial x_i}{\partial q_j} u(q_j)\right)^2} \tag{4}$$

All the parameters x_i that contribute in the definition of power losses have to be combined in order to obtain the final loss uncertainty $u_{TOT}(P_l)$ to be included in the corrected losses as follows:

$$u_{TOT}(P_l) = \sqrt{\sum_{i=1}^{n} (\frac{\partial y}{\partial x_i} u_{TOT}(x_i))^2} \quad \textbf{(5)}$$

Where y can be replaced by the measured loss, or the calculated efficiency in case of efficiency uncertainty evaluation.

Development of efficiency measurement and uncertainty estimation tool (EMUET)

A system including measurement instruments and software to interface with these instruments is developed for efficiency measurement and uncertainty estimation (PDS EMUET). PDS EMUET allows the real-time estimation of the efficiency, power losses, IE/IES definition and uncertainty of CDM, motor and PDS. The set of software tools is developed using National Instrument's LabVIEW and DIAdem development tools [21]. PDS EMUET can be connected with up to three measurement instruments and two electric drives and can send commands for initialization of instruments, acquire and manipulate data for the uncertainty and efficiency calculation and automatically create test reports for all the measurements and processed data.

The main structure of the PDS EMUET is shown in Figure 86 and it consists of five main parts, as follows:

1. Initialization: This action is required in order to initiate the communication with the instruments and to configure the respective settings. For each instrument, a customized window reproduces the actual setting screen, allowing the operator to change basic and advanced settings.

2. Drive control and measurement monitoring: Drive control can be performed along with electrical and thermal measurements. The control is customized on the drive model and its programming requirements. Main references (torque and speed) and customized parameters can be controlled from the tool through a MODBUS communication adapter attached with the drive which is interfaced to LabVIEW acquisition computer via Ethernet connection. A temperature logger and two power analyzers are connected via Ethernet as well, and their measurement can be visualized on the main frame as numeric values or graphs.

3. Test sequencing: Automated tests can be performed as the tool provides the option to visualize the test points on a speed Vs toque matrix.

4. Efficiency class and uncertainty evaluation: The acquired data are manipulated in order to evaluate the efficiency and the uncertainty of the products as per EN 50598-2. PDS, CDM and motor efficiencies and losses are calculated and visualized on the screen through graphical indicators. The calculation of efficiency and uncertainty can be performed accurately if all the information regarding the experimental setup is available for the tool. Information on the instrument configuration, accuracy datasheets, nameplates with rated values, tolerances are available automatically or as manual inputs for the operator. Datasheets of accuracies, tables with the reference losses of CDM and PDS, test point requirements for the CDM are available in the program sources directory. The tool combines the available data with the acquired measurements, performing a real time calculation of efficiency, losses, uncertainties and providing information and alarms if limits are exceeded or requirements are not met

5. Data logging: Measurements from the instruments, outputs from the drives and results of calculations can be all logged into a singular *.tdms file, organized in sheets as a common spreadsheet that can be edited in Excel or DIAdem.

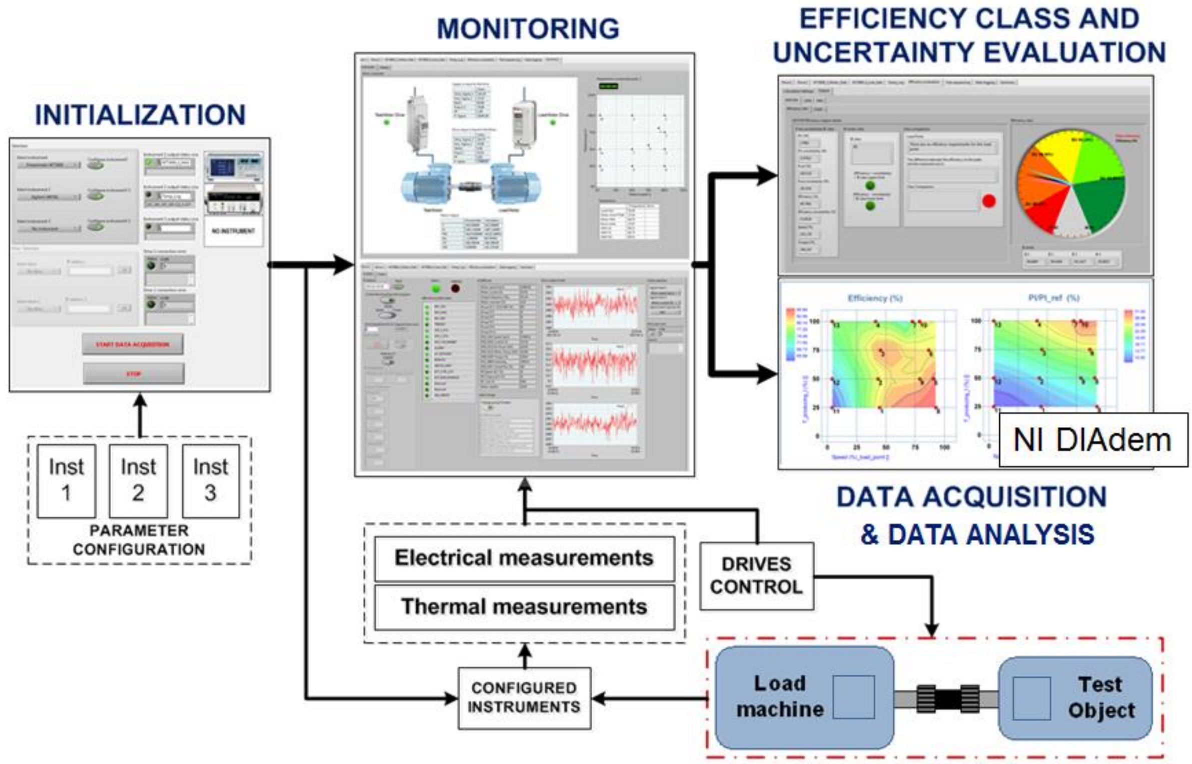

Figure 1: Structure of the online efficiency measurement and uncertainty estimation tool (EMUET)

Experimental measurements of PDS efficiency and online uncertainty estimation

Test setup

In order to evaluate the efficiency of motor, CDM and PDS, three different test series have been carried out. The test bench is the same for the three tests as shown in Figure 2. For the purposes of the investigation, all measurements are carried out on a converter-fed motor. The motor is fed with a 400 V supply and is connected to a 22 kW drive with 44 A rated output current. The drive connected to the test motor is the test CDM for which efficiency is to be measured. The test motor is coupled to a load machine and a torque transducer is utilized for the measurement of the associated mechanical quantities. The load motor is connected to a drive that provides the control of the torque to be applied at the shaft. Two power analyzers (Yokogawa WT3000) are employed in order to simultaneously perform electrical power input measurements to test drive and test motor and mechanical power output at motor shaft. One of the power analyzer, which is connected to measure motor input power is also interfaced with output from torque transducer allowing simultaneous measurement of motor output power. A temperature logger is used for the measurement of the room temperature, and the temperatures of the housing and the winding of the two motors.

The setup follows the guidelines of IEC60034-2-1 [5] and EN50598-2 [8] in terms of accuracy of the instrumentation. Various accuracies related to electrical and mechanical measurements for the above instruments are taken from respective datasheets and are tabulated in Table 1. Errors related to temperature influence and calibration interval are not considered in the uncertainty calculation. Moreover, the line filters in the power analyzers were disabled to include the powers from harmonic components associated with VSD supply.

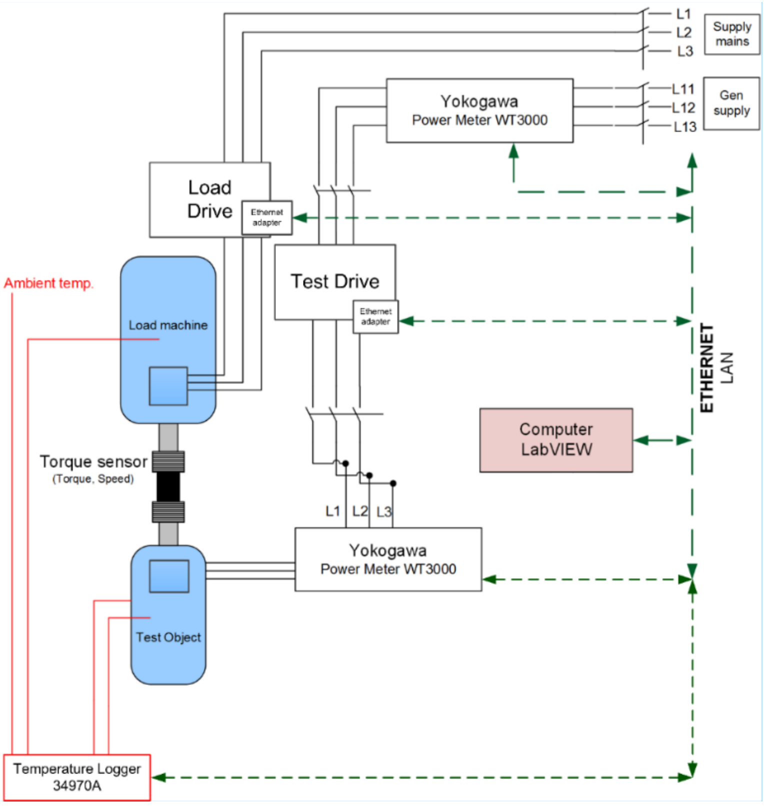

Figure 2: Electrical wiring schematic of measurement setups for input-output method

Measurement Tests

The tests which are carried out are as follows:

1. **Motor and PDS testing at thermal stability as per EN50598-2 [1]:** eight load points have been tested for 30 minutes each. The objective of the test was the measurement of the performance of the motor and the PDS as per standard. However, the cooling capabilities of the setup were insufficient for the operative points located on the zero speed axis. When a test is performed at speeds greater than zero the natural cooling produced by the rotor compensates for the temperature increase. Therefore, zero-speed load points were omitted from this test. Beside the standard load points, points located on the pump/fan type load (square torque load) curve have been tested. From this test, no evident trends for uncertainties in efficiency and loss have been observed.

2. **Motor and PDS testing on 4x4 matrix:** it was performed in order to facilitate the validation of the typical uncertainty trends presented in [1] and to investigate of the impact of error sources on total uncertainty values. The test points are defined on a 4 x 4 torque v/s speed matrix with 25% speed and load torque increments Figure 90. The thermal stability condition is neglected in this test. Each load point is tested for 10 minutes in order to collect a sufficient amount of samples. The shorter testing time, with respect to test 1, does not compromise the quality or validity of the results and by no means disregards the procedures described in the standard. As stated in [1], measurements over a period of 1 min to 3 min, equivalent of at least several slip cycles, are enough for a later

processing. However, the test is not following the standard in terms of sequencing of test points

3. **CDM testing:** thirteen load points were tested, for 5 minutes each, as per where the load for CDM testing is defined by the stator frequency and the torque producing current. In order to run the test with so strictly defined load points, the output current of the drive has to meet the requirements outlined in [1] in terms of relative values and displacement factor. Thus for the test to be valid at one particular load condition (as shown in Figure 6), the test operator has to implement the following steps:

    a. Check the minimum current (torque producing current) and accordingly the load of the machine
    b. Check the load displacement factor and modify other parameters, if possible.

Table 1: Accuracies of instrumentation and standards requirements

Instrument	Measured quantity	Error source	Accuracy	Requirements from standards
Digital power analyzer	Mechanical power	Torque input (Analog)	±0.1%reading error + , 0.1% measurement range error)	Minimum class 0,2 [IEC 60034-2-1]
		Speed input (pulse)	±0.05%reading error + 1 mHz	<0,1 rpm [IEC 60034-2-1]
	Electrical measurements	Current, Voltage	±(0,1% reading error + 0,05 % measurement range error)	0,2 % of rated apparent power S_{equ} (0,3 % of S_{equ} for limited bandwidth), including external sensors [EN 50598-2]
		Power	±(0,15% reading error + 0,1% measurement range error + tanφ*0,3% of reading)	
	Line filter influence (DISABLED)	Current	0,5% of reading	Shall not be used [EN 50598-2]
		Voltage	0,2% of reading	
		Power	1 % of reading	
	One year accuracy (not considered)	1,5 times 6 month accuracy		
	Temperature coefficient (Valid for range 5 to 18°C or 28 to 40°C)		Add ±0.02% of reading /°C	
Torque transducer	Torque	Accuracy	± 0,1% reading	Standards are not setting requirements on torque transducers:
		Rotating Speed influence	0,01% per 1000 rpm	
		Linearity + hysteresis	±0,1 % rated torque	
	Speed	Accuracy	-	
Current Transducer	Current	Accuracy	±(0,05% reading + 30 µA)	Shall not be used[EN 50598-2]
		Conductor position effect	± 0.01% of reading	

Influence of measurement conditions on the final results

Even though measurement procedures met most of the requirements described in EN50598-2 standards, the motor testing could not be carried out efficiently for all the load points. Three main limitations were incurred in order to meet the measurement guidelines given in EN50598-2 standard. This is summarized in Figure 3 and in Figure 4.

The first problem concerns the zero speed load points (encircled red in Figure 3) and is related to the thermal condition that could stress the machine. The second problem is related to partial load point conditions (encircled green in Figure 3 and in Figure 4). For these operation points, it has been noticed that the sensitivity of the instrumentation, which is scaled for nominal point measurement of the motor drive setup, was not sufficiently high to detect signals of low amplitude such as power factor and others. This fact has consequences on the calculation of parameters as uncertainties and efficiencies of test objects. The last problem is related to the change of the load point ((encircled gray in Figure 3 and in Figure 4). Such a change affects the measurement and the data processing because of the consequent transients. When the auto-range function is enabled, the power analyzer changes the range automatically according to the measured value. The power analyzers produces null measurements during recalibration period and it reflects in infinitive peaks or null samples for all the quantities during these times. Proper sampling and averaging of measurement data is required in such instances. But the first two problems cannot be resolved leading to loss of measurement at this points. The EN50598 standard should specifically describe the proper guidelines to follow at such measurement conditions.

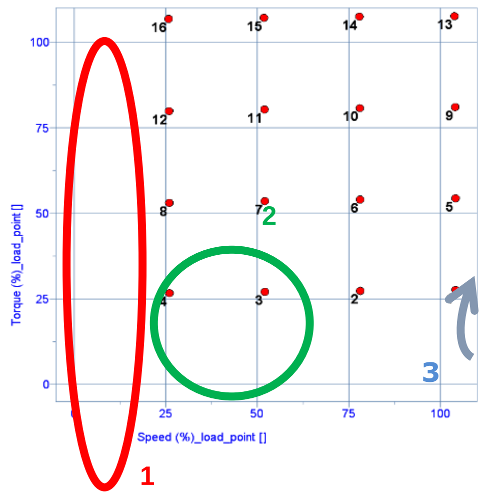

Figure 3: Critical test conditions

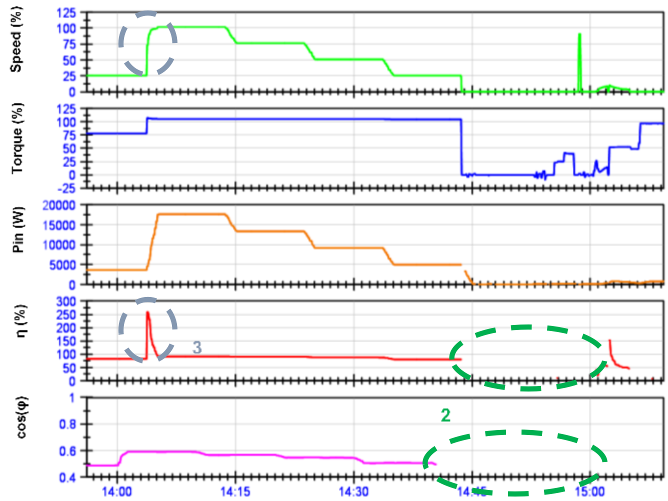

Figure 4: Effects of critical conditions

Measurement analysis

Efficiency and loss trends for test 2 with 4 x 4 load point matrix

This sections describes the efficiency and power loss values for each load point have been acquired in test 2 only, since it gives enough test points to derive the trends in measurement uncertainty and its dependence of various measurement quantities. The respective trends and numeric values for each load point are presented in Figure 5-Figure 8. All the logged values presented here are sampled every 5 seconds and averaged over 7 minutes in order avoid any errors due to spurious measurements and random noise. The relative losses for PDS and CDM are illustrated in Figure 7 and Figure 8.
As expected, power losses are increasing for higher loads. In PDS testing, losses for partial load point are erroneously calculated by the tool, giving null values, due to the problem related to the sensitivity of the instruments, discussed in the previous section.

Similarly, the motor efficiency uncertainty is evaluated online by EMUET tool for all measurement points based on the procedure described above. The typical variation of the uncertainty for the operation points is shown in Figure 9. It is evident that the uncertainty is higher for low torque and high speed values. A similar trend can be recognized in Figure 10 for the uncertainty of losses in PDS. This reflects the fact that both the quantities are related to the measurement of electrical and mechanical power, and the difference between the input powers of the two products is affected only by the losses of the drive. Therefore, uncertainties in efficiency or losses and other parameters, are equivalent. As far as CDM losses are concerned, as depicted in Figure 11, the resulting uncertainty values are highly influenced by the operating frequency (speed) and are less affected by the current variation.

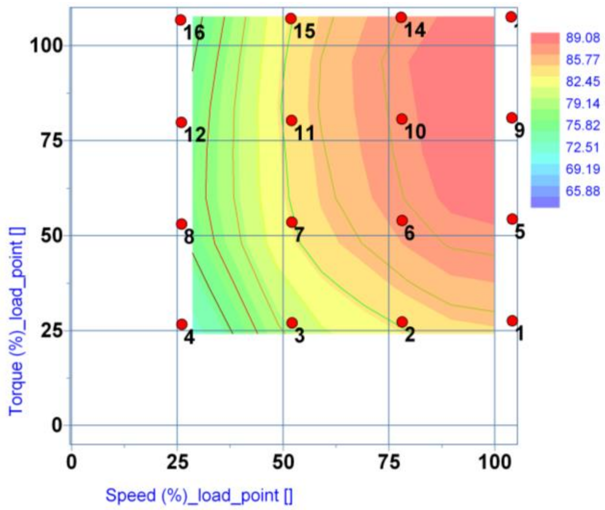

Figure 5 Test 2 - PDS efficiency

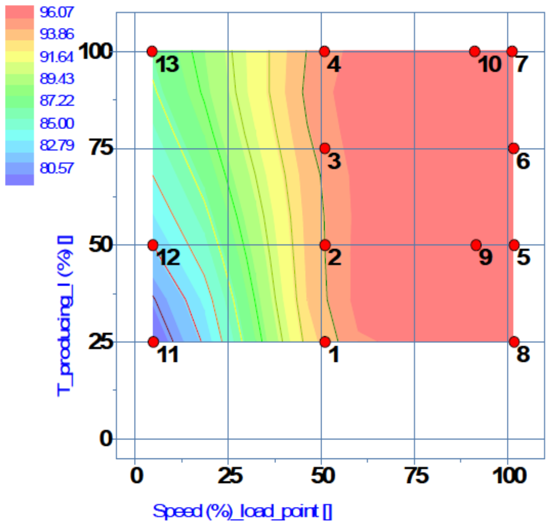

Figure 6 Test 3 - CDM efficiency

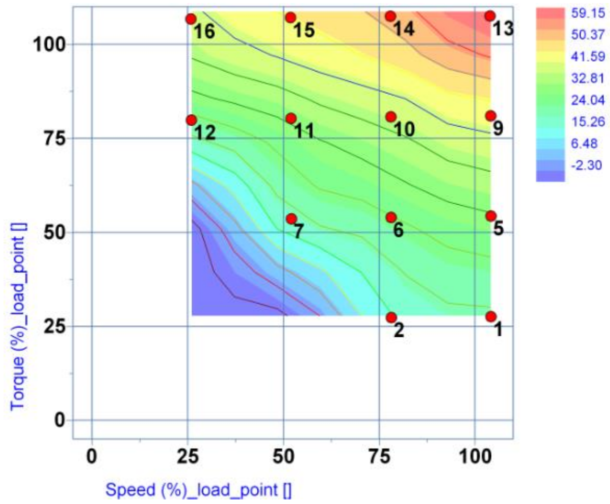

Figure 7: Test 2 - Relative losses for PDS

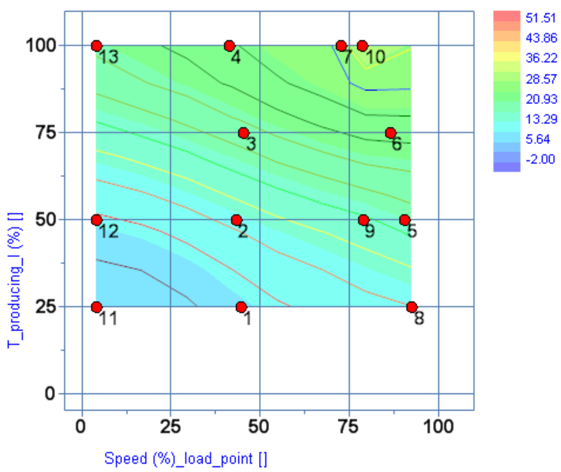

Figure 8: Test 3 - Relative losses for CDM

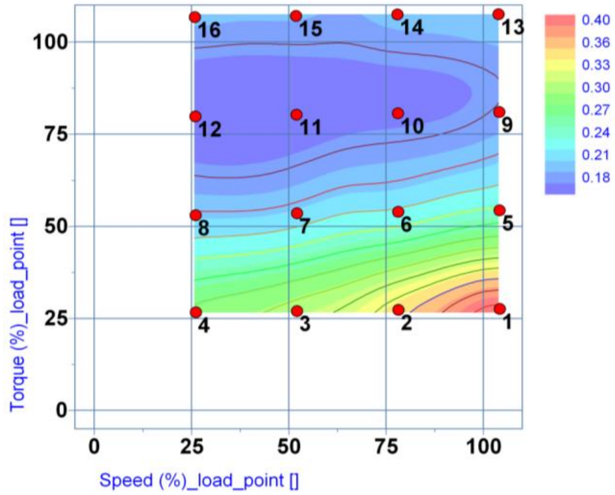

Figure 9: Test 2 - Relative uncertainty of efficiency of motor

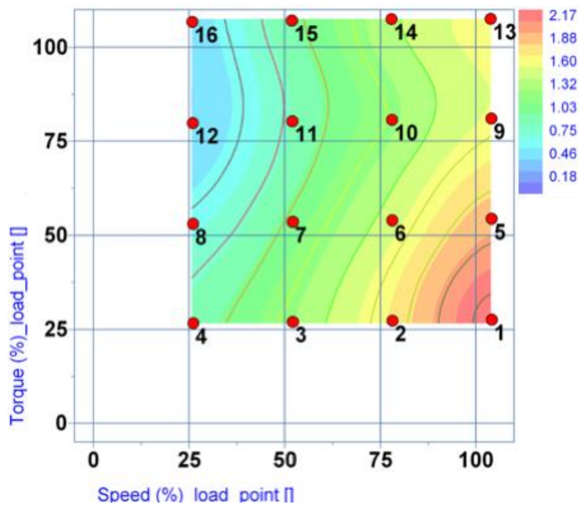

Figure 10: Test 2 - Relative uncertainty of complete PDS loss of PDS

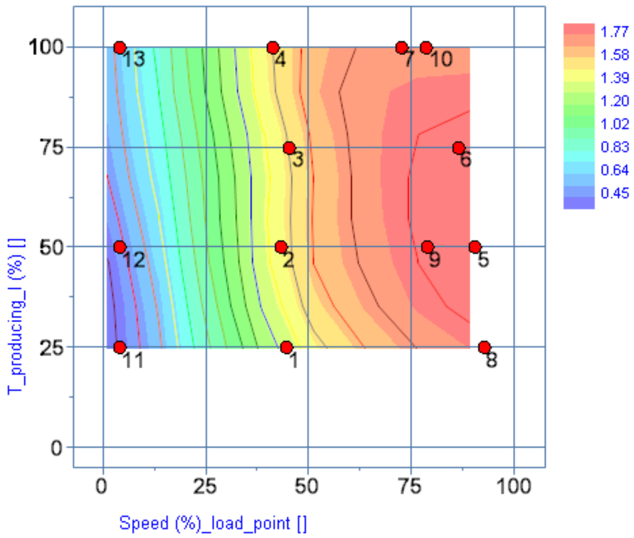

Figure 11: Test 3 - Relative uncertainty of CDM power loss

The influence of actual efficiency of motor on relative estimation uncertainty is analyzed as shown in Figure 12. It can be seen that the uncertainty in motor efficiency is not proportional to the actual efficiency of the motor. This is due to the fact that a motor can have the same efficiency for different load points. In the calculation of uncertainty in efficiency, apart from the accuracy related to measured quantities, there is the contribution of instrument range related errors which causes a non-linear relation between the measurements and uncertainty. A direct correlation between efficiency and uncertainty can be identified when the load torque is kept constant. For these operating points, the uncertainty in efficiency increases with the increase in the efficiency of the motor. It can be pointed out that the relative uncertainty is higher for lower torque values due to lighter loading of instrumentation which still have larger contribution of instrumentation range related uncertainty.

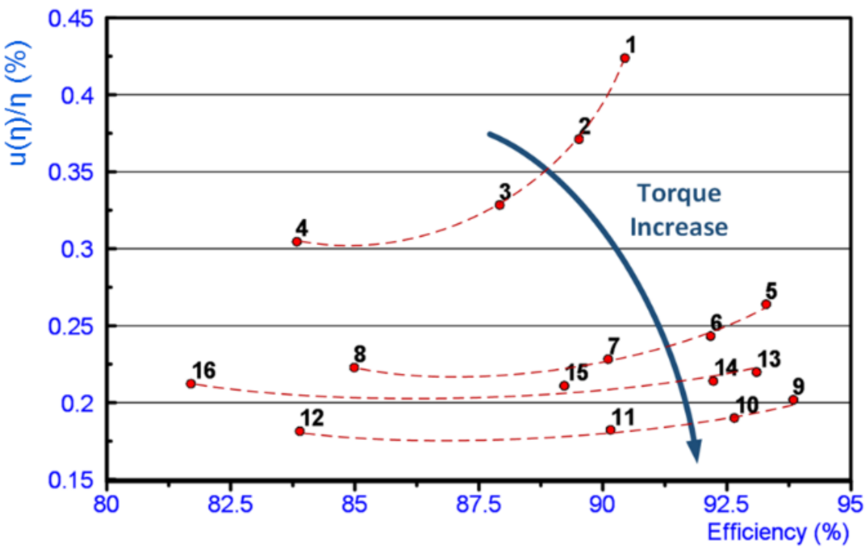

Figure 12: Test 2 – Relative efficiency versus efficiency (numbers indicate the measurement point as shown in Figure 90)

Similarly, influence of actual input and output power measurements on efficiency uncertainty u(η) is analyzed by plotting the uncertainty as a function of output and input power uncertainties (Figure 13 and Figure 14). The value of u(η) is loosely related to the input power uncertainty level. However, a linear relationship between uncertainty in efficiency and mechanical losses can be observed, as depicted in Figure 13. The effect of two main measurands contributing to mechanical power- speed and torque measurement values on the uncertainty is shown in Figure 15 and Figure 16, respectively. u(η) is increasing with the speed but the influence of the torque is quite significant. As seen in Figure 15, the variation of the uncertainty is not concretely varying with speed variation, but it is increasing when the torque decreases.

Thus it can be concluded that the torque range related contribution in the power analyzer dominates most on the overall measurement uncertainty

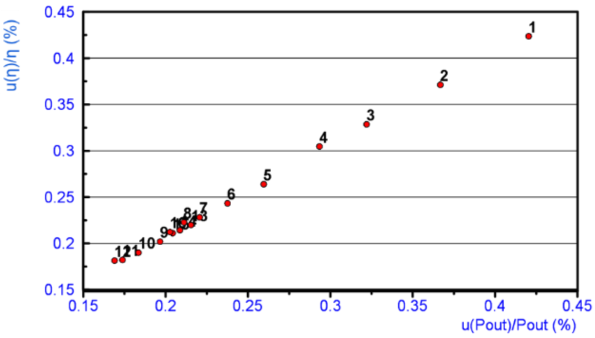

Figure 13: Test 2 - Motor efficiency uncertainty versus mechanical power uncertainty

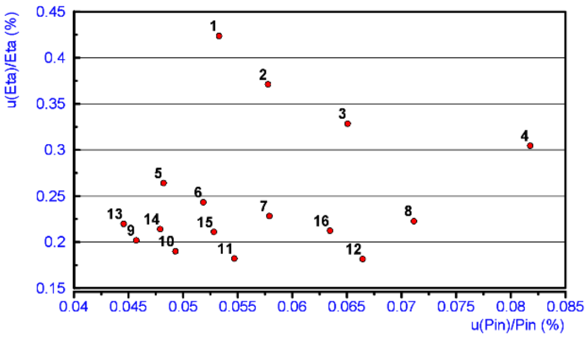

Figure 14: Test 2 - Motor efficiency uncertainty versus electrical power uncertainty

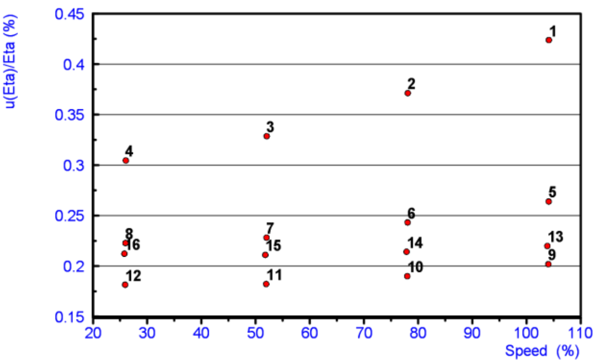

Figure 15: Test 2 - Motor efficiency uncertainty versus speed

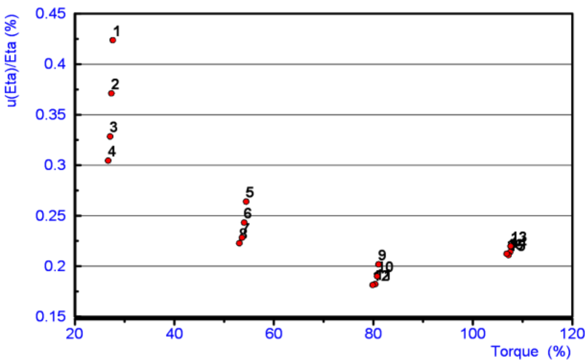

Figure 16: Test 2 - Motor efficiency uncertainty versus torque

Comparison with measurement uncertainty with EN 50598-2 standard

EN 50598-2 [8] describes typical uncertainty trends for different loss determination methods. The uncertainty indicated in the standard is based on a normal distribution for error occurring randomly associated to a total accuracy 0,2% of the rated apparent power S_{equ}. According to the standard, the uncertainty trend in losses has been calculated as

$$\frac{\Delta P_L}{P_L} = \frac{\sqrt{(k * P_{IN})^2 + (k * P_{OUT})^2}}{P_{IN} - P_{OUT}} = k\frac{\sqrt{1+\eta^2}}{1-\eta} \tag{6}$$

with coefficient k=0,2% related to the total accuracy of power meter, P_{IN} and P_{OUT} are measured input and output active powers. This approach is qualitatively right but too generalized but far simplified from the fact that accuracies are not just function of the reading error, but they include different contributions as described earlier. Thus, an operator who is not familiar with calculation of uncertainties can be misled by the standard guidelines. The results acquired by applying the above-mentioned definition to the measurement data yields the green curve in Figure 17.

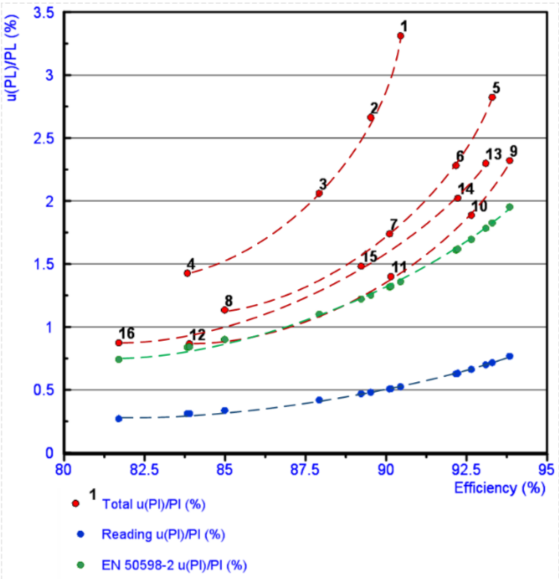

Figure 17: Test 2 - Loss uncertainty for motor

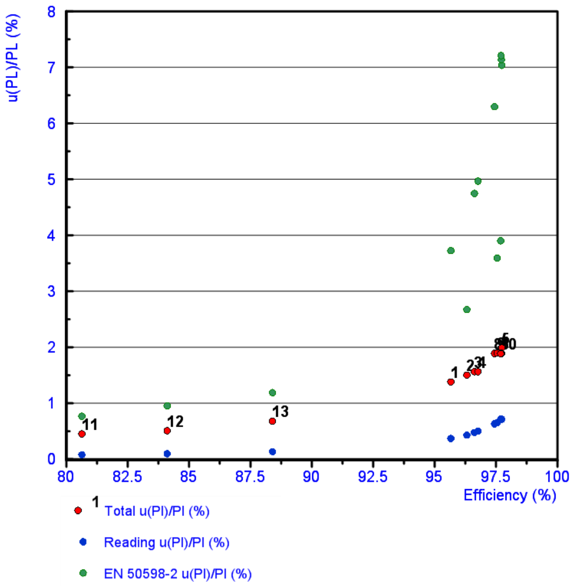

Figure 18: Test 3 - Loss uncertainty for CDM

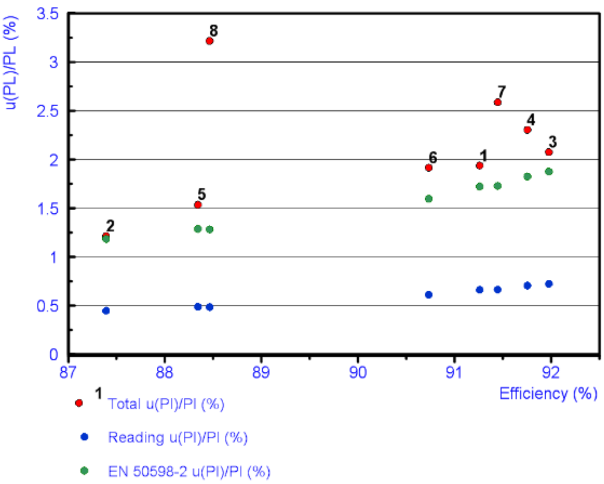

Figure 19: Test 1 - Losses uncertainty for PDS

The same generalized approach of assuming the accuracy as a percentage of the read quantity is repeated on the measurements, applying the actual reading accuracy of the instrumentation.

$$\frac{\Delta P_L}{P_L} = \frac{\sqrt{(k_1 * P_{IN})^2 + (k_2 * P_{OUT})^2}}{P_{IN} - P_{OUT}} \tag{7}$$

where the accuracy of measured quantity of electrical measurements is k_1=0,02% applied to measured electrical power $P_{el,}$ and total reading accuracy on mechanical measurements is k_2=0,1% of measured mechanical power $P_{mech.}$. This is shown in Figure 17 in **blue** curve, characterized by the application of uniform distribution.

The actual power loss uncertainty which includes both measured quantity errors and equipment range errors is represented by the **red** curves in Figure 17 and is calculated using following equation

$$\frac{\Delta P_L}{P_L} = \frac{\sqrt{u(P_{IN})^2 + u(P_{OUT})^2}}{P_{IN} - P_{OUT}} \qquad (8)$$

where the respective uncertainty of different power measurements are calculated as described in previous sections. The typical values of the estimated uncertainties are higher than the uncertainties presented in the EN50598-2 standard (**green** curve) or the ones related to the only reading errors since the range related errors have larger influence and are function of a mechanical measurement.

The same analysis, as described above, is repeated for test 3 and test 1 and the respective results are shown in Figure 18 and Figure 19. Since all test points could not be measured in test 1, a trend similar to the one reported in Figure 17 for test 2, cannot be easily recognized for test 2. For CDM test (test 3), the uncertainty of the losses is not dependent on the torque value as in motor testing, since the measurements are strictly related to electrical parameters, and the uncertainty are not as much amplified as it happens due to torque transducer used in Test 2 or Test 1. Since the range and the input and output power measurements are not significantly different, equation (8) gives an uncertainty trend coherent with the typical trend of [8], independently on the load torque point.

It can be concluded that the measurement uncertainty in efficiency or motor losses is generally higher than what is described by the EN50598-2 standard when all error sources related to range related errors are considered in estimation of measurement uncertainty. This consideration is missing in the present formulation of EN50598-2.

Summary of measurement results and recommendations for test procedure

This section summarizes various criticalities pointed out in previous sections as recommendations to further improve the test procedures and other guidelines described in EN50598-2. It shall be noted that the recommendations are based on authors experience with following test procedures for given rating of motor drive system as well as associated instrumentation.

Test type

EN50598-2 [1] indicates that in critical thermal conditions, the measurement test shall be performed over a time period of 10 minutes, involving a cooling system at full performance. For zero-speed load points, temperature could be an issue even with full performance operation of the cooling system. If a separate cooling system is not available, a shorter time period of testing for these particular points is required, such that the temperature rise should not be larger than the rated temperature rise at nominal operating point.

The instrumentation to be selected has to match the accuracy requirements described in EN50598-2 [1], expressed as percentage of S_{equ} [5]. This approach seems not appropriate because the apparent power S_{equ} cannot be used as a reference for the mechanical power accuracy. Furthermore, the apparent power value does not give useful information on the instrumentation choice because most instrument manufacturers display accuracy levels as percentages of reading and range or as constant errors.

Test points for PDS and CDM are defined by different parameters. Due to this measurement tests for a PDS does not provide loss information coherent with the load points defined for the CDM, as the respective requirements for current and power factor cannot be satisfied. Therefore, two tests have to be carried out separately for PDS and CDM.

Calculation of Measurement Uncertainty

EN50598-2 [1] generalizes the uncertainty calculation approach with the use of normal distributions. Since some manufacturers express the accuracy with a specific distribution of standard uncertainty, the inclusion of it can incur problems when the applied uncertainties are calculated for different laboratories that employ different instruments and quantities are measured by instruments using different uncertainty distributions. In case the instrument manufacturer provides uncertainty values calculated with a specific distribution (i.e. uniform), this specific distribution should be used [2].

Introduction of tolerance limits is necessary in order to make comparable loss measurements carried out in different laboratories (different instrumentation or environment conditions). Less accurate instruments, but included in tolerance limits stated in [3], could affect the efficiency class declaration of the product. Additionally, measurable criteria in term of tolerances, as presented in [4] for line fed motor, shall be included for CDM and PDS for both nominal operating points and partial load points. Such criterion can be used as a cross check for acceptance of the test results at different operating points.

All relevant sources of inaccuracies that could affect the uncertainty calculation should be considered as demonstrated in this paper, since some important accuracy contributions from the instruments could be involuntarily neglected, such as transducer contributions or errors related to other influential parameters.

CDM testing

For CDM testing the following remarks can be made:

The use of the rated apparent power of the motor, $P_{r,M}$, shall be revised in the context of testing for CDM. The references on $P_{r,M}$ included in EN50598-2 [1] can potentially create confusion in the choice of the reference values because they are referred to the drive and not to the motor. If information on the rated values of the drive are not available, $P_{r,M}$ is referred to the motor for the actual application. In this case, it can happen that the requirements on the current and displacement factor cannot be achieved and that the losses of the CDM exhibit lower values. Moreover, when the rated power of a drive is significantly different from the respective one for the motor, the requirements on power factor and current cannot be met. A comparison between reference and measured losses, as indicated in the standard is presented in Table 2.

Table 2: Comparison of reference losses with measurements with 44 A drive

Operation point (Torque producing current (%), frequency (%))	**(0; 25)**	**(0; 50)**	**(0; 100)**	**(50; 25)**	**(50; 50)**	**(50; 100)**	**(90; 50)**	**(90; 100)**
$P_{L,RCDM}$ (W)	550	633	896	570	689	1072	780	1410
I_{out} (A)	18,4	24,5	40,8	18,4	24,5	40,8	24,5	40,8
$P_{L,CDM}$ (W)	191	236	391	210	277	483	319	536
Actual I_{out}(A)	19,5	25,2	41,4	18,7	25,1	41,9	25,1	41,1
$P_{L,CDM}$ /$P_{L,RCDM}$ (%)	34,7	37,3	43,6	36,8	40,2	45,0	40,9	38,0
Required cosphii	0,49	0,71	0,85	0,49	0,71	0,85	0,71	0,85
Actual cosphii	-	-	-	0,46	0,51	0,57	0,69	0,76

If the actual drive is oversized, the situation is equivalent to the respective observation as previous point. Furthermore, when PDS and CDM tests are performed simultaneously, the strict requirements on the power factor are unlikely to be satisfied. Bigger deviation from the set values should be allowed when the load is the actual motor in the PDS.

The use of an equivalent electronic load is suggested when the CDM testing requirements are not achieved, as per [1]. This testing option is not feasible when a test lab carries out PDS and CDM measurements on the same setup.

Further improvisation of IE/IES definitions for CDM/PDS efficiency classes

The relative losses of the reference drive given in the EN50598-2 [1] are substantially higher than that of the most available drives in the market. Nowadays, electric drives are characterized by higher and higher levels of efficiency. In order to make the IE classification for drives a valid index of efficiency, which is useful for the customer for comparing different products, the class definition limits have to be properly set according to the actual state of the market. Also further efficiency classes need to be defined to segregate the higher efficiency drives, this is missing in the present formulation of efficiency classes for CDM as well as PDS.

Conclusions

This paper presents an investigation on efficiency measurement methods and classification as described in the recently published standard EN50598-2. The in-depth analysis of EN50598-2 [1] has pointed out several unclear definitions and procedures. An explicit calculation method for uncertainties of efficiency and power losses is proposed in this paper, which is not available in the published standard. Tools for automated testing of motor drives as per EN50598-2 were developed and experimental tests were performed on the test motor to further investigate the influence of external factors like measurement uncertainty of individual equipment and the uncertainty estimation of measured efficiency values for CDM and PDS. In addition to the uncertainty analysis, the tests allow for precise evaluation of the feasibility of the test procedures described in the standard, especially in the case of motor drive testing. The impact of this work can be summarized in the development of a set of guidelines by which a general procedure for measurement of efficiency and compliance of the same could be checked. The necessary instrumentation and software tools for automated sequencing of motor and drive testing was developed and proposed method of uncertainty estimation was implemented online so that the efficiency of measurement device i.e. CDM or PDS and its acceptance based on estimated uncertainty could be calculated online. In the end, the paper provides specific guidelines on how the EN50598-2 could be updated to make it more applicable by most of the test laboratories.

References

[1] «Ecodesign» European Commission, [Online]. Available: http://ec.europa.eu/growth/industry/sustainability/ecodesign/index_en.htm.

[2] Directive 2005/32/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Ecodesign requirements for energy-using products, 6 July 2005.

[3] Commission Regulation (EU) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC with regard to ecodesign requirements for electric motors, 2009.

[4] Rotating electrical machines – Part 1: Rating and performance, IEC 60034-1, Edition 12, February 2010.

[5] Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles), IEC 60034-2-1, Edition 2, May 2014.

[6] Rotating electrical machines – Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors, IEC 60034-2-3, Edition 1, November 2013.

[7] Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code), IEC 60034-30-1, Edition 1, March 2014.

[8] Ecodesign for power drive systems, motor starters, power electronics & their driven applications - Part 2: Energy efficiency indicators for power drive systems and motor starters, EN 50598, Dec. 2014.

[9] Evaluation of measurement data — Guide to the expression of uncertainty in measurement, Ed. 1, JCGM 100:2008, Sep. 2008.

[10] M. Doppelbauer, «Accuracy of the Determination Of Losses and Energy Efficiency of Induction Motors by the Indirect Test Procedure,» in EEMODS 2011, Washington, USA, 2011.

[11] R. Kanchan, R. Chitroju and F. Gyllensten, «Evaluation of efficiency measurement methods for sinusoidal and converter fed induction motors,» in EEMODS 2013, Rio de Janeiro, Brazil, 2013.

[12] NASA Measurement Quality Assurance Handbook - Annex 3, Measurement Uncertainty Analysis Principles and Methods, NASA-HDBK-8739.19-3, 2010.

Quantitative Analysis and Finite Element Modeling for Indirect Efficiency Determination of Permanent Magnet Machines

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Abstract

For high-power permanent magnet synchronous machines, the efficiency is usually in the range above 95 %. As previously introduced, a new approach of indirect efficiency determination by the summation of individual losses (current-depending and additional load losses, iron losses, and additional losses caused by inverter feeding) is examined.

In this paper the attention is turned to a quantitative analysis by means of measurement uncertainty of the measurement chain in use. On the electrical side, there is the voltage, current, power and power factor determination, while mechanically the torque transducer is significant.

Additionally, further measurements were done with a permanent magnet machine with distributed winding (84 kW at 2500/min). Like for a previously examined machine with distributed winding in the same power range, there is a good agreement between direct and indirect efficiency values for sine wave and for inverter operation. From the distinct measurement points, a loss characteristic over the whole base-speed range is calculated via interpolation.

In a third step, finite element models of the investigated machine were designed. This allows a comparison between the measurement data and numerical transient time-step simulations for the performed experiments: load test, no-load test, and removed rotor test.

Background

In [1] a new method for indirect efficiency determination of permanent magnet synchronous machines (PMSM) by summation of individual losses is introduced. The method consists of a separation of the loss components into voltage- und current-depending losses with help of the equivalent circuit of a PMSM with no difference between the d- and q-axis inductance.

Voltage-depending losses

The voltage-depending losses (iron losses, additional losses due to inverter feeding) are determined during the generator open-circuit [2] and the motor no-load experiment and then recalculated for the specific load case. The iron losses are represented by the iron resistance R_{Fe} in the equivalent circuit per phase (Fig. 18). For a given speed and stator frequency they depend on the square of the magnetic flux linkage and therefore on the square of the reactance voltage U_{x}.

The additional losses due to inverter feeding $P_{\mathrm{e,in,0,ad}}$ are nearly load-independent and are determined as the difference of the total electrical no-load input power $P_{\mathrm{e,in,0}}$ and the fundamental input power $P_{\mathrm{e,in,0,1}}$. These losses depend on the modulation degree of the inverter and can be calculated for load operation via the stator voltage U_{s} [1].

Current-depending losses

The current-depending losses $P_1 = P_{Cu,s} + P_{s,ad}$ (stator ohmic losses $P_{Cu,s}$ and additional load losses due to current displacement $P_{s,ad}$) are determined at the removed rotor experiment [2], where the stator is fed by sinusoidal current I_s with a given frequency f_s. The frequency is chosen according to the desired synchronous speed n at load operation with (1), where p is the number of pole pairs.

The current-depending losses are represented by the resistance $R_s + \Delta R_s$ in the equivalent circuit. As the resistance depends on the stator winding temperature, the temperature has to be monitored to acquire the correct losses. The small amount of iron losses $P_{Fe,B}$ during the removed rotor experiment can be calculated in the same manner as for load operation via $P_{Fe,B} \sim U_x^2$ [1].

$$f_s = \frac{n}{p} \tag{1}$$

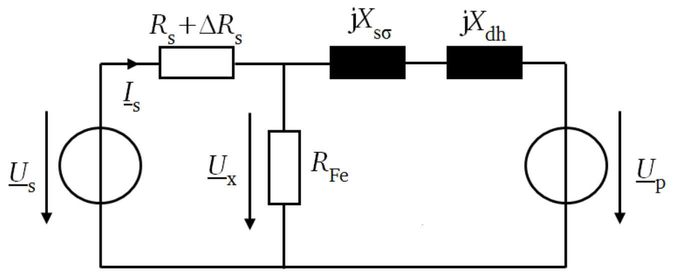

Fig. 1: Electrical equivalent circuit per phase of a synchronous machine with identical reluctance in d- and q-axis ($X_d = X_{s\sigma} + X_{dh} = X_q$) [1]

Friction and windage losses

The friction and windage losses P_{fr+w} occur already at no-load and cannot be separated via measurement. To minimize the error in the iron loss calculation, P_{fr+w} should be calculated by theoretical formulas [1, 6].

Efficiency

With knowledge of the mentioned loss components, the indirect efficiency can be calculated. As the current-depending losses, the iron losses, and the friction and windage losses are appear already at sinusoidal feeding, it is possible to define the efficiency at "sine wave operation" (**Fig. 2**) [1].

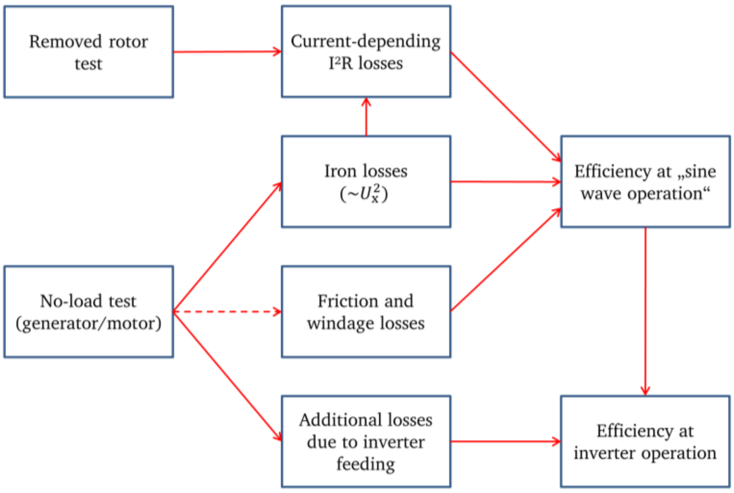

Fig. 2: Measurement chain for the indirect efficiency determination as described in [1]

By consideration of the additional losses due to inverter feeding, the total efficiency is determined according to (2) and (3):

- Motor operation: $$\eta_{\text{Mot}} = \frac{3U_s I_s \cos\varphi_s - P_{\text{Fe}} - P_1}{3U_s I_s \cos\varphi_s + P_{\text{e,in,0,ad}}} \quad (2)$$

- Generator operation: $$\eta_{\text{Gen}} = \frac{3U_s I_s \cos\varphi_s}{3U_s I_s \cos\varphi_s + P_{\text{Fe}} + P_1 + P_{\text{e,in,0,ad}}} \quad (3)$$

Here $\boldsymbol{P_{e,1} = 3U_s I_s \cos\varphi_s}$ is the fundamental electrical power with the stator voltage $\boldsymbol{U_s}$, the stator current $\boldsymbol{I_s}$, and the power factor $\boldsymbol{\cos\varphi_s}$.

The direct efficiency determination at inverter operation, on the other hand, is always a measurement of the input and output power, where the efficiency is calculated with (4) and (5):

- Motor operation: $$\eta_{\text{Mot}} = \frac{P_{\text{m,out}}}{P_{\text{e,in}}} \quad (4)$$

- Generator operation: $$\eta_{\text{Gen}} = \frac{P_{\text{e,out}}}{P_{\text{m,in}}} \quad (5)$$

$P_{\text{e,in}}$ and $P_{\text{e,out}}$ denote the total electrical input and output power, $P_{\text{m,in}}$ and $P_{\text{m,out}}$ is the mechanical input and output power $P_{\text{m}} = 2\pi \cdot n \cdot M$.

Measurement uncertainty

As each measurement contains an amount of uncertainty, these quantities should be investigated, when comparing the direct and indirect efficiency determination. For the mentioned experiments the following instruments are used (Table I):

Table I: Measurement instruments and error limits (RD = reading) [3, 4]

Quantity	Device	Error limit	Full scale (FS)
Voltage U	Fluke NORMA 5000	0.05 % FS + 0.05 % RD	1000 V
Current I		0.2 % RD	-
Phase angle φ		0.005° + 0.005° / kHz	-
Torque M	HBM T30FNA	0.2 % FS	500 Nm

The uncertainty of the electrical power measurement is calculated according to the specifications [3] via

$$u_P = \frac{2}{\sqrt{3}} \cdot \sqrt{u_U^2 + u_I^2 + u_\varphi^2} \quad , \tag{6}$$

where u_U, u_I, and u_φ are the respective uncertainties of the voltage, the current, and the phase angle.

For all further combined quantities the law of propagation of uncertainties is applied [5]:

$$u_c = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)} \tag{7}$$

The term $u(x_i)$ represents the uncertainty of the measurement quantity x_i.

In order to get the maximum agreement between the no-load and the rated load flux linkage, the no-load measurements are carried out after the related load experiments. This requires that the torque transducer is rated to the maximum allowed torque. Therefore the uncertainty is high during the generator open-circuit experiment, as there are relatively small torque values.

On the other hand, at the motor no-load experiment, only electrical quantities are measured. This leads to a reduced uncertainty, if the voltage is not too low. This effect will be shown at the measurement section, where the iron losses are determined by both the generator open-circuit test and the motor no-load test.

For the removed rotor test, the most significant losses are the current-depending losses. Therefore, mainly the uncertainties of the electrical measurement system are relevant, except for the case of high stray inductances, where the iron losses are higher. Then the assumptions concerning the generator/motor no-load are also applicable.

At the direct measurement for comparison, the uncertainty rises with lower torque values, as the dominant error limit of the torque transducer is related to the full scale.

The uncertainties in the speed and temperature measurement are not considered in the calculation.

Measurements

Test bench

In [1] the new method shows the best agreement between direct in indirect efficiency determination for a permanent magnet machine with distributed stator winding and surface-mounted rotor magnets. For this reason another PMSM with similar configuration was chosen for further measurements. To be consistent to the three previously examined machines, this new machine is named *Machine 4*.

Table II: Basic parameters of Machine 4

Rated power P_N	84 kW
Rated Torque M_N	320 Nm
Rated speed n	2500 min^{-1}
Rated voltage U_{sN} per phase	230 V
Rated current I_{sN}	148 A
Stator resistance $R_{s,20\,°C}$	16.4 mΩ
Synchronous inductance L_d	0.44 mH
Slots per pole and phase q	2
Air gap width δ	1.0 mm
Winding type	Single layer
Slot	Semi-closed
Tooth width	Constant
Rotor magnets (NdFeB)	Surface
Cooling system	External fan

Machine 4 has $2p = 8$ poles, a nominal speed of 2500 min^{-1} and a rated torque of 320 Nm, which gives a rated mechanical power of 84 kW. The machine parameters are shown in Table II.

At the test bench, the machine is fed by a voltage source inverter with a DC-link voltage of 600 V at a switching frequency of $4\,\mathrm{kHz}$. A DC railway motor is used as load (**Fig. 3**). This setup allows a 4-quadrant operation and a comparison of direct and indirect measurements.

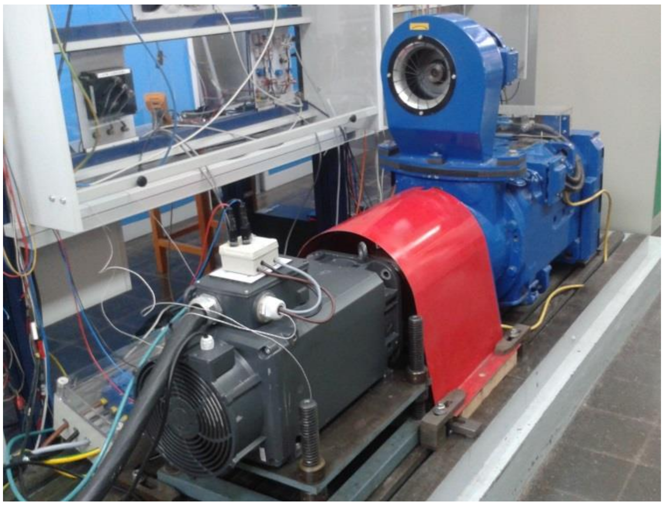

Fig. 3: Test bench with Machine 4 (on left-hand side) and a DC railway motor as load

Results

a) Generator open-circuit experiment

At the generator open-circuit experiment the no-load voltage U_0 and the no-load losses $P_{\mathrm{Fe,0}} + P_{\mathrm{fr+w}}$ are determined after thermal steady-state operation at rated load to get the best accordance of the no-load and load magnet temperature (Fig. 4). As expected, the voltage has a linear slope. The no-load losses are rising with an exponent between 1 and 2, as they consist mainly of eddy current losses and hysteresis losses in the iron sheets. The air friction losses were roughly calculated to a value of smaller than 10 W due to the rather small rotor diameter and speed and are therefore negligible.

a) b)

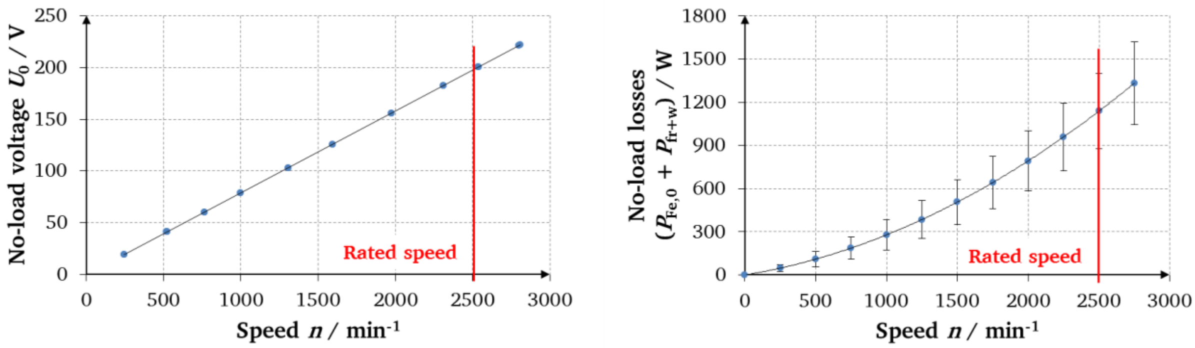

Fig. 4: Measured a) no-load voltage U_0, b) no-load losses $P_{\mathrm{Fe,0}} + P_{\mathrm{fr+w}}$ of Machine 4 at the generator open-circuit experiment

As described in the first paragraph, the measurement uncertainty of the mechanical system is very big at the open-circuit test. This generates also a significant uncertainty of the calculated indirect efficiency, which will be shown subsequently.

b) Motor no-load experiment

To cope with that problem, the iron losses may also be determined during the motor no-load experiment by consideration of the fundament of the electrical input power [1]

$$P_{\mathrm{e,in,0,1}} = P_{\mathrm{Fe,0}} + P_{\mathrm{fr+w}} + 3R_{\mathrm{s}} \cdot I_{\mathrm{s0}}^{2} \quad . \tag{8}$$

In this case only the smaller uncertainty of the electrical system remains.

Fig. 5a shows the measured losses during the motor no-load experiment. The fundamental input power is about 7 % lower. This leads to a slightly increased efficiency, when the iron losses at load are calculated via the motor no-load losses. The I²R-losses in the stator winding $3R_{\mathrm{s}} \cdot {I_{\mathrm{s}}}^{2}{}_{0}$ and the friction and windage losses $P_{\mathrm{fr+w}}$ are again negligibly small.

a) b)

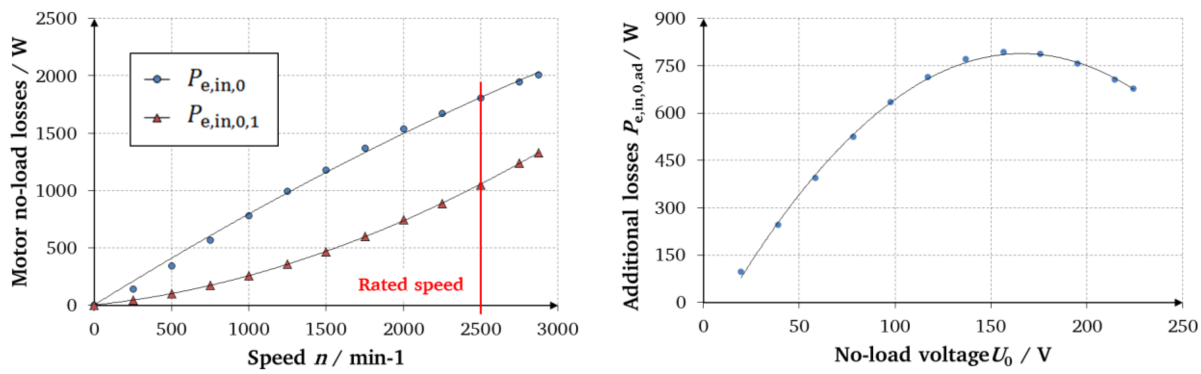

Fig. 5: a) Measured total losses $P_{\mathrm{e,in,0}}$ and fundamental losses $P_{\mathrm{e,in,0,1}}$ at the motor no-load experiment, b) Measured additional losses due to inverter feeding as difference between the total and fundamental no-load losses over the fundamental no-load voltage U_0

The difference of the total and the fundamental electrical input power gives the additional losses due to inverter feeding $P_{\mathrm{e,in,0,ad}} = P_{\mathrm{e,in,0}} - P_{\mathrm{e,in,0,1}}$, which depend on the modulation degree of the feeding inverter and therefore on the voltage (Fig. 4b). The small uncertainty of the measured electrical power is not displayed in the figure. The relative error at rated speed is about 0.4 %.

c) Removed rotor experiment

In the next step, the removed rotor experiment is performed to determine the current-depending losses in the stator winding. The stator is fed by a frequency-variable sinusoidal current source. As the input power $P_{\mathrm{e,in,B}}$ is the sum of the I²R losses $P_1 = P_{\mathrm{Cu,s}} + P_{\mathrm{s,ad}}$ and a small amount of iron losses $P_{\mathrm{Fe,B}}$ due to the stray and bore field, the iron losses are estimated by recalculation via $P_{\mathrm{Fe,0}}$ and $U_{\mathrm{x,B}}$ according to [1]. The remaining loss component $P_1 = P_{\mathrm{e,in,B}} - P_{\mathrm{Fe,B}}$ are shown in Fig. a. There is an increase of about 9 % due to current displacement in the stator conductors at the rated frequency $f_N = 166.7\ \mathrm{Hz}$. This is shown as the increase of the AC stator winding resistance in Fig.6b.

The uncertainty of the measured ohmic and additional load losses is nearly independent of how the no-load losses are determined, as the amount of iron losses during the removed rotor experiment is very small for Machine 4. Due to the rather small stator voltage, the uncertainty of the current-depending losses at rated current is about $1 \dots 2\ \%$.

a) b)

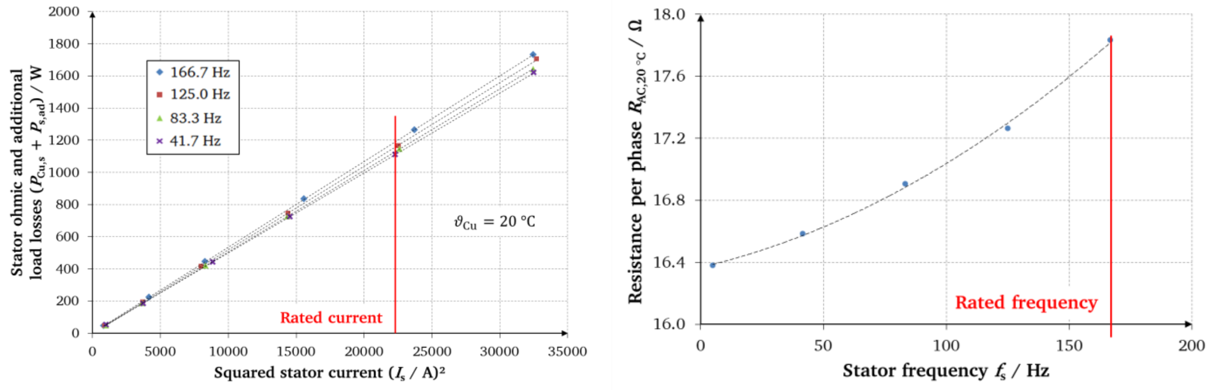

Fig. 6: a) Measured ohmic and additional load losses $P_{Cu,s} + P_{s,ad}$ at the removed rotor test for the stator of Machine 4; Converted to the winding temperature $\vartheta_{Cu} = 20\ °C$, b) Increase of the AC resistance per phase $R_{AC,20°C} = R_s + \Delta R_s$ over the stator frequency f_s

d) Efficiency at load

From the mentioned loss components, the indirect efficiency is determined for inverter operation. For comparison, direct measurements were performed in the range of 25 % to 125 % of rated torque and 25 % to 100 % of rated speed. Fig. 7 + 8 show the different efficiency values for motor and generator operation at $n = n_N/2 = 1250\ \mathrm{min}^{-1}$ and $n = n_N = 2500\ \mathrm{min}^{-1}$. There is a good accordance between the direct and indirect values for both motor and generator operation. The direct values are slightly higher for motor operation.

a) b)

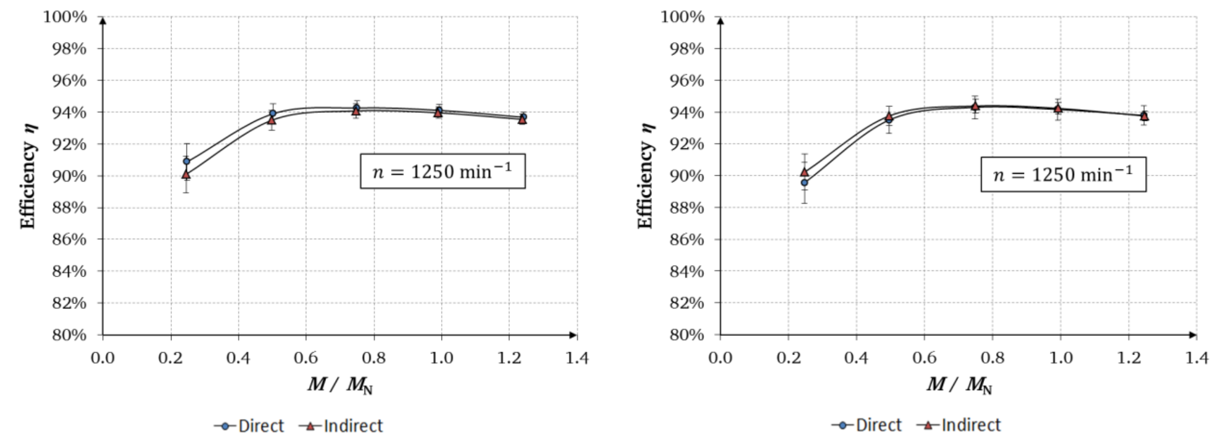

Fig. 7: Measured direct and indirect efficiency over the torque M at speed $n = n_N/2 = 1250\ \mathrm{min}^{-1}$, a) Motor operation, b) Generator operation

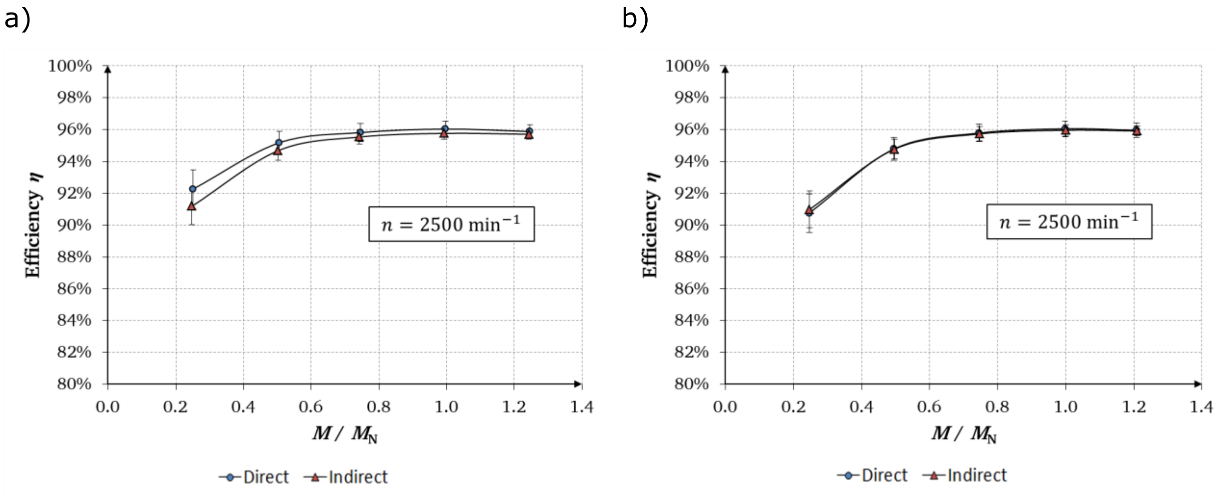

Fig. 8: Measured direct and indirect efficiency over the torque like Fig. , but at speed $n = n_{\mathrm{N}} = 2500\ \mathrm{min}^{-1}$

In order to compare the calculated values over the whole torque and speed range, an efficiency map is created by means of the proposed method in [7], which consists of an interpolation of the losses from 7 operating points. The result is shown in Fig. 9 for motor operation. Like noticed before, the indirect efficiency values are slightly lower than the direct ones, but show an acceptable agreement.

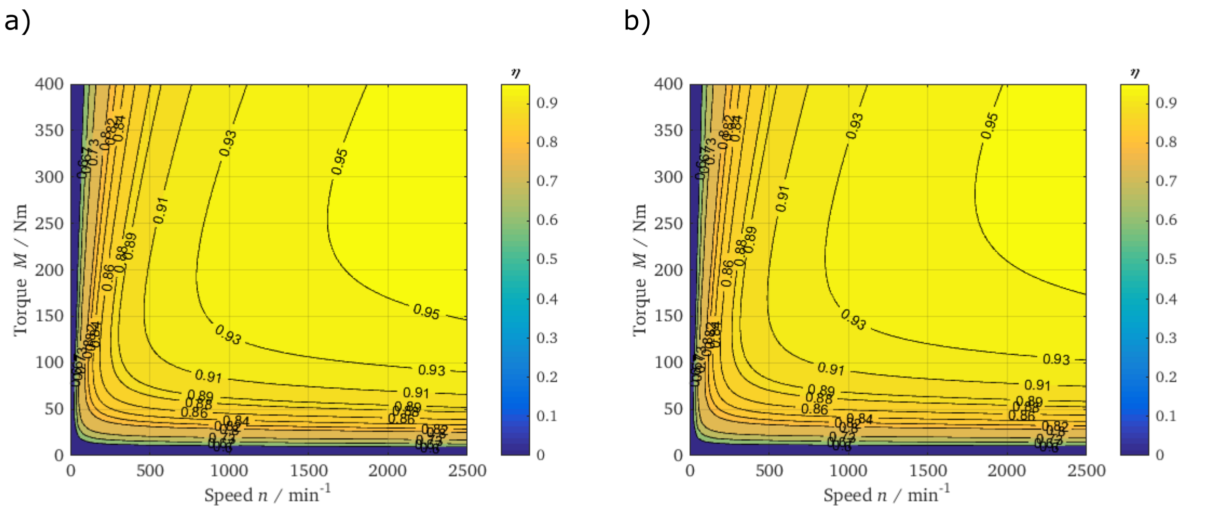

Fig. 9: Interpolated efficiency map of the measurement at motor operation, $M_{\mathrm{N}} = 320\ \mathrm{Nm}$, a) Direct efficiency, b) Indirect efficiency

Obviously, the direct measurement shows more uncertainty for lower torque values than for values near the rated torque. But as mentioned before, there is also a big influence of the no-load iron loss determination at the indirect efficiency. Therefore also the indirect efficiency values have an uncertainty of about $60\ \%$ of the direct values.

In order to increase the measurement accuracy, now the no-load losses and the respective iron losses at load are calculated just from the motor no-load experiment. The measurement uncertainty of the indirect efficiency can be significantly reduced, while the calculated efficiency values are close to the previous ones (Fig.10).

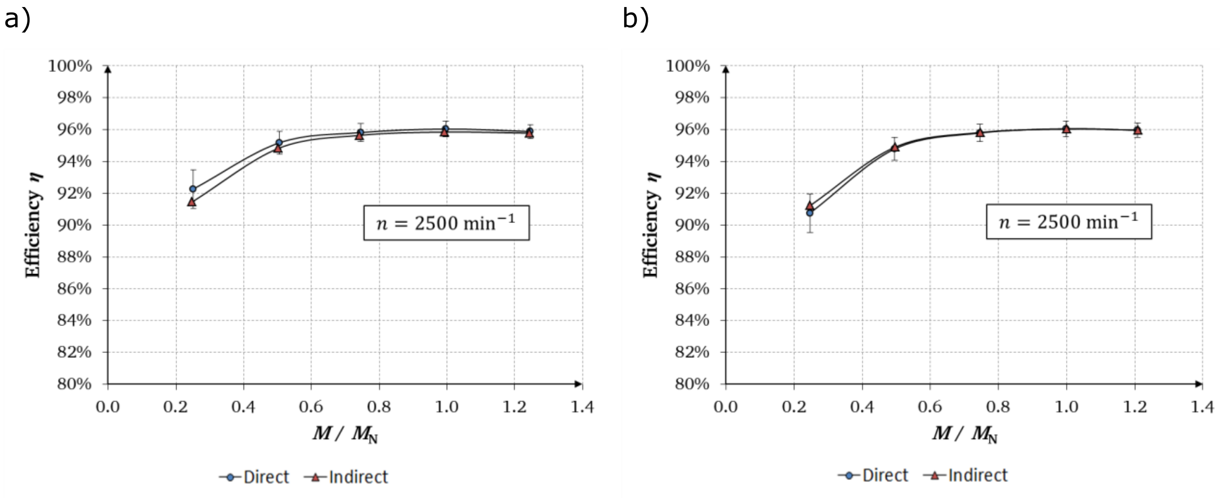

Fig. 10: Measured direct and indirect efficiency as Fig. 8, but with calculated iron losses from the motor no-load experiment

Finite element simulations

In order to evaluate the indirect efficiency determination method without any influence of measurement uncertainties, also transient time-step simulations were performed with JMAG®. The focus is set to the loss components at sine wave operation, i. e. all simulations were done with sinusoidal current feeding.

As not all details of Machine 4 are known, some parameters had to be estimated with help of the measured data.

To meet the correct no-load voltage of $U_0 = 197\ \mathrm{V}$ at the rated speed $n_\mathrm{N} = 2500\ \mathrm{min}^{-1}$ and warm machine according to Fig. 4a, the remanence flux density of the rotor magnets was chosen to $B_\mathrm{R} = 1.15\ \mathrm{T}$. The iron sheet material and loss data is set to SURA® M530-50A.

Due to symmetry, the model can be reduced to one pole-pair of the machine (Fig.). The stator winding is simplified to a massive conductor with switched-off eddy-current calculation, so that only iron losses are considered.

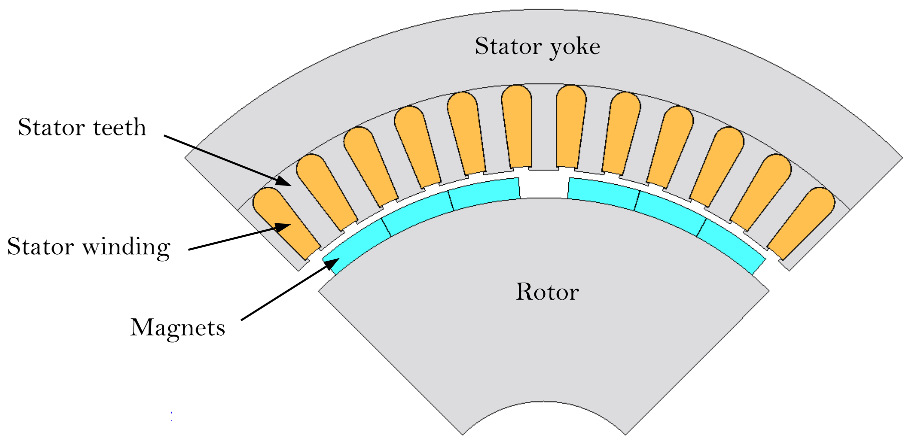

Fig. 11: One pole pair of the finite element model of Machine 4

Iron losses

a) No-load operation

At first, the iron losses during generator no-load operation $P_{\mathrm{Fe,0}}$ are calculated via post-processing of previous transient no-load simulations (Fig. 12). The iron losses are decomposed into eddy current losses ($\sim f_s^2$) and hysteresis losses ($\sim f_s$). The losses occur only in the stator yoke and teeth, the rotor iron losses are nearly zero.

a) b)

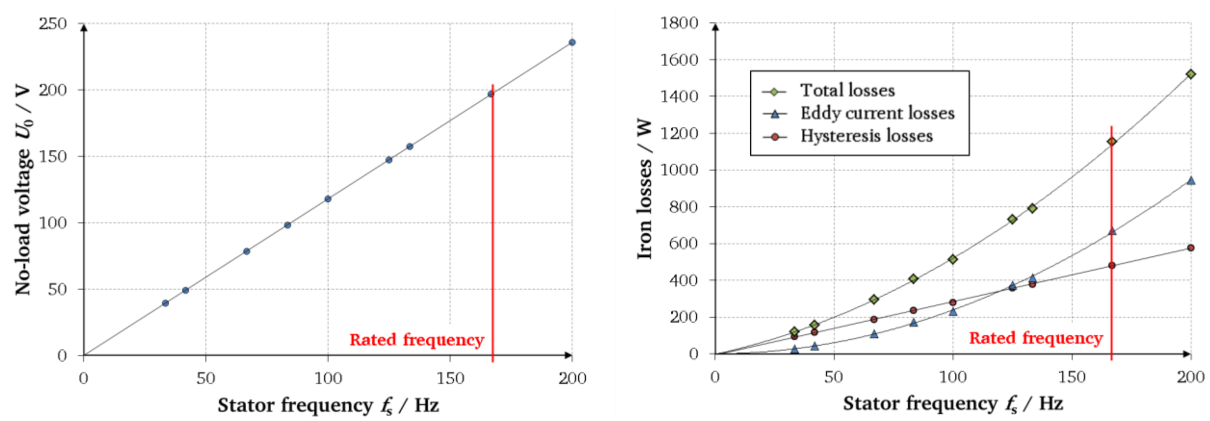

Fig. 12: Calculated a) no-load voltage U_0, b) no-load iron losses $P_{\mathrm{Fe,0}}$

b) Load operation

In the second step, the load operation of the machine was simulated for $n = n_{\mathrm{N}} = 2500\,\mathrm{min}^{-1}$ and $n = \frac{n_{\mathrm{N}}}{2} = 1250\,\mathrm{min}^{-1}$ at motor and generator q-current operation. According to the equivalent circuit (**Fig. 1**, the reactance voltage U_{x} can be calculated. With help of the no-load iron losses $P_{\mathrm{Fe,0}}$ and the no-load voltage U_0 the iron losses at load $P_{\mathrm{Fe,calc}}$ are determined like in [1] with (9):

$$P_{\mathrm{Fe,calc}} = P_{\mathrm{Fe,0}} \cdot \left(\frac{U_{\mathrm{x}}}{U_0}\right)^2 \quad . \tag{9}$$

For comparison, the iron losses at load are calculated directly via post-processing by JMAG. These losses are named $P_{\mathrm{Fe,sim}}$ here. The average of the ratio between $P_{\mathrm{Fe,calc}}$ and $P_{\mathrm{Fe,sim}}$ for different load cases shows a good accordance within the limits of numerical tolerances (Fig. 13). The average value is about $2 \ldots 3\ \%$ higher than unity for motor operation, as well as for generator operation, i. e. the losses are slightly overestimated.

a) b)

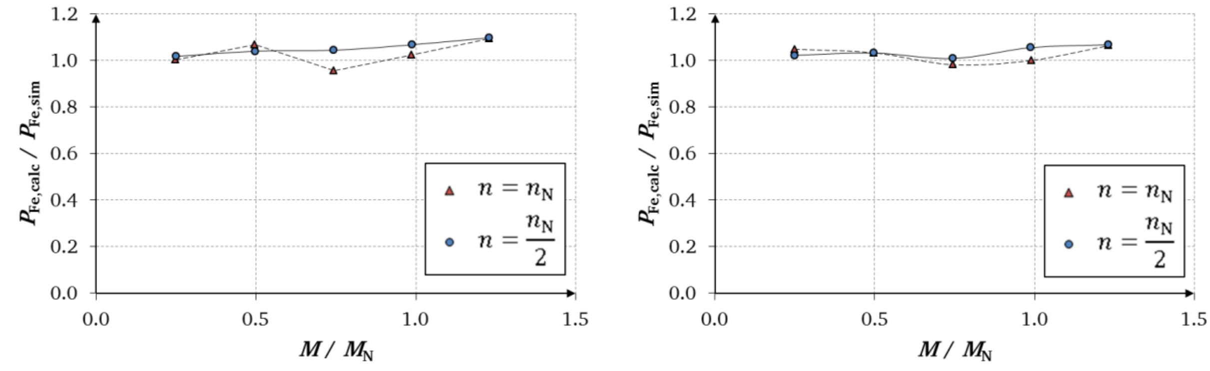

Fig. 13: Ratio of calculated iron losses $P_{Fe,calc}$ and simulated iron losses $P_{Fe,sim}$ at load simulation for $n = n_N = 2500\ min^{-1}$ and $n = n_N/2 = 1250\ min^{-1}$, a) Motor operation, b) Generator operation

c) Removed rotor

For determination of the iron losses during the removed rotor experiment, the procedure is similar. As there are no rotating parts any more, the variable parameters are now the stator frequency f_s and the stator current I_s.

Again, the iron losses $P_{Fe,B,calc}$ are calculated via the (small) reactance voltage with (9) and for comparison $P_{Fe,B,sim}$ via post-processing from the simulation (index "B" for "bore field"). The ratio shows, that the losses are under-estimated (Fig. 14). For rated stator frequency $f_s = f_{sN} = 166.7\ Hz$ the average ratio is about 0.9. As the absolute loss values are rather low ($< 3\ \%$ of the total losses), the influence during the removed rotor experiment is small.

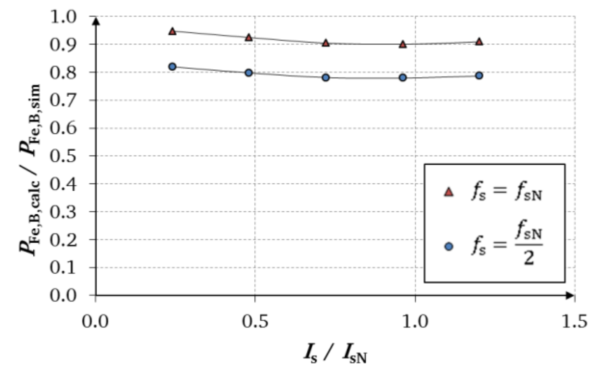

Fig. 14: Ratio of calculated iron losses $P_{Fe,B,calc}$ and simulated iron losses $P_{Fe,B,sim}$ at the removed rotor simulation for $f_s = f_{sN} = 166.7\ Hz$ and $f_s = f_s/2 = 83.3\ Hz$

I²R losses

To analyze the influence of the current-depending losses at the removed rotor experiment, the model is extended by replacing the massive conductor by individual single conductors. The machine has a round-wire winding with a number of turns per coil of $N_c = 6$ and a number of parallel sub-conductors of $a_i = 16$. The wire diameter is $d_{Cu} = 1.0$ mm. Fig. 15 shows the estimated arrangement of the sub-conductors. Each conductor set with the same color is connected in parallel. The mesh size in the conductors is $0.1\ mm$.

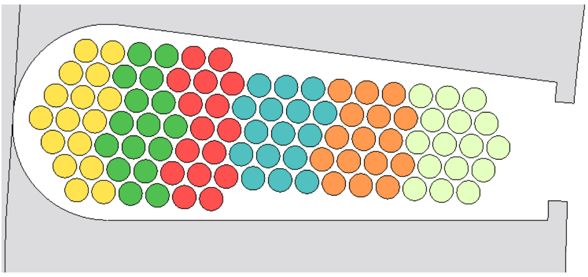

Fig. 15: Extended model of the stator slot with $N_\mathrm{c} = 6$ turns per coil and $a_\mathrm{i} = 16$ parallel sub-conductors

a) 2nd order eddy current losses

At first, only 2nd order eddy current are allowed, i. e. the parallel connections are artificially disconnected. As the diameter of the individual conductors is very small compared to the penetration depth d_E, the loss increase over the frequency is also small [8]. At the rated frequency $f_\mathrm{s} = 166.7\,\mathrm{Hz}$ the increase of the AC resistance is about $k_\mathrm{R} = 1.02$ at $d_\mathrm{Cu}/d_\mathrm{E} \approx 0.2$.

b) 1st order eddy current losses

As the AC resistance increase at the removed rotor experiment (**Fig. 6**) is about $9\,\%$, also 1st order eddy current losses due to circulating currents in the parallel conductors have to be considered. This leads to the problem, that for round wire windings it is hard to determine the exact position of the sub-conductors. Also a random transposition along the axial length and the winding overhang cannot be considered by a 2D calculation. For this reason the following results show approximately the best-case, if no transposition and twisting is applied. The current limiting influence of the winding overhang is approximated by additional resistances in the external circuit of the FEM software.

The simulations were carried out at rated current $I_\mathrm{s} = 148\,\mathrm{A}$ for different stator frequencies. For rated frequency the z-component of the current density J_z is shown in Fig. 16 at the current maximum in the related phase. Due to the parallel connection, the current displacement is acting like for a massive conductor, which leads to additional losses in the stator winding for this case at maximal tangential slot flux linkage (= slot stray flux linkage). For this configuration, the increase is about $k_\mathrm{R} = 1.07$ at rated frequency and thus lower than the measured value $k_\mathrm{R} = 1.09$.

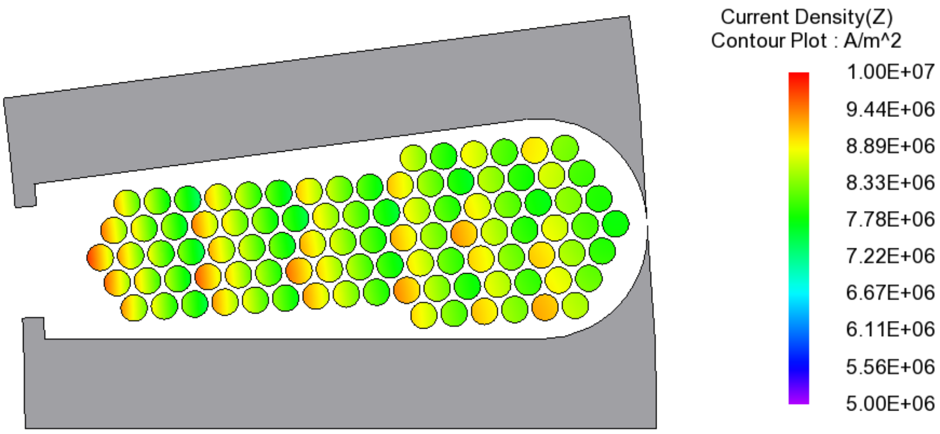

Fig. 16: Current density J_z in the sub-conductors at the current maximum and rated frequency $f_\mathrm{s} = 166.7\,\mathrm{Hz}$

The calculated losses $P_{1,\mathrm{FEM}}$ and the measured losses P_1 are shown in Fig. 17.

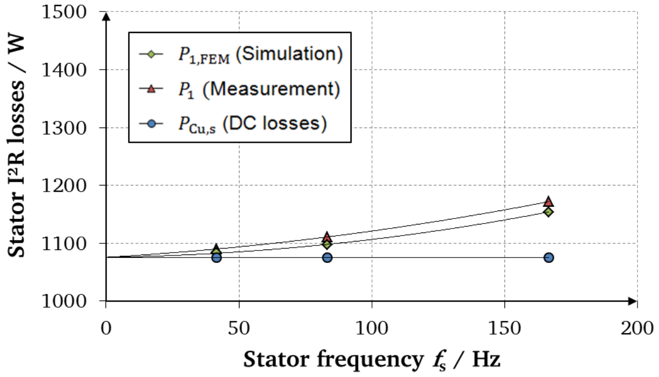

Fig. 17: Simulated and measured stator I²R losses for rated current $I_s = 148\ \mathrm{A}$ and rated frequency $f_s = 166.7\ \mathrm{Hz}$

Conclusion

As a new method of indirect efficiency determination of permanent magnet synchronous machines was introduced, further measurements are carried out on a 84 kW industry drive with distributed stator winding. The indirect efficiency is calculated with help of no-load experiments to determine the voltage-depending losses and a removed rotor experiment for the current-depending losses. By means of measurement accuracy, it is suggested to determine the iron losses at the motor no-load test with warm machine, or at the generator open-circuit test with a precise torque transducer at low torque values, to minimize the measurement uncertainty. The calculated efficiency values are compared to input/output measurements and show a good accordance especially at the rated torque for all considered speed values.

In addition, finite element models of the examined machine were created. The comparison of the directly calculated iron losses at load and the indirectly calculated losses with help of the no-load losses and the reactance voltage shows a good accordance. At the removed rotor simulation, the iron losses are $10 \ldots 20\ \%$ higher than expected, however the absolute error is small. As the machine has a round wire winding, the exact wire distribution is unidentified. A best-case simulation of the eddy current losses shows, that the measured additional load losses are reasonable.

References

[1] B. Deusinger, A. Binder, "Indirect Efficiency Determination of Permanent Magnet Synchronous Machines for Sine Wave and Inverter Operation", *Energy Efficiency in Motor Driven Systems (EEMODS 2015)*, 15-17 Sept., Helsinki, Finland, 14 pages

[2] *IEC/EN 60034-4: Rotating electrical machines - Part 4: Methods for determining synchronous machine quantities from tests*, Geneva, Switzerland, 2009

[3] *NORMA 4000/5000 Power Analyzer, Operators Manual*, Fluke Corporation, Everett (Washington), USA, 1999

[4] *Technische Daten T30 FNA*, Hottinger Baldwin Messtechnik, Darmstadt, Germany, http://www.hbm.de

[5] *JCGM 100:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement*, 1st corrected version, Geneva, Switzerland, 2010

[6] T. Lu, "Weiterentwicklung von hochtourigen permanenterregten Drehstromantrieben mit Hilfe von Finite-Elemente-Berechnungen und experimentellen Untersuchungen", Ph.D. thesis, Technische Universität Darmstadt, Shaker Verlag, Aachen, Germany, 2004

[7] M. Doppelbauer, "Interpolation Procedures for the Determination of Losses and Energy Efficiency of Electrical Machines", *Energy Efficiency in Motor Driven Systems (EEMODS 2015)*, 15-17 Sept., Helsinki, Finland, 13 pages

[8] J. Pyrhoenen, T. Jokinen, V. Hrabovcová, *Design of rotation electrical machines*, John Wiley & Sons, Chichester, United Kingdom, 2008

5 DRIVERS

High Efficiency Motor Controller Based on Double-sided Cooling IGBT Module and Active Gate Driver Technique

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Zhuzhou CRRC Times Electric Co., Ltd, Hunan, China; Dynex Semiconductor Ltd, Lincoln, U.K

Abstract

A highly integrated and high efficiency motor controller has been introduced in this paper. The controller is based on a double-sided cooling IGBT module that is packaged with latest 650V/600A trench field-stop IGBT device. With the double-sided cooling structure, double-sided planar bonding is realized which eliminates the traditional aluminium wire bonds, and as the results, greatly improves power cycling capability and long-time reliability for the developed IGBT module. In addition, double-sided cooling technic introduces a much bigger thermal exchanging area for IGBT dies, which helps to reduce the thermal resistance to about 77% of traditional single-sided cooling IGBT module. Furthermore, an active gate driving technic is developed in this work which utilizes di/dt control and decoupling of turn-on and turn-off processes control. Power losses of IGBT device during switching have been greatly reduced. Utilized with the mentioned advanced techniques, the developed motor controller achieved operation with 450V battery voltage and output 450Arms phase current, which enlarges the motor working area when is compared with traditional 400V/400Arms controllers. High efficiency (>95%) with wide area and vertical efficiency contour lines in the efficiency map of controller is realized, promising an extended driving range for the vehicle. With the high heat dissipation performance and reduced power losses, a power density of 27.3kW/L has been realized for the controller, which leads to a simplification of powertrain system integration.

1. Introduction

The rapid growth of electric vehicle such as Hybrid Electric Vehicle (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), pure Electric Vehicles (EVs) and Fuel Cell electric Vehicles (FCVs) brings a huge opportunity for the power semiconductor industry. On the other hand, much higher design requirements from the electric vehicle including high power density, high reliability and lower cost are also raised for the power electronics system [1]. It is becoming more and more difficult to meet these requirements with traditional IGBT module packaging technologies such as single-sided cooling, aluminium wire bonds etc. Novel IGBT module and motor controller technology were reported to achieve high temperature operation and high reliability [2]-[4]. Among these, IGBT module based on double-sided cooling package is believed to be a solution for the next generation power modules to increase the power density of the power electronics system while delivering higher reliability and lower cost. Based on the double-sided cooling concept, this paper presents a newly developed IGBT module and a motor controller which are referred to as Integrated Power Module (IPM) and Integrated Power Unit (IPU) respectively. Test results are also included.

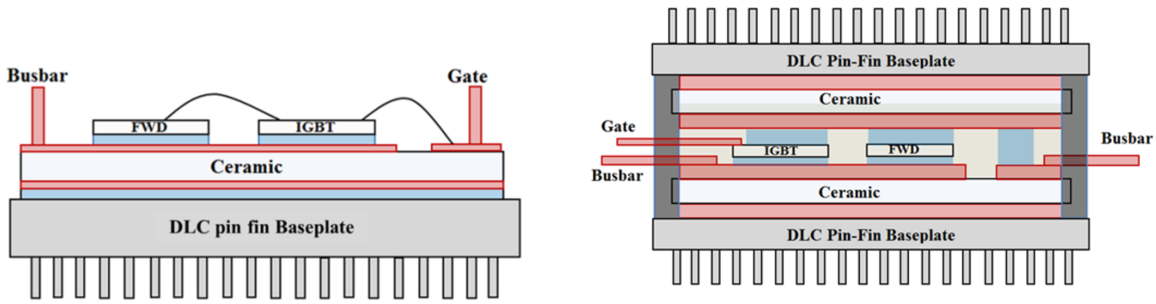
2. Double-sided Cooling IGBT Module

2.1. Single and Double-sided Cooling

As shown in **Fig. 1**, Direct Liquid Cooling (DLC) of IGBT module is now regarded as the mainstream package solution for electric vehicle. It eliminates Thermal Interface Material

(TIM) and external heatsink by integrating a DLC pin-fin baseplate. Thermal resistance from junction to cooling fluid is reduced to about half of that of the conventional indirect cooled module with TIM and heatsink [5].

With the DLC technique, IGBT module packages can be classified into two categories which are Single-sided Cooling (SSC) and Double-sided Cooling (DSC). **Fig. 1** shows the two different concepts. As illustrated in **Fig. 1**, power semiconductor dies in SSC module are usually interconnected by aluminium wire bonds that are required to flow high current and becoming the primary failure point from a reliability point of view. Meanwhile, heat generated by the dies is dissipated dominantly downward, which limits heat transfer efficiency and power handling capability of the IGBT module. While in the DSC concept, a metal plate is used to realize circuit interconnections and the traditional aluminium wire bonds are eliminated. Therefore, the reliability issues caused by the wire bonds are fundamentally resolved. Meanwhile, heat generated by dies is dissipated from both downward and upward in the DSC structure, which significantly enlarges heat exchange area for the IGBT dies. The DSC technique not only greatly reduces thermal resistance from junction to cooling fluid, but also introduces more even temperature distribution on these dies. All of these advantages will benefit a high reliability and high power density design of the power electronics system.

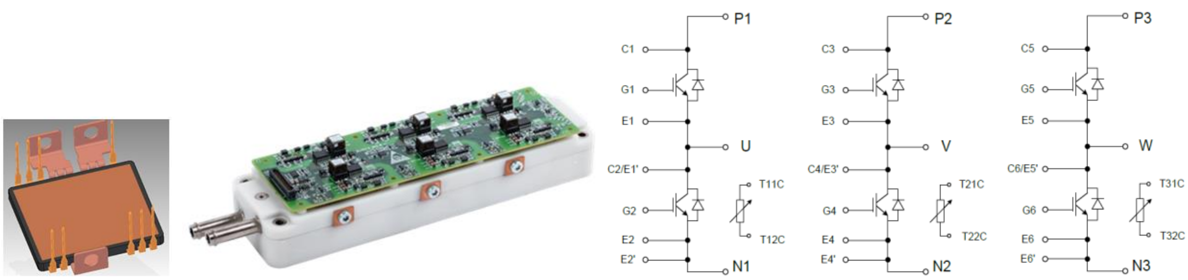


(a) **(b)**

Fig. 1 IGBT module packaging with DLC: (a) Single-sided cooling; (b) Double-sided cooling

2.2. Integrated Power Module

A 650V/600A DSC IGBT module with half bridge circuit has been developed as shown in **Fig. 2** (a) [6]. By using three of these DSC modules and two aluminium cold plates that are designed with Pin-Fin structure, an IPM is developed as shown in **Fig. 2** (b). With the integrated heatsink solution, there is no need for the customer to design the heatsink sealing, which makes it easier to develop a motor controller. Circuit diagram of the IPM is given in **Fig. 2** (c).



(a) (b) (c)

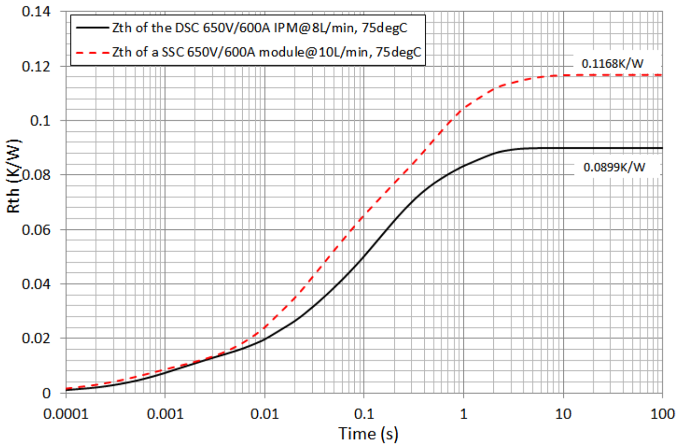
Fig. 2 A new designed DSC IGBT module: (a) Prototype of half bridge DSC module; (b) Prototype of developed IPM; (c) Circuit diagram of the IPM

Fig. 3 gives the key specifications of the IPM and the comparison of transient thermal performance between the developed IPM and an existing SSC 650V/600A IGBT module on the market. As indicated in **Fig. 2** (c), the developed IPM is a "6 in 1" IGBT module rate at 650V collector-emitter voltage and 600A DC continuous collector current at 75℃ fluid. Substrates made from Aluminium Nitride (AlN) are selected to form the insulation layer that is designed to withstand an AC 2500V isolation voltage. The substrates also provide lower thermal dissipation path and better Coefficient of Thermal Expansion (CTE) match for IGBT dies. Three Negative Temperature Coefficient (NTC) thermistors are integrated on substrates, which can be used to realize temperature monitoring in the controller system. With the DSC technique, thermal performance of the developed IGBT module has been greatly improved. **Fig. 3** (b) shows that the steady state $R_{th\ j\text{-}F}$ is 0.0899K/W for the DSC IPM compared with 0.1168K/W of the selected SSC 650V/600A rated module. A 23% reduction of $R_{thj\text{-}F}$ has been achieved. It should be pointed out that the cooling liquid flow rate for the DSC IPM is 8L/min while it is 10L/min for the comparison module. Reduced thermal impedance results in higher power handling capability, which will benefit a high utilization of the semiconductor devices, a high-power density and cost-effective design of the motor controller.

Type	Integrated Power Module
Circuit configuration	6 in 1 IGBT module with thermal monitoring
Rated voltage and current	650V/600A
Maximum temperature under switching conditions	150°C
Cooling method	Double-sided liquid cooling
$R_{th\ J\text{-}F}$, per IGBT *	0.0899K/W
$R_{th\ J\text{-}F}$, per Diode*	0.1455K/W
L_M, stray inductance	12nH
R_M, parasitic resistance	0.2mΩ
Weight	1000g

*50% water/50% ethylene glycol, 8L/min

(a)



(b)

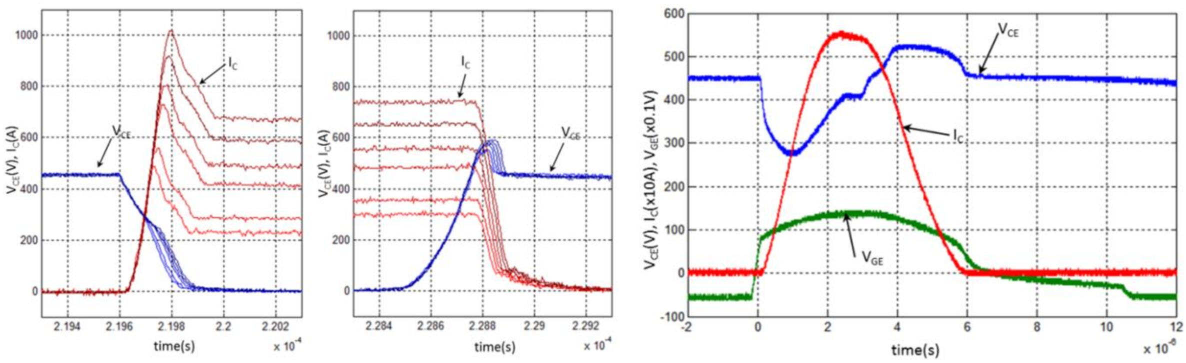
Fig. 3 Performance of the developed IPM: (a) Key specifications; (b) Comparison of transient thermal impedance with the a SSC 650V/600A module

A further benefit from the planar bonding is an extremely low parasitic resistance of 0.2mΩ that is achieved in DSC module, which is much lower than 0.8-1.0 mΩ of a similar traditional wire bonded module. Lower resistance loss not only helps to control the temperature rise within the module, but also delivers a higher efficiency for the whole controller. A longer mileage of the electric vehicle can be expected.

2.3. Active Gate Driver

IGBT gate driver plays a great role to the robustness and long life reliability of power electronics system. In addition to keeping IGBT switching in their safe operating area, the control of turn-off surge voltage and optimizing of switching losses are the two main objectives for a gate driver. An Active Gate Driver (AGD) technique has been developed dedicated for the developed IPM in this work which utilizes di/dt control and turn-on and turn-off processes decoupling control for the IGBT device.

In order to utilize the advanced di/dt control of IGBT, an extra auxiliary pin Ex' (x=1, 2… 6) is designed as shown in **Fig. 2** (c) with the common stray inductance split into two parts – the control part L_{Ee} and the additional part L_{EE}. The control part inductance L_{Ee} has been accurately designed by Finite Element Analysis (FEA) method to achieve a uniform design both for top and bottom switches. By using the specially designed Ex', di/dt control, turn-on and turn-off processes decoupling control of IGBT switching are achieved. **Fig. 4** gives turn-on, turn-off and short circuit test waveforms for the developed AGD and IPM. IGBT switching processes have been carefully and accurately optimized, and a stable, consistent and robust switching both for IGBT and Diode are achieved. Furthermore, in a traditional design, TVS diodes are usually used to clamp the surge voltage for protection at IGBT turn-off. These TVS diodes have a wide tolerance of breakdown voltage creating the need for more voltage margin for safety. In addition, they have high power dissipation while clamping at high voltage, which results in a common failure mode. All of these disadvantages have been eliminated in this work. With the AGD technique, surge voltage at IGBT turn-off can be stably controlled at 600V independent of turn-off current as shown in **Fig. 4** (b). This makes safe operation of the motor controller at 450V DC voltage for a 650V device achievable. **Fig. 4** (c) gives waveforms in type-1 short circuit test for the IPM at 450V battery voltage and 5.5kA short circuit current which is nearly 9 times of the module rated current. The test is repeatable, which not only proves the positive effectiveness of AGD technique but also gives evidence of design robustness of the IPM.

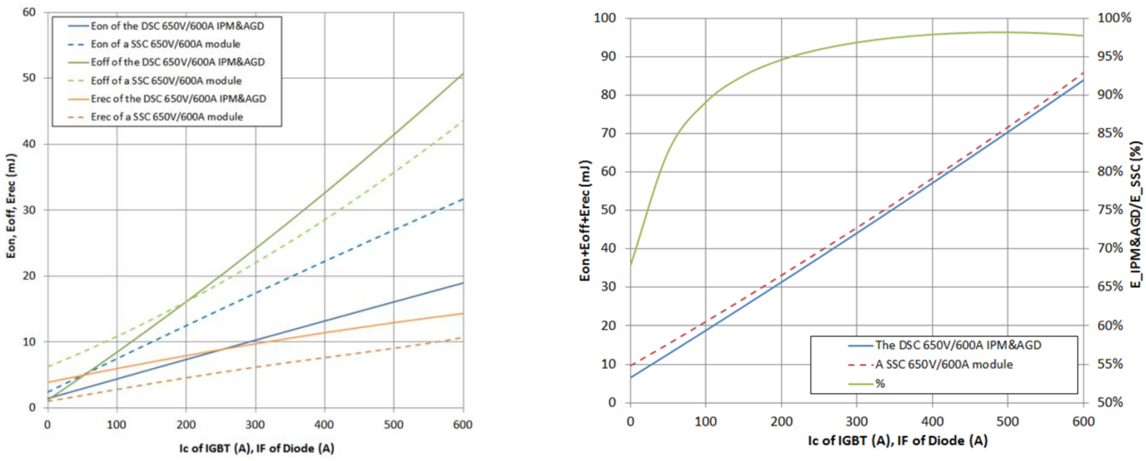


(a) (b) (c)

Fig. 4 IPM switching performance with AGD technology: (a) Turn-on test waveforms; (b) Turn-off test waveforms; (c) Type-1 short circuit test waveforms;

Reducing power losses of IGBT modules including conduction loss and switching loss is another key design objective. The conduction loss is related to the saturation voltage of IGBT and Diode. IGBT dies used in this IPM features the latest "Trench+Fieldstop" technology and are specified for automotive applications. Benefits of this technology including low saturation voltage and positive temperature coefficient help to reduce the conduction losses and parallel multiple dies easily. Furthermore, the low parasitic resistance mentioned above also helps to reduce the conduction loss generated by the circuit interconnections.

Switching losses are not only related to the switching characteristics of the IGBT devices, but also the power loop circuit parasitic inductance from the DC-Link capacitor to power dies. The former is more dependent on the gate driver technology and the performance of device itself. With the developed AGD technique, turn-on and turn-off processes are greatly optimized and switching losses have been reduced.



(a) (b)

Fig. 5 Switching losses comparison: (a) Eon, Eoff and Erec comparing respectively; (b) Sum value comparing of Eon, Eoff and Erec ;

Fig. 5 indicates the switching losses comparison between the DSC IPM and the compared SSC 650V/600A IGBT module at 400V DC voltage and 125°C junction temperature. Values of the comparison module are derived from its datasheet with 3.3Ω turn-on and 3.7Ω turn-off gate resistors. While values of DSC IPM losses are directly extracted from double pulse testing results with the AGD equipped. As the test condition used in the datasheet of comparison module is ideal and does not take the surge voltage suppression effects into consideration, the E_{off} at turn-off is lower than the one of DSC IPM as illustrated in **Fig. 5** (a). The comparison of sum value of all the switching losses is plotted in **Fig. 5** (b), which is clearly showing the advantages of using the DSC IPM and AGD technology especially at lower device current. Even the switching losses of this newly designed IPM are extracted from testing setup with components in the developed motor controller, it is still comparable with the datasheet values of the comparison module. This will contribute to a high efficiency motor controller design, which will be demonstrated in the following section.

3. Integrated Power Unit

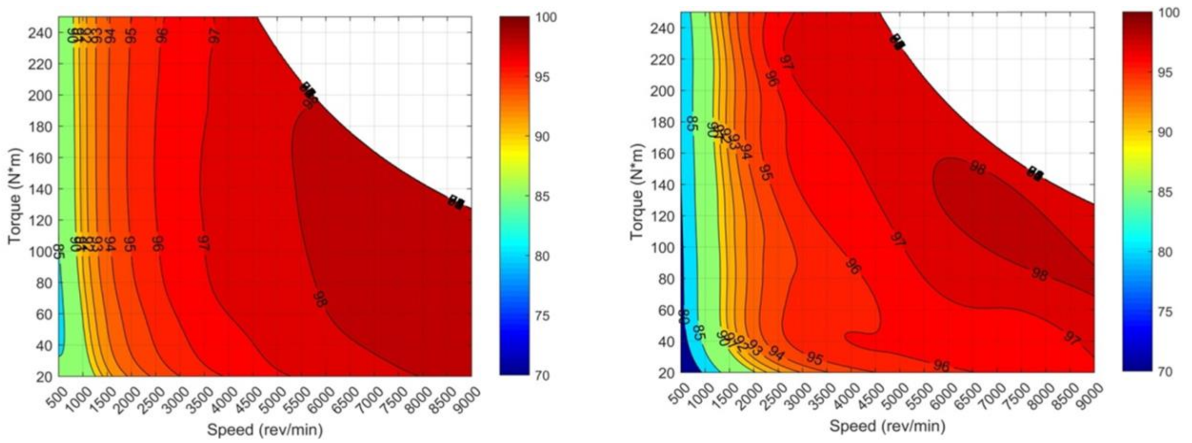
Based on the IPM and AGD, a motor controller named IPU 85-150 has been developed for the electric vehicle application which is shown in **Fig. 6**. It has achieved 150kW output peak power for 30 seconds at 450V battery voltage, 450Arms output phase current, 10kHz switching frequency, 85°C ambient temperature, 75°C cooling liquid and 8L/min liquid flow rate. 85kW continuous operation with 250Arms output phase current at the mentioned conditions is also achieved. Operation at 450V battery voltage and 450Arms output phase current provides a much wider operating area for the traction motor used by electric vehicle when compared with the traditional DC400V/AC400Arms controller assembled with 650V/600A devices. In addition, benefit from high thermal performance of the DSC IPM, a 27.3kW/L power density has achieved for the IPU 85-150. These advantages will contribute to a highly integrated and efficient powertrain system for the electric vehicle.

Model	IPU 85-150
Battery voltage without derating	DC100V-DC450V
Rated power	85kW
Rated output current	250Arms
Peak power	150kW
Peak output current	450Arms@30s
Switching frequency	Up to 12kHz
Cooling fluid	50% water/50% ethylene glycol, 8L/min, up to 75℃
Operating temperature	-40℃-105℃
Designed life	>15 years
Dimension, volume, mass	266×160×130, 5.5L
Power density	27.3kW/L

(a) (b)

Fig. 6 IPU 85-150 overview: (a) Outline; (b) Key specification;

IPU 85-150 also has higher efficiency than the compared SSC 650V/600A module based controller which was developed in a former project for an OEM customer. The comparison is done at 400V battery voltage, traction mode with the same Permanent Magnet Synchronous Motor (PMSM), and the result is shown in **Fig. 7**. It can be seen obviously that IPU 85-150 has higher efficiency at the same speed such as 97% at 3500rpm and 95% at 2000rpm. Furthermore, because of lower switching losses as indicated in **Fig. 5** (b) especially at lower device current for the DSC IPM, the efficiency contour lines of IPU 85-150 are vertical but more horizontal for the comparison controller. This means that the IPU 85-150 delivers higher efficiency at low torque area from 50Nm to 150Nm in the whole speed range. Since most of the vehicles drive dominantly at low torque area, vehicles will benefit from having higher efficiency and turn out with longer mileage.



(a) (b)

Fig. 7 Motor controller efficiency comparison (tested at DC400V and traction mode): (a) IPU 85-150; (b) Controller based on compared SSC 650V/600A IGBT module

For purpose of demonstrating the benefits of high efficiency introduced by IPU 85-150 for a vehicle powertrain, energy consumption in the New European Driving Cycle (NEDC) with a whole vehicle model has been simulated using Matlab/Simulink. The model that has been implemented contains IGBT device, PMSM motor with Field Oriented Control (FOC) control algorithm, transmission gear box, tires, dynamic vehicle model etc. Component losses in the powertrain are also included in this model, and can be captured in real-time simulation. Model accuracy has been verified in the cooperation projects with OEMs. In addition, it is worth noting that IGBT power losses are simulated based on the Pulse Width Modulation (PWM) technique and 3D lookup table including data of saturation voltage and switching losses with respect to transient battery voltage, device switching current and junction temperature. This kind of simulation approach can guarantee a more accurate power loss calculation for the IGBT device when compared with the traditional equation based method. **Fig. 8** gives energy consumption comparison of two different motor controllers that are based on the DSC IPM&AGD and the compared SSC 650V/600A IGBT module with a traditional resistive gate driver respectively. It clearly shows that with DSC IPM and AGD technology, energy consumption in one NEDC drive cycle can be reduced by 6.88%. This not only helps to reduce the required battery capacity and potential cost of the whole vehicle, but also helps to achieve longer mileage range when considering reduced battery capacity and related component masses.

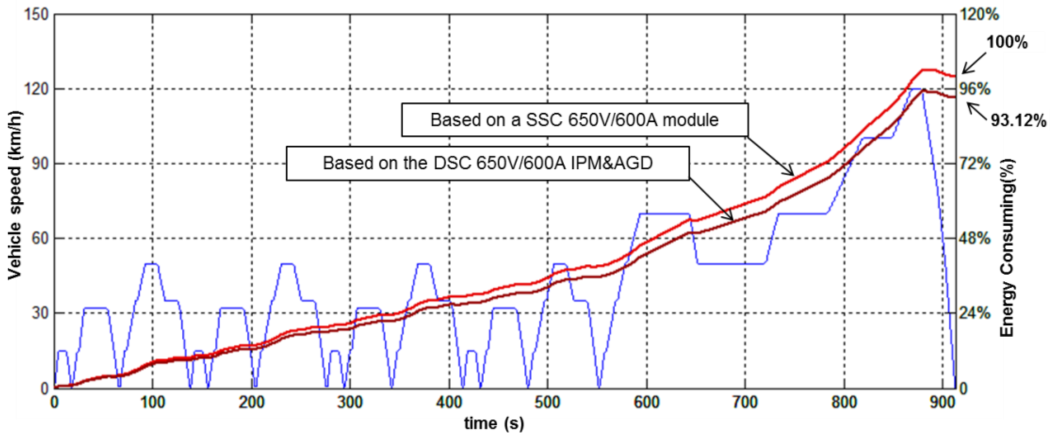


Fig. 8 Simulation results of energy consuming in one NEDC drive cycle

Moreover, the IPU 85-125 is equipped with abundant advanced technologies such as advanced PMSM motor control algorithm, ultra-low battery side ripple voltage, AUTOSAR based software development and emphasis on functional safety according to ISO26262 etc. which make it more suitable for the electric vehicle applications.

4. Conclusion

The double-sided cooling IPM delivers significant advantages in thermal performance and long-term reliability. Utilizing the advanced active gate driver technique, a motor controller IPU 85-150 has been developed. Through adoption of all the proposed innovative technologies, IPU 85-150 has achieved technical breakthroughs including but not limited to power density, power handling capability, and system efficiency.

References:

[1] Zhenxian Liang, “Status and Trend of Automotive Power Packaging,” ISPSD2012, Bruges Belgium, June 2012, pp. 325-331.

[2] Y. Nishimura, F. Momose, H. Gohara, Y. Inaba, A.Kitamura, “Power Module Technology for Automotive Power Electronics,” PCIM Europe 2015, Nuremberg Germany, May 2015,

[3] A. Grassmann, O. Geitner, W. Hable, C. Neugirg, A. Schwarz, F. Winter, I. Yoo, “Double Sided Cooled Module concept for High Power Density in HEV Applications”, PCIM Europe 2015, Nuremberg Germany, May 2015, pp. 442-228

[4] Takashi Kimura Ryuichi Saitou Kenji Kubo Kinya Nakatsu Hideaki Ishikawa Kaname Sasak, “High-power-density Inverter Technology for Hybrid and Electric Vehicle Applications,” Hitachi Review Vol. 63 (2014), No. 2, pp. 41-47

[5] A. Wintrich, U. Nicolai, W. Tursky and T. Reimann, "Application Manual Power Semiconductors", 2011, published by Semikron.

[6] Yangang Wang, “Development of High Thermal Performance Automotive Power Modules with Dual Sided Cooling Capability,” unpublished.

Evaluation of variable speed driven motor systems with emphasis on efficiency classification standards and conceivable implications in respect of global challenges

Freddy Gyllensten

ABB Motors and Generators

Abstract

The Paris Agreement entered into force on 4 November 2016, following the fact that the threshold number of parties, members of the United Nations, that have ratified the agreement was achieved. The central aim with the agreement is to act on keeping the global temperature rise this century well below 2 degrees Celsius above pre-industrial levels, which in practice means extraordinary reductions of CO_2 emissions in all influential sectors. About 50 % of the total global electric energy consumption is converted in electric motors, which are the largest consumers of electricity per component type and industrial motors alone is accounting for around 30 % of all electricity. Therefore, electric motors, and especially motors operated with variable speed drives, are key components that can achieve huge electricity savings, and the potential has been identified by policy makers and standardization organizations. This paper aims at evaluating variable speed driven motor systems, relevant standards and effects on progress of energy savings.

A benchmark study of 10 different commercially available motor drive systems from five different global manufacturers, and with three different rated powers of 7,5, 11 and 15 kW at 1500 rpm, have been tested using drives of the same type. All tested motor drive systems have been found to fall within the highest IES2 efficiency class, as defined by the international standard IEC 61800-9-2, with ease. However, the energy savings between the most efficient and the least efficient motor drive system is more than 5 % at the rated working point and even higher for partial load and speed points, corresponding to loss savings of around 40 % and more. This saving is simply a result of using different motors and will come on top of the greater benefit of variable speed operation, instead of constant speed operation. Clearly, more differentiation on system efficiency classification is needed for enhancing performance transparency, so that incentives are created for promoting more efficient motor drive systems.

A change towards more efficient motor drive systems will benefit most stakeholders, like the users through reduced electricity costs, the manufacturers of efficient products through higher sales, and not least our common world through reduced greenhouse gas emissions on the targeted pathway to a sustainable society for the next generations. This is a win-win situation of enormous proportions that is currently wasted and delayed due to unawareness and resulting slow progress. The paper makes proposals for actions that can influence for change towards more efficient electricity use of motors.

1. Introduction

Global warming, climate change and use of energy and material resources is the most important subject area of our time and the decisions and actions taken now will immensely influence the planet for future generations. This paper lists some very central references, see [1-4], that is strongly recommended literature for detailed understanding of the scientific platform that the discussed research is based on. There are many relevant energy saving potentials in the world today, and the primary focus will be on electric motors and drives and how they are operated in this paper.

The paper is organized with the following structure. In Section 1, an introduction is given, and in Section 2 an outlook on global effects and trends about climate change, energy use and some characteristic examples of the energy chain including electrical motors are described. Measurements of 10 different commercially available motor drive systems from five different global manufacturers, and with three different rated powers of 7,5, 11 and 15 kW at 1500 rpm, have been tested using drives of the same type, and the results are presented in Section 3. A discussion on potentials for energy savings is given in Section 4, and in Section 5 proposals for actions towards more efficient electricity use of motors are given. Conclusions are given in Section 6.

2. Global outlook

2.1 Global warming and climate change

The Paris Agreement entered into force on 4 November 2016, following the fact that the threshold number of parties, members of the United Nations, that have ratified the agreement was achieved. The central aim with the agreement is to act on keeping the global temperature rise this century well below 2 degrees Celsius above pre-industrial levels. Delaying mitigation efforts beyond today is estimated to substantially increase the difficulty of the transition to low longer-term emissions levels. The concentration of all greenhouse gases (GHG) reached a value of 403 ppm CO_2 equivalents in 2010, which at the time was unprecedented in at least the last 800,000 years. Many aspects of climate change and associated impacts will continue for centuries, even if GHG emissions would stop today. The risks of abrupt or irreversible changes escalate as the magnitude of the warming rises [1-4].

The annual mean atmospheric concentrations of carbon dioxide, the most dominating GHG component, from year 1750 to 2016 are given in Figure 1a [5-6]. The combined land-surface air and sea-surface water annual mean temperature anomalies, which are represented as deviations from the corresponding 1951-1980 means, are given in Figure 1b [7]. The highest mean temperature anomaly ever measured was for the year 2016 with 1.0 °C higher temperature than the reference period, followed by 2015, 2014 and 2010. All years after 1978 have had higher mean temperatures than the reference period, with increasing deviation trend. Oceans have stabilizing effects on temperature variations, due to their heat absorbing capability. It is estimated that 90 % of the heat caused by global warming between 1971 and 2010 has been accumulated in the oceans. The temperatures of the oceans therefore continue to climb [1]. The evidence data that have been accumulated over decades and centuries leaves no other reasonable explanation of global warming than that the effect is caused by human activities, primarily due to the accelerating burning of fossil fuels, from the industrial revolution (which was the transition period to new manufacturing processes, with the growing use of for instance coal powered steam engines, in the period from around 1760-1840) until now. Global warming could, if the current emissions level does not go down, cause catastrophic consequences with increasing frequency, like among others rising sea level, more drought and higher average wind speeds, resulting into lack of water and food supply, lack of livable land, more migration problems and associated extreme social pressure within and among different nations. The window for action is rapidly closing and 65 % of our carbon budget or 1900 $GtCO_2$, which is compatible with a maximum 2 °C global mean temperature rise target, is already used in the period 1870-2011 and the remaining budget is approximately 1000 $GtCO_2$ [3].

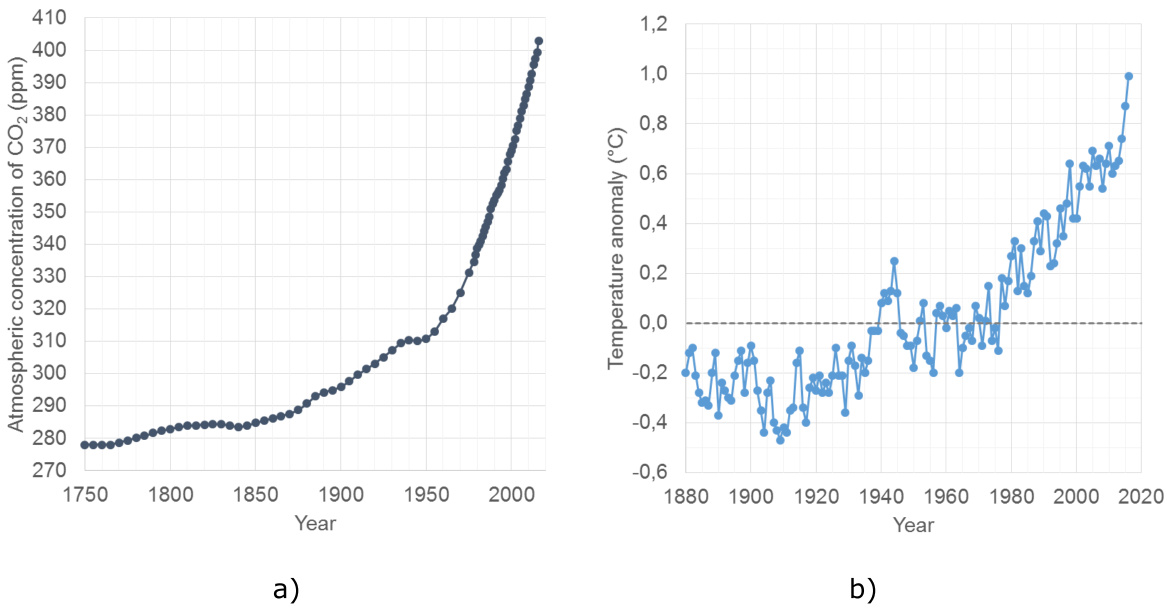


Figure 1. a) Annual mean atmospheric concentration of carbon dioxide (ppm) from 1750 to 2016. b) Combined land-surface air and sea-surface water annual mean temperature anomalies (i.e. deviations from the corresponding 1951-1980 means) from 1880 to 2016.

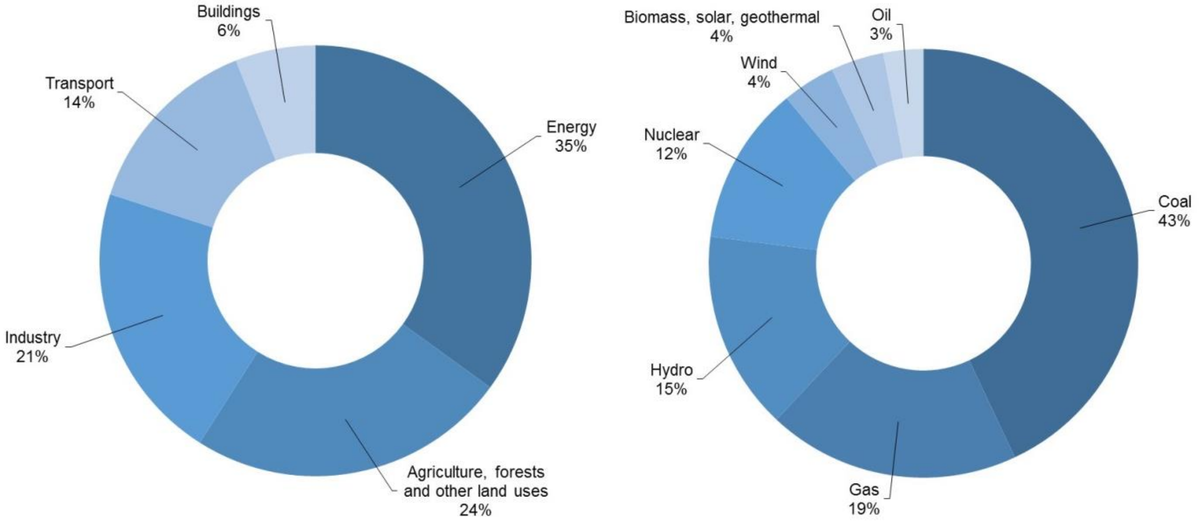
Some major mitigation measures proposed by the UN for preventing accelerated global warming include [3]:

- More efficient use of energy,
    - The energy saved does not need to be produced,
    - Saved energy is also associated with a scaling effect through elimination of losses in the energy transfer chain,
- Greater use of low-carbon and no-carbon energy,
    - Added investments in renewable energy technologies,
    - Replacement and phase-out of carbon intensive power plants,
- Improved energy carbon sinks,
    - Reduced deforestation,
    - Bio-energy with carbon capture and storage,
- Lifestyle and behavioral changes,
    - Thoughtful actions by selection of most sustainable alternatives in daily life.

There are many possible ways of reducing GHG emissions to the atmosphere as seen above, and it is not a coincidence that the mitigation measure of more efficient use of energy is mentioned first by the United Nations' Intergovernmental Panel on Climate Change (IPCC) [3]. The main reason is that this measure is the most easy and cost effective to perform, and the greatest challenge towards change is probably to make stakeholders at large aware about and ultimately exploit the potentials. The world population reached 7,3 billion people in 2015, and is projected to increase to 8,5 billion in 2030, 9,7 billion in 2050 and 11,2 billion in 2100 [8]. In other words, at the same time as the greenhouse gas emissions are targeted to be reduced, the world population will grow by 33 % to 2050, and is another challenge that is also stressing the urgency for an early adaptation of sustainable energy sources and usage.

2.2 Global use of energy

The global total amount of greenhouse gas emissions was 49 gigatons (Gt) of CO_2 equivalents in year 2010. Energy production is the primary driver of GHG emissions, and the energy sector had the largest share of 35 % of the emissions, as seen in Figure 2 [3]. Coal is the by far largest energy source for electricity production, with a share of 43 % of the total global generation of 20 000 TWh in the year 2015 [9]. The current average efficiency rate of coal power plants is 33 % [10].



a) b)

Figure 2. a) Global greenhouse gas emissions shares by economic sector, with a total emission amount of 49 Gt CO_2 equivalents in year 2010. b) Global electricity productions shares by energy source, with a total generation of 20 000 TWh in 2015.

2.3 Economic considerations, challenges and opportunities

The International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) have together made a report that analysis the investment needs for a low-carbon energy system in the light of the Paris Agreement [11]. The key target of the Paris Agreement is, as mentioned before, to keep the average global temperature rise well below 2 degrees Celsius throughout the 21st century. However, the agreement does not clearly describe what "well below" means in practice nor what probabilities should be attached to the target. Therefore, the report in [11] focused on a scenario with a 66 % probability of limiting the rise in global mean temperature to 2 degrees Celsius by 2100, without temporary overshoot during this century, for the reason of clarity and to be able to calculate the impacts of the scenario. The relationship between the average global surface temperature rise and the cumulative emissions of CO_2 is almost linear. Therefore, the concept of a global budget of carbon dioxide emissions associated with a temperature rise target comes out useful. The report in [11] estimates that the CO_2 budget between 2015 and 2100 is 880 $GtCO_2$, when using the above mentioned assumptions. The study concludes that the objective of the Paris Agreement is technically possible, but it will require substantial policy reforms, aggressive carbon pricing and more technological innovation. Improvements to energy and material efficiency and more use of renewable energy are crucial features with the largest share of the carbon emissions reduction potential up to 2050. In the 66 % and 2 °C scenario, annual energy intensity reductions of 2,5 % on average is needed, which is 3,5 times more ambitious than seen in the past 15 years. In parallel, wind and solar combined would become the largest source of electricity by 2030. The IEA estimates, following the same scenario, that by 2050, almost 95 % of electricity production would be from low-carbon sources, 70 % of new cars would be electric, the total existing building stock would have been retrofitted, and the CO_2 emissions from industry would be 80 % lower than today. This would require investments in the energy sector of USD 3,5 trillion on average each year between 2016 and 2050, which is an increase of almost the double compared to USD 1,8 trillion in 2015. However, the additional net total investments amount to be equivalent to only 0,3 % of the global gross domestic product (GDP) in 2050, relative to the trends according to the current climate pledges [11]. A seemingly realistic and affordable goal, not least conceivable when considering that investments in renewables and energy efficiency will generate many new jobs and economic growth, and more than offset job losses in the fossil fuel industry, and boost global GDP by 0,8 % in 2050, according to IRENA [11].

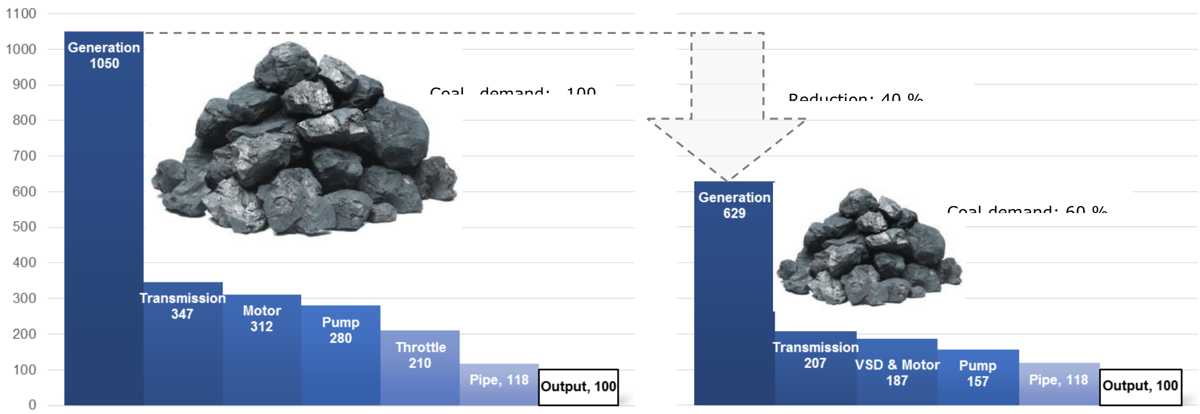
Some positive examples that are indicating that the transition towards a low-carbon energy system has already started are identified below. The current price of solar power in parts of the USA of 6 cents per kilowatt-hour is beating the price of coal power of 11 cents per kilowatt-hour, and 135 coal-fired power stations has been closed in the USA during the past two years [12]. The French government has unveiled plans in order to reduce France’s carbon footprint. Among the measures are closing down the last coal-fired power plant by 2022, confirming the objective of a 32 % share for renewables in the energy mix by 2030, implementing an increase of the carbon price per ton by 40 % up to 140 euros by 2030, ending gasoline and diesel cars sales by 2040 and setting 2050 as deadline for achieving domestic carbon neutrality [13]. The Swedish Parliament passed a new law on a climate policy framework that will go into force on 1 January 2018, which states that Sweden latest in 2045 shall not have any net GHG emissions to the atmosphere and that emissions from domestic transport shall decline by at least 70 % latest in 2030 compared with 2010 level [14].

2.4 Electric motors, their driven applications and impact on GHG emissions

About 50 % of the total global electric energy consumption is converted in electric motors, which are the largest consumers of electricity per component type and industrial motors alone is accounting for around 30 % of all electricity [15-17]. The remaining around 20 % electricity is consumed in electric motors for other sectors like commercial, residential, transport and agriculture [15]. The installed base of industrial low voltage motors is estimated to be more than 750 million units [18]. The share of motors equipped with electronic speed control is only about 12 % of the installed motor base [19]. It is estimated that it would be beneficial for energy savings that this share should be more than 50 %. Replacing an old direct on line motor with a new motor with a higher efficiency class is a simple measure to improve energy efficiency. However, the greatest energy saving potentials associated with electric motors is mainly determined by the way the motor speed is controlled, and such control can replace less efficient mechanical control equipment like throttle valves for pumps, which is one of the greatest saving potentials. When taking life cycle costs into account, investments in energy saving measures can often pay off within just a few years, or even months. The cost of electricity accounts for up to 96 % of the total life cycle cost, while the investment and installation costs only account for around 2,5 %, and maintenance costs account for the remaining 1,5 % [19]. This means that taking a holistic approach rather than a single-minded component price optimization strategy can be incredibly profitable, when purchasing motors and drives. Pump systems presently account for more than 25 % of the industrial electricity consumed worldwide, and it is estimated that around 40 % of this energy could be saved. Centrifugal pumps in particular, accounting for a 73 % market share, represent great potentials for energy savings because around 75 % of these pumps are oversized [19]. Fan systems, likewise centrifugal pumps, also have a load profile that rises quadratically versus speed, resulting in a cubic power profile with vast energy saving potentials when run with variable speed control. These two applications alone account for 52 % of the low voltage industrial motor market [18].

For the sake of illustrating the energy saving potential by replacing throttle valve control with variable speed control for adjusting the flow of a pump, an example is given below.

Consider filling water from a tap with a given flow and pressure and equivalent to an output power of 100 %. In a global perspective it is likely that the required power for the water transport comes from a coal power plant. On the way from the primary energy source, coal, to the output, there are several transfer parts involved [20]. Starting with the power plant, the chemical energy stored in the coal is used for generating electricity, which is transmitted and distributed in the grid network, a motor is converting electrical energy into mechanical by driving a pump. The pump makes the water flow and the flow is controlled by a throttle valve. The water flows through a pipe system before reaching the tap. The efficiencies in the chain are 33 % for the coal plant, 90 % for the transmission and distribution network, 90 % for the motor, 75 % for the pump, 56 % for the throttle valve and 85 % for the pipe system. The input power is 1050 % for the whole system for an output of 100 %, which means that more than 90 % of the used energy is losses. If the throttle valve was replaced with a frequency converter, for controlling motor speed and in turn water flow, then the input power would only be 629 % or a reduction of 40 %. The efficiencies are assumed unchanged, except for the throttle valve efficiency that is removed and the direct fed motor efficiency that is replaced with a combined motor and drive system efficiency of 84 %, taking into account additional drive losses and an assumed lower efficiency at partial load operation. It is important to be aware of the fact that an improved efficiency, somewhere in the energy chain, is profited by energy loss savings in all previous chain steps as well. The efficiencies can approximately be considered unchanged, but since the power demand is less, the result is reductions in loss magnitudes. The example is illustrated in Figure 3. Looking from the perspective of the user of the electric motor and drive system, an electricity cost saving of 40 % is achieved, compared to the reference system with the throttle valve, but in a wider perspective, also 40 % of coal and the same level of GHG emissions are saved, which should not be ignored.



a) b)

Figure 3. Total input powers in percent per part of transfer chain of coal plant powered electricity generation for two different control methods in a pump application normalized on the same output power: a) mechanical throttle control and b) variable speed control.

2.4 Standards on efficiency classifications of motors and drives

2.4.1 IEC 60034-30-1

The international standard IEC 60034-30-1 deals with efficiency classifications of direct-on-line (DOL) operated motors [21]. The classification working point is at rated speed and rated power. The number of defined efficiency classes is four, labelled IE1, IE2, IE3 and IE4, where a higher ordinal number means a higher efficiency. The loss reduction when going from one IE level to the next higher is roughly 20 %. All industrial low voltage AC motors that are rated for DOL operation is governed by this standard, even when the same motors are used for variable speed operation, i.e. with a drive.

2.4.2 IEC TS 60034-30-2

The international technical specification IEC TS 60034-30-2 deals with efficiency classifications of AC motors especially designed for variable speed drives (VSD) [22]. The classification working point is at 90 % of rated speed and 100 % of rated torque, which means at 90 % of rated power. The defined efficiency classes are IE1, IE2, IE3, IE4 and IE5, in increasing order of efficiency. Motors that can run direct on line, and are defined according to IEC 60034-30-1, are not included. This is unfortunate, since such motors are capable of operating with variable speed drives and account for more than 98 % of the industrial low voltage AC motor market. Users are therefore left with poorer transparency when comparing motors of different technologies.

2.4.3 IEC 61800-9-2

The international standard IEC 61800-9-2, which is based on the European standard EN 50598-2, deals with efficiency classifications of frequency converters and variable speed drive motor systems [23-24]. The standard also defines test procedures for motors, drives and systems, however, the defined procedures are not stringent enough to enable fair comparisons, nor does the standard offer sufficient system efficiency classes for fair product differentiation, which will be discussed more below.

Determinations of losses based on calculations are for instance allowed, as alternatives to measurements. However, some mathematical procedures follow very detailed calculation steps based on undocumented empirical models, while alternative calculation procedures seem to be left open for own definitions by component manufacturers, which seem quite inappropriate for a standard that per definition should secure objectivity, transparency and equality for applied comparisons. Moreover, the defined working points for tests or calculations for motors and systems differ from the working points defined for drive modules. Relative speeds and relative torques are used for defining working points for motors and systems, while relative stator frequency and relative torque producing current (equal to rotor current for asynchronous motors) are used for defining working points for drive modules. Then it is allowed to sum up losses determined for motors and drive modules, respectively, for the calculation of total system losses. Since the speed in an asynchronous motor is not constantly linked with the stator frequency, as in a synchronous motor, but a function of load and slip, the presented model does simply not offer adequate consistency for being accurate and trustful. There is a huge risk that the loss determination errors are much larger than the real loss differences between different products, so that erroneous conclusions easily can be made, which renders objective product comparisons meaningless, by using the methodologies in the standard. Instead, the standard is a useful tool for calculating typical losses of motor drive systems, for general guidance on operations with different applications, which should be the proper use of the document. Furthermore, the highest system efficiency class definition in the standard is IES2, with efficiency limits that are easily achieved by most modern motor drive systems and therefore do not offer adequate differentiation, and is an essential weakness with the standard, which will be demonstrated below in Section 3.

3. Measurements of electric motor and drive systems

3.1 Test procedure

The involved motor drive systems have all been tested using the direct input-output method, which means that the electrical power before and after the frequency converter and the mechanical power after the motor have all been measured simultaneously. State of the art instruments with high precision have been used, with Yokogawa WT3000 power analyzers for electrical quantities and HBM T12 torque transducers for mechanical quantities. The rated point has been tested to thermal equilibrium, while partial working points have been tested without the same restriction, in accordance with common practice on testing of variable speed systems. The same type of frequency converter have been used for all tests, namely the ABB ACS850, in a few different current rating variants depending on the rated requirements of the tested motors.

The systems have been tested in 16 different working points as defined in Figure 4. The normalized power levels are in the range from 100 % down to 6,25 %, as seen in the same figure. In order to be able to calculate the total weighted efficiency and energy consumption in a wide operating range, a duty cycle with time distributions has been defined in Figure 4. The duty cycle has an average output power of 40,5 % of rated power and is thought to simulate realistic conditions with higher weighted time distribution shares in the middle of the operating window, especially suitable for quadratic torque applications, but also quite appropriate for constant torque applications, depending on use and changing load requirements. The relatively low average output power is assumed more correct for a variable speed motor drive system, motivated by the inherited energy saving potential in the driven system enabled by variable speed, and if the required power hypothetically would be close to constant nominal power, then it could be expected that a direct-on-line motor alternative would likely be chosen instead.

3.2 Test results

The benchmark study involves 10 different commercially available motor drive systems from five different global manufacturers, and with three different rated powers of 7,5, 11 and 15 kW at 1500 rpm, and have all been tested using ABB ACS850 drives with three different current ratings. The rated powers have been chosen to coincide with the power range where most electrical energy is consumed by electrical motors. The main declared data and the measured data of the tested motors and drives systems are given in Table 1. The selected motors have declared IE efficiency classes of IE2, IE3 and IE4, and come from two different technology types, namely the induction machine (IM) and the synchronous reluctance machine (SynRM), which makes an extensive overview possible.

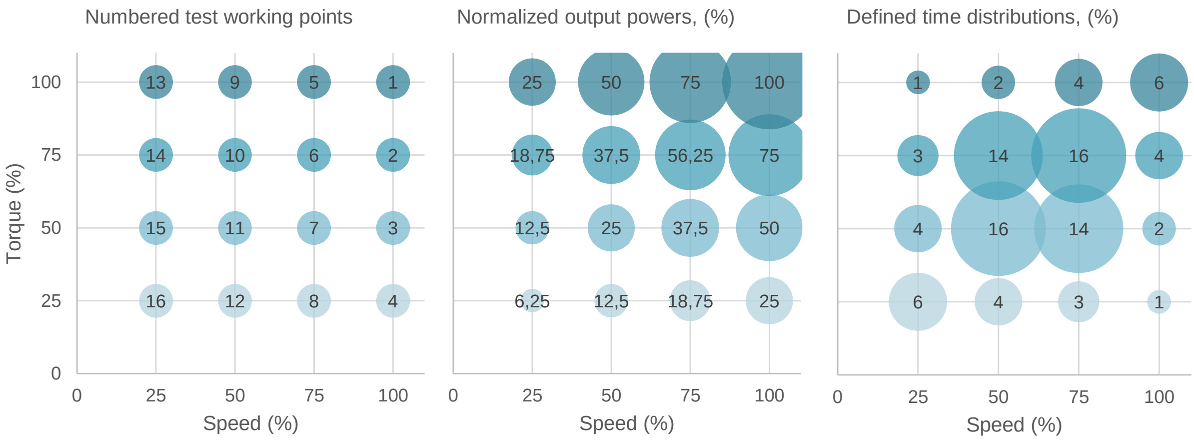


Figure 4. Definitions of the tested working points, the normalized output powers and the time distributions per working point for a duty cycle used to calculate energy consumption.

Table 1. Declared and measured data of tested motors and drives systems.

System	Identification number	1	2	3	4	5	6	7	8	9	10
Motor	Rated power, (kW)	7,5	7,5	11	11	11	11	11	15	15	15
	Rated synchronous speed, (rpm)	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
	Rated frequency, (Hz)	50	50	50	50	50	50	50	50	50	50
	Declared IE class complience[1]	IE4	IE4	IE2	IE2	IE2	IE3	IE4	IE2	IE4	IE4
	Type[2]	IM	SynRM	IM	IM	IM	IM	SynRM	IM	SynRM	SynRM
Inverter	Model (ABB ACS850-■■■■)	018A	018A	044A	044A	044A	035A	035A	035A	035A	035A
	Switching frequency, (kHz)	3	3	3	3	3	3	3	3	3	3
Measured system data (Motor + Inverter)	Efficiency at (100,100), (%)[3]	89,3	91,3	86,6	87,4	87,9	89,2	91,4	88,4	91,1	92,0
	Energy saving at (100,100), (%)[4]	0	2,3	0	0,9	1,5	3,0	5,2	0	3,0	3,9
	Efficiency at duty cycle, (%)[5]	85,2	88,9	84,0	85,7	85,7	87,1	88,8	86,1	88,6	89,9
	Energy saving at duty cycle (%)	0	4,2	0	1,9	2,0	3,5	5,4	0	2,8	4,2

1 IE class according to IEC 60034-30-1
2 IM - Induction Machine, SynRM - Synchronous Reluctance Machine
3 (100,100) means (100 % of rated synchronous speed,100 % of torque normalized at rated power and rated synchronous speed)
4 Energy saving is normalized on system with lowest measured efficiency performance per power level
5 Duty cycle according to 16 working points and associated time distributions as defined in Section 3

As can be seen in Table 1, the energy savings when using the most efficient system instead of the least efficient system, with a rated power of 11 kW, is 5,2 % at the nominal point and 5,4 % for the whole duty cycle. Even within the same efficiency class and for the same machine type, there are motors that perform quite differently, and energy savings of 1,5 % in the nominal point and 2,0 % for the duty cycle are experienced, both with a rated power of 11 kW. For motors from different machine types and a rated power of 7,5 kW, with the same declared efficiency class, energy savings of 2,3 % at the nominal point and 4,2 % for the duty cycle are seen. Motors with a rated power of 15 kW show similar characteristics, and energy savings of 3,9 % at the nominal point and 4,2 % for the duty cycle are detected, between IE2 and IE4 motors from different machine types.

The efficiency performances for all 10 motor drive systems, tested at the 16 different working points as defined in Figure 4, are given as radar plots in Figure 5. The shapes of the different plots are quite similar, which indicates physical relationships associated with the different operating conditions. All motors are also designed with the same number of poles, four, and are related in constructions. The drive type used is as mentioned the same for all systems. However, when it comes to the magnitudes of the efficiencies, there are significant differences in performances. These differences can be translated into major energy savings of up to more than 10 % on component level at partial speed and load points, between different motors alone.

The IEC 61800-9-2 standard defines the efficiency classes of VSD systems. The highest class is IES2. In order to illustrate the degree of difficulty of achieving the highest class, all tested motor drive systems have been included in the same graph, normalized on IES2 maximum loss limits, in Figure 6. As can be seen, it is not difficult at all, but rather easy to achieve the requirements, since all systems including motors from IE2 to IE4 motor efficiency classes are compliant with large margins. Even the weakest performing system has a loss reduction of more than 10 %, compared to the loss limit of the IES2 class, while likewise for the best performing system has a loss reduction of more than 50 %.

Since there seem to be a lack of system efficiency classes, it is proposed in this paper to include three new classes in a future revision of the standard, namely “IES3”, “IES4” and “IES5”, defined to have a loss reduction of 20 % compared to the next lower efficiency class, respectively. The proposed new efficiency classes are also included in Figure 6, for reference. It can be observed that the best performing system in relative sense, System 2, is already compliant with "IES5", a commercially available system, and should therefore not be assumed to be any theoretical limit.

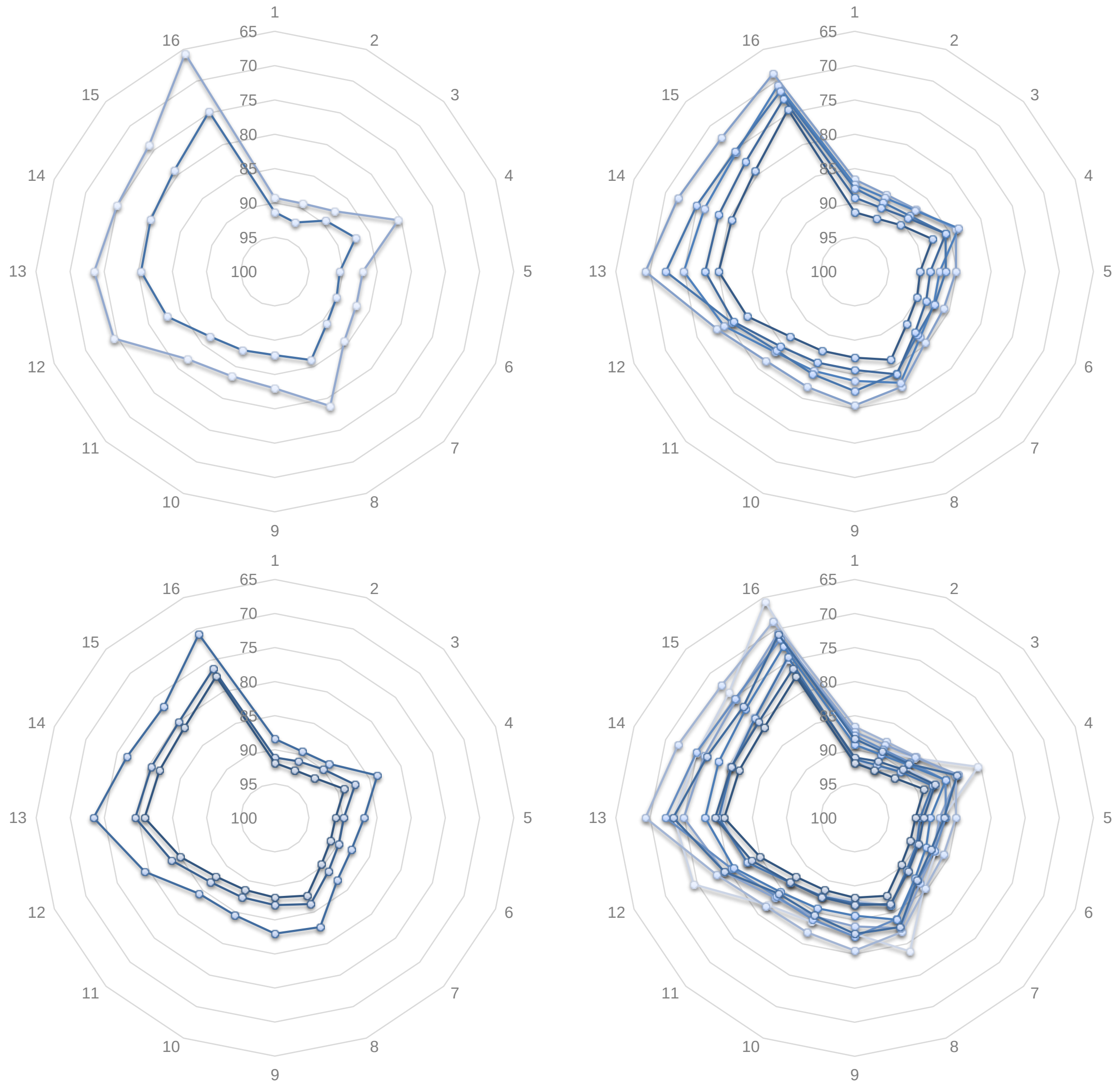


Figure 5. Radar plots of the 10 tested motor drive systems and respective system efficiencies in the 16 test points, with an efficiency of 100 % at the center and 65% at the outer gridline, for rated powers of 7,5 kW (top, left), 11 kW (top, right), 15 kW (bottom, left) and all included (bottom, right).

4. Potentials for energy savings

There are many energy saving potentials associated with the use and operation of electric motors and drives, and some significant potentials are described below.

4.1 Switch from DOL to VSD operation

It is estimated that more than 50 % of installed base of motor applications would benefit on energy savings by switching from constant speed or DOL operation to variable speed drives operation, while the current base with VSD is estimated at 12 %. This is partly motivated by the large application share of more than 50 % for pumps and fans with mainly quadratic load dependence versus speed, currently controlled with mainly mechanical means like throttle valves. The energy saving potential depends on many different factors, and the duty cycle is a major one. An average saving potential of 25-50 % when changing from DOL to VSD operation is believed to be representative.

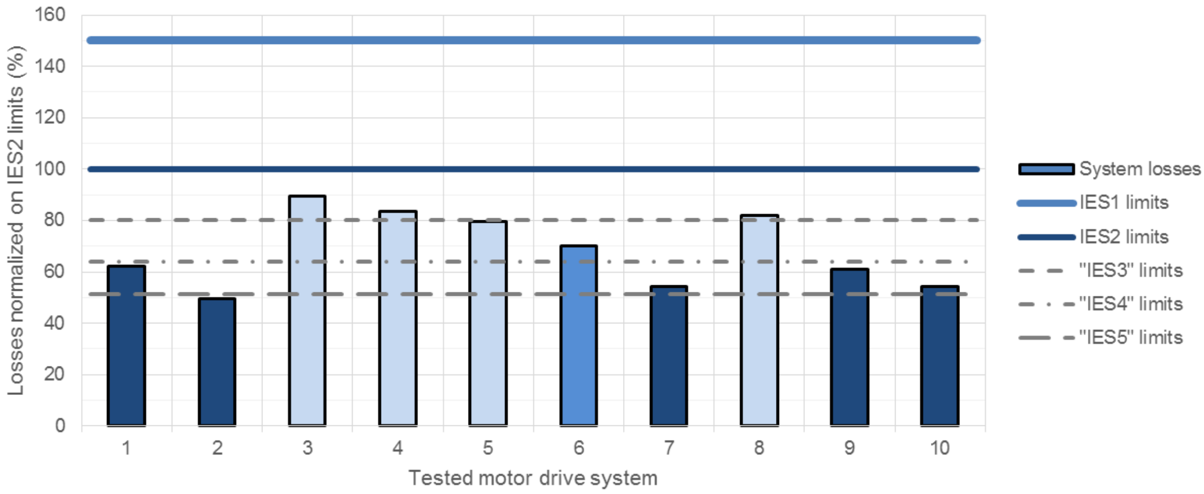


Figure 6. Measured losses for 10 tested motor drive systems normalized on IES2 maximum loss limits, according to IEC 61800-9-2, illustrated together with defined IES1 and IES2 efficiency class limits and proposed new additional class limits called "IES3", "IES4" and "IES5". (The bar colors indicate the declared motor efficiency class, according to IEC 60034-30-1, for IE2 (light), IE3 (medium) and IE4 (dark), respectively).

4.2 Switch from standard efficiency to super efficiency components

A saving of more than 5 % when changing from a standard efficiency motor (IE2) to a super-efficient motor (IE4) is estimated, as demonstrated in Section 3, for the common power levels of 7,5-15 kW. Lower and higher relative savings are estimated for higher and lower power ratings, respectively, due to their usual differences in efficiencies. Since the global electric energy consumption among motors peaks for motors in the studied power range, the relative saving potential is estimated to give a fair representation in an overall perspective. The average efficiency in the installed base of motors is estimated to be equivalent with efficiency class IE1 performance, due to motor lifetime expectations of more than 20 years and knowing the historic market data categorized by declared efficiencies [16].

4.3 Other saving potentials

Other important saving potentials with motors, drives and their driven applications are including optimization of the load equipment for variable speed control (like right selection of pump and pipes) as well as efficiency optimization of the system for a given working point (like electronic control for loss minimization in components overall).

4.4 Summary

Combining the energy saving potentials for motor and drive systems from the previous sub-sections results in the following scenario. If the share of variable speed operated industrial motors today rose from 12 % to 50 % and all industrial motors, including the remaining 50 % DOL motors, would have efficiency performances equal to the IE4 efficiency class, then the energy saving would be more than 21 %. The calculation is under the assumptions that changing from constant speed to variable speed control makes a typical energy saving of 40 % and changing motor efficiency performance from IE1 class on average in the installed base to IE4 class makes a typical energy saving of 6 %, but of course discretely dependent of rated motor power and duty as mentioned before. Since around 30 % of the total global electric energy consumption is converted in industrial electric motors, a total electricity saving of more than 6 % for the whole world could be realized. This saving could be translated into the potential of being able to close down 14 % of the coal-fired power plants in the world. The most promising aspect with this scenario is that the investments needed for the purchases and installations of the motors and drives are economically profitable with payback times within a few years, because of the predominating electricity costs associated with the lifetime expenditures of electric motors and drives. More energy saving potentials using motors and drives can also be found in other sectors. The transport sector is for instance rapidly developing an increasing share of electrified powertrains for the reason of reducing fuel consumption in vehicles, and many manufacturers are even offering all electric vehicles with zero emissions. Thus, the prospects for a low-carbon society is good, if all stakeholders work together and the best technology use win ground.

5. Proposals for actions towards more efficient electricity use of motors

5.1 Users

The following recommendations are given.

- Strive for insight by learning from trustful sources on energy analysis.
- Don’t buy marketing information at first glance, but demand to get in-depth descriptions of actual performance of products from potential suppliers.
- Calculate the life cycle cost of an investment – the payback time is normally short for efficient motor drive systems.
- Invest in the most economically profitable motor drive system. The environmental and social benefits will be added as bonus, and boost business in the modern era of sustainable focus.

5.2 Standardization organizations

As have been seen in Section 3, the actual performances of real motor drive systems, in comparison with the highest defined motor drive system efficiency class levels, are not at all aligned. This is a pity, since huge energy saving potentials are hidden as a result, and the current standard IEC 61800-9-2 does not give enough incentives to develop more efficient systems. This is a contradiction, since the mandate for starting up the development of a new standard should transparently state the targets with the project. There is clearly a need for a revision, and urgently, if the climate change issue is considered.

Work through targets and ethical aspects in working groups before initiating revisions or new launches of standards. Agree on priorities and define a guideline with work principles in ranked order. Such a formal background declaration would enable more transparent work processes and help out on avoiding conflicts of interests that may arise along the course of a document work, since there exist a consensus agreement on the higher objectives.

Propose new efficiency class definitions for power drive systems (PDS), higher than IES2, and up to the proposed “IES5” is realistic, as already demonstrated.

5.3 Policy-makers

Give standardization committees sufficient mandates with adequate target mission, when initiating work on standards within the area of energy efficiency. The target should include motivations that are promoting standardization levels also beyond state of the art performance, which will benefit research, development of ever improved products and systems, and ultimately enable society with different options in a true competitive and fair spirit.

Launch and strengthen policies that builds economic incentives for energy efficient systems and use, since encouragement is a powerful tool for rapid change in viable development.

6. Conclusions

Motor drive systems are important factors for energy savings in the world. Replacing mechanical control devices with variable speed control can reduce the energy consumption by 40 %. The saving potential is enormous, but it does not seem like the society is commonly aware of the incredibly rewarding economic opportunities associated with such investments, mainly an effect of the dominating electricity cost in a life cycle cost assessment.

When investing in new motor drive systems, then a super-efficient motor alone can contribute with energy savings of more than 5 % in duty cycles for industrial applications, compared with a standard IE2 motor, in the studied important rated power range of 7,5-15 kW. This is a significant saving potential, which goes on top of the higher saving potential of changing control methods.

Motors and drives are regarded to be key systems in the future towards the global goal of greenhouse gas emissions on the same level as for pre-industrial ages, together with parallel advancements in the energy, transport, buildings and other sectors. The prospects for a low-carbon society is good, if all stakeholders work together and the right technologies win ground.

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References

[1] IPCC, 2013: Frequently Asked Questions. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [T. F. Stocker, D. Qin, G-K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. University of Bern, Bern, Switzerland, March, 2014.

[2] IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

[3] IPCC, 2014: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

[4] R. K. Pachauri, et al, "CLIMATE CHANGE 2014, Synthesis Report – Summary for Policy-makers", United Nations, IPCC, 2014.

[5] European Environment Agency, URL: https://www.eea.europa.eu/data-and-maps/indicators/, 11 July 2017.

[6] U.S. Department of Commerce, National Oceanic & Atmospheric Administration (NOAA), NOAA Research, Earth System Research Laboratory, Global Monitoring Division, URL: https://www.esrl.noaa.gov/gmd/, 11 July 2017.

[7] NASA, Goddard Space Flight Center/Sciences and Exploration Directorate/Earth Sciences Division, USA, URL: https://data.giss.nasa.gov/gistemp/, 3 February 2017.

[8] United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.241, New York, USA, 2015.

[9] Global Energy Trends, 2016 Edition, Enerdata, Paris, France, 2016.

[10] World Coal Association, URL: https://www.worldcoal.org/reducing-co2-emissions/, 8 February 2017.

[11] International Energy Agency (IEA) and International Renewable Energy Agency (IRENA), Report: "Perspectives for the energy transition – Investment needs for a low-carbon energy system", March, 2017.

[12] E. Dienel, "The growing business risks in fossil fuels", BSR: Business for Social Responsibility, Blog, 29 March 2017.

[13] Enerdata, "The French government has unveiled its climate plan until 2040", Newsletter, 7 July 2017.

[14] Government Offices of Sweden, Article: "The climate policy framework", URL: http://www.government.se/articles/2017/06/the-climate-policy-framework/, 14 July 2017.

[15] P. Waide, C. Brunner, "Energy-efficiency policy opportunities for electric motor-driven systems", Working paper, International Energy Agency (IEA), Paris, France, 2011.

[16] Energy Efficient End-use Equipment (4E) International Energy Agency, "Policy guidelines for motor driven units – Part 1: Analysis of standards and regulations for pumps, fans and compressors", October, 2016.

[17] International Energy Agency (IEA), Report: "World energy outlook 2016 – Executive summary", Paris, France; 2016.

[18] M. Meza, "Industrial LV Motors & Drives: A Global Market Update", Motor & Drive Systems 2014 – Advancements in Motion Control and Power Electronic Technology, Orlando, USA, January 29-30, 2014.

[19] Federal Ministry for Economic Affairs and Energy, Germany, URL: http://www.bmwi.de/ Navigation/EN/Home/home.html, February, 2017.

[20] T. Fleiter, W. Eichhammer, "Energy efficiency in electric motor systems: Technology saving potentials and policy options for developing countries", Working paper 11/2011, United Nations, Industrial Development Organization, Vienna, Austria, 2012.

[21] International Standard, IEC 60034-30-1, Edition 1.0, "Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code), Geneva, Switzerland, March, 2014.

[22] Technical Specification, IEC TS 60034-30-2, Edition 1.0, "Rotating electrical machines – Part 30-2: Efficiency classes of variable speed AC motors (IE code), Geneva, Switzerland, December, 2016.

[23] European Standard, EN 50598-2, "Ecodesign for power drive systems, motor starters, power electronics & their driven applications – Part 2: Energy efficiency indicators for power drive systems and motor starters", Brussels, Belgium, December, 2014.

[24] International Standard, IEC 61800-9-2, Edition 1.0, "Adjustable speed electrical power drive systems – Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications – Energy efficiency indicators for power drive systems and motor starters", Geneva, Switzerland, March, 2017.

Visualizing the Efficiency of a Continuously Variable Transmission

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Abstract

This paper investigates how the efficiency of a Continuously Variable Transmission (CVT) can be visualized in a compact way. At this point there is no standardized method to describe CVT efficiency as there are many inputs which affect the efficiency. Input speed, load torque, speed ratio and clamping force have been identified as dominant factors influencing efficiency. By analyzing the impact of each parameter a method is proposed based on an efficiency map and a scaling law. Efficiency maps are used because they represent the efficiency in the complete operating range and not only in the optimal conditions. The results of this study are of importance for constructors and end users of CVTs. The constructors benefit from the fact that they can plot the efficiency data in a compact format while the end users can use the data to optimize their drivetrain. The approach where efficiency data is used by the end users to optimize the drivetrain in terms of efficiency is called the Extended Product Approach (EPA). By implementing EPA in the design process, large savings on the long term are possible.

1. Introduction

Due to increasing fuel prices, the efficiency of drive trains and their individual components has gained a lot of interest. By optimizing the efficiency of each component in the drivetrain, large savings on the long term are possible. This is called the Extended Product Approach (EPA) and is mentioned in EN 50598.

Due to this system level optimization, knowledge of the energy efficiency over a wide range of working points of these components is vital. In contrast to the electrical parts in the drivetrain [1], [2], this information is not available for mechanical parts such as a gearbox or a Continuously Variable Transmission (CVT) which is a device with a variable speed ratio.

As with gearboxes there are many types of CVTs of which the belt CVT and the half/full toroidal CVT are the most commonly used. To limit the scope of the paper the half toroidal CVT has been chosen as subject for this study. In the half toroidal CVT, power is transmitted from the input disc to the output disc through a system of rollers (Figure 1). From the geometrical speed ratio, defined as the ratio of r_1 and r_3, it can be seen that by varying the contact points of the rollers given by the distances r_1 and r_3 respectively, the speed ratio can be varied in a continuous way. Indeed, these contact points can be changed smoothly by manipulating the tilting angle γ of the rollers. To avoid a moving contact between two metal components and the corresponding wear, a traction fluid is used. To limit the slip in the device and thus controlling efficiency, a force called the clamping force (F_{Din}) is applied at the input disc which puts all components under a certain pressure. The main advantages of the toroidal CVT are the high torque capacity and efficiency while the main drawback is the complexity of the system.

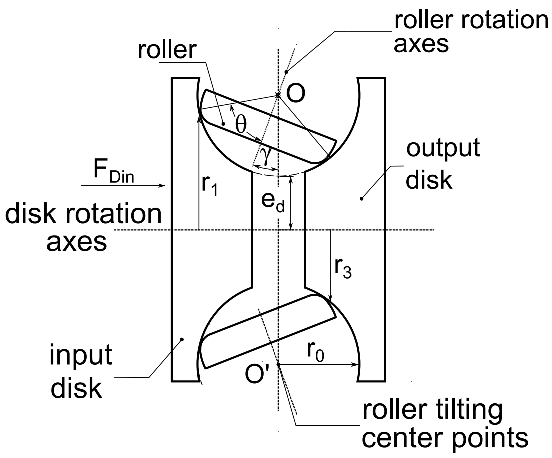

Figure 1: Schematic of a half toroidal CVT.

Some effort has already been done concerning characterization of gearboxes [3]–[5] where efficiency maps have been created displaying efficiency as function of input speed and output torque. However, for the CVT, there is not even a consensus on how to visualize the efficiency. In [6],[7] the dependency of the speed ratio and load torque on the efficiency is studied. The impact of input speed has not been considered in these studies. However, based on the measurements done in [8] some dependency on the input speed is observed.

Because there are 4 parameters (input speed, load torque, speed ratio and clamping force) which all have an impact on the efficiency, the efficiency is no longer displayable in maps. Therefore this paper presents a method to visualize efficiency data in a smart and compact format which is easy to read and understand.

This paper is structured as follows. Section 2 gives a short introduction on the model which was used to determine the efficiency values in different operating conditions. In Section 3, the boundary conditions which define the operating range of a toroidal CVT are given. Section 4 discusses the parameters which have an impact on the efficiency. In Section 5 the impact of the input speed on the efficiency is taken into account and in Section 6 an example of the proposed method is given. Finally, in Section 7 the conclusions of the research are formulated.

2. Model of the half toroidal CVT

In this paper a model of a half toroidal CVT is used to obtain the necessary efficiency data. This validated model is discussed in detail in [6] and [9] and is briefly summarized in this section.

The model consists of a contact model, a mechanical model, a simple load and a slip controller (Figure 2). In the contact model the traction conditions are determined based on the clamping force (F_{Din}), the tilting angle (γ), the input speed (ω_{in}) and output speed (ω_{out}) of the CVT. The traction conditions are used to calculate the generated torque at the input (T_{in}) and output (T_{out}).

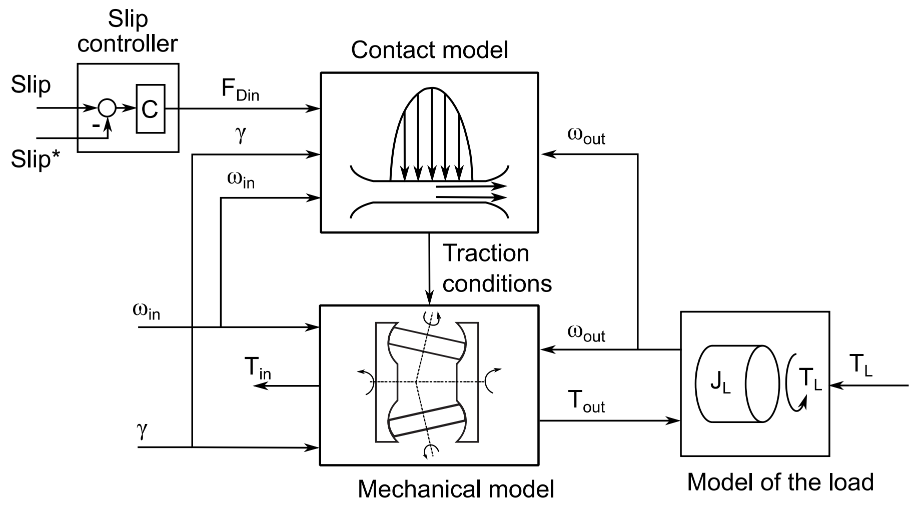

Figure 2: Model structure of the half toroidal CVT.

Slip is inevitable in a toroidal CVT and must therefore be controlled. In order to attain stable operation, slip is limited to a maximum value of 3% by the slip controller [6]. Slip can be calculated based on the following equation:

$$Slip = 1 - \frac{\tau}{S_{rID}} = 1 - \frac{\frac{\omega_{out}}{\omega_{in}}}{\frac{r_1}{r_3}} \tag{1}$$

In eq. (1), the actual speed ratio is defined as τ and the geometrical speed ratio as S_{rID}. The dynamics of the slip controller are ignored as in this paper only steady state results are considered.

3. Boundary conditions of the CVT

Boundary conditions determine the operating area of a device, in this case a CVT. A good definition of the boundary conditions is of great importance because it determines for which combination of inputs (torque, speed, speed ratio, clamping force) the efficiency should be known or not.

There are 2 types of boundary conditions: the speed ratio range and the maximum torque. The speed ratio range is defined by geometrical parameters and is limited by the input speed. Based on the geometrical parameters the maximum speed ratio $S_{rID_{max}}$ is given by:

$$S_{rID_{max}} = \frac{1 + a_r}{1 + a_r - \cos\left(2\theta - \frac{\pi}{2}\right)} \tag{2}$$

Where a_r is the aspect ratio which is equal to $\frac{e_d}{r_0}$ and θ is the half cone-angle (see Figure 1). When the maximum speed ratio is known, the minimum speed ratio can easily be calculated as the inverse.

As stated in the previous paragraph the input speed can limit the maximum speed ratio. If the input speed increases, the roller speed increases. Due to the heavy loading of the rollers, special axial thrust bearings [10],[11] are used which have a rather limited maximum permissible speed. For the simulation in this paper, bearings are used with a maximum permissible speed of 6000 r/min. Figure 3a) visualizes the speed ratio limit as function of the input speed. It states that for an input speed of for example 4500 r/min the rollers will reach their limiting speed for a speed ratio of approximately 1.1.

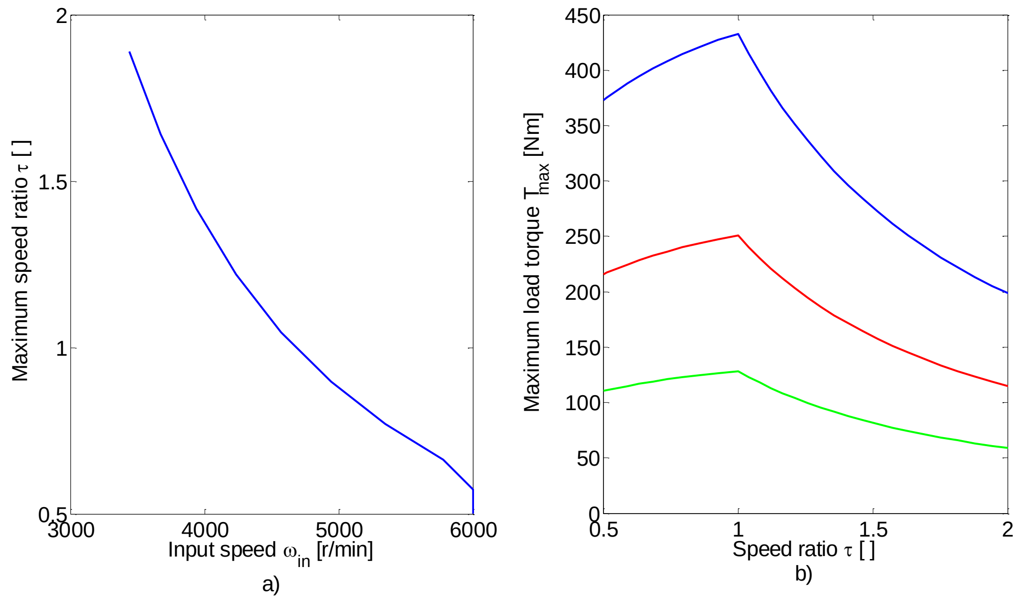

Figure 3: a) Effect of the input speed on the maximum allowable speed ratio. b) Maximum load torque as function of speed ratio for 3 maximum pressure values: 2.4 GPa (blue), 2 GPa (red) and 1.6 GPa (green).

The second boundary condition is the maximum load torque T_{max} which depends on the position of the roller γ which is related with the speed ratio τ, the maximum allowable pressure p_{max} imposed by the clamping force F_{Din} and the geometrical parameters of the CVT [9]. Figure 3b) shows that the maximum pressure plays a vital role in the torque capacity of the CVT. As the maximum pressure is defined in the design stage, the pressure will be kept constant at 2.4 GPa for the remainder of the paper. Speed has no impact on the torque capacity.

4. Efficiency of the CVT

The steady state efficiency of a CVT is calculated as follows:

$$\eta = \frac{T_L \omega_{out}}{T_{in} \omega_{in}} \qquad (3)$$

This efficiency formulation can be split up in an efficiency term for speed η_ω and torque η_T:

$$\eta = \eta_\omega \eta_T \qquad (4)$$

The speed efficiency term η_ω is related to the slip (see eq. (1)) while the torque efficiency η_T can be expressed in terms of traction coefficients:

$$\eta_T = \frac{\mu_{out} - \chi_{out} \sin(\theta - \gamma)}{\mu_{in} - \chi_{in} \sin(\theta + \gamma)} \qquad (5)$$

In eq. (5) the input and output traction coefficients are respectively μ_{in} and μ_{out}. The spin coefficients are denoted as χ_{in} and χ_{out}. The main problem of this analytical formulation of the efficiency is that the relation with measurable parameters is lost. Therefore, the authors chose to work with eq. (3).

Based on eq. (3) it is possible to reformulate efficiency as a function F of 4 input parameters:

$$\eta = \mathrm{F}(\omega_{in}, T_L, \tau, F_{Din}) \quad (6)$$

This 5 dimensional relation cannot be visualized in an efficiency map but the function F includes both stable as unstable conditions. Unstable conditions are combinations of input speed, load torque, speed ratio and clamping force for which slip will increase above feasible values. It is for instance impossible to transmit torque without clamping force, independent on the input speed and speed ratio. If the unstable conditions are excluded by proper slip control through F_{Din}, eq. (6) can be rewritten as:

$$\eta_s = f(\omega_{in}, T_L, \tau) \quad (7)$$

This means that, with a proper slip controller implemented, the efficiency depends only on the input speed, the load torque and the speed ratio. This does not result in a restriction on the proposed method as a CVT is always provided to the end user with proper slip control.

The problem is now reduced from 5 to 4 dimensions. This reduction makes it possible to visualize the efficiency in an contour plot (3 dimensions) where one of the parameters is kept constant. The question remains which parameter will be kept constant and how significant the impact of that parameter is on the efficiency.

On the contour plot (Figure 4), efficiency is be plotted as function of speed ratio and load torque. This option is chosen because literature mentions torque and speed ratio as dominant parameters in terms of efficiency. Furthermore, CVTs are often used in applications where the input speed is held as constant as possible by manipulating the speed ratio as function of the load characteristics. As a consequence, input speed is kept constant but as stated in the previous paragraph, its effect on efficiency will be analyzed later on.

a) Impact of the speed ratio and load torque on the efficiency

Visualizing the efficiency in an efficiency map tells much more than a single efficiency value in optimal conditions (see Figure 4). It gives an overview on the operating range and gives an idea on how the efficiency is influenced by the operating point. The blue line on top of the operating range is the maximum torque (also shown in Figure 3b)) based on the equation presented in [9].

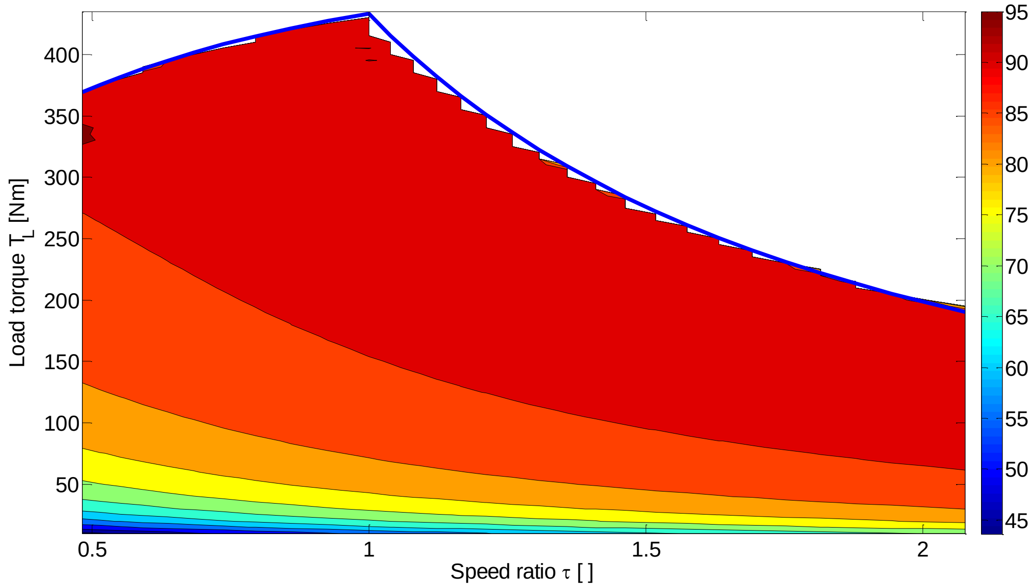

Figure 4: Efficiency of the CVT as function of speed ratio and load torque for an input speed of 3000 r/min.

b) Impact of input speed on the efficiency

The efficiency map presented in the previous subsection describes the energetic behavior at a specific input speed i.e. 3000 r/min. The question remains what the impact will be if the input speed is changed.

In Figure 5a) the input speed is varied for several different load torques and a constant speed ratio. From this figure it is possible to conclude that there is a linear trend between efficiency and input speed in the greater part of the operating range. It is also noticeable that the effect of the input speed becomes smaller for a larger load torque. In Figure 5b) the efficiency as function of varying input speed and speed ratio is shown. In terms of speed ratio it is possible to state that for a higher speed ratio, the impact of increasing input speed becomes more dominant. As with Figure 5a) there is again a linear trend noticeable. Only at low speed ratio (blue dots in Figure 5b) and low input speed there is a deviation from the linear prediction.

The bearing losses are responsible for these deviating results. The conditions for these outliers are characterized by a low bearing speed for which the losses increase rapidly for increasing input speed [12]. As the losses increase, the efficiency of the CVT decreases until an input speed of 2000 r/min. This effect diminishes at higher input speed because the bearing losses become less dominant in comparison with traction losses inside the CVT.

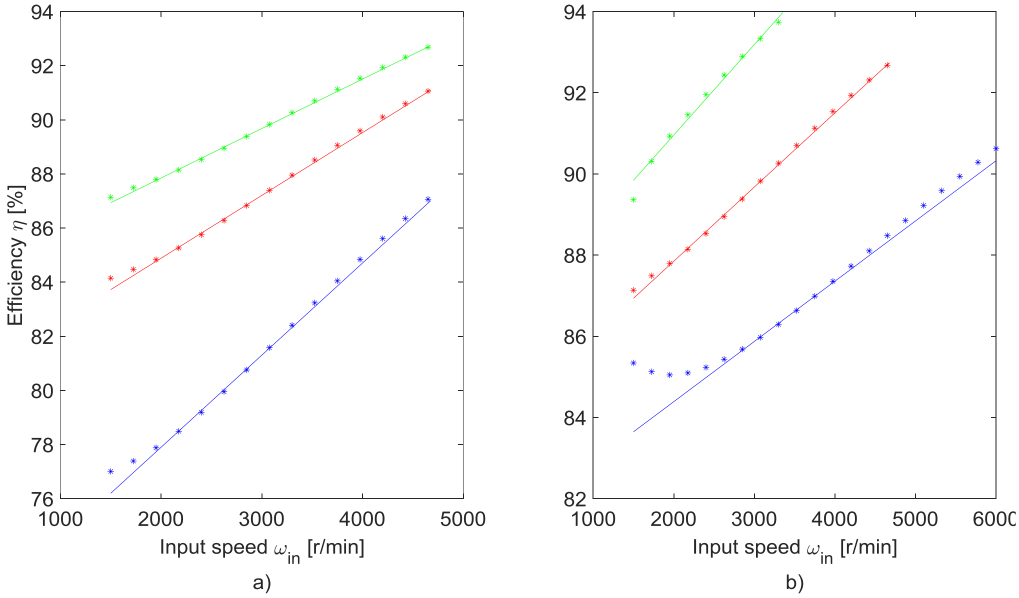

Figure 5: a) Efficiency as a function of the input speed at a speed ratio of 1 for 3 different load torques: 50Nm (blue), 100Nm (red) and 150 Nm (green). b) Efficiency as a function of the input speed at a load torque of 150Nm for 3 different speed ratio values: 0.5 (blue), 1 (red) and 2 (green).

5. Linearized efficiency

In the previous subsection a quasi linear relation was observed between input speed and efficiency. This means that the relation can be written as:

$$\eta(\tau, T_L) \approx k(\tau, T_L)\omega_{in} + c(\tau, T_L) \quad (8)$$

With k, the slope of the line, depending on speed ratio and load torque, and c the efficiency at standstill of the input shaft. As c has no physical meaning in this definition (no efficiency at standstill), eq. (8) has been rewritten as:

$$\eta(\tau, T_L) \approx k(\tau, T_L)\left(\omega_{in} - \omega_{ref}\right) + \eta_{ref}(\tau, T_L) \quad (6)$$

With ω_{ref} a certain reference speed in rad/s and η_{ref} the efficiency at the chosen reference speed for a given speed ratio and load torque. This expression describes the relation between an efficiency map $\eta_{ref}(\tau, T_L)$ defined at a certain reference speed ω_{ref} and an efficiency map $\eta(\tau, T_L)$ at a different input speed ω_{in} via the factor $k(\tau, T_L)$. In other words: the reference efficiency map becomes scalable via $k(\tau, T_L)$. The only question which remains is how $k(\tau, T_L)$ has to be defined.

Because it is not feasible to determine k for all possible speed ratio and load torque combinations a selection of points is proposed where k will be determined. These points are chosen based on speed ratio values which are spread throughout the speed ratio range and corresponding torque values which are equal to 95%, 50% and 25% of the maximum load torque (Figure 6). Another feature which has been added to Figure 6 are red lines indication the maximum speed ratio for a given input speed. These lines are a projection of Figure 3a on the operating range and indicate clearly how the input speed will limit the operating range.

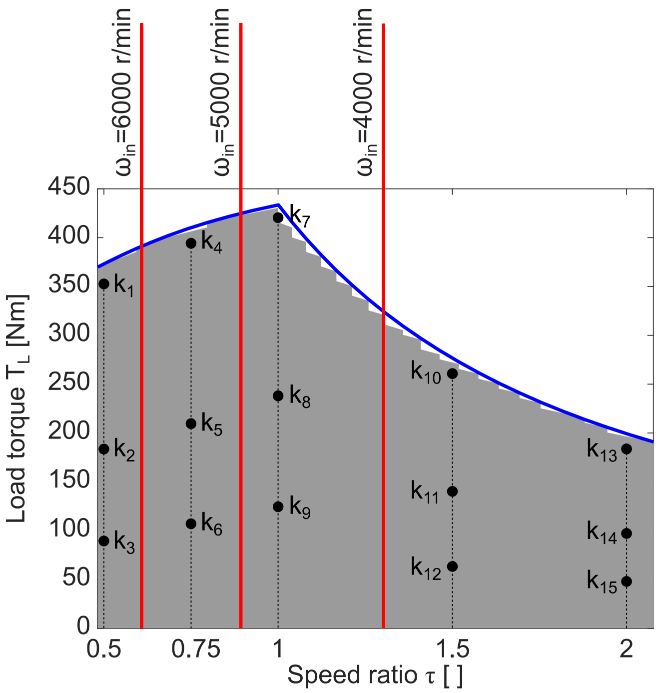

Figure 6: Location of the k values and boundary condition for torque (blue line) and speed ratio (red lines).

The results for the k values are given below:

$$K = \begin{bmatrix} k_1 & k_4 & k_7 & k_{10} & k_{13} \\ k_2 & k_5 & k_8 & k_{11} & k_{14} \\ k_3 & k_6 & k_9 & k_{12} & k_{15} \end{bmatrix} = 10^{-6} \times \begin{bmatrix} 83.82 & 91.75 & 94.72 & 148.15 & 188.85 \\ 124.41 & 142.45 & 140.55 & 208.43 & 266.12 \\ 187.04 & 204.07 & 211.62 & 307.04 & 391.52 \end{bmatrix} \quad (7)$$

The corresponding efficiencies can be found in the efficiency map (Figure 4) but are given here for the convenience.

$$\eta_{ref} = \begin{bmatrix} \eta_1 & \eta_4 & \eta_7 & \eta_{10} & \eta_{13} \\ \eta_2 & \eta_5 & \eta_8 & \eta_{11} & \eta_{14} \\ \eta_3 & \eta_6 & \eta_9 & \eta_{12} & \eta_{15} \end{bmatrix} = 10^{-2} \times \begin{bmatrix} 90.93 & 92.26 & 92.96 & 93.6 & 93.87 \\ 87.42 & 89.86 & 91.35 & 91.51 & 91.67 \\ 81.61 & 85.36 & 87.74 & 87.79 & 88.02 \end{bmatrix} \quad (8)$$

6. Numerical example

Figure 7 gives an overview of a numerical example at an input speed of 2000 r/min and 4000 r/min. The reference input speed is 3000 r/min. In Figure 7 simulation results (a) and b) are compared with calculated results (c) and d). To demonstrate the ease of the procedure, the highlighted number in Figure 7 c) is elaborated in the next paragraph.

The input speed is 4000 r/min and the reference speed is 3000 r/min. The marked location on Figure 7 c) is known as location 8 in Figure 6 which means k_8 and η_8 are needed. When these numbers are filled out in eq. (9), this results in:

$$\eta(\tau, T_L) \approx 140.55 \times 10^{-6} \left(\frac{4000.2\pi}{60} - \frac{3000.2\pi}{60} \right) + 91.35 \times 10^{-2} = 0.928 \quad (9)$$

The actual efficiency for that operating point, as simulated, is 93,1% which means that the efficiency is estimated with an error of 0.3%. If all considered points are taken into account, it is possible to state that the efficiency can be estimated with a mean error of 0.33% and a maximum error of 1%. This proves that a combination of Figure 4 and 6 could be very useful for end users of CVTs as it enables them to calculate the efficiency of every possible operating point within reasonable error bands.

If the end users are interested in a point for which there is no predefined k value, for example for a speed ratio of 0.9 and a load torque of 150Nm, it is possible to calculate the efficiency by interpolation between the surrounding efficiencies (location 5, 6, 8 and 9).

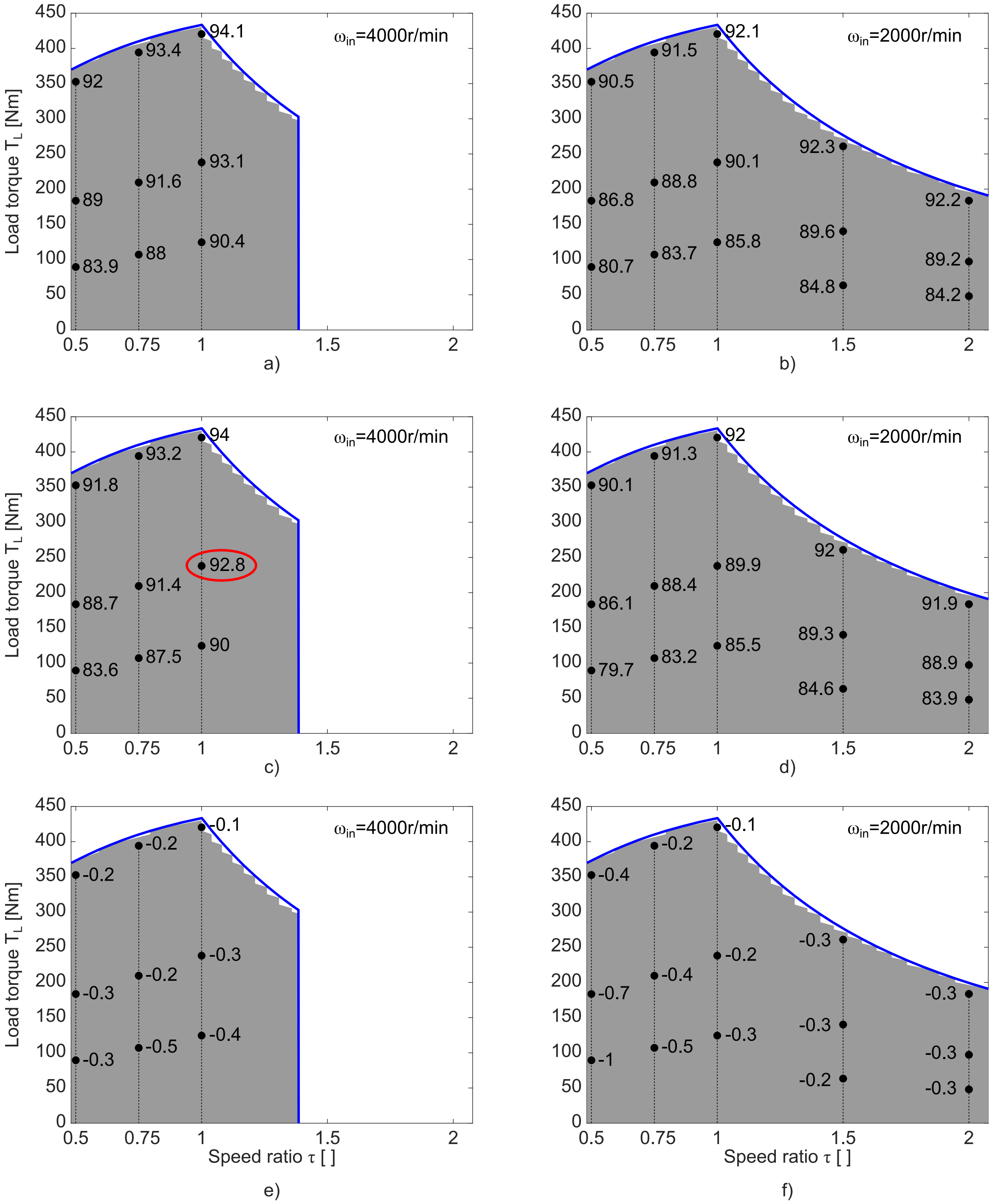

Figure 7: a) - b) Simulated efficiency values [%]. c) - d) Calculated efficiency values [%] based on eq. (9). e) - f) Error [%] on the presented method.

7. Conclusion

This paper discusses how the efficiency of a Continuously Variable Transmission can be visualized in a compact format. Efficiency can be written as function of input speed, load torque, speed ratio and clamping force which makes it unpractical to visualize efficiency in contour plots. The impact of clamping force can be eliminated if a proper slip controller is considered. By defining efficiency as a function of speed ratio and load torque it is possible to visualize the efficiency on a contour plot but then the impact of the input speed is neglected. In this paper it is shown that there is a linear relation between the efficiency and the input speed. By characterizing this linear relation, an equation could be set up which makes it possible to rescale a given efficiency map at a certain input speed to an efficiency map defined at a different input speed. A numerical example is added and it is shown that the mean error of the method is limited to 0.33%.

8. Acknowledgement

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9. References

[1] K. Stockman, S. Dereyne, D. Vanhooydonck, W. Symens, J. Lemmens, and W. Deprez, "Iso efficiency contour measurement results for variable speed drives," in *19th International Conference on Electrical Machines, ICEM 2010*, 2010.

[2] "Manufacturer's statement on Abb.com, (2017). ABB IE4 SynRM Motor-Drive Packages - Synchronous Reluctance Motor-Drive Packages.," *Accessed 26 June 2017*. [Online]. Available: http://www.abb.com/product/seitp322/51c4b5bba1fa1372c125785d003d389b.aspx .

[3] S. Dereyne, E. Algoet, P. Defreyne, and K. Stockman, "An energy efficiency measurement test bench for gearboxes," in *Energy efficieny of Motor Driven Systems*, 2013.

[4] S. Derammelaere, S. Dereyne, P. Defreyne, E. Algoet, F. Verbelen, and K. Stockman, "Energy efficiency measurement procedure for gearboxes in their entire operating range," *Ind. Appl. Soc. Annu. Meet. 2014 IEEE*, pp. 1–9, 2014.

[5] S. Dereyne, P. Defreyne, E. Algoet, and S. Derammelaere, "Efficiency measurement campaign on gearboxes," in *Energy efficieny of Motor Driven Systems*, 2015, pp. 1–11.

[6] G. Carbone, L. Mangialardi, and G. Mantriota, "A comparison of the performances of full and half toroidal traction drives," *Mech. Mach. Theory*, vol. 39, no. 9, pp. 921–942, 2004.

[7] H. Tanaka, N. Toyoda, H. Machida, and T. Imanishi, "Development of a 6 Power-Roller Half-Toroidal CVT," *NSK Tech. J. Motion Control*, vol. 9, pp. 15–26, 2000.

[8] T. Yamamoto, "Analysis of the efficiency of a half-toroidal CVT," *JSAE Rev.*, vol. 22, no. 4, pp. 565–570, 2001.

[9] F. Verbelen, S. Derammelaere, P. Sergeant, and K. Stockman, "Half toroidal continuously variable transmission: trade-off between dynamics of ratio variation and efficiency," *Mech. Mach. Theory*, vol. 107, pp. 183–196, 2017.

[10] T. Imanishi and S. Miyata, "Development of the Next-Generation Half-Toroidal CVT," *Motion Control*, vol. 14, no. 5, pp. 20–24, 2003.

[11] R. Fuchs, N. Mccullough, and K. Matsumoto, "The Making of the Full Toroidal Variator," *JTEKT Eng. J.*, no. 1006E, pp. 31–36, 2009.

[12] SKF, "Rolling bearing catalogue," 2013

Induction Motor Drive System Losses

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Abstract

This paper presents the results of standard 4-pole squirrel-cage induction motors' efficiency with a sinusoidal supply and with a PWM supply. The rated powers of these IE3 efficiency class motors are 15 kW, 37 kW and 75 kW. Each of these motors are tested using several different commercial frequency converters that use different control strategies and modulation methods to get an overview on motor loss rise with PWM supply. With frequency converter supply 16 to 30 operating points in speed-torque plane were measured to cover the normal operating range of VSDs. The losses are more carefully analyzed in 50 Hz and in 45 Hz operation points. Also, the losses of total drive systems are given. The motors' rated voltage level is used as the converter terminal voltage level as in normal industrial environment.

Introduction

Reference losses with sinusoidal supply are measured with IEC 60034-2-1 segregation of losses method performing the heat run test, no-load test and load curve test, and analyzing the different loss components [1]. The converter driven tests with multiple measurement points in frequency-torque plane have been performed using semi-automatic computer aided system controlled via LabVIEW. The parameters of the converters are factory defaults with the exception of slip compensation that is disabled in all converters. Normal input-output measurement procedure is utilized. One power analyzer is continuously measuring the electric power from converter input terminals and motor terminals. Two additional snapshot power analyzers are used to capture the voltage and current waveforms for further analysis such as harmonic analysis and switching frequency calculation. The torque and speed are measured using a state-of-the-art torque transducer.

Losses with sinusoidal supply

The reference losses are acquired applying IEC60043-2-1 segregation of losses procedure. The name plate values, power loss components and shares are presented in the Tables 1…3.

Table 1. The name plate values and power loss component shares for the 15 kW IM.

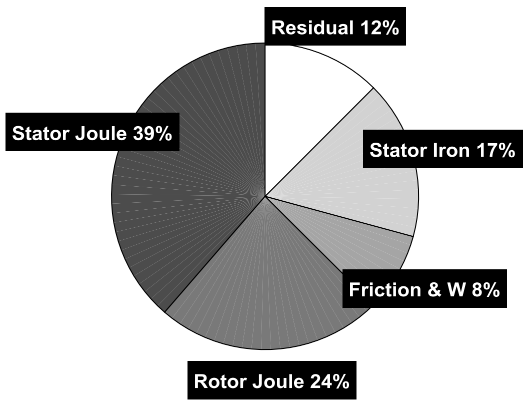
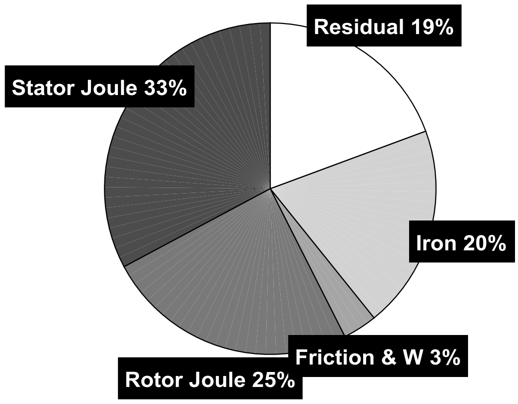
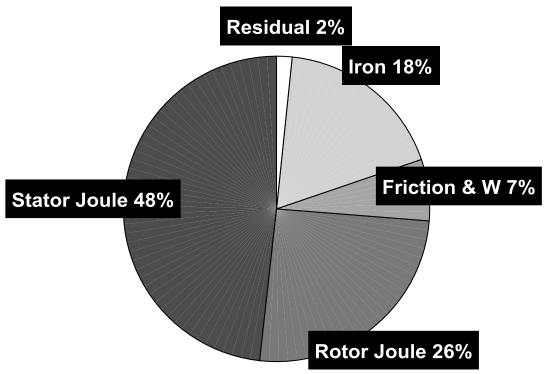
Motor 1. Name plate values.		**IEC loss share**
Power	15 kW	
Connection	Delta	
Voltage	400 V	
Current	27.8 A	
cos φ	0.84	
Efficiency	92.7% (IE3)	
Nominal speed	1474 rpm	

Table 2. The name plate values and power loss component shares for the 37 kW IM.

Motor 2. Name plate values.		**IEC loss share**
Power	37 kW	
Connection	Delta	
Voltage	400 V	
Current	65.4 A	
cos φ	0.86	
Efficiency	94.9% (IE3)	
Nominal speed	1482 rpm	

The 37 kW motor is the oldest one of these motors and it has been running much higher hours than the other two motors. The friction and windage losses have decreased over time as a result of thermal cycling and excess grease has moved off from the bearings.

Table 3. The name plate values and power loss component shares for the 75 kW IM.

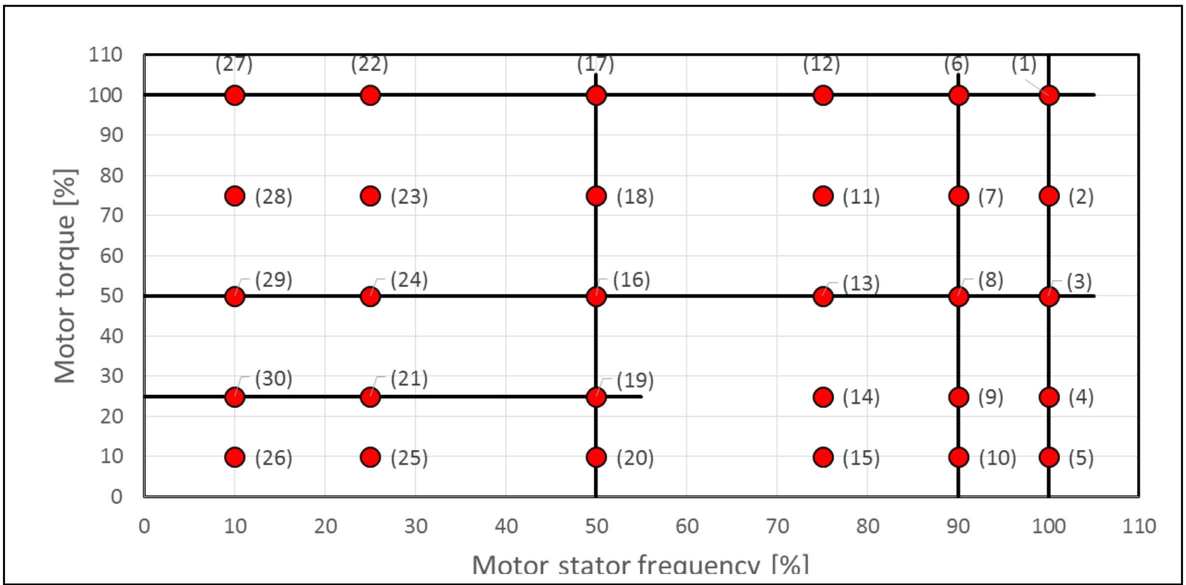
Motor 3. Name plate values.		**IEC loss share**
Power	75 kW	
Connection	Delta	
Voltage	400 V	
Current	133 A	
cos φ	0.85	
Efficiency	95.7% (IE3)	
Nominal speed	1486 rpm	

When comparing the motor loss shares in Tables 1, 2 and 3 we see that the general assumption that the stator joule losses are decreasing when we move to larger motors is not relevant in this case. Based on the IEC efficiency measurement [1] results of these three motors from the same product family and with the same efficiency classification, a general rule between motor size and loss component cannot be established.

Converter fed motor losses

In converter-fed measurements the motors' rated voltage was used as an input voltage level for the converter measured from the converter terminals. The voltage level can be considered to be normal in industrial environment. The measurements were performed in 30 points. The measurement points are shown as Figure 1. In the first point of the matrix (1) the motor is driven to thermal equilibrium and the measurements are continued with changing the load torque values and keeping the frequency constant. After 50 Hz frequency the 45 Hz output frequency was used and the load torque values was set in the descending order. After 45 Hz measurement points, the frequency was changed to 37.5 Hz (75%) and the motor was kept running 30 minutes in points (11) as well as in as in the rest of diagonal points of the matrix (16), (21) and (26) to stabilize the motor temperature closer to normal operating temperature near these points.

Figure 1. The order or the measurement points with frequency converter supply.

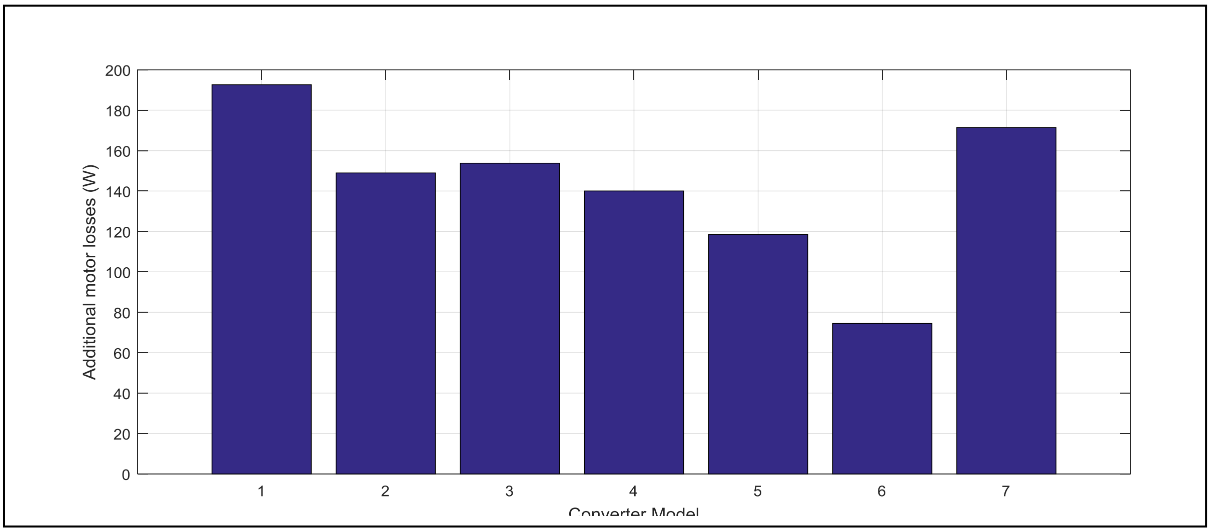


Since the comparison between the converters at all load points is impossible in the scope of this paper, the analysis is based on selected points. In the measurements, the frequency converter parameters were factory defaults, but the slip compensation was disabled in all converters to keep the frequency values fixed and to keep the slip value more reliable indicator of the motor losses.

Converter-fed 15 kW IM at 50 Hz operating point

The 15 kW motor loss rise compared to the sinusoidal supply is shown in Figure. 2 with 7 different converters.

Figure 2. 15 kW IE3 induction motor's additional losses with 50 Hz converter supply compared to the sinusoidal supply with nominal load torque. The numbers represent different converter models.



The losses in the normal 50 Hz operating point are increased due to lower fundamental wave voltage resulting in higher current value and increased voltage distortion due to overmodulation and due to decreased switching frequency that is caused by maximizing the voltage using long voltage vectors. The loss increase compared to the sinusoidal supply was from 5.7% (converter 6) to 14.9% (converter 1). To further analyze the results, we can calculate the increased stator and rotor Joule losses using the well-known equations

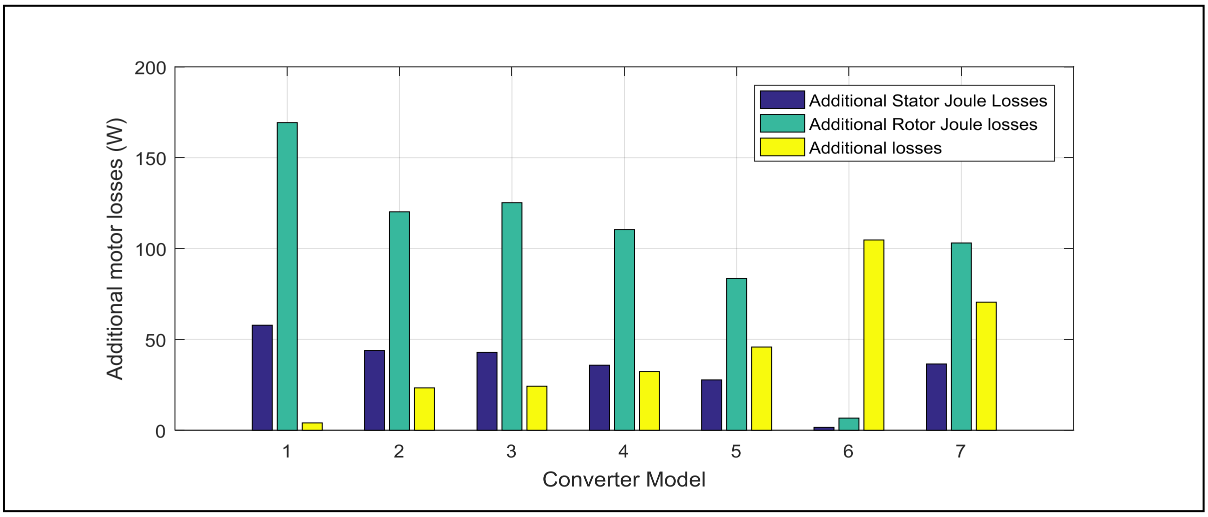
$$P_s = 1.5 R_H I_H^2 \tag{1}$$

where I_H is the stator phase current and R_H is the winding line-to-line resistance during heat run test; and

$$P_r = (P_1 - P_s - P_{Fe})s, \tag{2}$$

where $P_1$is the electric input power, P_s is the stator winding losses, P_{Fe} is the iron loss from the no-load test, and s is the slip. The stator Joule losses can be calculated using the temperature corrected resistance value equal to converter heat run. Similarly, the rotor Joule losses can be calculated using the sinusoidal supply iron loss value with electric power and slip value obtained from frequency converter heat run. The additional stator and rotor Joule losses as well as the remaining additional loss component are shown in Figure 3.

Figure 3. 15 kW IE3 motor's additional loss components with 50 Hz converter supply compared to the sinusoidal supply.

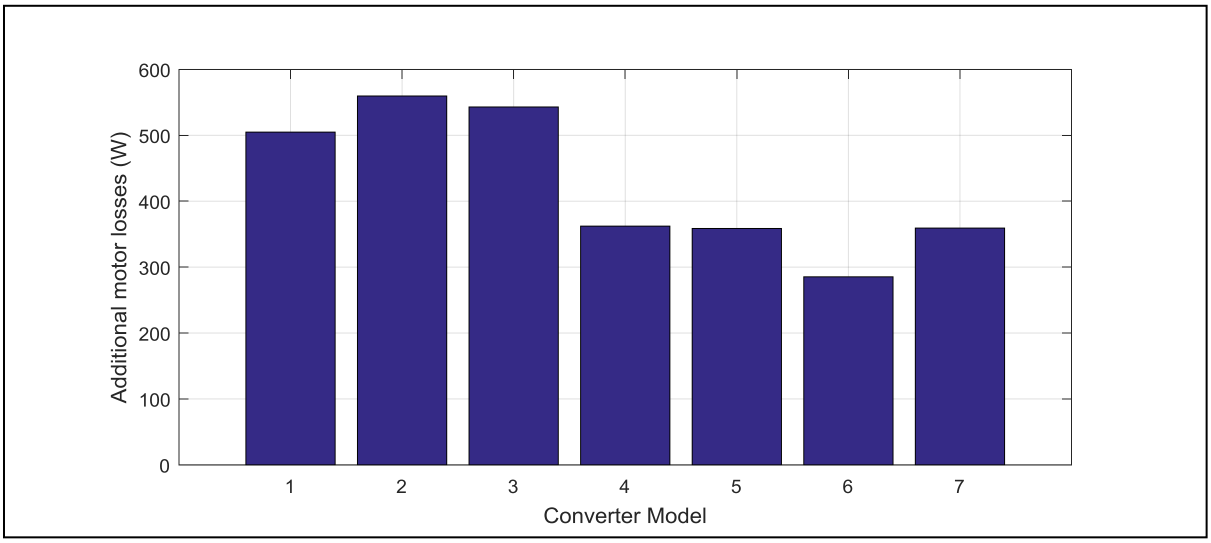


The loss components in the Figure 3 cannot be considered to be absolute right since the fundamental wave voltage and the resulting iron losses can be slightly different with different converters. In general, the trend is obvious, the increased stator current value is resulting in higher Joule losses in the stator and the increased stator temperature due to increased loss value results also to higher slip related rotor Joule losses. The additional loss bar in the figure can be thought to be an indicator for voltage waveform quality produced by the converter modulation method in this point. The following conclusion can be made from the results in Figures 2 and 3: the higher the voltage level is, the less additional losses are generated to the motor and the voltage quality is not as important as the fundamental wave amplitude.

Converter-fed 37 kW IM at 50 Hz operating point

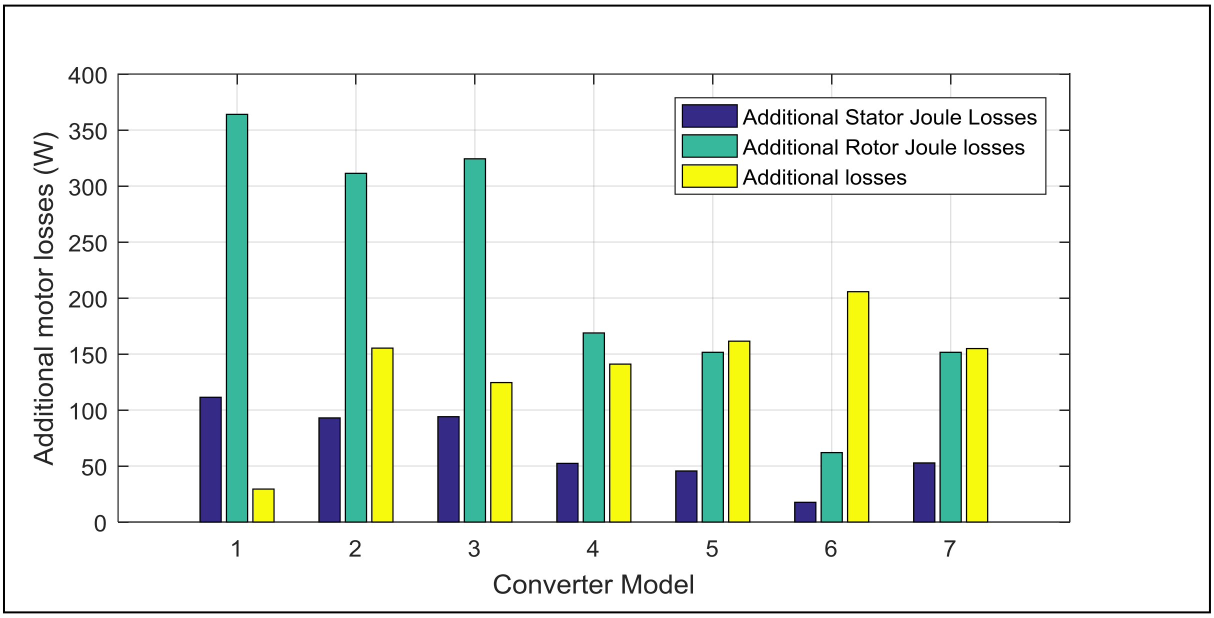
Similar procedure was used for 37 kW motor as with 15 kW motor. The converter models and numbering in the figures are the same for both motors. Converters of the same brand and model but with higher power rating are used to drive the 37 kW motor as the 15 kW motor. The loss rise compared to the sinusoidal supply is shown in Figure 4.

Figure 4. 37 kW IE3 induction motor's additional losses with 50 Hz converter supply compared to the sinusoidal supply with nominal load torque. The numbers represent different converter models.



The loss rise compared to sinusoidal supply in this case is from 13% (converter 6) to 25.5% (converter 2). In general, the additional losses in frequency converter use are much higher with 37 kW machine than with 15 kW machine. The converter model '6' is best for both power ratings. The IEC loss component shares (see Table 1 and Table 2) of these two machines are not very different but the additional load losses of this 37 kW motor are extremely high. The additional loss components for the 37 kW motor are shown in Figure 5.

Figure 5. 37 kW IE3 motor's additional loss components with 50 Hz converter supply compared to the sinusoidal supply.

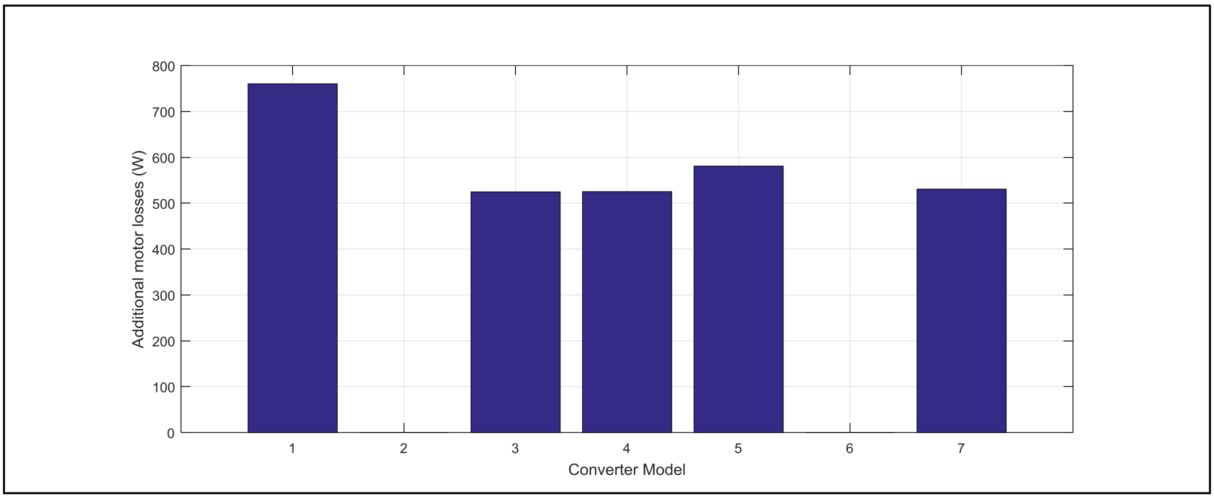


The trend in the loss components behaves similarly as for 15 kW motor. The additional loss value that can be considered to be a voltage quality index is smallest with converter 1 for 15 kW motor and the value increases as the converter model number increases. In the 37 kW motor results the only difference to this trend is converter 2.

Converter-fed 75 kW IM at 50 Hz operating point

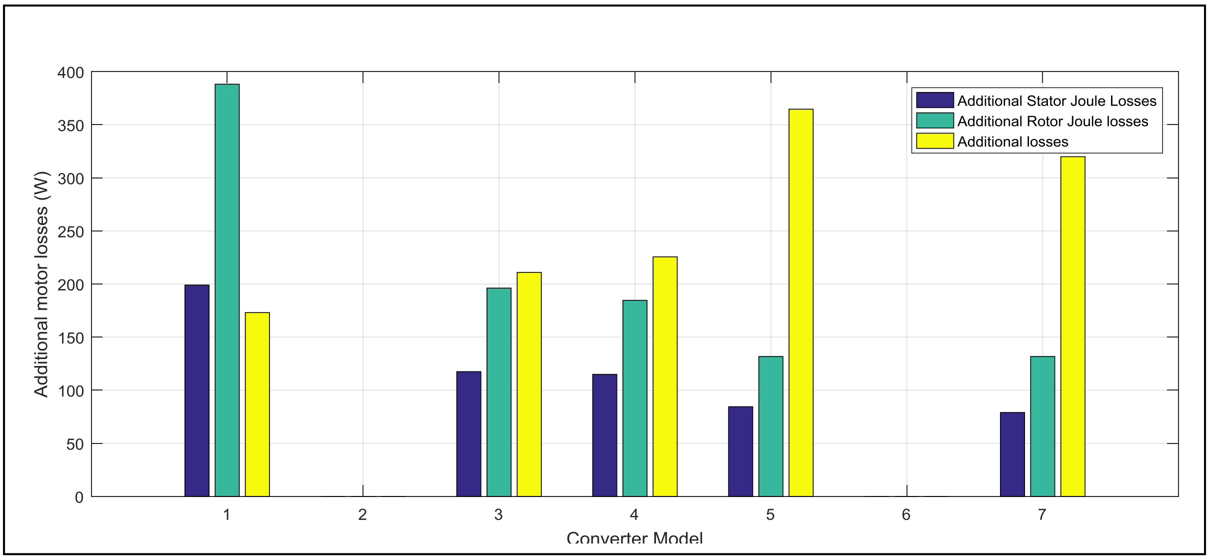
Again, a similar procedure was used for the 75 kW motor as with the two smaller motors. Also the converter models and numbering in the figures are the same, but the 75 kW motor measurements were performed with only five converters (converters '1', '3', '4', '5' and '7'). The loss rise compared to the sinusoidal supply is shown in Figure 6.

Figure 6. 75 kW IE3 induction motor's additional losses with 50 Hz converter supply compared to the sinusoidal supply with nominal load torque. The numbers represent different converter models. Models 2 and 6 were not available for the measurements with the 75 kW motor.



The motor loss rise compared to sinusoidal supply is from 17.3% with converter '3' to 25.1% with converter '1'. The converter model '6', which gave the smallest loss rise for the 15 kW and 37 kW motors, is missing from this series. While the average loss rise for the 15 kW motor was 11%, the exactly same 19.3% average loss rise was measured for both 37 kW and 75 kW motors in this 50 Hz operating point.

Figure 7. 75 kW IE3 motor's additional loss components with 50 Hz converter supply compared to the sinusoidal supply



Similar behaviour of the loss compontes is examined here as with the smaller motors. The lower voltage value gives rise to the stator current value and resulting stator Joule losses are higher. With smaller motors the rotor joule loss is the most dominating additional loss component, but here its impact is smaller while the additional losses component is more dominating.

Converter-fed IM at 45 Hz operating point

The 45 Hz point is an interesting measurement point in the standardization point of view. At 45 Hz point the voltage waveform is not as distorted as in the 50 Hz point since there is more voltage available for the converter to generate the output voltage waveform. The 45 Hz point can be normally driven with constant *U*/*f* ratio without field-weakening or overmodulation. The motors have not been measured with sinusoidal supply at 45 Hz stator frequency and thus we don't have direct loss results for comparison. Therefore, we compare the total loss values. The total motor losses with the different converters at 45 Hz operating frequency and 100% torque are shown in Figures 8, 9 and 10.

The order of the converters is different in Figure 8 than in Figure 2 presenting the 50 Hz point results. The order of the converters at 50 Hz point was: 1,7,3,2,4,5,6 in the descending order of additional motor losses. An average of 2.7% loss rise is seen here at 45 Hz point with 100% load torque compared to sinusoidal supply losses obtained with IEC 60034-2-1 segregation of losses method. The converter number '6' is driving the motor with smallest losses also in this point while the order of the other converters is mixed.

Figure 8. 15 kW IE3 motor losses with converter supply (45 Hz, *T*=100%). The dashed line presents the loss level obtained with IEC 60034-2-1 segregation of losses method with 50 Hz sinusoidal supply.

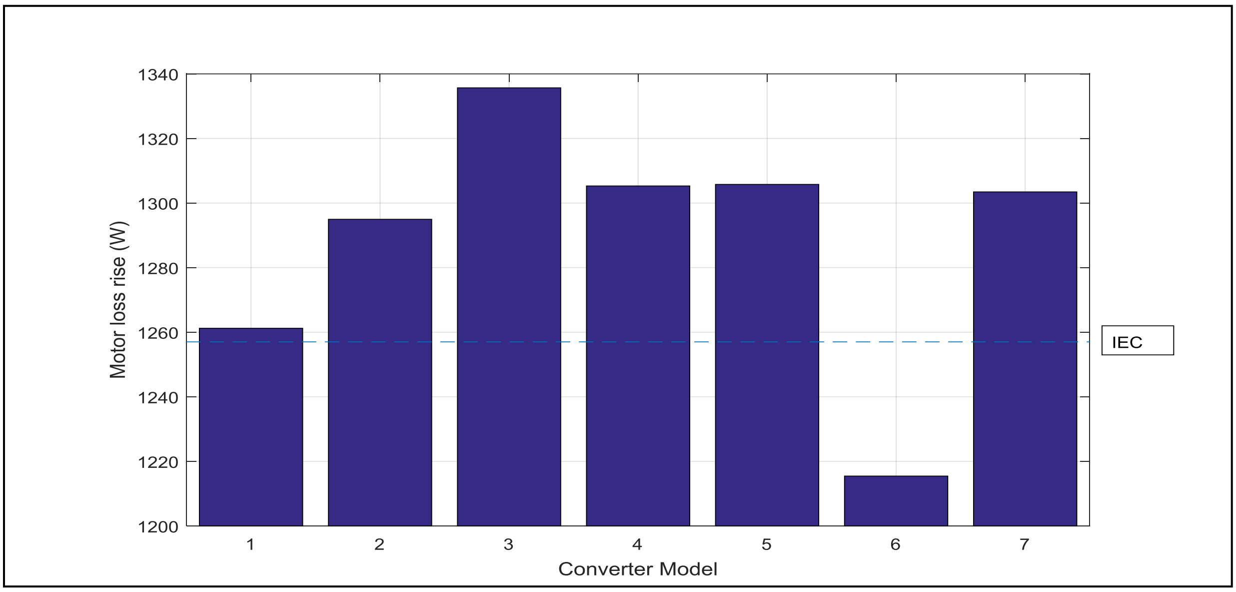
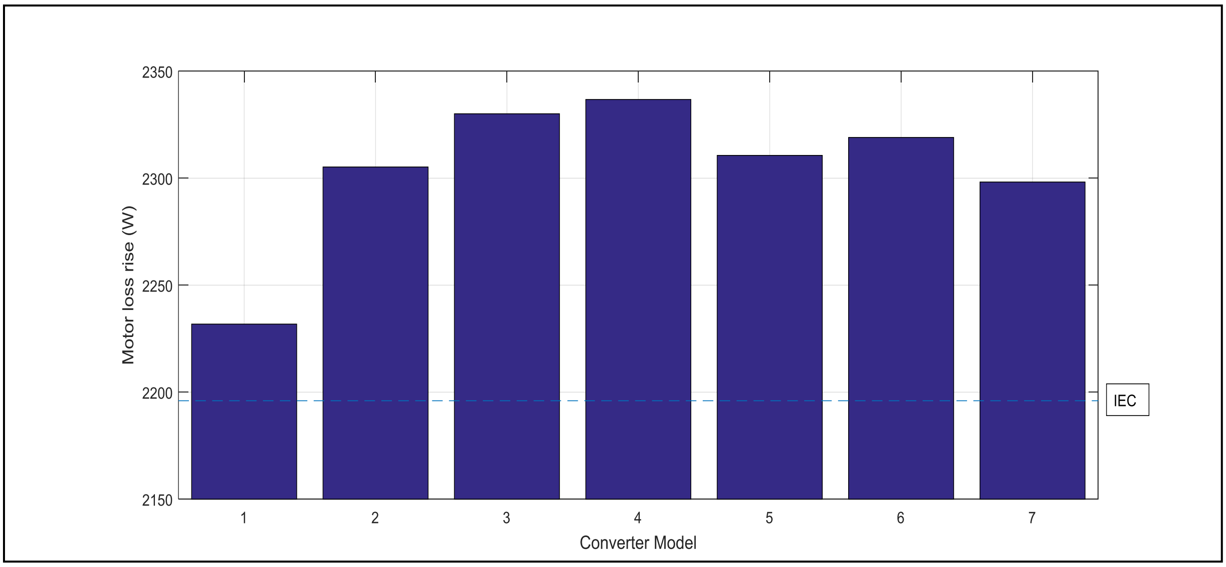
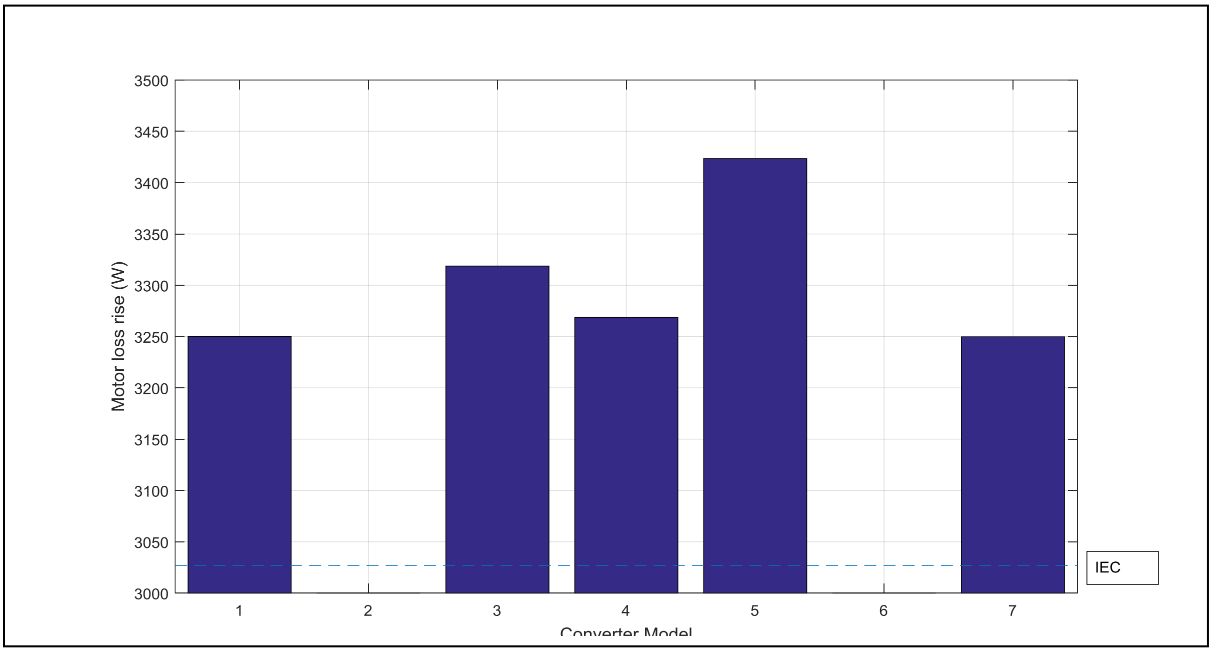


Figure 9. 37 kW IE3 motor losses with converter supply (45 Hz, *T*=100%). The dashed line presents the loss level obtained with IEC 60034-2-1 segregation of losses method with 50 Hz sinusoidal supply.



The 37 kW motor losses behave totally differently than the 15 kW motor losses when using the 45 Hz stator frequency. The motor losses obtained with all converters are above the sinusoidal supply losses at 50 Hz point. Also the converter models and the resulting losses between the 45 Hz point and 50 Hz do not match. With 15 kW motor, the converter '6' was the best in the both operating points and with 37 kW machine at 50 Hz point but now it has third highest loss value. The motor losses obtained with converter '1' were the third highest at 50 Hz point but here it gives by far the smallest motor losses. Naturally, the voltage quality affects more to the loss rise in the 45 Hz point than in the 50 Hz point, and in the 50 Hz point the additional loss component (Figure 5) with converter '1' is smallest and with converter '6' highest. The loss behavior difference between 15 kW and 37 kW motors can be thought to be a result of the additional load losses with sinusoidal supply. The high value of additional load losses with sinusoidal supply may also indicate higher amount of harmonic losses with converter supply.

Figure 10. 75 kW IE3 motor losses with converter supply (45 Hz, *T*=100%). The dashed line presents the loss level obtained with IEC 60034-2-1 segregation of losses method with 50 Hz sinusoidal supply.

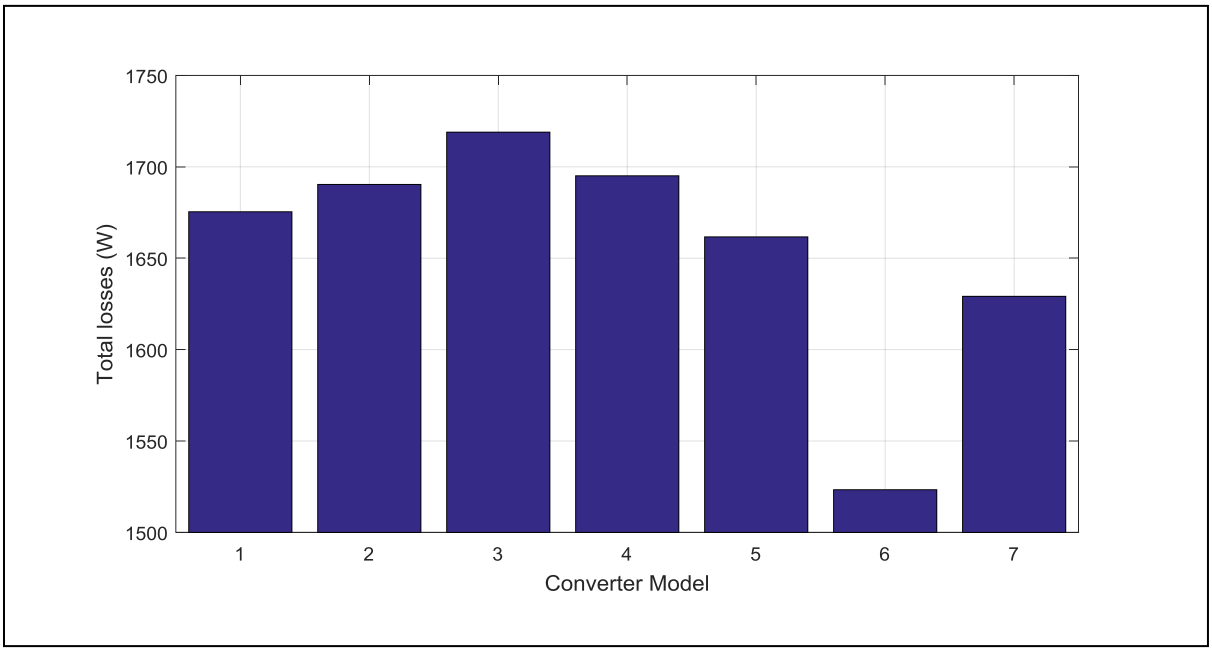


The average motor loss rise of the 75 kW motor at 45 Hz point is 9% compared to sinusoidal supply losses at 50 Hz point. With 37 kW motor the average was 4.7% and for 15 kW motor 11%. For 75 kW motor the converter '1' was the worst in 50 Hz point while it is best in the 45 Hz point.

Total drive system losses

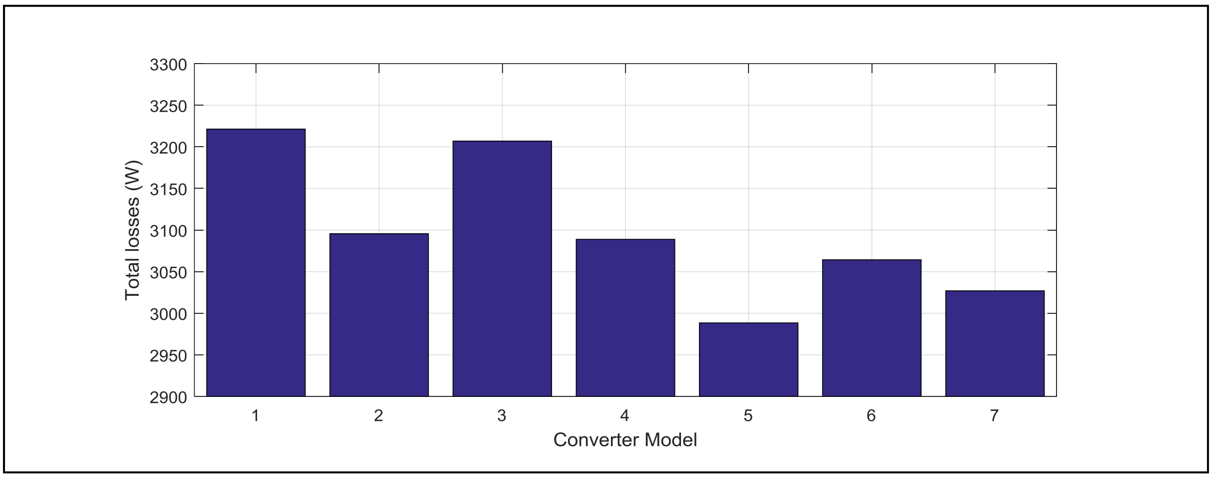
The switching frequency is the crucial parameter in dividing the losses between the converter and the motor. The true applied switching frequency can be calculated from the measured waveform [2]. In general, the higher the switching frequency the lower the motor loss rise compared to the sinusoidal supply is, but the higher switching frequency gives rise to the losses at the inverter bridge. Therefore, it is more convenient to compare the total drive system losses [3] that are the sum of the converter losses and the motor losses. The drive system losses at 45 Hz operating point with 100% load torque are given in Figures 11, 12 and 13 for 15 kW motor and drives, 37 kW motor and drives and 75 kW motor and drives, respectively.

Figure 11. 15 kW IE3 drive system losses with different converters.



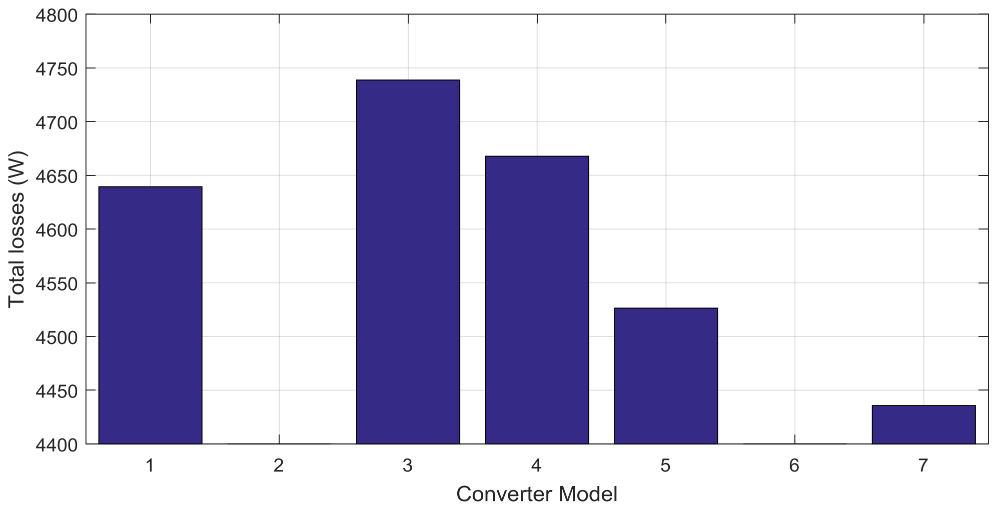
The differences between the total drive system losses are quite small. For comparison the IES1 level is 2997 Watts and therefore we can denote all these drive systems to be highly energy efficiency. It should be noted that the classification assumes IE2 level instead of IE3 motor used here, but still the difference is huge. The converter '6' was driving the motor with smallest losses and also the total drive system losses are smallest. The average loss value for the 15 kW drive system is 1656 W resulting to a 90.0% conversion efficiency measured from converter terminals to shaft power.

Figure 12. 37 kW IE3 drive system losses with different converters.



The 37 kW total drive system losses are extremely hard to analyze. In this operating point the converter '1' was driving the motor with lowest loss value but still the total drive system losses are highest. The low motor losses ends up with lower current value and also as a follow-up effect also the converter current related losses are minimized, but if relatively high switching frequency is used the switching losses are rapidly increased. The motor losses with converters 2 to 7 were in-between 40 watts but in the total drive system losses, more than 200 W difference between the converters '5' and '3' can be seen. The average losses with 37 kW drive system are 3099 Watts and the conversion efficiency is 92.3%.

Figure 13. 75 kW IE3 drive system losses with different converters.



The average losses of 75 kW drive system are 4601 W and the conversion efficiency 94.2%. The system loss differences between different converters are very small, less than 350 W that is around 7% of the system losses while the converted power is around 68 kW in this operating point.

Discussion

The results presented in this paper highlight how complicated is it to compare the energy efficiency of the different commercial converters driving the same motor. No single value can be used to present the energy efficiency in general without specific application. If an absolute order for different converters is needed, the only possible solution is to select a single operating point for comparison or a specific load cycle where the total consumed energy is examined. The energy savings arises using high efficient motors and driving the motors with converter based on the application needs. Using converters will save energy in applications where the control of rotational speed or fluid flow is needed but they will consume energy and they create additional harmonic losses to the motor and reduce motor lifetime, therefore they should not be installed in every system. All the converters tested here can be said to be highly efficient and they can be used to reduce the system energy consumption. The converters were driven here with factory defaults for simplicity and the losses might be totally different if the parameters would have been optimized. The 50 Hz point is the most complicated point for comparison but it actually gives a hint how good the converter-fed motor's energy efficiency is if the motor is driven above nominal speed. The 45 Hz point should be at linear region and it can be used to examine the converter energy efficiency driving the motor below nominal speed. Some of the converters measured here are using the voltage as a motor control variable while others are using the flux linkage. This fundamental difference gives slightly different voltage values with different load torque values and results in slightly different loss shares.

Conclusion

Based on the results of these three four pole IE3 motors with power ratings of 15 kW, 37 kW and 75 kW, no general rule between the sinusoidal supply efficiency, IEC loss components, motor power rating and the additional harmonic losses when used with a frequency converter can be drawn. The differences between losses obtained with the converters manufactured by different companies can be relatively large and they can vary between motor operating points. The IES loss levels are generally really high and the highest energy efficiency classification for drive system can be easily achieved.

References

[1] Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles), Ed. 2, IEC 60034-2-1, June 2014.

[2] L. Aarniovuori, H. Kärkkäinen, M. Niemelä and J. Pyrhönen, "PWM power distribution and switching frequency analysis in motor drives," *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, Florence, 2016, pp. 4356-4361.

[3] Ecodesign for Power Drive Systems, Motor Starters, Power Electronics & Their Driven Applications—Part 2: Energy Efficiency Indicators for Power Drive Systems and Motor Starters, European Std. EN 50598-2, Dec. 2014.

Performance Comparison of Three Different AC Variable Speed Motor Drives

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Abstract

Electric motors consume a substantial part of the electric energy generated worldwide. However, the concerns related to energy resources shortage are leading to the adoption of measures to improve energy efficiency and, hence, reduce the share of energy consumed by electric drives. The use of Variable Frequency Drives (VFDs) provides an effective way to reach such efficiency targets. Besides allowing the speed control of electric motors, enabling relevant energy savings in certain applications, VFDs are becoming increasingly popular due to their new capabilities and improved efficiency. To assess the performance of the latest state-of-the-art electric drives, this paper presents a comparison study of the most relevant AC electric drives based on three different motor types: squirrel cage induction motor (IM), permanent magnet synchronous motor (PMSM) and synchronous reluctance motor (SynRM). A detailed performance analysis is performed for each kind of drive by evaluating important parameters such as drive global efficiency, motor efficiency, power factor, input current and operating temperature. Then, a comparison analysis is made in order to highlight the most relevant advantages and disadvantages of each drive system.

1. Introduction

Electric motors play an important role in a wide number of applications. It is estimated that 44% to 46% of the electrical energy generated worldwide is consumed by this type of load. Currently, industry is the most important activity sector contributing to these numbers. Nearly 64% of the worldwide electricity consumption related to this sector is made by electric motors [1].

Implementation of measures that increment energy efficiency and cut the share of energy consumed by electric drives are underway. The development of motor standards aimed to promoting the adoption of highly energy efficient electric drives is one of those measures. The International Electrotechnical Commission (IEC), one of the most important organizations involved in the development of standards related to electric and electronic technologies, has developed standards concerning energy efficiency classifications for electric motors. The IEC 60034-30 standard created four levels of energy efficiency: Standard Efficiency (IE1), High-Efficiency (IE2), Premium Efficiency (IE3), and Super-Premium Efficiency (IE4) [2]. Many manufacturers have already introduced, in their portfolios, electric drives designed to comply with the IE4 efficiency class, allowing for lower operating costs and, consequently, higher economical revenue.

However, the development and proliferation of highly efficiency motors does not ensure, by itself, that the prominent energy efficiency targets are achieved in the industry sector. Other solutions should be implemented as well.

The main motor applications running in the industry include conveyors, pumps, fans and compressors. Some of those applications have potential to attain significant energy savings, as it is the case of fans and pumps, by simply controlling the motor speed according to the application requirements. Currently, this is not achieved in most cases, as the three-phase squirrel cage induction machine directly connected to the grid is, by far, the most prevalent electric drive used in the industry [3]. Variable Frequency Drives (VFDs) can effectively solve this problem. Recent developments in the power electronics field are boosting the diffusion of VFDs that are now more efficient and reliable than ever.

Power semiconductors are the key elements of a power converter, which means that efficiency, reliability and cost-effectiveness of a power converter depend mainly on the features of these devices. The development of the Silicon IGBT, for instance, allowed the development of lighter and cheaper power converters, with switching frequencies in the order of kHz, capable of handling medium to high power levels [4]. Other advantages of these kind of semiconductors include the low on-state resistance, high-voltage capability and insulated gate.

However, with the development of new materials in the semiconductor production, namely wide bandgap materials, it is expected that VFDs will become even more efficient, reliable, and cost-effective. The main advantages of these materials lie on their high electrical and thermal conductivity properties, and high blocking voltage capability. Several advancements in the power conversion, such as reduction of the thermal stress, lower switching and conduction losses, higher switching frequencies, and power converters with smaller passive components, will be possible as soon as wide bandgap semiconductors penetrate in the market in a large scale [5].

To evaluate the performance of the most common electric drives available in the industry, the next sections present a comparison study of the most relevant AC electric drives, based on three different motor types: squirrel cage induction motor (IM), permanent magnet synchronous motor (PMSM) and synchronous reluctance motor (SynRM). The comparison makes a general evaluation of each drive, supported by experimental results, considering parameters such as the motor and global drive efficiency, supply current and voltage, power factor and stator temperature.

2. Experimental Test Bench

To evaluate the performance of the three AC electric drives, the test bench shown in Figure 1 was built. It consists of a power converter, compatible with the three electric motors under analysis, supplying the AC electric motor, a digital power analyser, a hysteresis dynamometer and its controller.

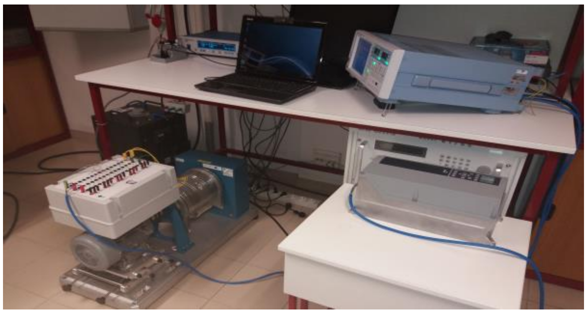


Figure 1: Experimental Test Bench

The motor speed is controlled by the power converter PumpDrive R (KSB202). The power converter uses a Voltage Vector Control (VVC+) strategy for the three drives. The load torque is imposed by the hysteresis dynamometer Magtrol HD-815, which is controlled by its programmable controller Magtrol DSP7001. Speed and load torque signals are sent from the programmable controller to the power analyser. Besides speed and load torque, other relevant signals are acquired/computed using the power analyser Yokogawa WT1800. The power analyser, connected in series with the power circuit in two distinctive points - input of the power converter KSB202 and input of the AC electric motor - measures the voltage, current and active power on those points, and computes other important parameters used for the drive performance analysis, such as power factor, mechanical power and efficiency. Figure 2 depicts an overview of the experimental setup.

The mechanical power at the motor shaft P_{mec} is determined using the load torque T_{mec} and the angular speed of the motor shaft ω_{mec} (1):

$$P_{mec} = T_{mec} \times \omega_{mec} \quad (1)$$

The converter and motor efficiency levels are important metrics in the assessment of the electric motor drive system performance. They are determined using the active power values, computed at the different points of the circuit.

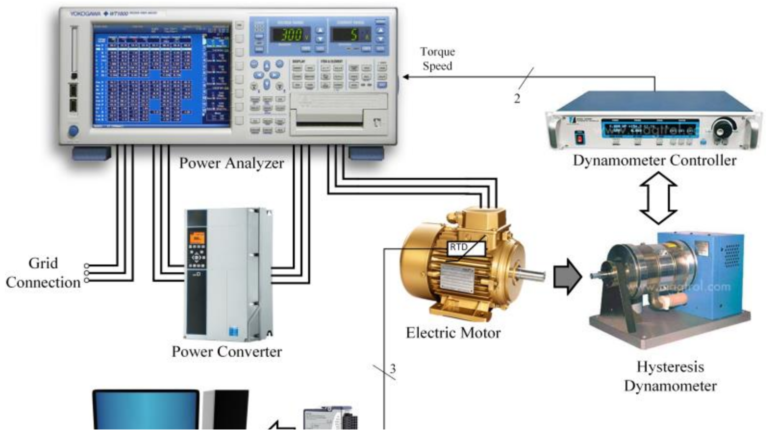


Figure 2: Experimental setup schematic view.

The converter efficiency η_{conv} is computed as the ratio between the active power at the converter input P_{in} and the active power at the motor input P_{motor}:

$$\eta_{conv} = \frac{P_{in}}{P_{motor}} \times 100\% \quad (2)$$

In the case of the motor, the ratio between the active power at the motor input P_{motor} and the mechanical power at the shaft P_{mec} gives the motor efficiency η_{motor}:

$$\eta_{motor} = \frac{P_{motor}}{P_{mec}} \times 100\% \quad (3)$$

In turn, the global drive efficiency η_{drive} is computed as the ratio between the input power and the mechanical power developed by the electric motor:

$$\eta_{drive} = \frac{P_{in}}{P_{mec}} \times 100\% \quad (4)$$

Another relevant metric of the drive performance is the power factor of the motor supply. It is calculated using the motor input power P_{motor}, the motor supply voltage $V_{ph\text{-}ph}$ and its line current I_l :

$$\cos(\theta) = \frac{P_{motor}}{S_{motor}} = \frac{P_{motor}}{\sqrt{3} \times V_{ph-ph} \times I_l} \quad (5)$$

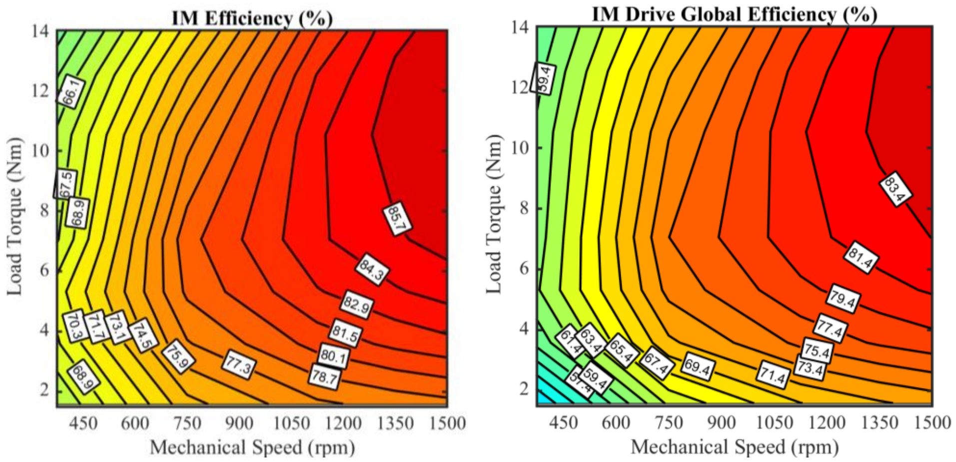
Detailed information regarding the technical parameters of the three electric motors used in the experiment can be found in Table I of the Appendix.

3. Experimental Results

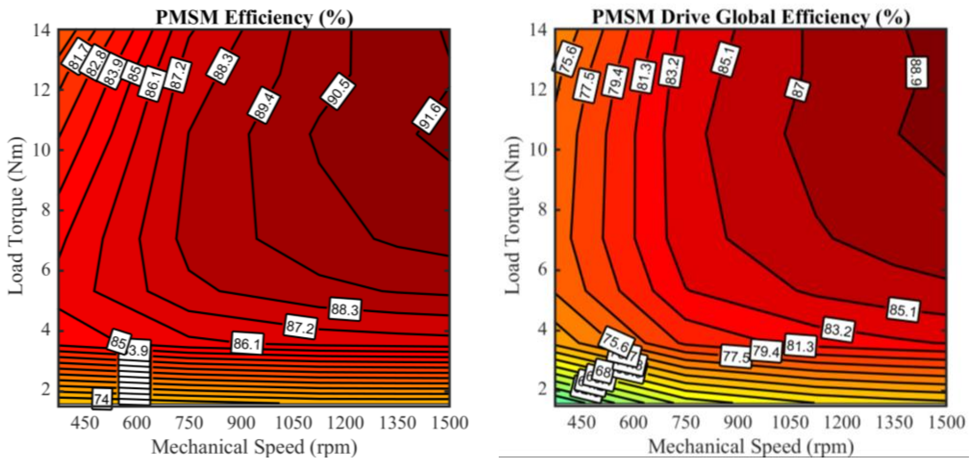
With the aim of fully understanding the capabilities and advantages of each electric drive, contour maps with the most relevant variables are plotted. A brief analysis of those maps is also presented. All three electric drives were operated over a wide range of load torque values, comprised between 1.4 Nm and 14 Nm (from 10% to 100% of rated torque), as well as a wide range of mechanical speeds, comprised in the range of 375 to 1500 rpm (from 25% to 100% of rated speed). The operation below 375 rpm was not considered in this work, as some electric drives subjected to the experimental tests were unable to operate under rated load torque condition for such low mechanical speed values (below 375 rpm), precluding a fair comparison between all three electric drives for such operating conditions.

3.1. **Efficiency**

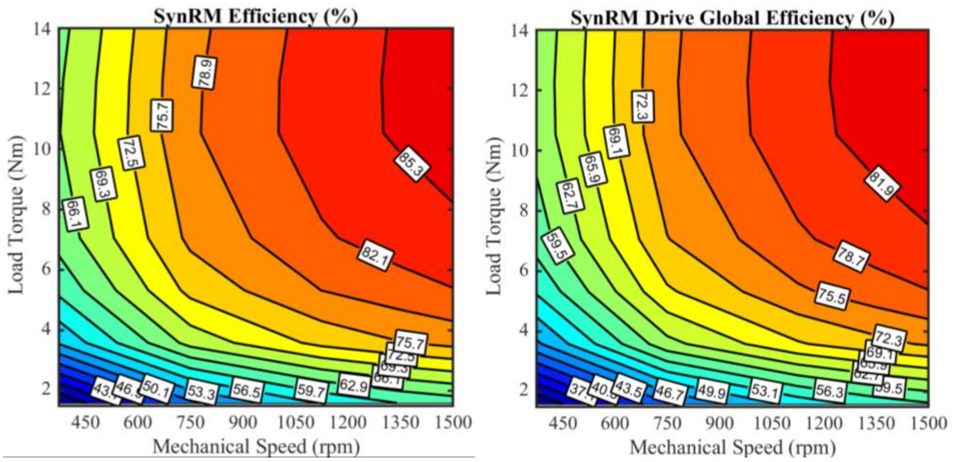
Figure 3 shows the efficiency maps of each electric drive under analysis.



(a)



(b)



(c)

Figure 3: Efficiency maps of the electric drives under analysis: (a) IM; (b) PMSM; (c) SynRM.

Efficiency maps on the left side are related to the AC electric motors, while the efficiency maps on the right side are related to the global electric drives, i.e., the set power-converter + motor.

Considering the AC electric motors efficiency maps (left side of Figure 3), it can be observed that, as expected, all the motors share the feature of high efficiency levels while operating at high rotational speed and load torque. At rated operating conditions, the PMSM shows the higher efficiency (91.7%), followed by the SynRM (86.6%), and the IM (86.3%). Nevertheless, a low variation of the PMSM efficiency with the speed is verified while the PMSM operates at low load conditions. The decay in the motor efficiency with the reduction of the motor speed is significantly higher in the case of the IM and the SynRM, if compared to the PMSM, demonstrating the high dependence of the IM and SynRM efficiency with the mechanical speed. Furthermore, the PMSM efficiency map shows a somehow significant decrease in efficiency, proportional to the load torque, when the load torque decreases below 4 Nm. The IM efficiency range is [66.1 - 86.3] %; in turn, the SynRM efficiency range is [34.2 - 86.9] %; and the PMSM efficiency range is [72.9 - 91.7] %.

Considering now the efficiency maps for the global drives shown on the right side of Figure 3, it is visible that no significant changes are introduced in their appearance when compared to the corresponding motor efficiency values. The efficiency increases with the motor rotational speed, reaching its peak for rated operating conditions. A more in-depth comparison between the motor efficiency and global drive efficiency also allow to testify a small reduction of the global drive efficiency as the load torque increases, as a result of higher conduction losses in the converter semiconductors. This trend is common to all drives, as the power converter used in the drive is a common element in all of them. At rated operating conditions, the IM and SynRM drives global efficiency reach 84.32%, while the PMSM drive reaches a global efficiency of 89.4%.

Small deviations between the experimental data and the expected values are verified in some of the efficiency maps presented in the paper. Such deviations might be a consequence of the power converter auto-tuning function, which determines some of the motor parameters autonomously. A thinner and more in-depth tuning of the motor parameters in the power converter would banish these small deviations.

3.2. Motor Supply Voltage and Current

Figure 4 presents the motor supply voltage (left side of Figure 4) and current (right side of Figure 4) related to each of the electric drives under study.

It can be stated that the supply voltage maps differ significantly between each other. In the IM drive (Figure 4a), the supply voltage is proportional to the mechanical speed and load level, especially while the drive operates at low load torque. However, the supply voltage tends to depend exclusively on the mechanical speed when the load torque is higher than 7 Nm (half rated torque). For the PMSM (Figure 4b) and SynRM drives (Figure 4c), the supply voltage shows a strong correlation with the mechanical speed, but meaningless correlation with the load torque.

Considering now the supply current (right side of Figure 4), it is easily stated that the supply current of the electric drives under analysis depend, most of all, on the load torque. Nevertheless, a small deviation from this behavior is stated in the IM drive (Figure 4a). Under rated load operation and low mechanical speed, a relatively significant increment in the supply current is verified. Also, the SynRM drive supply current map has a deviation from its typical variation at low speed and torque, where the supply current increases.

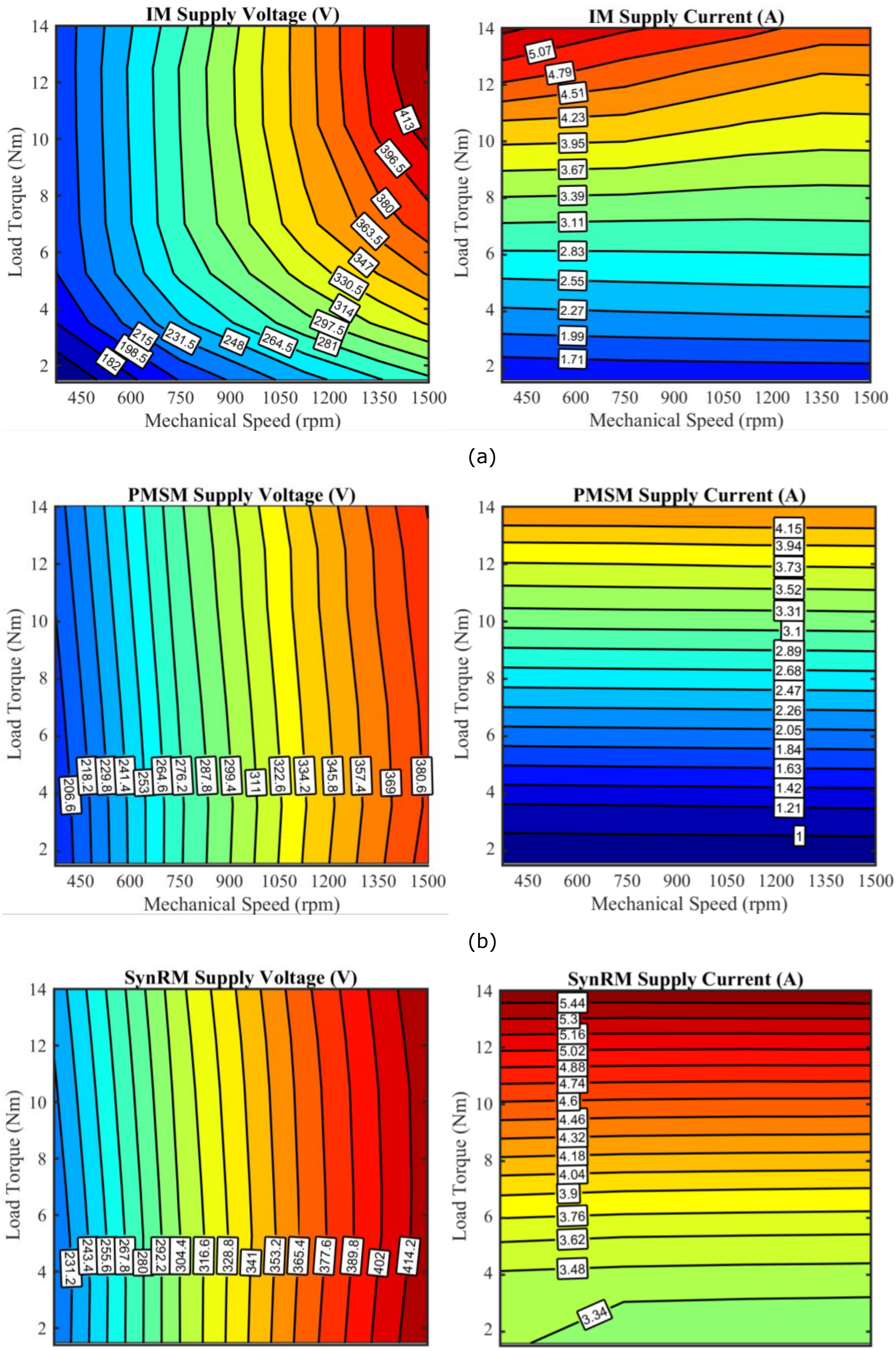
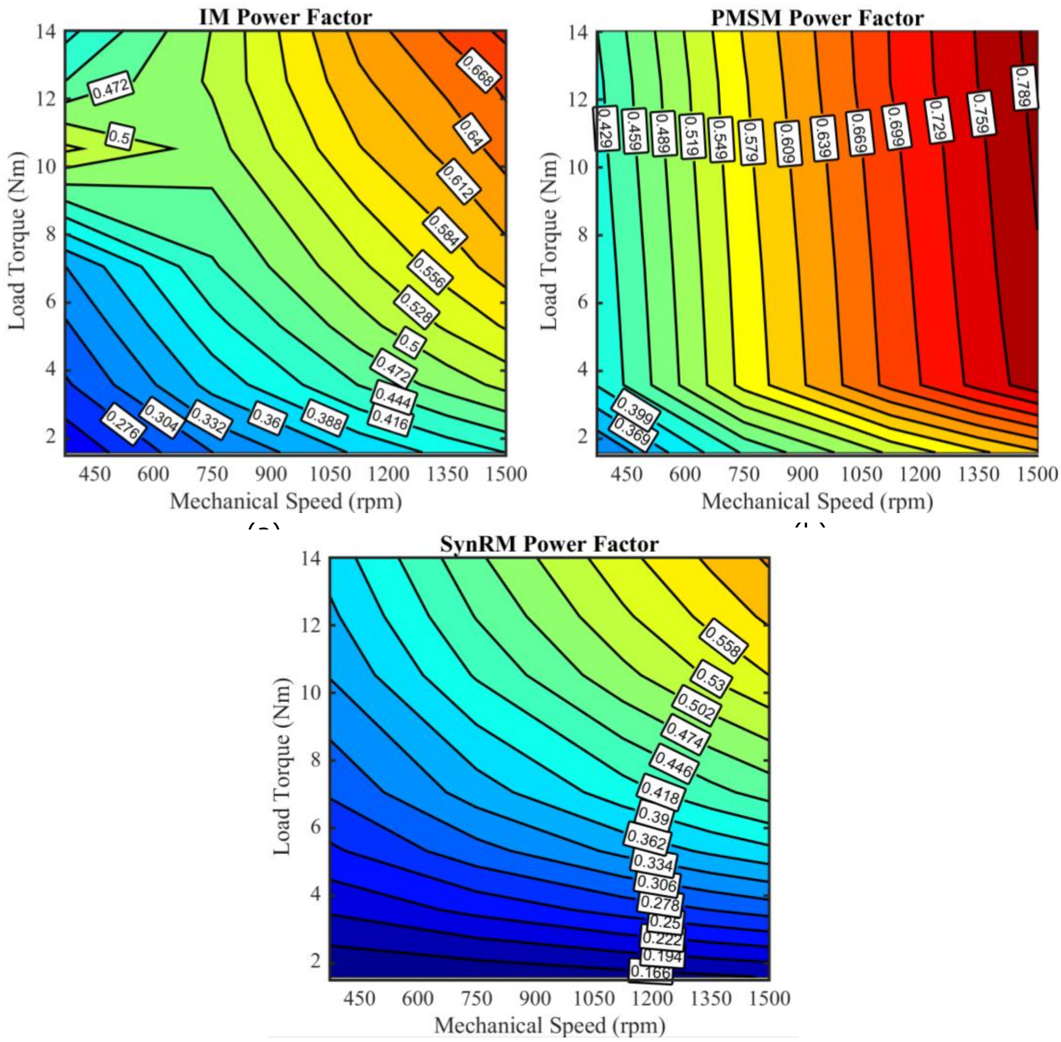


Figure 4: Motor supply voltage (left) and current (right) for: (a) IM; (b) PMSM; (c) SynRM.

3.3. Motor Power Factor

Figure 5 shows the power factor maps for the three electric drives used in the experiment. The power factor was calculated using the RMS phase-phase voltage $V_{ph\text{-}ph}$, RMS line current I_l, and motor input power P_{in} values, acquired with the power analyser. Equation (5) was used to compute the power factor for each operation point.



(c)

Figure 5: Motor power factor: (a) IM; (b) PMSM; (c) SynRM.

As depicted in Figure 5, the IM (Figure 5a) and SynRM (Figure 5c) drives power factor is proportional to the mechanical speed and load torque level. However, a small deviation occurs in the IM drive, when a high load torque and low mechanical speed is imposed. The power factor decrement results from the higher supply current of the drive on this operating condition, as visible in Figure 4a. For the PMSM drive, the power factor (Figure 5b) depends mainly on the drive mechanical speed, especially when the load torque is higher than 4 Nm. Below this torque level, the power factor has a proportional relation with the mechanical speed and load torque. As expected, the PSMM drive shows the highest power factor at rated operating conditions (0.80), followed by the IM (0.70) and the SynRM (0.62).

3.4. Efficiency at different operating points

Figure 6 and Figure 7 depict the efficiency curves for both motor and global drive, considering changes in a single parameter: load torque (Figure 6) or mechanical speed (Figure 7)

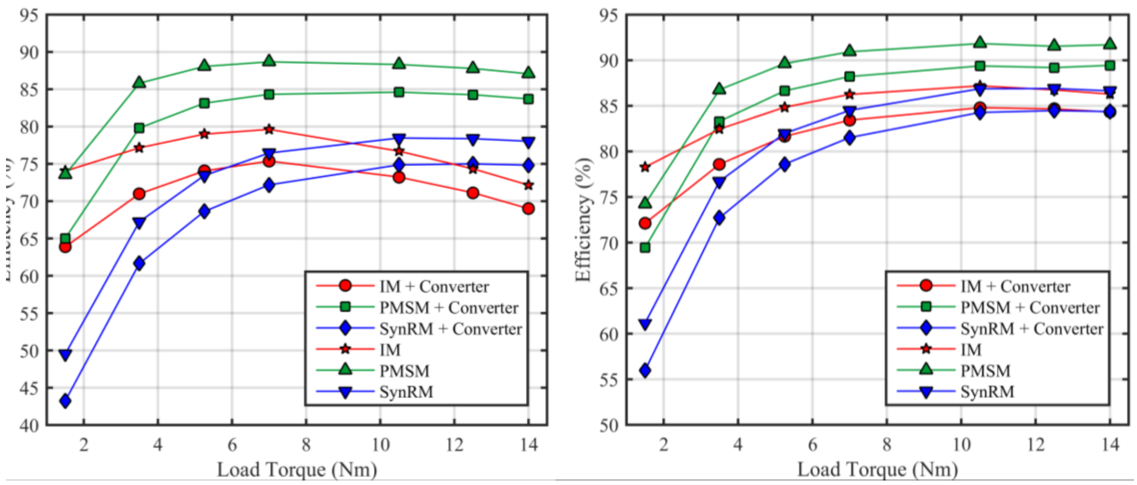


Figure 6: Motor and global drive efficiency, considering different mechanical speed levels: (a) 750 rpm; (b) 1500 rpm (rated speed).

A detailed analysis of Figure 6 allows to conclude that the motor and global drive efficiency is low when the motor is subjected to low load torque values. Additionally, the difference between the motor and global drive efficiency shortens as the load torque increases. This behavior is common to all drives, but it is more evident for the PMSM and IM drives.

Comparing Figure 6a and Figure 6b, it is seen that the speed variation does not introduce significant changes on the evolution of the efficiency curves of the PMSM and SynRM drives; only a small increment of the efficiency occurs when the speed increases. However, the IM drive shows a degradation of the performance while it operates at lower speed and higher torque (Figure 6a), that does not occur at rated mechanical speed (Figure 6b). At rated speed, the IM drive efficiency curves surpass the efficiency curves of the PMSM drive when the load torque decreases below 2 Nm and, at the same time, tend to superimpose with the SynRM ones when the load torque approaches to the nominal value.

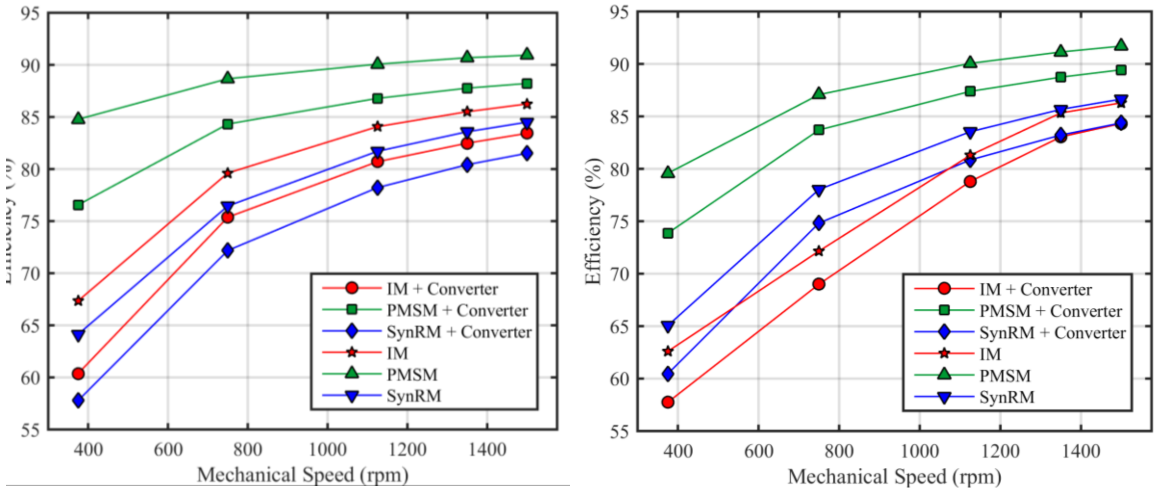


Figure 7: Motor and global drive efficiency, considering different load torque levels: (a) 7 Nm; (b) 14 Nm (rated load torque).

The results of Figure 7 show that the efficiency of both motor and global drive increases with the mechanical speed. Comparing Figure 7a and Figure 7b, and considering the operation at lower mechanical speed, it is also stated that there is a decrease of the PMSM efficiency (from 84.8% to 79.6%) and IM efficiency (from 67.4% to 62.6%), but an increase in the SynRM efficiency (from 64.1% to 65.0%). At rated mechanical speed, there is a general increment on the drives efficiency as the load increases. Furthermore, the difference between the motor and global drive efficiency shortens as the mechanical speed increases. This behavior is common to all three drives.

3.5. Thermal Performance

To assess the thermal performance of the three drives under analysis, the drives were operated at half-load condition (rated speed and 50% of the rated load torque). The temperature values were acquired using a PT100 sensor probe placed inside the motor frame, next to the motor front cover. Figure 6 depicts the temperature sensor arrangement inside the motor frame.

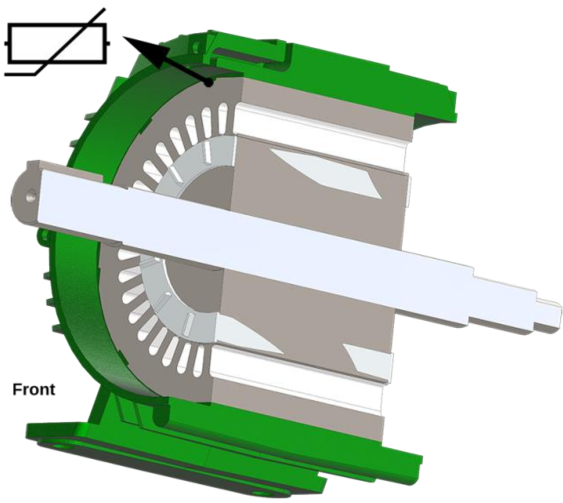
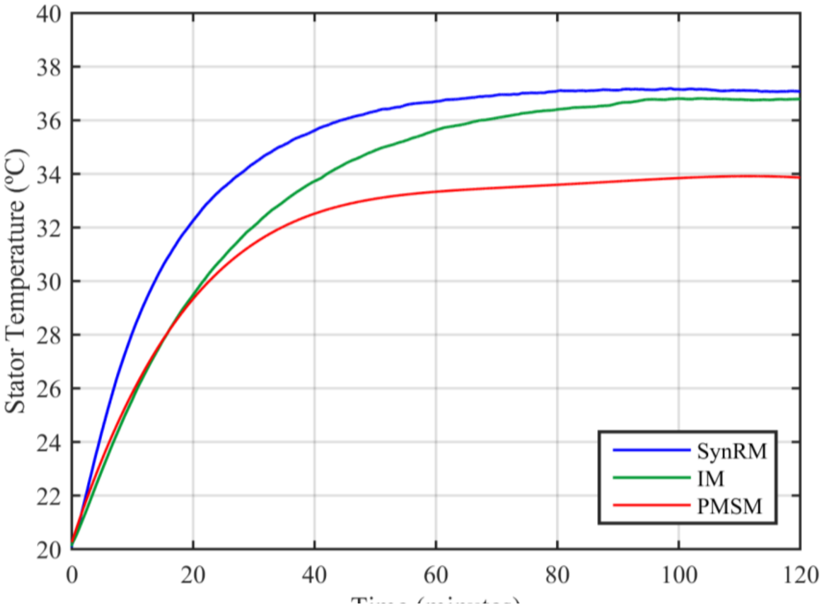


Figure 8: PT100 sensor position.

Environment temperature was also measured and recorded, in order to adjust the stator temperature according to the environment temperature evolution during the experiment. The data was acquired and sent to a computer using a National Instruments NI cDAQ-9174 data acquisition board and a NI 9217 module. Temperatures are recorded until the motor thermal steady-state condition is met. This condition, defined by standard IEC 60034-1:2004 [6], is reached when the gradient of the straight line between corresponding points of successive duty cycles on a temperature plot is lower than 2 K/h



(Kelvin per hour).

Figure 9: Stator temperature evolution.

The results show that the SynRM temperature increment during the first hour of the experiment is higher than in the IM and PMSM. It is also observed that the SynRM stator temperature stabilizes much faster than in the IM and PMSM. At the end of the experiment, the temperature of both the IM and SynRM is quite similar, despite the differences in the behavior of the IM and SynRM. During the first 20 minutes, the PMSM and IM temperature values are quite similar. Then, the PMSM temperature increases at a lower rate, leading to a lower temperature at the end of the experiment. The PMSM stator temperature stabilizes at 33.9 ºC; the IM stator temperature reaches 36.8 ºC, while the SynRM stator temperature increases until 37.1 ºC.

As stated in [3], such evolution can be influenced by several factors. However, the main reason for this behavior lies on the SynRM frame materials and their physical properties. The quick increment of the SynRM temperature verified in the first half of the experiment is a result of the higher current used to supply the SynRM. At the same time, the temperature evolution of the IM and PMSM during this period is a result of the similar physical properties of both motor frames. Then, the SynRM thermal stability is achieved in less time due to the high thermal conductivity of the SynRM stator/frame, which allows a more effective heat transfer to the environment and a counterbalance of the higher Joule losses of this motor. On the other hand, the low temperature of the PMSM stator at the end of the experiment is a consequence of the lower Joule losses and higher efficiency of this motor, when compared to the IM and SynRM.

4. Conclusions

This paper has presented a performance analysis of the most common electric drives available in the industry. To obtain a high resemblance degree between all drives, the same power converter is used to supply the motors, using a vector control strategy.

A detailed results analysis shows that all drives reach their efficiency peak at rated operating conditions, or close to that point. It is relevant to refer the good indicators of the SynRM drive performance for low speed operating conditions, which are very similar to those of the PMSM. This feature makes this type of drive desirable for applications where speed regulation is important.

The results also demonstrate the good performance of the power converter used to control each motor. The converter shows high efficiency levels, without relevant changes, for all the operating range, in all drives. Despite that, the power converter performance on the SynRM drive should be highlighted, as the converter efficiency remains almost unchanged over the entire operating range of this drive.

It is stated that the SynRM drive has a good thermal performance, comparable to the IM and PMSM drives, despite the higher supply current related to the SynRM.

Acknowledgement

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Appendix

Table I – Parameters of the electric motors

	IM	**PMSM**	**SynRM**
Power (kW)	2.2	2.2	2.2
Speed (rpm)	1435	1500	1500
Frequency (Hz)	50	75	50
Torque (Nm)	14.6	14	14
Voltage (V)	400	400	400
Current (A)	4.56	4.4	5.7
Efficiency (%)	87	91.6	89.5
Frame Size	100L	90L	100L
Frame Material	Cast Iron	Cast Iron	Aluminium
Weight (kg)	33	17	25
Efficiency Class	IE3	IE4	IE4

References

[1] Paul WaIde, and Conrad U. Brunner, *Energy-efficiency policy opportunities for electric motor-driven systems*, p. 39, 2011.

[2] A. T. de Almeida, F. Ferreira and A. Quintino, "Economical considerations of super high-efficiency three-phase motors", *48th IEEE Industrial & Commercial Power Systems Conference*, Louisville, KY, 2012, pp. 1-13.

[3] J. O. Estima and A. J. M. Cardoso, "Super Premium Synchronous Reluctance Motor Evaluation", *International Conference on Energy Efficiency in Motor Driven Systems,* 28-30 October, 2013.

[4] Bimal K. Bose, *Power electronics and motor drives: advances and trends*, Academic press, 2010.

[5] Peter Friedrichs and Marc Buschkühle, "The Future of Power Semiconductors | PowerGuru - Power Electronics Information Portal", 2016.

[6] IEC 60034-1, *Rotating electrical machines – Part 1: Rating and performance*, 2004.

Assessment of Control Strategies for Synchronous Reluctance Motors

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Abstract

This paper discusses the different control strategies adopted to optimize the operation of the synchronous reluctance motor and how these techniques apply for an actual prototype.

At first, based on the Park model of the machine, the most popular optimization techniques are recalled in terms of current control requirements, such as maximum torque/current, maximum power factor, and maximum torque/flux. A speed vector control scheme is presented, able to implement such techniques by taking account the physical limits of the feeding voltage and current.

The further criterion of maximum efficiency is also considered, not evaluable in terms of analytical relations. Due to the non linearity of the magnetic circuit, cross-coupling effects and iron losses, the optimizing control trajectories are evaluated by means of a numerical Finite Elements model analysis and validated by experiments.

The study is applied to a prototype of synchronous reluctance motor with flux barriers rotor, designed to have the same stator core of a commercial three-phase 3kW induction motor. The results outline the performance of such machine, able to compete with permanent magnet or induction motors in inverter driven application.

Introduction

Synchronous Reluctance motors (SRM) are going to assume a relevant role among the AC drives for the next future. The interest is motivated by the fact that SRMs present several advantages such as the low inertia, the high power-to-weight ratio, the acceleration performance, and the flux weakening operation, characteristics which match the requirements of many industrial and transportation applications, [1]. Moreover, the SRMs have a cool rotor without windings or magnets, a feature making this solution attractive from an economic point of view, which is a must in household and consumer appliances.

Although these interesting characteristics are known since many years, and almost all the worldwide manufactures have SRMs in their catalogues, they are not yet used extensively. The reason of this is often traced to the alleged lower torque-to-current ratio respect to induction or permanent magnet motors, i.e. machines which have an excitation source (windings or magnets) on the rotor, [2].

Really the torque capability of SRMs is strictly related to the level of magnetic anisotropy featured by the rotor shape. Nevertheless, the advances in electromagnetic design by powerful finite elements tools, joined to sophisticated optimization algorithm, has allowed to achieve high anisotropy structures and performance very close to that of the AC motors with rotor excitation source, [3].

But another aspect is often invoked as one of the factors limiting the diffusion of the SRMs: the complexity in control. In fact, these machines have intrinsically non linear features, including saturation and cross-coupling effects, strictly related to the specific rotor structure: these aspects must be necessarily taken into account to achieve the designed capability, and this avoids the standardization of the drive set-up. Moreover, the relationship between the torque and the current is quadratic, making it difficult the design of the control loops [4]-[7]. This paper will issue these aspects.

A prototype of SRMs motor with four flux barriers rotor, designed starting from the stator core of a commercial three-phase induction motor of equivalent size (3kW, 4 pole, 400V, 50 Hz) is considered, Figure 1. The mapping of different control strategies from the finite element analyses and their experimental verification will be presented, both for the constant-torque and the flux weakening operations.

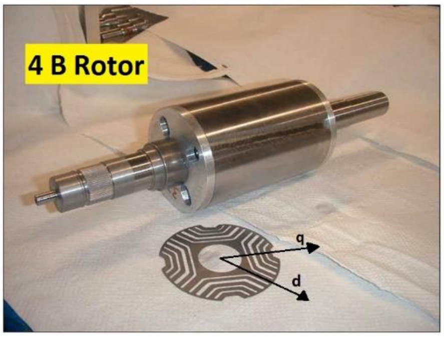


Figure 1: Optimized SRM: rotor core with denoted the direct (d) and quadrature (q) axes (left) and its assembly in the case of a standard 3kW induction motor (right).

Operation in the d-q Currents Plane

This section recalls some basic aspects of SRM, in order to make clear how performances can be optimized by proper current vector control strategy.

The Park equivalent two-phase (d-q) model of the machine is considered, under the simplifying hypothesis of linearity of the flux model, i.e. saturation and cross-couplings effects among the d and q axes are neglected, such as the effects of the iron losses.

Thereafter, the steady-state stator voltages, the flux linkages, and the electromagnetic torque are given by (the nomenclature is detailed in the Appendix):

$$V_d = RI_d - \omega\Psi_q, \quad V_q = RI_q + \omega\Psi_d \tag{3}$$

$$\Psi_d = L_d I_d, \quad \Psi_q = L_q I_q \tag{4}$$

$$T_e = \frac{3}{2}p\left(\Psi_d I_q - \Psi_q I_d\right) \tag{5}$$

Simple manipulations of these relations provide the basic expressions of the constant voltage, torque, and current loci in the d-q currents plane, respectively given as follows:

$$V_s^2 = (R^2 + \omega^2 L_d^2)I_d^2 + \left(R^2 + \omega^2 L_q^2\right)I_q^2 + 2R\omega\left(L_d - L_q\right)I_d I_q, \quad \text{constant voltage ellipse} \tag{6}$$

$$T_e = \tfrac{3}{2}p\left(L_d - L_q\right)I_d I_q, \quad \text{constant torque hyperbole} \tag{7}$$

$$I_s^2 = I_d^2 + I_q^2, \quad \text{constant current circle} \quad (8$$

)

where $V_s^2 = V_d^2 + V_q^2$.

The constant loci in the d-q currents plane are represented in Figure 6, assuming variable speed and torque, and fixed (rated) voltage and current.

At rated conditions (torque and speed) the curves share a point which is the "base" operating point of the SRM (point A); according to (6), for increasing speed (and fixed rated voltage) one has a family of voltage "limit" ellipses which converges to the axes center, where the speed is theoretically infinite and the torque is zero.

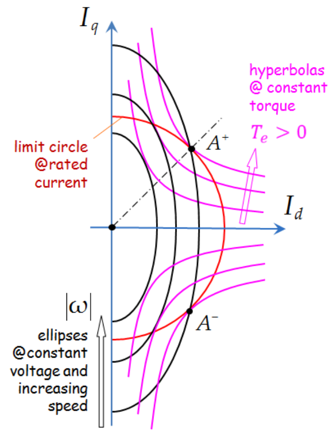


Figure 6: Constant torque, voltage and current loci in the d-q currents plane

Optimum Control Strategies

According to well established literature, the optimization criteria of the SRM refer to maximum torque/current, maximum torque/flux, and maximum power factor [8]. In this paper, the further strategy of maximum efficiency is considered. Each of these strategies corresponds to a given curve on the d-q currents plane.

The maximum torque/current curve is the locus of the points closest to the origin over each constant torque hyperbola, given by:

$$I_{qc} = I_{dc} \quad (9)$$

The maximum power factor criterion, achieved by neglecting the phase resistance, requires that:

$$I_{q\psi} = \sqrt{\frac{L_d}{L_q}} I_{d\psi} \quad (10)$$

The maximum torque/flux is the locus of the points at maximum torque over each voltage ellipse (this last built with fixed rated voltage and increasing speed). By neglecting the phase resistance one finds:

$$I_{q\psi} = \frac{L_d}{L_q} I_{d\psi} \quad (11)$$

Figure 7 shows the three control strategies. To avoid magnetic saturation, the d component is limited to about one-half of the rated current in standard design. Being $L_d > L_q$ the highest torque may be obtained with maximum torque/flux, while the maximum power factor criteria is preferable for the flux weakening operation (above the rated speed).

Thereafter, the trajectory for the optimum operation of a SRM in the d-q currents plane can be thought as represented in Figure 108, where a more realistic behavior of the constant loci is assumed.

a) when the speed is below the rated value (constant torque region) there is no problem for the voltage limit, the operation lie over the maximum torque/current locus since the saturation limit is reached (at point 1) and the copper losses are minimized for each torque value; then, at increasing load the operation is done at constant d-current up to the rated point A, where the maximum power factor operation is obtained in an optimized motor design;

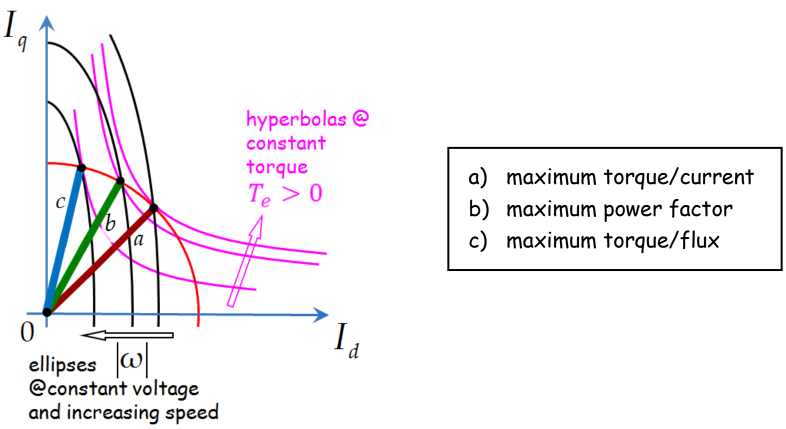


Figure 7: Control criteria of the SRM

b) above the rated speed ("flux weakening" region), the operating zone is limited by the voltage limit ellipses (collapsing toward their center at increasing speed) and the rated current circle; depending on the application, maximum power factor or maximum torque/flux operation may be applied moving on the respective loci up to (in theory) infinite speed and null torque (from point 2 to the axes origin 0, or from 3 to 0 respectively);

To achieve fast and smooth transient during the switch between the constant torque and the flux-weakening region, the rated current circle must be tracked (from point A to point 2 for maximum power factor, or from point A to point 3 for maximum torque/flux), a goal which requires the implementation of proper control skills.

These basic conditions of optimization, although achieved by a simplified modeling of the motor, give a good idea of the complexity of the current control for a SRM. Differently from the "surface" permanent magnet motor (SPM), where the torque is simply proportional to the q-current (and d-current set point is always set to zero), in case of the SRM both the d-q currents need to be commanded according to the torque/speed operating point. Moreover, this relation depends on the motor parameters and for an actual design it is affected by the usually un-modeled effects such as saturation, cross-coupling and iron losses [9]-[11].

From here it arises the necessity of an accurate (design and/or test based) characterization of the motor, in order to set-up the controller able to attain the expected performance. This becomes necessary when maximum efficiency optimization is concerned, because this strategy is not evaluable by the Park model which neglects the iron losses.

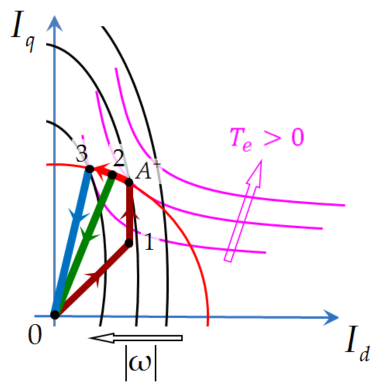


Figure 8: Optimum operation of the SRM

Vector Control Scheme

For the sake of implementation in a drive system, the better choice is to traduce the optimization criteria of the SRM in term of proper current or flux "vector control" characteristics, meaning the vectors related to the d-q components of the Park model. By considering the current space vector, the following relations exist (cartesian-to-polar transformation):

$$I_d = I_s cos\epsilon \ , \qquad I_q = I_s sin\epsilon \tag{12}$$

and the torque expression (7) becomes:

$$T_e = \frac{3}{4} p\left(L_d - L_q\right) I_s^2 sin2\epsilon \tag{13}$$

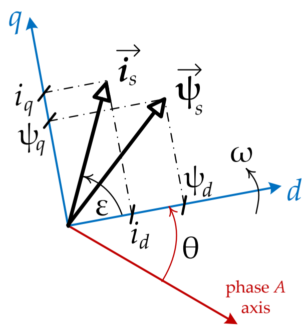


Figure 9: Current and flux space vectors

Then, a possible control scheme for speed regulation can be arranged as in Figure 10.

The vector-control characteristics F_T, F_d and the algorithm A_{dq} provide the set points of the d-q currents as functions of the (signed) amplitude (i_s^*) and phase angle (ε) of the current vector. The optimization criteria are expressed in term of the phase angles $\varepsilon_a, \varepsilon_b$, or ε_c corresponding to the relations (9) to (11) as follows:

$$\varepsilon_a = \frac{\pi}{4}; \quad \varepsilon_b = atan\left(\sqrt{\frac{L_d}{L_q}}\right); \quad \varepsilon_c = atan\left(\frac{L_d}{L_q}\right) \tag{14}$$

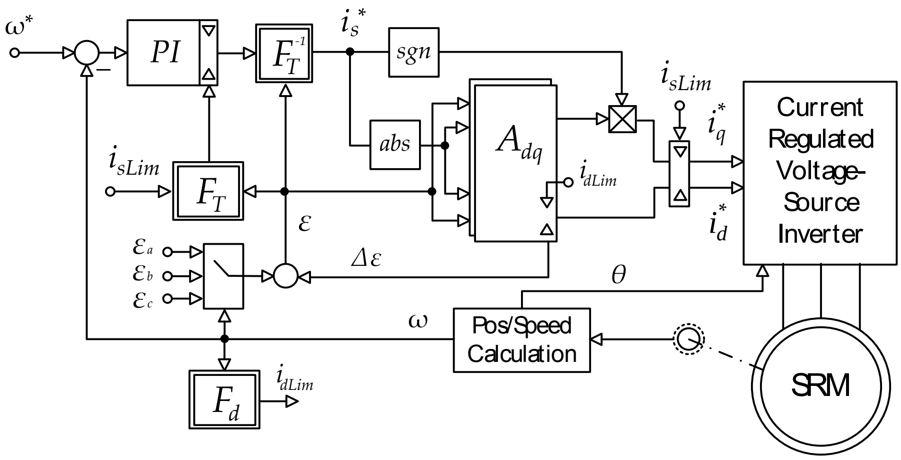


Figure 10: Speed control scheme of SRM

A proportional and integral (PI) speed regulator provides the torque command, which is turned into (amplitude) current command by means of the inverse torque-current relation (13). According to the selected optimization criteria, the current references i_d^*, i_q^* are calculated, inputs of the current regulated voltage source inverter.

The limitation of the PI speed regulator is done by the direct torque-current function. This is computed with the current limit and the imposed phase angle eventually corrected in case of d-current limitation. By this mechanism, the maximum torque obtainable from the SRM is achieved within the current and the voltage limits, and proper operation of the anti-windup feature of the regulator is assured.

The d-current limit is a speed dependent function obtained by the intersection between the current limit circle and the speed varying voltage ellipses.

A simulation test of this scheme is presented in Figure 11. The maximum torque/current and maximum torque/flux criteria are considered, meaning angles ε_a and ε_c are imposed respectively below and above the base speed. The SRM is simulated by the linear flux model, with the inductance parameters arranged to match the rated point operation of the actual prototype. The test concerns the motor start-up with no-load, the reaching of a speed set-point located above the base speed in the flux-weakening region, and the occurrence of a sudden load step when the speed steady state is attained.

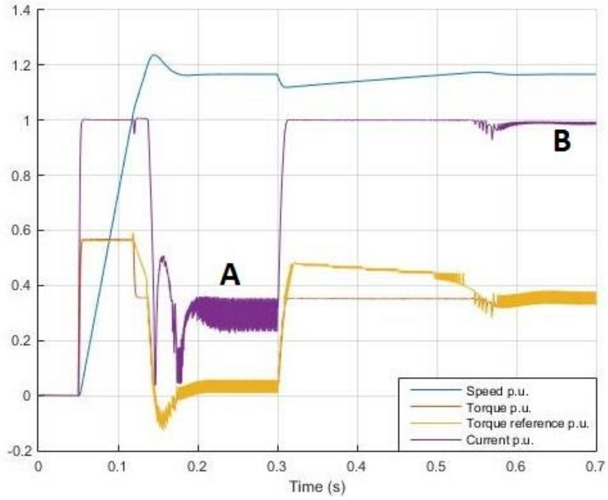


Figure 11: Speed control of the SRM

One notices the limitation of the torque reference during the start-up, due to the reaching of the current limit. When the base speed is reached, the torque suddenly reduces due to the commutation between the ε_a and ε_c criteria (in the meanwhile the current tracks the limit circle at increasing speed) and the acceleration is reduced too; finally, the set-point is reached with a limited overshoot. The steady state condition "A" denotes the (almost) no-load-flux-weakening operation. Thereafter, at time 0.3, the sudden load step occurs, which depresses the speed; then the controller reacts by increasing (up to limitation) the torque command, and then the set-point is again reached at point "B", working a little below the current limit.

The trajectory of the current vector in the d-q plane is shown in Figure 12, both for the reference and the actual current. The reference is compliant with the optimization criteria and allows the steady state operation at maximum torque/flux in points A and B. During transients the trajectory of the actual currents differs from the reference, both for the natural response of the current controller (current transients) and for the occurrence of physical limitations (speed transients).

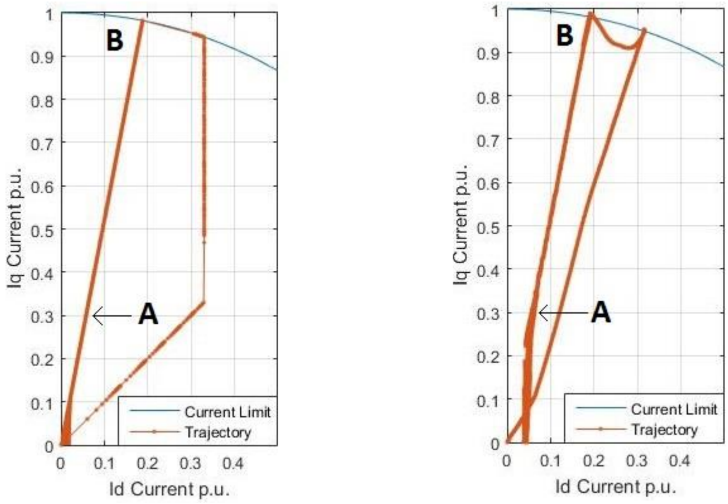


Figure 12: Current trajectories: reference (left) and actual current (right)

Maximum Efficiency Control

In order to implement a maximum efficiency control strategy it is necessary to take all the motor losses into account, namely Joule and rotational (iron plus additional) losses [9].

Focusing on the electrical losses, whereas the Joule losses can be evaluated by the measurable motor current and winding resistance (and temperature), the iron losses depend (among others) on the level of magnetic field in the different sections of the machine, which is not measurable.

Then, in a practical implementation, maximum efficiency can be achieved by minimizing in real-time the (measurable) input power of the machine. Perturbation algorithms are considered, which works modifying the steady-state operating point (in a deterministic or stochastic manner) until the given "objective function" (the input power) is minimized. Such algorithms operate in closed loop and, for their nature, can introduce instability when applied to high dynamics non-linear machines such as SRM, especially when the perturbation range is relatively large.

In this paper we experience a different solution based on the off-line computation and the mapping of the iron losses in the operative range of the machine.

To this purpose, a Finite Element (FE) model of the SRM motor prototype has been used as follows:

1) For each value of the d-q currents currents, the induction field has been computed in the different sections of the machine;
2) From the field values, considering the specified maximum core losses of the electrical steel used, the losses at the reference frequency are computed (normally 50 or 60 Hz) via a first empirical formula;
3) Then these losses are computed at variable frequency (i.e. motor speed) over the whole operating range via a second empirical formula;
4) Finally, the additional losses are calculated as a percentage of the mechanical power (friction and ventilation losses are ascribed to the external load)

The FE model and the mapping of the rotational losses has been integrated in a new model of the SRM allowing to evaluate the steady state performance of the machine by taking all the losses and the non-linearity of the magnetic circuit (saturation and the cross-magnetization) into account. This model has been used to evaluate more accurately the optimum trajectories and the performance of the machine, as shown in the next section.

Experimental Results

The experimental set up is shown in Figure 13. It includes the SRM, the power converter, the loading bench, control and debugging tools. The converter is general purpose voltage source inverter feed by a DC power supply (Elektro Automatik, 600V, 15kW). The inverter is equipped with IGBT power modules running at 10kHz PWM frequency. The control module is a Spectrum Digital "ezDSP" board with embedded TMS 320C2812 micro-controller, linked to a host PC both by serial RS232 and JTAG interface.

The host PC is used both to run the software development environment and to exchange data with the real-time controller, i.e. setting of parameters and receiving the computed data and control measures. The control module includes a digital-to-analog converter to display in real-time the variables computed by the controller on an oscilloscope.

A three-phase digital power wattmeter Yokogawa WT3000 is used to measure the terminal quantities of the motor: input electrical power, phase currents and voltages (first harmonics), power factor.

A hysteresis brake dynamometer Magtrol HD-815 (28Nm, 12000 rpm) provides the load torque and the measures of the mechanical speed and power.

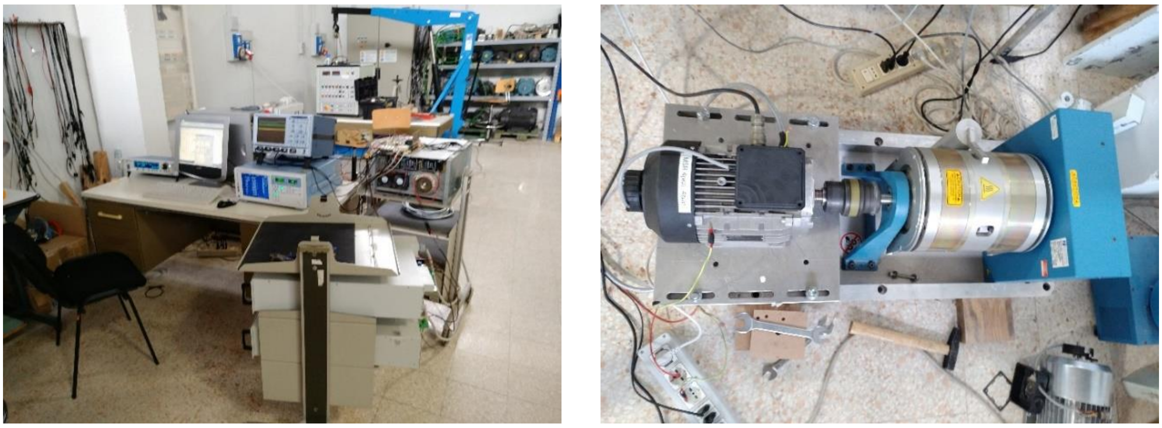


Figure 13: Experimental set-up and test-bench

Figures 14 and 15 show the constant torque loci and the trajectories for optimum control obtained experimentally and those computed by the FE model. The rated speed (1500 rpm), a speed in the constant torque range (1000 rpm) and a speed at flux weakening (2000 rpm) are considered. The figures also show the base current limit and the speed dependent voltage limit computed by the FE model with the base voltage.

One can see the excellent correspondence between the experimental and the computed loci. By looking at the motor base values assumed in Table 47 (design data), the base current is able to provide the rated torque in the constant torque range (with base d-q currents), and this point falls exactly on the maximum toque/current curve.

At rated speed the voltage limit reduces the working area in term of d-current. The rated torque is attained experimentally by a little more current (about +3%) and different couple of d-q currents. Both the maximum torque/current and maximum efficiency curves fall on the voltage limit at high torque.

At flux weakening speed the voltage limit reduces still more the operable d-current range. All the optimum control trajectories fall on the voltage limit at high torque. The maximum torque produced is around 15Nm by the maximum power factor control.

The maximum efficiency trajectory is located between the maximum power factor and the maximum torque/current ones. This is realistic because the sum of Joule (current) and the iron (flux) losses are minimized. The maximum efficiency trajectory is closer to the maximum torque/current, but it tends to approach more the maximum power factor curve at high speed where the iron losses increase respect the Joule ones due to the frequency increase.

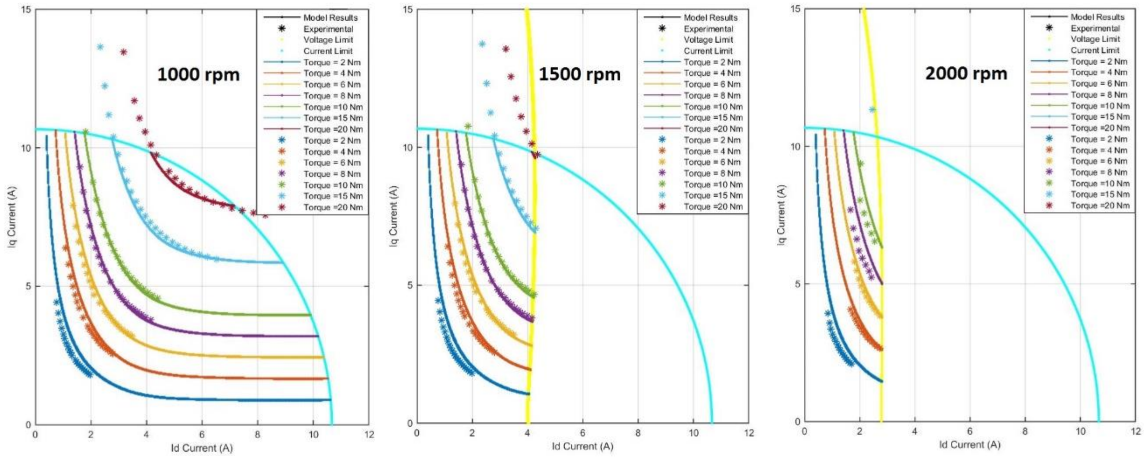


Figure 14: Constant torque loci (experimental vs. FE model)

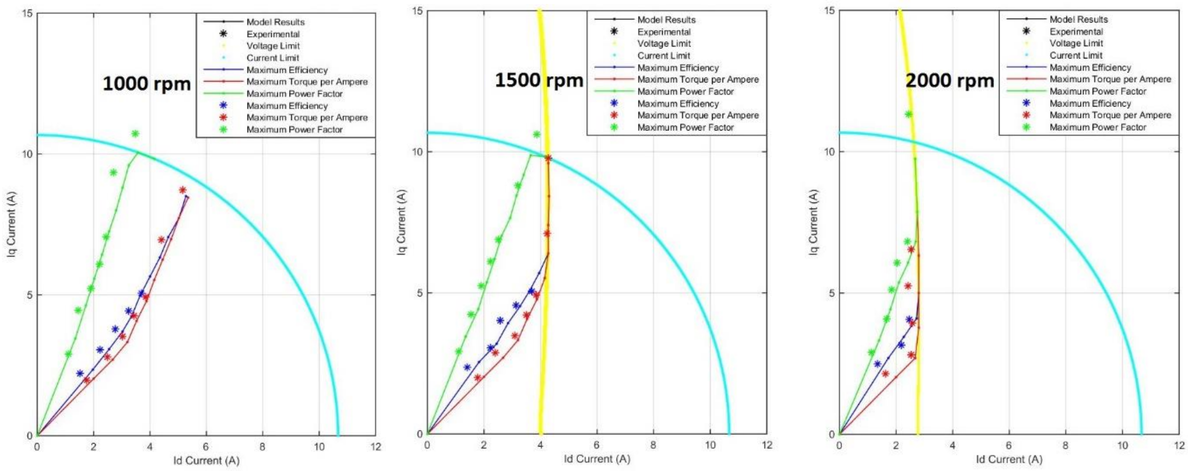


Figure 15: Control trajectories (experimental vs. FE model)

Figures 16 and 17 show the efficiency and the power factor experimentally evaluated on the prototype and those computed by its FE model. In this case the difference between test results and computation is more evident but nevertheless acceptable if one consider the approximations of the empirical formulas and the influence of the temperature on the losses.

At rated speed and torque the operating points are practically the same for the maximum torque/current and maximum efficiency, the efficiency is about 87% and the power factor 0.725. In case of maximum power factor control the efficiency is slightly lower (85.5%) while the power factor is slightly higher (0.73) than the other controls. At decreasing torque the efficiency increases up to 90% at 2Nm and rated speed (maximum efficiency control). At flux weakening, the efficiency is generally around 90% in the whole (possible) torque range.

Differently from the efficiency, the power factor decreases at reduced torque, while it seems not affected by the speed for all the controls. The maximum power factor control allows the increase of the power factor of several percentage points (up to 10%) over the whole (possible) torque range.

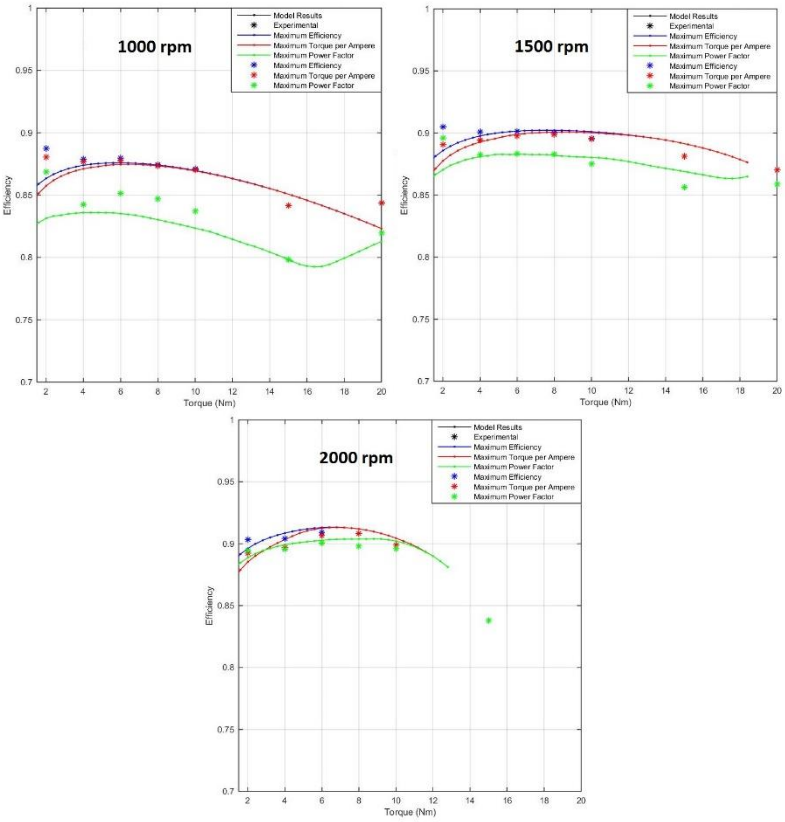
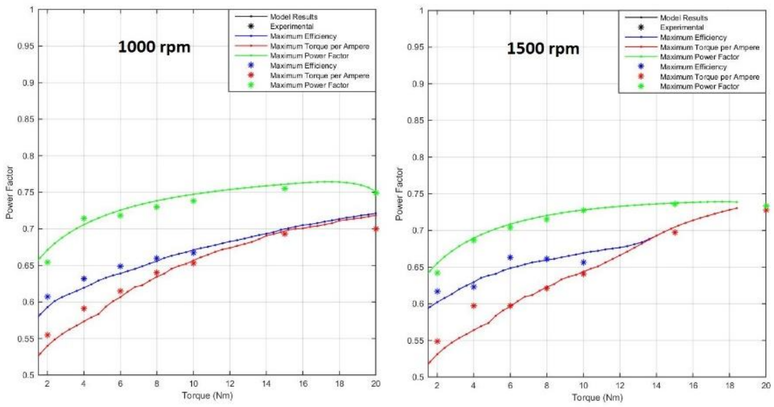


Figure 16: Efficiency with different control strategies (experimental vs. FE model)



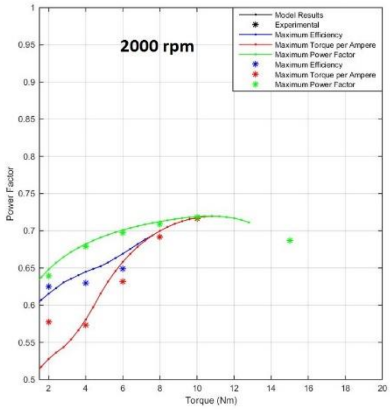


Figure 17: Power factor with different control strategies (experimental vs. FE model)

Conclusions

In this paper, the optimization criteria of the SRM aiming to maximum torque/current, maximum torque/flux, maximum power factor, and maximum efficiency operations are analyzed, and a vector control scheme suitable for their implementation is shown.

A prototype of SRM with four flux barriers rotor and the same stator core of a commercial three-phase induction motor of equivalent size (3kW, 4 pole, 400V, 50 Hz) is considered.

The finite element analyses and the experimental verification of the control criteria are presented, both for the constant-torque and the flux weakening operations.

Laboratory tests at rated conditions (3kW) show that the SRM has a higher efficiency (87.0% vs. 84.2%, control losses excluded) and a lower power factor (0.73 vs. 0.76) respect to the equivalent (line fed) induction machine. In the next steps of the research, systematic comparisons are planned by assuming the same inverter feeding for the induction motor and fixing the comparison conditions (i.e. same speed or same frequency at given load).

Table 1: Main data of the considered SRM

Rated values	
phase (base) voltage	$\hat{V}_n = 220 \times \sqrt{2}\, V_{pk}$
phase (base) current	$\hat{I}_n = 10.67\, A_{pk}$
direct current	$\hat{I}_{dn} = 3.93\, A_{pk}$
quadrature current	$\hat{I}_{qn} = 9.92\, A_{pk}$
speed (base)	$n_n = 1500\, rpm$
power	$P_n = 3.142\, kW$
torque	$T_{en} = 20\, Nm$
Parameters	
number of pole pairs	$p = 2$
direct inductance	$L_d = 186\, mH$
quadrature inductance	$L_q = 34.1\, mH$
phase resistance	$R = 1.83\Omega$ @$20°C$
saliency ratio	5.45

Appendix

Nomenclature of the main symbols

Ψ_d, Ψ_q	d-q flux linkages;
I_d, I_q	d-q current components and amplitude;
V_d, V_q	d-q voltage components and amplitude;
L_d, L_q	d-q synchronous inductances;
R	Phase winding resistance;
ω	Angular (electrical) rotor speed;
θ	Angular (electrical) position;
T_e	Electromagnetic torque;
p	Motor pole pairs.

References

[1] A. Vagati *The synchronous reluctance solution: a new alternative in AC drives* 20th Int. Conf. on Industrial Electronics, Control and Instrumentation (IECON), 1994, Vol. 1, pp. 1-13, DOI: 10.1109/IECON.1994.397741

[2] Boglietti A., Cavagnino A. Pastorelli M., and Vagati A. *Experimental comparison of induction and synchronous reluctance motors performance*. Fourtieth IAS Annual Meeting. Conf., 2005 Vol. 1, pp. 474-479, DOI: 10.1109/IAS.2005.1518350

[3] Parasiliti F., Villani M., *Synchronous reluctance motors design and performance prediction using an analytical procedure* Electrical Engineering and Electromagnetics, WIT Press, 2003, , pp. 147-156, ISBN- 1-85312-981-X

[4] Xu L., Xu X., Lipo T. A., Novotny D. W. *Vector control of a synchronous reluctance motor including saturation and iron loss*. IEEE Trans. on Industry Applications, 1991, Vol. 27, Issue 5, pp. 977-985, DOI: 10.1109/28.90356

[5] Betz R. E., Lagerquist R., Jovanovic, M., Miller, T. J. E., and Middleton R. H.: *Control of synchronous reluctance machines*. IEEE Trans. on Industry Applications, 1993, Vol. 29, Issue 6, pp. 1110-1122, DOI: 10.1109/28.259721

[6] Malekian K., Sharif M. R., Milimonfared J. *An Optimal Current Vector Control for Synchronous Reluctance Motors Incorporating Field Weakening*. 2008 10th IEEE Proc. of Int. Workshop on Advanced Motion Control, 2008, pp. 393-398, DOI: 10.1109/AMC.2008.4516099

[7] Hoffer A. E., Moncada R. H., Pavez B. J., Tapia J. A., and Laurila L. *A High Efficiency Control Strategy for Synchronous Reluctance Generator Including Saturation*. Proc. of XXII Int. Conf. on Electrical Machines (ICEM), 2016, pp. 39-45, DOI: 10.1109/ ICELMACH.2016.7732503

[8] Boldea I. *Reluctance Synchronous Machines and Drives*. Clarendon Press, Oxford (UK), 1996.

[9] Yahia K., Matos D., Estima J. O., Cardoso A. J. M. *Modeling Synchronous Reluctance Motors Including Saturation, Iron Losses and Mechanical Losses*. 2014 Proc. of Int. Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2014, pp. 601-606, DOI: 10.1109/SPEEDAM.2014.6871965

[10] Truong P. H., Flieller D., Nguyen N. K., Mercklé J., Mai T. *Optimal Efficiency Control of Synchronous Reluctance Motors-based ANN Considering Cross Magnetic Saturation and Iron Losses*. Proc. of 41st Annual Conf. of the IEEE Industrial Electronics Society, 2015, pp. 4690-4695, DOI: 10.1109/IECON.2015.7392832

[11] Ibrahim M. N., Sergeant P., and Rashad E. M. *Relevance of Including Saturation and Position Dependence in the Inductances for Accurate Dynamic Modeling and Control of SynRMs.* IEEE Trans. on Industry Applications, 2017, Vol. 53, Issue 1

6 PUMPS

Energy Efficient Pump Systems for Indian Agriculture

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Abstract

The agricultural sector is responsible for some 18% of electricity use in India. The average emission factor in the power production, is due to the high share of coal, oil and gas 0.82 kg CO_2 per kWh. The largest part of the 170 TWh/a agriculture electricity is consumed by 20 million irrigation pumps. In recent years the use of agricultural irrigation systems with submersible open well and borehole pumps has increased. The necessary boreholes to reach underground water reservoirs are drilled deeper and deeper. Thus, the use of more powerful irrigation pumps is increasing every year.

The existing Indian efficiency standards and energylabels for submersible pumps are voluntary. In 2012 [1], 24% of pumps sold in the Indian market (by value) are without energy efficiency classification by the Bureau of Indian Standards (BIS). According to Bureau of Energy Efficiency (BEE), 24% of pump sales in 2014 were carrying the 5-star label. Thus 76% of the pumps can be below the 1-star or simply not showing the label.

A major barrier to the use of energy efficient pumps in the agricultural sector is that farmers are not required to pay the regular electricity tariff or not even meter their consumption. Because a large number of agricultural consumers draw power irregularly from the electric grid, it makes the supply highly volatile leading to heavy voltage drops and power failures. The use of energy efficient pumps is hampered by the instability of the grid supply. Besides mechanical failure of pump parts, burnouts of the pump motors happen frequently due to under-voltage.

In partnership with TERI and funded by the Swiss Agency for Development and Cooperation, Impact Energy is working on an efficiency program in the agricultural sector which includes irrigation efficiency, cost based electricity tariffs and incentives for the use of energy efficient pumps. Indian pump manufacturers, regional professional engineering associations and local testing laboratories will become part of a nationwide training, testing and incentive program. The immediate goal is to stimulate the production and sales of efficient pumps and lower the respective market barriers. The long term goal is to make irrigation more energy efficient, more ecological and more economical.

Irrigation pumps in India

Irrigation is the predominant use of electricity in Indian agriculture. It consumes around 18% of the national electricity demand. With its current fleet of power plants (82% is fossil power) and existing transportation and feeder lines, supplying farms in remote areas with power of constant frequency and voltage is a big challenge. Traditionally farmers in India are considered poor and receive access to very low priced or free electricity. The result of this policy gives only low incentives for power utilities for electricity supply and distribution companies (Discoms) to expand power production and transportation capacity respectively. Many publicly owned power utilities operate on deficits and are barely able to raise sufficient capital for their operating business. Governments subsidize on state and federal level this development, which is economically not sustainable. Also, for the farmers, the electricity supply is often reduced to a few hours per day and suffers from severe variation of voltage. Beyond the "acceptable" under-voltage of -15%, often times under-voltage down to -40% is observed which of course can interrupt the proper functioning of pumps and their motors and cause damage to any machine operating on the grid.

With very low priced electricity the farmers have no incentive to install and operate efficient irrigation pumps. They are aware of "when power is on, irrigations needs to run", even when and where it is not necessary. On the other hand they pay the price for damaged motors and pumps that suffer through overheating and burnouts while operating at under voltage.

The general observation in India [2] is that the percentage of farmers using electric pumps is steadily increasing, the pump efficiency is stagnant and the water table all over India according to the National Groundwater Board is sinking in dry areas steadily. A drop of the water table of up to 1 m per year has been monitored in certain dry areas for the last 10 years. Between 39% and 56% of the more than 20'000 wells monitored regularly [3] show a constant fall of the water table. The observations of the wells are monitored 4 times a year, before and after monsoon. In 11% to 15% of the water table of the wells the fall is more than 20 cm to 40 cm per year (see data of water table changes from 20'000 wells averaged over 10 years in Table 1).

The older open wells are now replaced by deeper drilled boreholes, which can easily go down to 100 m and beyond. But, without better use of surface water after the monsoon in check dams and without recharging of open wells the water table will continue to go down.

Table 1 - Groundwater rise and fall in last decade during different season (Source: [3])

Groundwater Variation in India per Decade	DECADAL MEAN			
	(PREMONSOON-2004 TO PREMONSOON-2013) TO PREMONSOON-2014	(AUGUST-2004 TO AUGUST-2013) TO AUGUST-2014	(NOV-2004 TO NOV-2013) TO NOV-2014	(JAN 2005 TO JAN 2014) TO JAN 2015
From				
To				
Rise	60%	49%	43%	46%
less than 2 m	43%	39%	36%	38%
2 - 4 m	11%	8%	5%	6%
more than 4 m	6%	3%	2%	3%
Fall	39%	50%	56%	54%
less than 2 m	28%	35%	42%	39%
2 - 4 m	6%	9%	9%	8%
more than 4 m	5%	6%	6%	6%
Decline	Delhi, Gujarat, Haryana, Karnataka, Punjab, Rajasthan and Tamil Nadu	Andhra Pradesh, Chandigarh, Delhi, Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, Telangana and Tamil Nadu.	Andhra Pradesh, Delhi, Gujarat, Haryana, , Madhya Pradesh, Maharashtra, Punjab, Rajasthan, Telangana ,Tamil Nadu and Uttarakhand.	Delhi, Gujarat, Haryana, Telangana, Punjab, Rajasthan, Andhra Pradesh and Tamil Nadu.
Maximum decline	in and around parts of Punjab, Rajasthan and Tamil Nadu.	in almost all parts of the country.	in and around parts of Punjab, Rajasthan, Gujarat, Karnataka, Uttar Pradesh, Assam and Tamil Nadu.	

Also, the irrigation methods widely used in Indian agriculture are still based on "flooding" the fields. The fountain spills out a large amount of water from the source which cannot be used efficiently near the roots of the crops. Modern water saving irrigation methods like sprinklers and dripping tubes are still rarely seen in the fields.

A large number of stakeholders are involved to improve the overall energy efficiency and to render agricultural irrigation more sustainable. From the central government, besides the Bureau of Indian Standards (BIS), the Bureau of Energy Efficiency (BEE) also the Central Groundwater Board are involved. Then, the Discoms, the pump manufacturers and their associations, the borehole drillers and the eventual users, the farmers are engaged in the entire process. In many cases old rules, also taboos, are involved which are difficult to change.

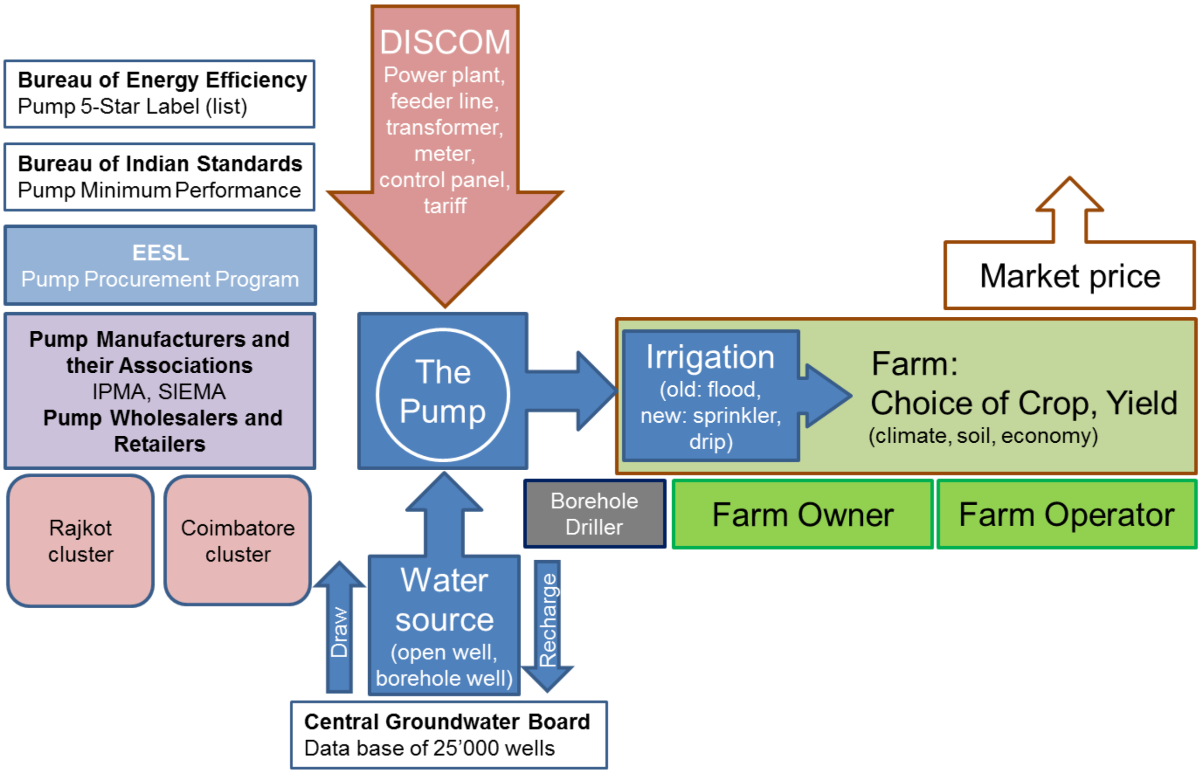


Figure 1 The key stakeholders involved in Indian agricultural irrigation

Pump use for irrigation

Electricity is used to pump surface water from open wells and underground water from boreholes. The atmospheric pressure limits the installation of simple surface mounted pumps (Monobloc) to about 6 m in depth, see Figure 2. Below this depth submersible pumps are used in open wells down to some 10 or 20 meters with the pump hung from a cable guiding also the electric line, see Figure 3, left.

The current drop of the water table has increasingly favored the use of borehole pumps (see Figure 3, right). This includes the costly borehole-drilling, sometimes also the insertion of a sleeve on the upper part of the hole and then the installation below ground of the pump which is linked with an electric cable and hooked to a robust vertical tube towards the surface. Specialized companies for drilling, hydraulic and electric installation support the farmers.

Figure 2 Surface Monobloc pump (Source: Prakash Pumps, 2016)

Submersible pump for open wells
(Source: Lowara, 2016)

Vertical submersible borehole pump
(multi-stage)
(Source: Grundfos pump handbook, 2004)

Figure 3 Submersible pumps

The borehole drilling bares a high risk of not being successful in tapping a sufficiently abundant water source. Depending on the soil condition (rock, sand) and its permeability the chances are 1:10 to 1:3 to find a sufficient well with the borehole.

Ideally, the irrigation for most crops should happen during the cooler part of the day, mainly between evening and morning, to avoid inefficient evaporation. On the other hand, the Discom is looking for an even distribution of its capacity. This means, it allocates most of the times power not according to transparent daily and weekly cycles of water need.

Electricity use in submersible pumps

The majority of the pumps use 2-pole induction motors trimmed to the special geometry of the borehole: a 10 to 20 cm diameter is most often used with an elongated motor of between 1 kW and 10 kW to reach sufficient torque.

Based on the current stage of knowledge, after desk research and interviews of a number of stakeholders, a submersible pump in a borehole for agricultural irrigation India has the following typical properties:

Table 2 Typical properties of borehole pump in India

•	Diameter of the borehole and the pump is 10 cm (V4) to 15 cm (V6)
•	The borehole depth (static head) is 60 m to 150 m for V4 pumps and 200 m to 300 m for V6 pumps
•	The flow of water for the irrigation is 5 to 12.5 liter per second for V4 pumps and around 2.5 liter per second for V6 pumps
•	Electric motors have an output power of 0.7 - 1.1 kW for V4 pumps and 3.7 - 7.4 kW for V6 pumps
•	Electric motors are mostly 2-pole with synchronous speed of 3'000 rpm at 50 Hz
•	Electric pump motors are designed for and operated at 415 V (accepted variation in Indian pump standards is +6%, -15%). The real voltage varies often down to -40% (250 V) and below, causing severe operating problems and damages[67]. The voltage variations have to do with large and unannounced heavy electric loads from not-metered consumers within the same area of the grid.
•	A typical pump uses (when operated 2 - 5 hours per day during 300 days a year, total circa 1'200 to 1'500 hours per year) circa 5'000 to 7'000 kWh/a electricity (the national average from statistics of national electricity consumption for agriculture and number of pumps is 6'143 kWh/a).
•	With a nominal price for electricity of 0.01 cents/kWh for agriculture in India[68] the electricity cost of a pump amounts to about 40 to 70 EUR per year.
•	A major issue is that farmers in India often consume electricity without a metering system, and generally pay between zero and only 20% of the actual electricity price and thereby distorting the economy and destroying the cost savings incentive of high efficient pumps.
•	The pump purchase costs are about 200 to 400 EUR for 2.2 kW and 3.7 kW five star labeled pumps. A smart control panel with additional capabilities (remote control, etc.) costs more than the pump.
•	To drill the borehole costs about 2.4 to 3 EUR per meter: for a 60 m borehole circa 180 EUR, for 150 m circa 450 EUR, for 200 m circa 600 EUR, for 300 m circa 900 EUR.
•	The replacement of pumps is typically made by farmers every 5 - 10 years due to wear.

According to a consumer survey in Rajkot, cost of accessories like cable, piping, normal control panel costs more than the pump cost; these costs are external to the pump cost and are cost burden to farmers as no subsidy is available for accessories.

The pump is rarely professionally sized by head and flow during the purchase and installation process. A typical size (by neighbors or the farmer's own experience) is bought, lowered into the borehole, installed and then the water supply is inspected. If it is sufficient, the pump was well chosen. If the supply is lower than expected, a stronger pump (or pump motor) is chosen and installed. If during operation the supply due to sand and subsequent wear of the impeller goes down the pumps are overhauled and eventually replaced typically by a more performant pump. Also, with the water table going down, after 3 to 5 years the pump has to be lowered and/or the borehole has to be drilled deeper.

[67] Under-voltage shoots up the current and lowers the efficiency and the flow of water, so often motors are overheated and get damaged.

[68] Information from IPMA and distribution companies (Discom), 2016

The farmers have no professional support. The electrical and mechanical installations are mostly primitive and self-made. The owner has no metering of the pressure and the electric power; sometimes an empty barrel is available to meter the flow by clocking the time to fill the barrel. If the farmer is lucky the Discom has installed a kWh-meter and he can check his current and voltage as well as the monthly and annually electricity consumption.

Pump manufacturers and their local dealers compete for clients. The performance data are printed in catalogues and should be based on Indian standard (BIS: For submersible borehole pumps in IS no 8034, see Figure 4 and Figure 5). The motor efficiencies are given in Table 4. Theoretically, also pump diagrams with data for head, flow and efficiency (for motors, pumps and combined) should be available in the technical documentation accompanying the pump. The more efficient pumps should carry an energylabel (5-star scheme by BEE, see Table 5). The evidence [1] is that 24% of the pumps in 2012 are not explicitly IS-rated and 93% do not carry a 5-Star Label (see Table 5).

Indian pump efficiency standards

India has a long-standing tradition for national performance standards for a variety of pump types, issued by the Bureau of Indian Standards (BIS). In Table 50 the major standards for submersible pumps are shown.

Table 3 Indian standards for submersible pumps (BIS)

Number	Title	Type of standard: T (testing) C (classification)	Date of publication (last revision)
IS 8034	Submersible Pumpsets - Specification (MED 20: Mechanical Engineering)	C	2002 Second revision, Amendment no. 4: June 2015, see Figure 121 and Figure 122, Table 51
IS 9079	Electric Monoset Pumps for Clear, Cold Water for Agricultural and Water Supply purposes (MED 20: Mechanical Engineering)	C	2002 Second Revision: September 2004
IS 11346	Tests for Agricultural and Water Supply Pumps - Code of Acceptance (MED 20: Pumps)	T	2002 First Revision: December 2002
IS 14220	Openwell Submersible Pumpsets (MED 20: Mechanical Engineering)	C	1994 First Revision: 1994, Amendment 5: November 2002, New WC draft February 2015

IS 8034 is the major Indian performance standard for submersible pumps giving MEPS for the pump based on head and flow (see Figure 4 and Figure 5) as well as for the pump motor (see Table 4).

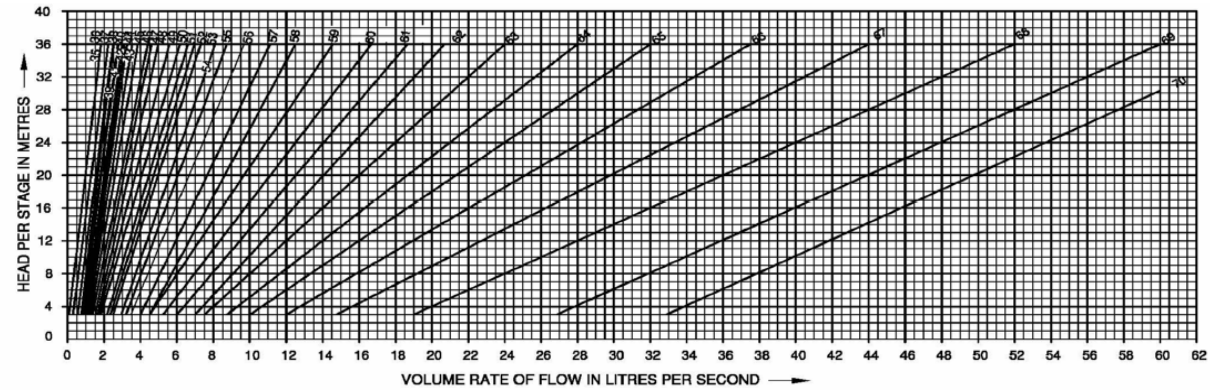


Figure 4 Minimal efficiency (%) for 2-pole submersible borehole pumps with 3 or more stages between 4 and 60 l/s in India (Source: BIS 8034, amendment 2012)

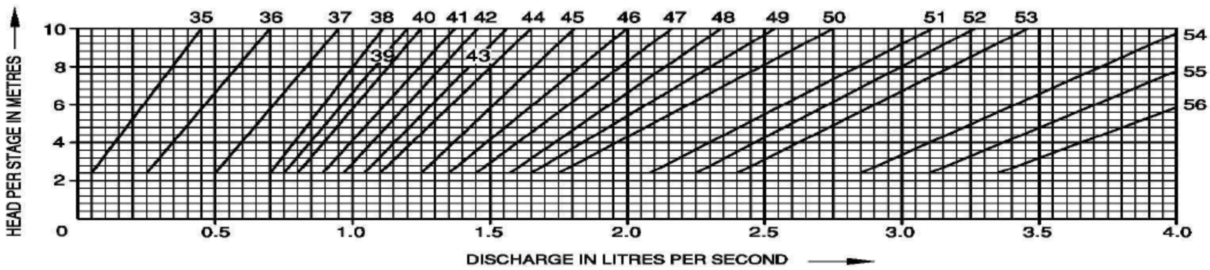


Figure 5 Minimal efficiency (%) for 2-pole submersible borehole pumps with 3 or more stages between 0 and 4 l/s in India (Source: BIS 8034, amendment 2012)

Motor MEPS for submersible pumps are given in Table 4. It is obvious that a motor with only 10 to 20 cm diameter for a borehole pump cannot reach the efficiencies of standard motors with IE1-IE4 (IEC 60034-30-1). The geometry leads to small diameters and long frames. The operation of pump motors in boreholes requires the filling of the stator with water. Also, the inclusion of a waterproofing can for the protection of the stator, increases the gap between rotor and stator. All these special elements of submersible pump motors diminish the motor efficiency to a level below or around IE1 for standard motors (see Figure 6).

Table 4 Performance characteristics for 2-pole, 415 Volt, 3-phase, motors for submersible pumps with 150 mm in India (Source: BIS 8034, amendment 3, 2012)

Motor Rating	Maximum Current	Permissible Limit of Maximum Current in the Operating Head Range for Checking the Non-overloading Requirements	Minimum Starting Torque(In terms of percentage of Full Load Torque)	Motor Efficiency factor
(kW)	(Amp)	(Amp)	(percent)	
(1)	(2)	(3)	(4)	(5)
1.1	3.3	3.5	125	57
1.5	4.5	4.8	125	66
2.2	6.5	6.9	125	67
3.0	8.5	9.1	125	67
3.7	10.0	10.7	125	68
4.5	12.0	12.8	125	70
5.5	14.5	15.5	125	73
7.5	19.5	20.9	125	74
9.3	25.0	26.7	125	75
11.0	29.0	31.0	125	76
13.0	34.0	36.4	125	77
15.0	39.0	41.7	125	78

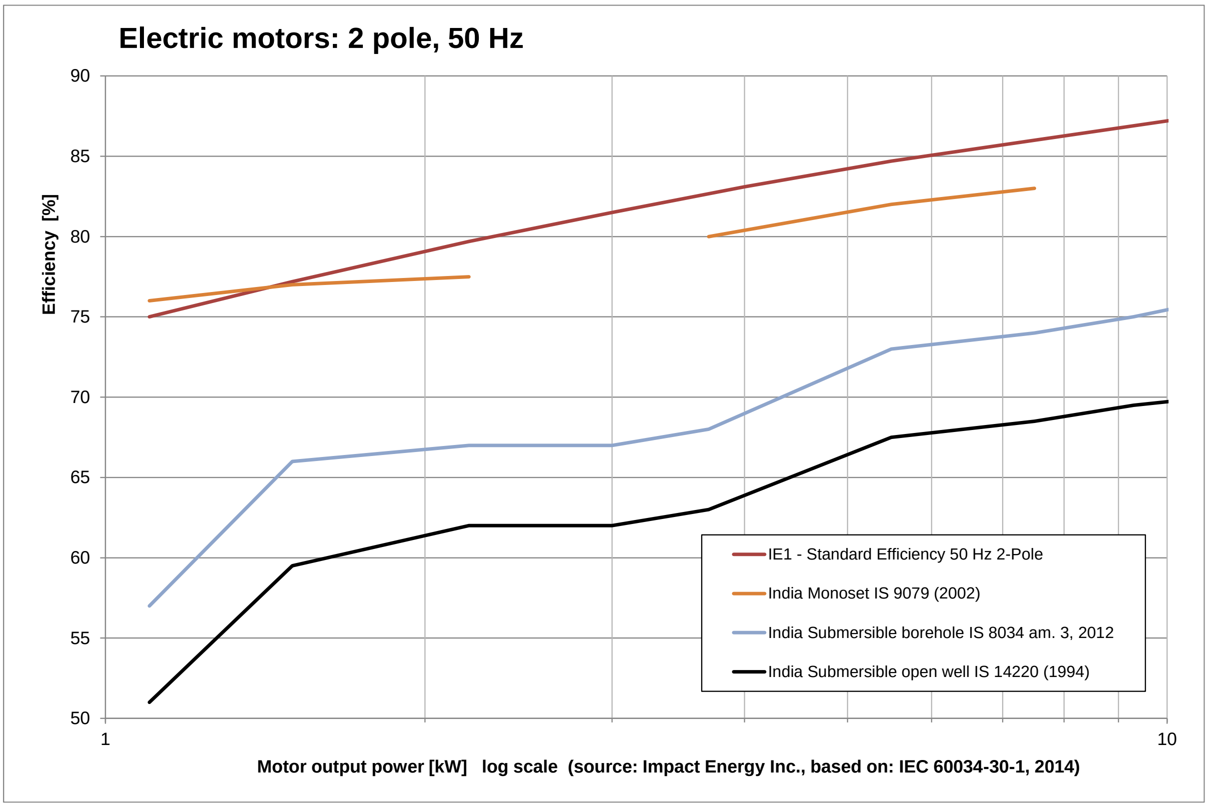
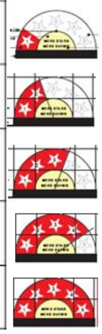


Figure 6 Comparison of Indian minimum standards (2-pole motors from 1 to 10 kW) for submersible pumps with IE-code for standard motors

Based on the MEPS for submersible pumps in IS 8034, the Indian Bureau of Energy Efficiency (BEE) has issued an energy label, based on a 5-star rating (see Table 5), for pumps exceeding the MEPS by 5 to over 20% (see Figure 9). With the current low MEPS level from the BIS 8034 standard, the more efficient 5-star rating is easily achievable.

Table 5 **Definition of Indian Star Label rating for pump sets based on BIS Minimum Energy Performance Standards (Source: BEE, Schedule No.: 7 Pump Set, Revision: 3, 3 November, 2015)**

Star Rating	Overall Efficiency of the Pump Set* (higher than the BIS value)
1 Star	≥ 0 to < 5%
2 Star	≥ 5 to < 10%
3 Star	≥ 10 to < 15%
4 Star	≥ 15 to < 20%
5 Star	≥ 20%



Market survey of Indian and global pump manufacturers

Pump manufacturers in India

According to the Indian Pump Manufacturer's Association IPMA, in 2016 there are 3'000 Indian pump manufacturers, 2 millions of agricultural pumps are sold annually and 21 millions of pumps are the installed base in the Indian agricultural sector [4]. India has a wide range of small, medium and large pump manufacturers that supply mostly for the Indian market. Interestingly, a large percentage of pump manufacturers are located in two clusters in India: in Rajkot in Gujarat in the West and Coimbatore in Tamil Nadu in the South.

In order to compare Indian and internationally produced pump efficiencies, a survey with 11 Indian pump manufacturers supplying data for borehole pumps was made from December 2016 to January 2017. The 61 pump and motor efficiency data were supplied by manufacturers and/or taken from publicly accessible BEE-label registration data files. They have not been verified by tests.

For this, a set of 10 most often sold pump sizes were chosen from the vast numbers of types and size. They were identified to be the most widely used types in Indian irrigation pumps for agriculture (see Table **6**).

Table 6 **Head and flow of the 10 most often used borehole pump types in India, with 15 cm diameter and 2-poles**

Diameter	Head	Flow
cm	m	m3/h
15	35	23
15	40	32
15	40	44
15	55	27
15	60	15
15	70	13
15	70	23
15	100	13
15	100	16
15	110	13

The Indian data for efficiency and cost were also checked with compliance to the BIS 8034 MEPS as well as their 5-star rating.

Also, besides performance and cost, the type of impeller manufacturing was compared. The most often used types and materials of impeller manufacturing are:

- Cast iron
- Cast stainless steel
- Welded stainless steel
- One piece pressed stainless steel

In wells with various water qualities, content of solids, sand, etc., stainless steel impellers have a durability advantage against corrosion. On the other hand, cast impellers with thicker walls have an advantage for wear from erosion from sand, cavitation, etc. Stainless steel sheet metal for welded or stamped impellers is thinner and makes them more lightweight and has an efficiency advantage.

The comparison of Indian pump, motor and combined pump efficiencies shows a wide variation between best and lowest products. The pump efficiencies have the widest spread while motor efficiencies are considerably closer together (see results of efficiency comparison vs. pump head in Figure 7 and vs. pump flow in Figure 8).

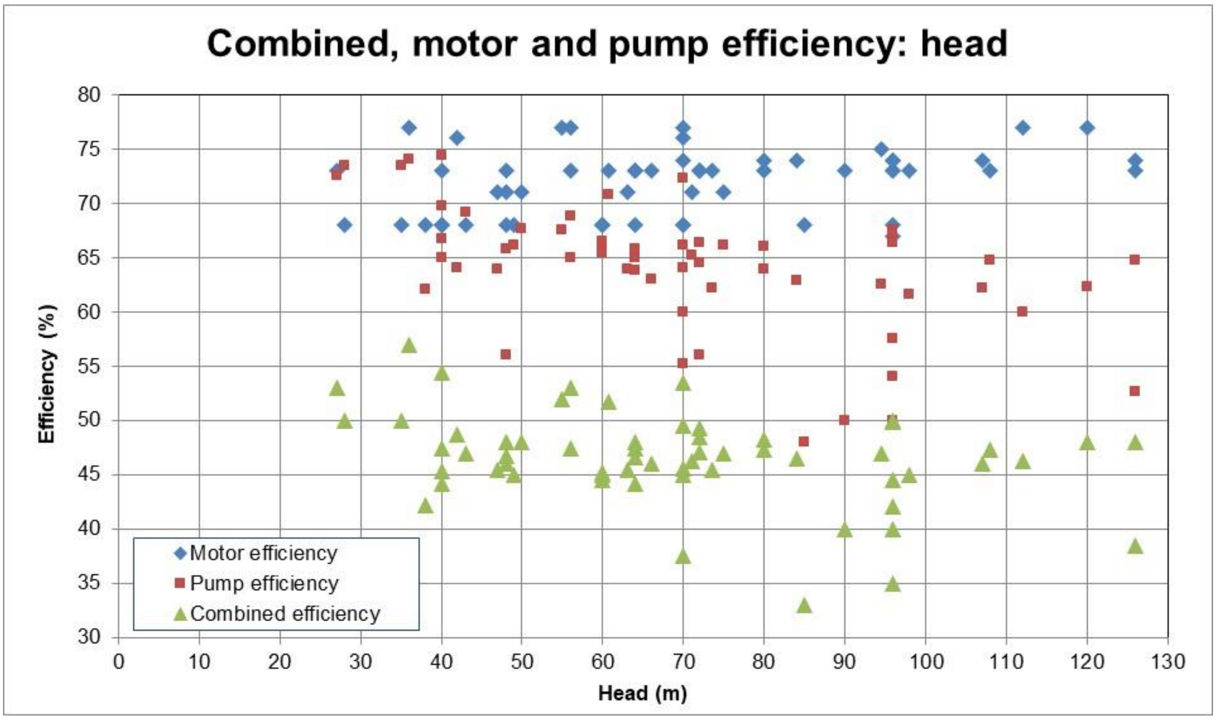


Figure 7 Comparison of Indian pumps: efficiency vs. head

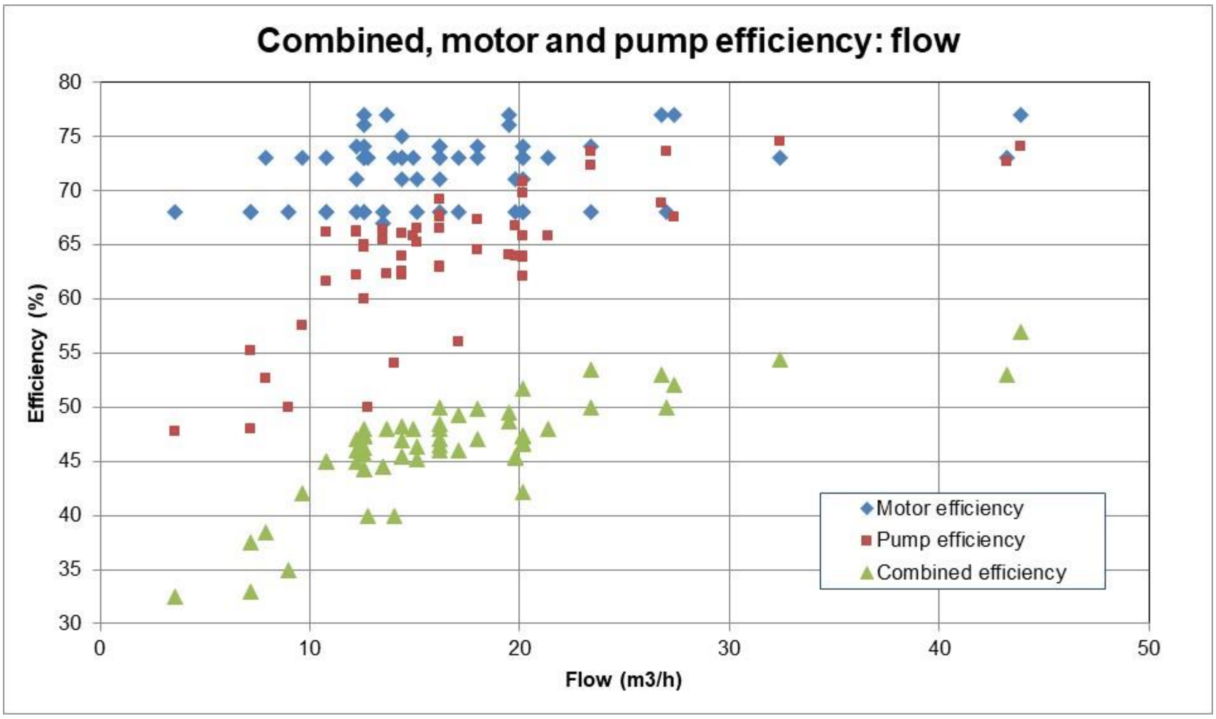


Figure 8 Comparison of Indian pumps: efficiency vs. flow

The relationship of the Indian pumps with Indian MEPS and 5-star label scheme shows that all pumps except 2 pass the BIS-MEPS and 10 are on or even exceed the 5-Star label line.

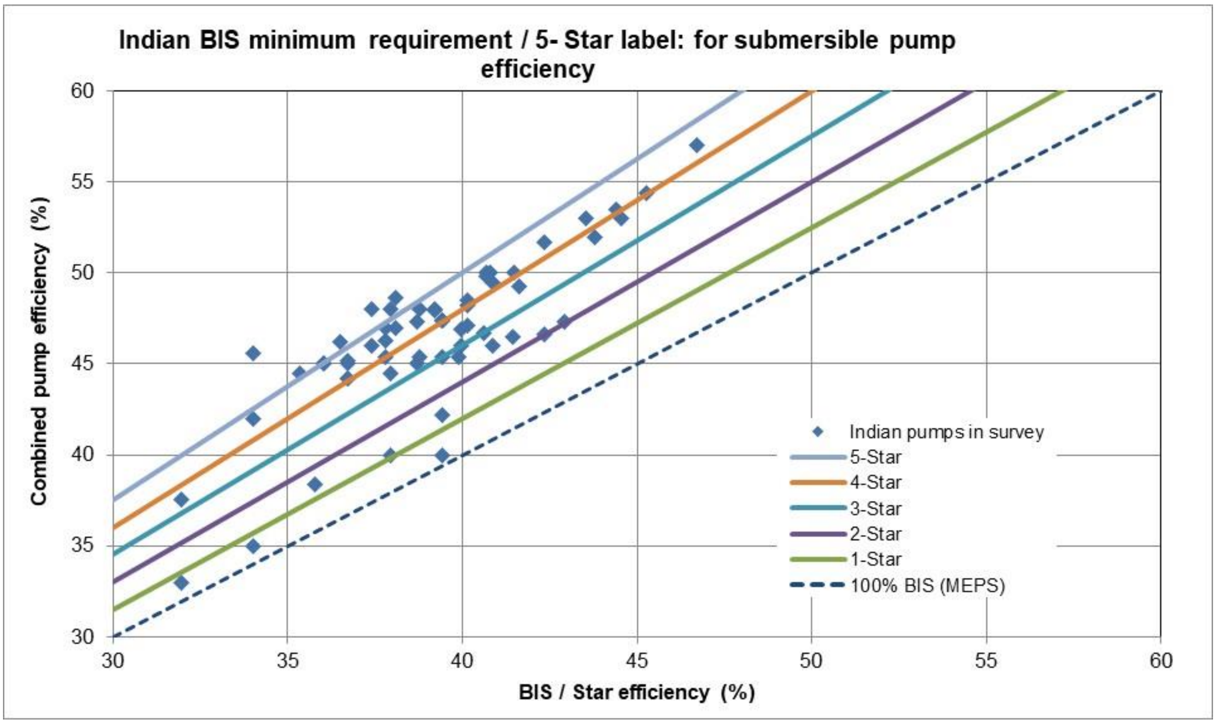


Figure 9 Indian pump efficiency requirements compared to market products

International pump manufacturers

There are a number of globally active pump manufacturers that supply submersible pumps for agriculture. In Europe, the Minimum Performance Standards for pumps (Ecodesign no 547, 2012), defines the required Minimum Efficiency Index for pumps (MEI). In February and March 2017 a survey was made with major 3 international pump manufactures using the same typology of most often used pumps in India. These manufactures delivered their data for performance, efficiency and impeller manufacturing for 30 submersible pumps. Also, these data were not verified by tests.

Comparison of Indian and international borehole pump performance

The comparison of the efficiencies with Indian and international products shows that the international products show a considerably higher overall efficiency when compared with head, flow and mechanical output (see Figure 10, Figure 11 and Figure 12). The efficiencies are all compared at the same level (best efficiency point) and do not take part load conditions into account.

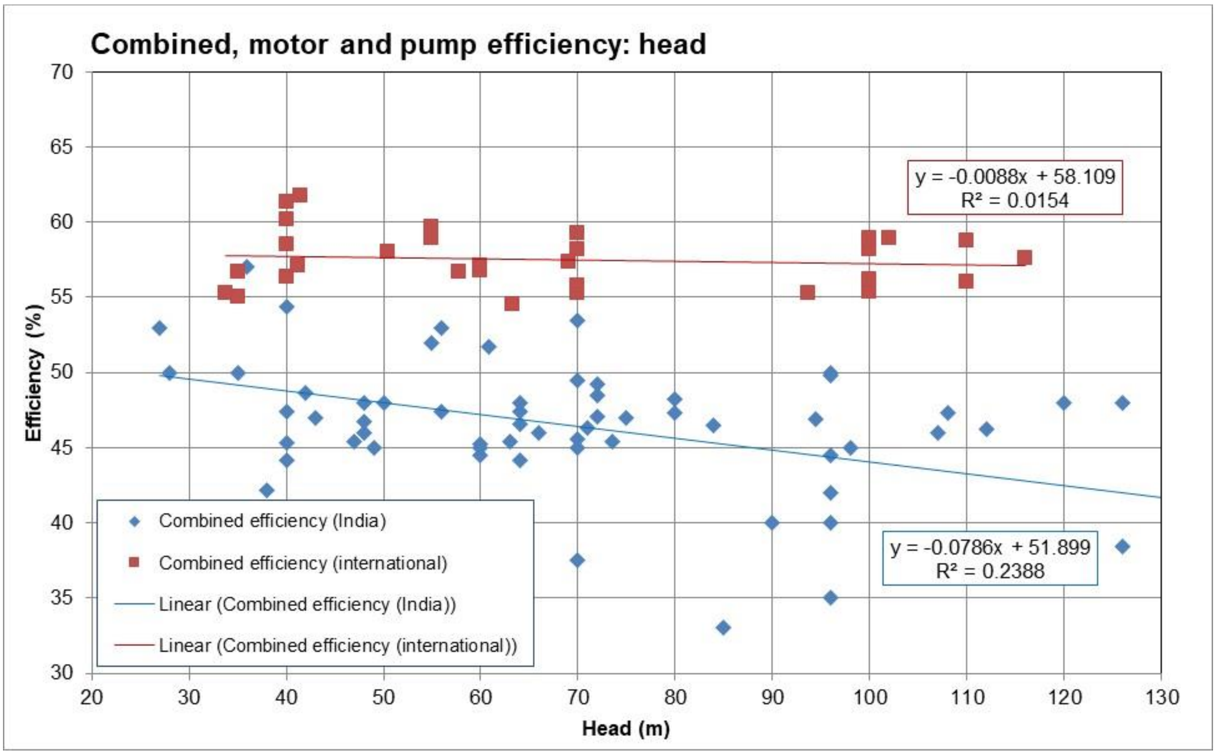


Figure 10 Indian and international pumps, combined efficiency: head
(linear correlation with equation and R^2 is given for Indian and international pumps)

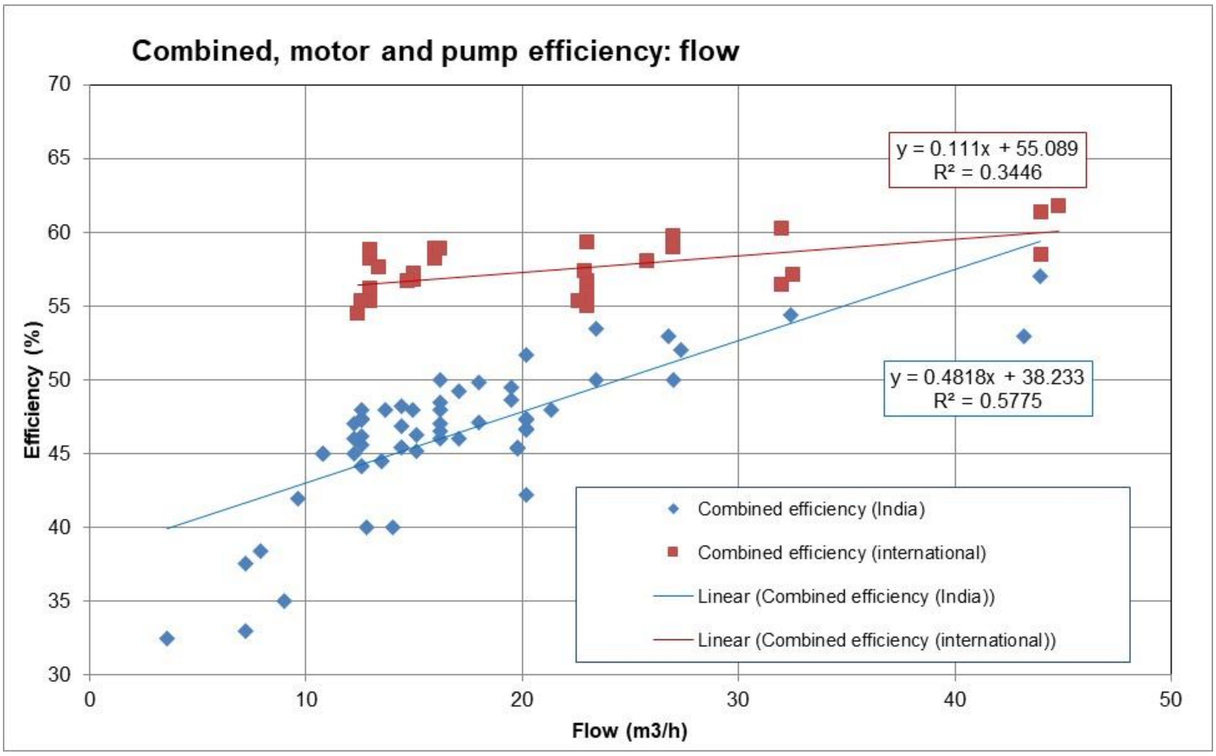


Figure 11 Indian and international pumps, combined efficiency: flow
(linear correlation with equation and R^2 is given for Indian and international pumps)

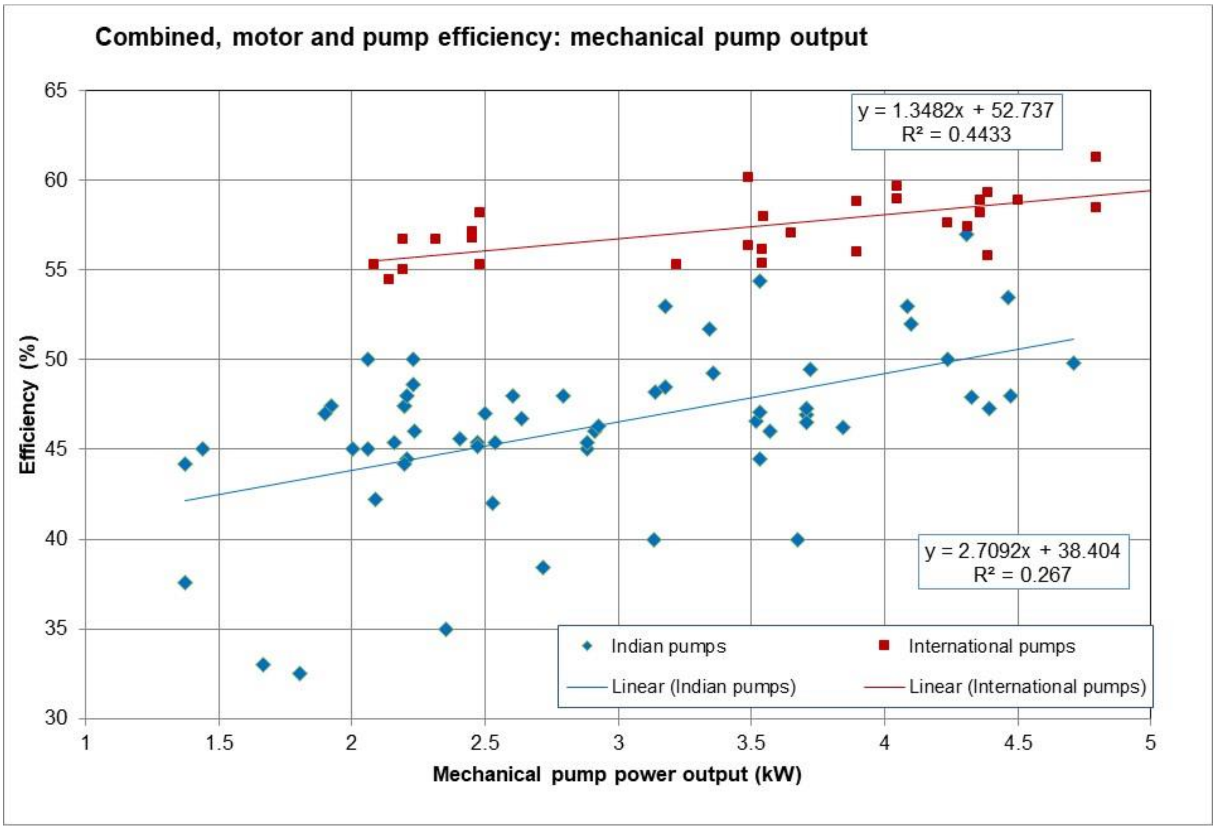


Figure 12 Indian and international pumps, combined efficiency: mechanical, output pump
(linear correlation with equation and R^2 is given for Indian and international pumps)

Indian procurement program

The goal of the Indian procurement and financial incentive programs is to increase the market share of 5-Str pumps and due to bulk purchase lower their price premium. The current tendering and allocation program in 6 states with 5-star pumps by the Energy Efficiency Services Limited (EESL) program is a good point in case. EESL, an energy service company under administrative control of Ministry of Power, Government of India, has taken up the initiative of accelerating the implementation of Agriculture Demand Side Management (AgDSM) program in India. Initially, the program aims to expand through four states targeting nearly 7 million pump sets across the states of Andhra Pradesh, Maharashtra, Rajasthan and Karnataka. EESL has successfully completed its first AgDSM pilot project for 590 pump sets in Byadgi and Nippani circles under the Hubli Electricity Supply Company Limited (HESCOM) in the State of Karnataka. Additionally, it has also completed the replacement of 1'337 pump sets in Mandya District under the Chamundeshwari Electricity Supply Corporation Limited (CESC) in the State of Karnataka. Presently, EESL is replacing 2'496 pump sets at Rajanagaram Mandal in East Godavari District under the Eastern Power Distribution Company of A.P. Limited in the State of Andhra Pradesh.

Under AgDSM projects, EESL would bear the upfront capital cost in implementation of the AgDSM projects, hence leading to no upfront capital investment of the State Electricity Utilities or the State Governments. The investments made by EESL are recovered from the State Electricity Utilities over a fixed project duration through the energy savings achieved by replacement of the existing inefficient pump sets with Energy Efficient Pump Sets. By replacing the existing inefficient pump sets with BEE Star Rated Energy Efficient Pump Sets, the demand of electricity consumption in the Agricultural Sector in India is expected to reduce, and thereby help in the Prime Minister’s vision of achieving energy efficiency and reduction of carbon footprint.

Table 7 Features of National Energy Efficient Agriculture Pumps program by EESL

Smart BEE star rated Energy Efficient Agricultural Pump sets be distributed to farmers.
Farmers can replace their inefficient agricultural pump sets free of cost.
Pumps to come with Smart Control Panes that has a SIM card and a Smart Meter.
Smart Control Panel will enable a farmer to switch on or switch off these pumps through his mobile and sitting at the comfort of his home.
Smart meters to ensure the farmers to monitor consumption on real time basis.
EESL to distribute 200'000 BEE star rated pump sets to the farmers under this program, which will lead to 30% of energy savings by 2019. This translates into an annual savings of approximately EUR 3 billion (INR 200 billion) on agricultural subsidies or electricity savings of 50 TWh/a.

Source: Press Information Bureau, Government of India, Ministry of Power, 7 April 2016

The way forward: pilot projects

It is evident that energy efficient pumps alone cannot solve the problem of sustainable irrigation in Indian agriculture. Besides opting for further improvement of efficiency and durability of domestic pumps and motors and the respective market transformation with more efficient pumps, the following pilot projects are under consideration:

1. Technical assistance: Know how exchange for pump manufacturers and support the development of testing and training centers to improve the efficiency and durability of pumps and motors.

2. Capacity building: Training programs for borehole drillers and farmers to bring efficient pumps into efficient operation.

3. Adaptation: Pilot field with new irrigation methods and harvesting of water during monsoon in order to better recharge the wells. The irrigation method and water source and their necessary recharging techniques have to be readjusted in order to provide well growing nutritional crops with much less water.

4. Policy dialogue. To improve and internationally harmonize Indian standards and labels for pumps with round robin tests.

5. Documentation. Publish guidelines for sustainable irrigation, best practices in pump manufacturing, maintenance and installation practices

6. Electric power: Pilot electric installations, controls and monitoring for pump stations. This serves as a basic element for the electric power production, supply and distribution system to developing more economical terms for consumers.

Only with positive economic incentives (separate from subsidies for crop production) the power plants, the Discoms and the farmers can survive sustainably on the Indian market.

Summary

Preliminary findings from a survey of 61 Indian pumps from 11 Indian manufacturers with 30 international pumps from 3 global manufacturers seem to confirm that the Indian products still have some possibilities to improve their efficiencies, both in the motor, the pump and combined. This means also that the Indian MEPS and the based upon 5-Star label scheme can be upgraded in the next years and converted into a mandatory scheme. The market transformation envisaged in the next decade that can replace the entire pump stock within their expected lifecycle will require considerable investments both from manufacturers and discoms and will also have to include farmers.

On the other hand, this efficiency research also shows that the larger problem of sustainable irrigation for Indian agriculture also needs to engage both in the water side (more efficient irrigation techniques and sustainable wells with recharging) as well as in the electricity supply which has so far been outside of the economic sphere and thus providing negative incentives for efficiency improvement and sustainability. The proposed pilot projects will help to develop a clearer avenue for a larger campaign toward sustainable agriculture.

Impact Energy and TERI would like to thank the Swiss Agency for Development and Cooperation for continuous support of this project.

References

[1] Netscribes: Market Research of Agriculture Pump-sets Industry of India, Delhi, India, 2012

[2] Conrad U. Brunner, Rolf Tieben, Girish Sethi, Prosanto Pal: EPIA, Promoting energy efficient agricultural pump sets in India EPIA, Results of feasibility study and proposed way forward, March 2017, Zurich Switzerland

[3] Central Ground Water Board of India: Ground Water Year Book- India 2014-15, Delhi, 2016

[4] TERI: Promoting energy efficient pumps in industry in India: Addressing the energy and climate change problem, Delhi, India, 2012

Experimental and numerical investigation of centrifugal Pumps As Turbines

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Abstract

Installation of Pumps As Turbines (PATs) in Water Distribution Networks (WDNs) is a relevant topic in the field of innovative management of WDNs. In case of excess head over a WDN, PATs can be used for both pressure regulation and hydropower generation. Unlike traditional turbines, a PAT can be selected among a wide set of available models, with lower investment and maintenance costs. On the other hand, PATs show a relatively narrow operating range, even though hydraulic and/or electrical regulations can be used.

The main issue preventing the use of PATs is that performance curves are not available from manufactures. Thus, experimental and theoretical relations have been developed to predict the PAT performances and to simulate the internal fluid dynamics. To this end, Computational Fluid Dynamic (CFD) models are widely applied to both simulate the actual flow field of a machine and assess the efficiency improvements resulting from a geometry modification.

In the present study, results from experimental and numerical investigations on different models of centrifugal PATs are discussed. A laboratory rig has been installed at the University of Naples Federico II to test both horizontal and vertical axis (single-stage and multi-stage) centrifugal PATs. The analysis was carried out by considering flow rates ranging between 10 and 50 l/s and head drops between 1 and 72 m. The generated power varied from few Watts up to 16.3 kW.

The performance was assessed as a function of the number of stages and the motor Efficiency Class, and the reliability of analytic relationships from the literature was verified. Finally, experiments were compared with results of a CFD model, which showed slight differences against laboratory measurements.

Keywords: Characteristic Curves, Computational Fluid Dynamics, Experimental Analysis, Motor Efficiency Class, Single and Multi-Stage PAT, Pump As Turbine.

Introduction

Hydropower generation in urban areas is a recent approach in the management of water systems, aiming at exploiting excess energy instead of its dissipation. In Water Distribution Networks (WDNs), Energy Recovery (ER) can be coupled to pressure regulation and water losses reduction by using micro-turbines or Pumps As Turbines (PATs). PATs can be used for hydropower generation by inverting the internal flux and using the motor as electrical generator.

Many models of PATs are available in the market, with different geometry and performance. Thus, their use requires low investment and maintenance costs, with easier spare parts procurement and limited payback period [1].

Conversely, PATs generally have lower performances than turbines, with narrower operative fields and lower hydraulic elasticity. Such limitations can be overcome by means of hydraulic and/or electrical regulation [2-4]. Another critical issue is the lack of information about PAT performances. A few experimental and theoretical models are available in the literature, which can be used only for specific models and limited operating conditions.

Among such approaches, analytical relationships (Table 1) were proposed to predict the operating conditions of a PAT at the Best Efficiency Point (BEP), as a function of the machine characteristics in normal (direct) mode.

Table 1 Flow rate and head ratios at BEP between turbine and pump mode

Model	**Flow Rate Ratio** Q_{tb}/Q_{pb} **[-]**	**Head Ratio** H_{tb}/H_{pb} **[-]**
Stepanoff [5]	$\eta_{pb}^{-1/2}$	η_{pb}^{-1}
Childs [6]	η_{pb}^{-1}	η_{pb}^{-1}
Hancock [7]	η_{tb}^{-1}	η_{tb}^{-1}
Grover [8]	$2.379-0.0264N_{st}$	$2.693-0.0229N_{st}$
Hergt [9]	$1.3-1.6/(N_{sp}-5)$	$1.3-6/(N_{sp}-3)$
Sharma [10]	$\eta_{pb}^{-0.8}$	$\eta_{pb}^{-1.2}$
Schmiedl [11]	$-1.5+2.4/\eta^2_{hpb}$	$-1.4+2.5/\eta_{hpb}$
Alatorre–Frenk and Thomas [12]	$(0.85\eta_{pb}^5+0.385)/$ $(2\eta_{pb}^{9.5}+0.205)$	$1/(0.85\eta_{pb}^5+0.385)$
Joshi et al. [13]	1.50	1.60
Derakhshan and Nourbakhsh [14]	$f(N_{sp})$	$f(N_{sp})$
Nautiyal et al. [15]	$30.303[(\eta_{pb}-0.212)/$ $\ln(N_{Sp})]-3.424$	$41.667[(\eta_{pb}-0.212)/$ $\ln(N_{Sp})]-5.042$
Yang et al. [16]	$1.2/\eta_{pb}^{0.55}$	$1.2/\eta_{pb}^{1.1}$
Tan and Engeda [17]	$\omega D^3/(N_{st}D_{st}^3g^{3/4}Q_{pb})$	$(\omega D)^2/(N_{st}^2D_{st}^2g^{3/2}H_{pb})$

In Table 1 η is the efficiency, N_s the specific speed, ω the angular velocity, D_s the specific diameter (1), g the acceleration of gravity, Q the flow rate, H the head. Subscripts p, t and b indicate the pump mode, the turbine mode and the BEP conditions, respectively:

$$D_s = \frac{DH_b^{0.25}}{Q_b^{0.5}} \qquad (1)$$

where D is the impeller diameter.

At the same time, only a few models are able to predict PAT characteristic curves. Among these, the model of Derakhshan and Nourbakhsh [14] allows to predict the head drop curve H_t, power curve P_t and efficiency curve η_t of a horizontal axis centrifugal PAT, as a function of the pump operation at the BEP. Pugliese et al. [18], carried out extensive experimental analysis on both horizontal and vertical axis PATs, showing the reliability of

Derakhshan and Nourbakhsh [5]'s model only for flow rate number $\phi \leq 0.40$, being ϕ a dimensionless parameter derived by the application of the Affinity Laws [19]:

$$\phi = \frac{Q}{ND^3} \qquad (2)$$

with Q the flow rate (m^3/s), N the rotational speed (rps) and D the impeller diameter (m).

The authors proposed a new equation, which minimizes deviations between experimental and theoretical data for a horizontal PAT. Such equation is also reliable for Vertical Multi-Stage PATs, with deviations always lower than 30%.

As an alternative, Computational Fluid Dynamics (CFD) models can be used to predict the performances of turbo-machines. Such models are able to reproduce the kinematic and dynamic flow fields across the PAT, taking into account the turbulence phenomena [20-22]. The application of CFD models requires proper calibration and validation through experimental data [23]. Nevertheless, CFD simulations can be useful to assess the effectiveness of any possible improvement to the machine, e.g. modifying the geometry of the impeller.

To assess the reliability of models available in the literature for predicting the performances of centrifugal PATs, useful in water systems for hydropower generation, experimental and numerical investigation was carried out in the paper. From the experimental side, four PATs were tested: 1) a Horizontal Axis Single-Stage PAT (HA SS PAT); 2) a Vertical Axis Single-Stage PAT (VA SS PAT) with motor efficiency class IE2; 3) two Vertical Axis Multi-Stage PATs (VA MS_1 PAT and VA MS_2 PAT) with motor efficiency class IE3. For the HA SS PAT, a CFD model was also implemented, aiming at assessing the reliability of CFD simulations to predict the characteristic curves of a centrifugal PAT.

Experimental investigation of centrifugal Pumps As Turbines

Experiments were performed with the aim of analyzing the performance of several centrifugal PAT models, to be used in water systems for both pressure regulation and small-scale hydropower generation.

A four loops WDN laboratory prototype was installed at the Department of Civil, Architectural and Environmental Engineering (DICEA) of the University of Naples Federico II, according to the schematic in Figure 1.

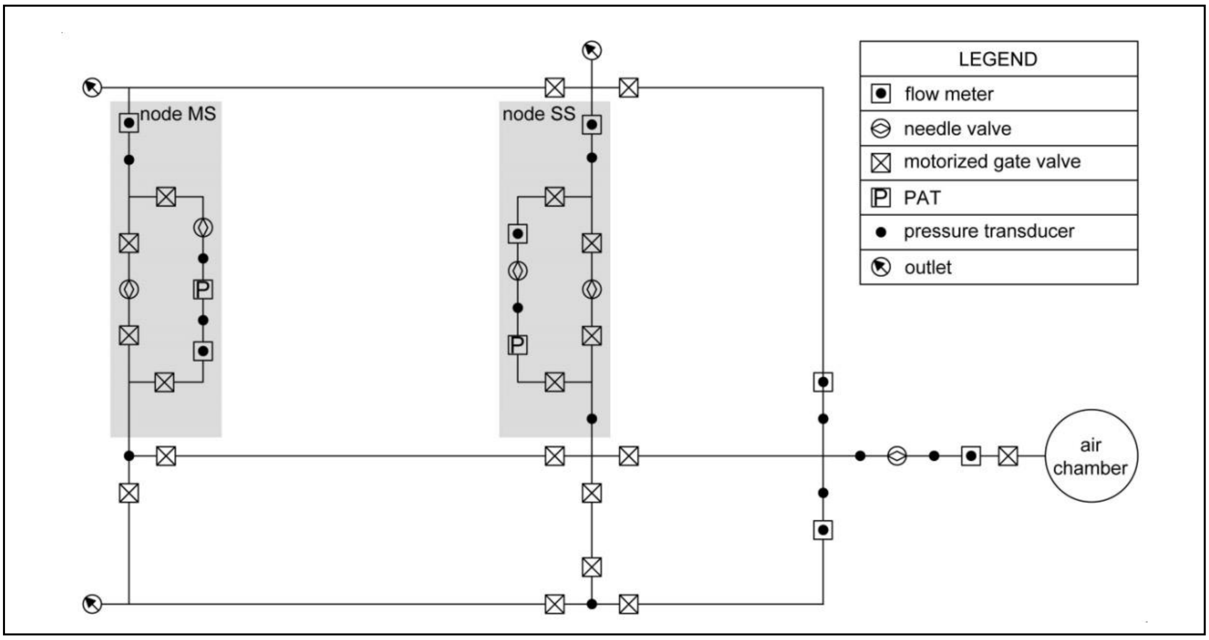

Figure 1 Layout of laboratory network at DICEA Hydraulic Laboratory [6]

The WDN is made of cast iron pipes with diameter DN150, and allows two centrifugal PATs to be installed at nodes SS and MS. Flow rate varied from 8 l/s to 50 l/s, whereas an inverter was used to vary the impeller rotational speed *N*, ranging from 5 rps to the value allowed by the discharge running the PAT, with a maximum of 50 rps. The HA SS PAT was tested at node SS. The PAT is LOWARA pump, model FHE 80-200/220, with a IE2 [24,25] motor efficiency class. At node MS, the VA PATs were tested. The VA SS PAT (model LOWARA 92SV1G75T) was equipped with a IE3 efficiency motor class, whereas the two VA MS PATs (model LOWARA 92SV2G150T) were equipped with a IE2 motor (VA MS_1 PAT) and a IE3 motor (VA MS_2 PAT), respectively.

In the following Table 2, the characteristics of the pumps and at the operation at the BEP are summarized, according to the manufacturer's datasheets.

Table 2 Characteristics of the tested PATs in pump mode

PAT	Nominal Power *NP*	Impeller Diameter *D*	Number of Impellers	Motor Efficiency Class	Rotational Speed *N*	Efficiency at BEP η_{tb}	Flow Rate at BEP Q_{tb}	Head at BEP H_{tb}	Power at BEP P_{tb}	Specific Speed Ns_p
	[kW]	**[m]**	**[-]**	**[-]**	**[rps]**	**[%]**	**[m³/h]**	**[m]**	**[kW]**	**[rpm, m³/s]**
HA SS	22.0	0.189	1	IE2	48.33	78.7	148.0	39.0	20.0	37.75
VA SS	7.5	0.146	1	IE3	48.33	76.5	88.5	22.0	7.0	44.76
VA MS_1	15.0	0.146	2	IE2	48.33	76.5	88.5	44.0	14.0	44.76
VA MS_2	15.0	0.146	2	IE3	48.33	76.5	88.5	44.0	14.0	44.76

The PATs characteristic curves were determined, by measuring, per each flow rate Q_t, the head drop H_t, the produced power P_t and the overall efficiency η_t. The head drop H_t was calculated as the difference between the pressure measured by the pressure transducers (with accuracy 0.25% of full-scale) installed upstream and downstream of the PAT. The flow rate Q_t was measured through an electromagnetic flow meter (with accuracy 0.2% ± 2.5 mms-1 of full-scale). The produced power P_t was given as output by the inverter (accuracy 1%) connected to the machine. The overall efficiency η_t was therefore calculated as:

$$\eta_t = \frac{P_t}{\gamma_w Q_t H_t} \quad (3)$$

being γ_w the water specific weight.

Data were acquired through a Supervisory Control And Data Acquisition (SCADA) unit, at 1 s time interval. After steady state conditions were achieved, measured values were averaged over a time interval at least 60 s, so as to remove the random error. Uncertainty analysis [26] was also applied to assess the level of confidence of the measurements, resulting uncertainties of ±0.26%, ±2.09%, ±2.93% and ±3.61%, for flow rate, head drop, power and efficiency, respectively. Results from experiments are summarized in the following Table 3.

Table 3 Experimental operative ranges of tested PATs

PAT	Number of Experiments	Flow Rate Q_t	Head Drop H_t	Power P_t	Efficiency η_t
	[-]	[l/s]	[m]	[kW]	[%]
HA SS	3232	8 - 50	1.24 – 55.80	0.06 – 16.28	4.0 – 61.3
VA SS	1348	9 – 33	2.73 – 47.34	0.04 – 7.40	5.0 – 65.5
VA MS$_1$	1684	8 – 28	4.07 – 54.38	0.04 – 9.91	1.6 – 72.1
VA MS$_2$	1166	8 - 31	4.06 – 72.34	0.11- 13.37	3.2 – 72.1

In Figs. 2a-c results for the HA SS PAT are plotted. Data were given in dimensionless terms, by using the flow rate number ϕ (2), the head number ψ (4) and the power number π (5).

$$\psi = \frac{gH_t}{N^2D^2} \qquad (4)$$

$$\pi = \frac{P_t}{\rho_w N^3 D^5} \qquad (5)$$

being ρ_w the water density.

For comparison, the models of Derakshshan and Nourbakhsh [14] and Pugliese et al. [18] are also plotted.

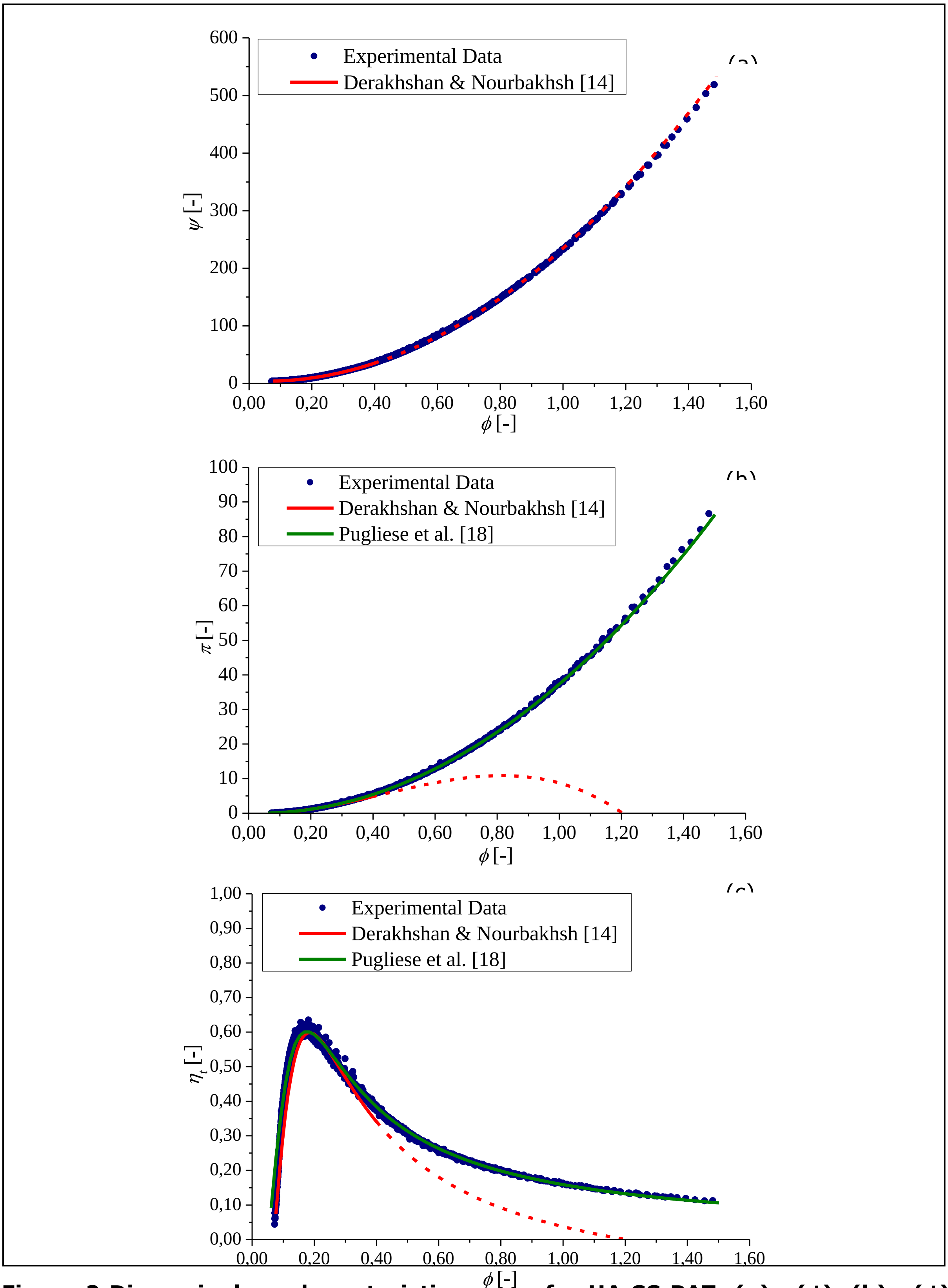

Figure 2 Dimensionless characteristic curves for HA SS PAT: (a) $\psi(\phi)$, (b) $\pi(\phi)$ and (c) $\eta_t(\phi)$

Figure 2a shows that the model of Derakhshan and Nourbakhsh [14] for the head drop function $\psi(\phi)$, is reliable within the whole set of investigated flow rates, also for values of ϕ outside the range investigated by the authors ($\phi \leq 0.40$). Conversely, for both the power curve and the efficiency curve, the model resulted reliable only within the investigated range, returning even negative values for ϕ > 1.20. Pugliese et al. [18] proposed a new equation for the power curve (Figure 2b):

$$\frac{P_t}{P_{tb}} = 4.0 \cdot 10^{-3}\left(\frac{Q_t}{Q_{tb}}\right)^3 + 1.386\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.390\left(\frac{Q_t}{Q_{tb}}\right) \tag{6}$$

and for the efficiency curve (Figure 2c).

$$\frac{\eta_t}{\eta_{tb}} = \frac{4.0 \cdot 10^{-3}\left(\frac{Q_t}{Q_{tb}}\right)^3 + 1.386\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.390\left(\frac{Q_t}{Q_{tb}}\right)}{1.0283\left(\frac{Q_t}{Q_{tb}}\right)^3 - 0.5468\left(\frac{Q_t}{Q_{tb}}\right)^2 + 0.5314\left(\frac{Q_t}{Q_{tb}}\right)} \tag{7}$$

which are reliable for flow rate numbers ϕ up to 1.50.

To predict the BEP of a PAT as a function of the operation in pump mode, relations in Table 1 were applied to calculate flow rate Q_{tb}/Q_{pb} and head H_{tb}/H_{pb} ratios. Predicted values and relative errors are summarized in the following Table 4.

Table 4 Experimental flow rate and head ratios for HA SS PAT

Model	**Flow Rate Ratio** Q_{tb}/Q_{pb}	**Head Rate Ratio** H_{tb}/H_{pb}	**Flow Rate Ratio Relative Error** $\Delta(Q_{tb}/Q_{pb})$	**Head Ratio Relative Error** $\Delta(H_{tb}/H_{pb})$
	[-]	**[-]**	**[%]**	**[%]**
Stepanoff [5]	1.13	1.27	-23.18%	-31.62%
Childs [6]	1.27	1.27	-13.41%	-31.62%
Hancock [7]	1.63	1.63	11.22%	-12.17%
Grover [8]	1.62	2.04	10.44%	9.51%
Hergt [9]	1.23	1.07	-16.00%	-42.59%
Sharma [10]	1.21	1.33	-17.46%	-28.27%
Schmiedl [11]	1.96	1.60	33.31%	-13.90%
Alatorre–Frenk and Thomas [12]	1.56	1.56	6.52%	-16.13%
Joshi et al. [13]	1.50	1.60	2.15%	-13.90%
Derakhshan and Nourbakhsh [14]	1.39	1.54	-5.08%	-16.98%
Nautiyal et al. [15]	1.37	1.56	-6.31%	-16.25%
Yang et al. [16]	1.37	1.56	-6.71%	-15.96%
Tan and Engeda [17]	1.10	1.28	-24.76%	-31.37%

Relative errors in the order of ±30% were estimated with most of the considered models. The Grover models [8] achieve the best performance, with deviations for both flow rate and head ratio of around 10%.

Similar considerations apply for the VA PATs. Results of experiments were plotted in Figure 3a for $\psi(\phi)$, Figure 3b for $\pi(\phi)$ and Figure 3c for $\eta(\phi)$. For multi stage PATs, results were plotted in terms of a single stage, for ease of comparison.

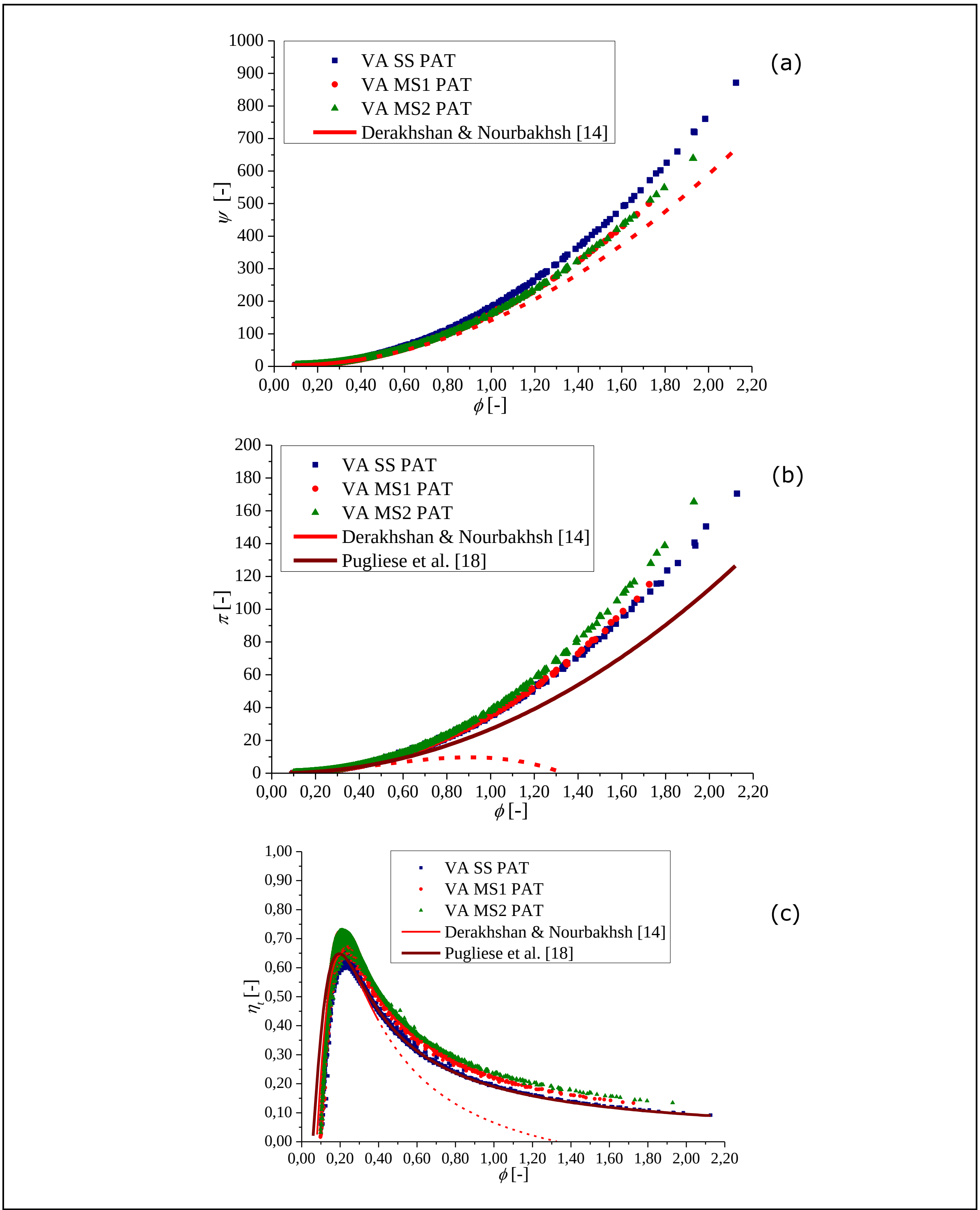

Figure 3 Dimensionless characteristic curves for VA SS, MS_1 and MS_2 PATs: (a) $\psi(\phi)$, (b) $\pi(\phi)$ and (c) $\eta_t(\phi)$

Figure 3a shows slight differences between the head curves of MS PATs and SS PAT. The model of Derakhshan and Nourbakhsh [14] underestimates the experiments by 14% and 23%, respectively. Similar considerations apply for the power curves (Figure 3b). Maximum produced power was observed for the VA MS_2 PAT, which is equipped with a IE3 motor class, for $\phi > 0.80$. For lower flow rate numbers, differences between the three PATs are quite negligible. It is worth noting that flow rate numbers greater than 0.80 corresponds to PATs running at lower rotational speeds *N*. As for the SS PAT, the model of Derakhshan and Nourbakhsh [14] for power curve is valid only for $\phi \leq 0.40$, whereas the model of Pugliese et al. [18] shows consistent pattern and maximum differences in the order of 30%.

All the VA PATs achieved the BEP at the same flow rate number ϕ_b = 0.21. Both the VA MS PATs exhibited the same maximum efficiency η_{tb} = 72.1%, whereas the VA SS PAT returned a lower efficiency at the BEP η_{tb} = 65.5%. The efficiency curves for all PATs show a very similar pattern, with slightly lower values for the VA SS PAT. The VA MS_2 PAT returned instead a slightly higher efficiency for $\phi > 0.80$, because of the greater power generated at lower rotational speeds *N*.

Results of the relations to predict flow rate and head ratios at the BEP are given in Table 5 for the VA SS PAT and in Table 6 for the VA MS PATs. The Stepanoff [5], Sharma [10], Childs [6] and Tan and Engeda [17] relations showed the best agreement with experiments, with maximum errors in the order of 10%.

Table 5 Experimental flow rate and head ratios for VA SS PAT

Model	**Flow Rate Ratio** Q_{tb}/Q_{pb}	**Head Rate Ratio** H_{tb}/H_{pb}	**Flow Rate Ratio Relative Error** $\Delta(Q_{tb}/Q_{pb})$	**Head Ratio Relative Error** $\Delta(H_{tb}/H_{pb})$
	[-]	**[-]**	**[%]**	**[%]**
Stepanoff [5]	1.14	1.31	-8.90%	-10.69%
Childs [6]	1.31	1.31	4.15%	-10.69%
Hancock [7]	1.53	1.53	21.61%	4.27%
Grover [8]	1.38	1.83	10.29%	25.03%
Hergt [9]	1.25	1.13	-0.32%	-23.00%
Sharma [10]	1.24	1.38	-1.28%	-5.78%
Schmiedl [11]	1.89	1.57	50.59%	7.34%
Alatorre–Frenk and Thomas [12]	1.68	1.65	33.77%	12.42%
Joshi et al. [13]	1.50	1.60	19.51%	9.31%
Derakhshan and Nourbakhsh [14]	1.29	1.44	2.91%	-1.91%
Nautiyal et al. [15]	0.98	1.02	-21.57%	-30.35%
Yang et al. [16]	1.39	1.61	10.79%	10.08%
Tan and Engeda [17]	1.16	1.36	-7.42%	-7.16%

Table 6 Experimental flow rate and head ratios for VA MS PATs

Model	Flow Rate Ratio Q_{tb}/Q_{pb}	Head Rate Ratio H_{tb}/H_{pb}	Flow Rate Ratio Relative Error $\Delta(Q_{tb}/Q_{pb})$	Head Ratio Relative Error $\Delta(H_{tb}/H_{pb})$
	[-]	[-]	[%]	[%]
Stepanoff [5]	1.14	1.31	-8.90%	-4.04%
Childs [6]	1.31	1.31	4.15%	-4.04%
Hancock [7]	1.39	1.39	10.48%	1.80%
Grover [8]	1.33	1.78	5.89%	30.84%
Hergt [9]	1.25	1.14	-0.09%	-16.54%
Sharma [10]	1.24	1.38	-1.28%	1.25%
Schmiedl [11]	1.73	1.50	37.93%	10.18%
Alatorre–Frenk and Thomas [12]	1.68	1.65	33.77%	20.80%
Joshi et al. [13]	1.50	1.60	19.51%	17.46%
Derakhshan and Nourbakhsh [14]	1.52	1.74	21.50%	27.68%
Nautiyal et al. [15]	0.98	1.02	-21.57%	-25.16%
Yang et al. [16]	1.39	1.61	10.79%	18.28%
Tan and Engeda [17]	1.16	1.36	-7.42%	-0.23%

CFD modeling of centrifugal Pumps As Turbines

A CFD model was also developed to simulate the fluid dynamics of the VA SS PAT. A 3D scanning model of the considered turbo-machine was developed, provided by the Department of Industrial Engineering of the University of Naples Federico II [27,28]. The ANSYS® DesignModeler™ tool was used to extract the fluid domain of both the impeller (diameter D = 0.189 m, with 6 blades) and the volute. Connection pipes were also introduced at inlet and outlet to set the boundary conditions. The mesh was generated using the ANSYS® ICEM CFD™ tool. A structured hexahedral mesh was used for both inlet and outlet pipes, whereas an unstructured tetrahedral mesh was generated for the impeller and the volute, because of their complex geometry. Specific refinements were also applied to both the volute tongue region and the impeller blades, in order to improve the mesh regularity and connection around the blades. Finally, a sensitivity analysis was performed to assess the best trade off between mesh resolution and computational times, considering three resolution levels (Table 7).

Table 7 Number of elements for each mesh resolution level

Resolution Level	Impeller	Volute	Inlet Pipe	Outlet Pipe	Total
	[-]	**[-]**	**[-]**	**[-]**	**[-]**
Low	96'023	488'654	12'654	12'470	**609'801**
Medium	240'094	657'973	12'654	11'426	**922'147**
High	452'911	1'083'355	10'659	14'094	**1'561'019**

The medium resolution has a total number of 922'147 elements: 240'094 elements for the impeller (Figure 4a); 657'973 elements for the volute (Figure 4b); 12'654 elements for the inlet pipe; and 11'426 elements for the outlet pipe. Such resolution corresponded to the best trade off between accuracy of the results and computational effort. In the following Table 8, the average relative deviations between experimental and numerical results are given, in terms of static pressure at the inlet section. Values were calculated at the BEP for rotational speeds N = 25, 35 and 48.5 rps. The average computational time efforts was also reported.

Table 8 Relative scatters and computational times for three levels of resolution

Resolution Level	Experimental-Numerical deviation	Computational Time
	[%]	**[hh:mm]**
Low	23.1	10:36
Medium	9.2	28:24
High	5.7	96:37

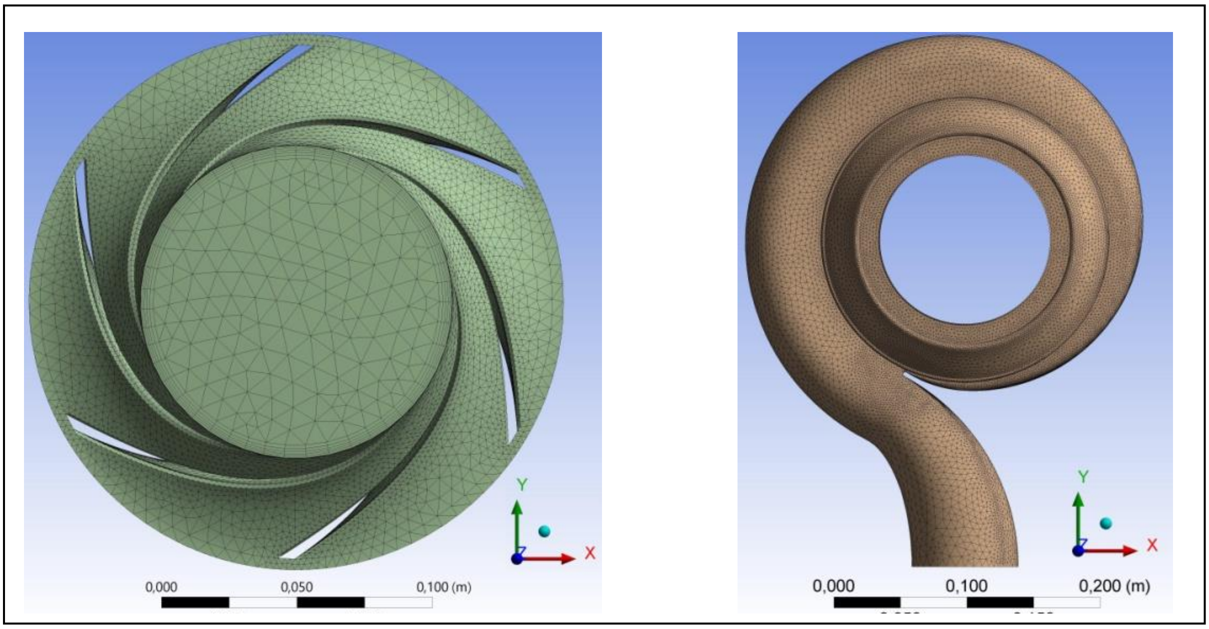

Figure 4 (a) Meshing of the impeller front; (b) Meshing of the volute front

Flow simulations were developed using the ANSYS® Fluent™ code [29]. The Standard *k-ε* turbulence model was considered [30], with standard wall functions for the near-wall treatment. The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm [31] was set and second-order spatial upwind discretization was applied with high order term relaxation. Three planar interfaces were introduced to generate the interaction between inlet-volute, volute-impeller and impeller-outlet, respectively.

A uniform velocity distribution and a static pressure were set as boundary conditions at inlet and outlet, respectively [20]. Simulations were run with the following calculation steps:

- *Steady-state calculations*, performed through the *Moving Reference Frame* (*MRF*) criterion, based on a frozen-rotor interface, able to characterize the impeller-volute interaction for a fixed angular position of the impeller;
- *Unsteady-state calculations*, acting as second step, after reaching the convergence with the steady-state mode. Calculations were initialized by using the velocity and the pressure fields from the steady-state mode and the *Sliding Mesh* (*MS*) technique was considered to reproduce the relative motion between impeller and volute. The time step duration was calculated in such a way that a complete impeller revolution was carried out in 150 time steps. At least 5 complete impeller revolutions were performed before calculating the mean value of flow variables corresponding to a single blade passage (25 time steps), in order to reach the periodicity of flow variables in the unsteady-state simulations [21].

The head drop generated by the PAT was calculated as the difference between the pressure at inlet and outlet, whereas the generated power P_t was estimated by applying an integrative process on the instantaneous pressure and shear stress distribution on the blade walls, useful to estimate the torque on the impeller. Thus, the hydraulic efficiency η_{ht} was estimated through the Eq. (2) and comparison with experimental results was performed, by plotting the $H_t(Q_t)$, $P_t(Q_t)$, $\eta_{ht}(Q_t)$ curves. In order to account for the volumetric, the internal and the motor efficiencies, an efficiency reduction at the 94% was estimated, being each rate set equal to 98%.

As an example, for a rotational speed N = 25 rps results are plotted against the experiments (Figure 5).

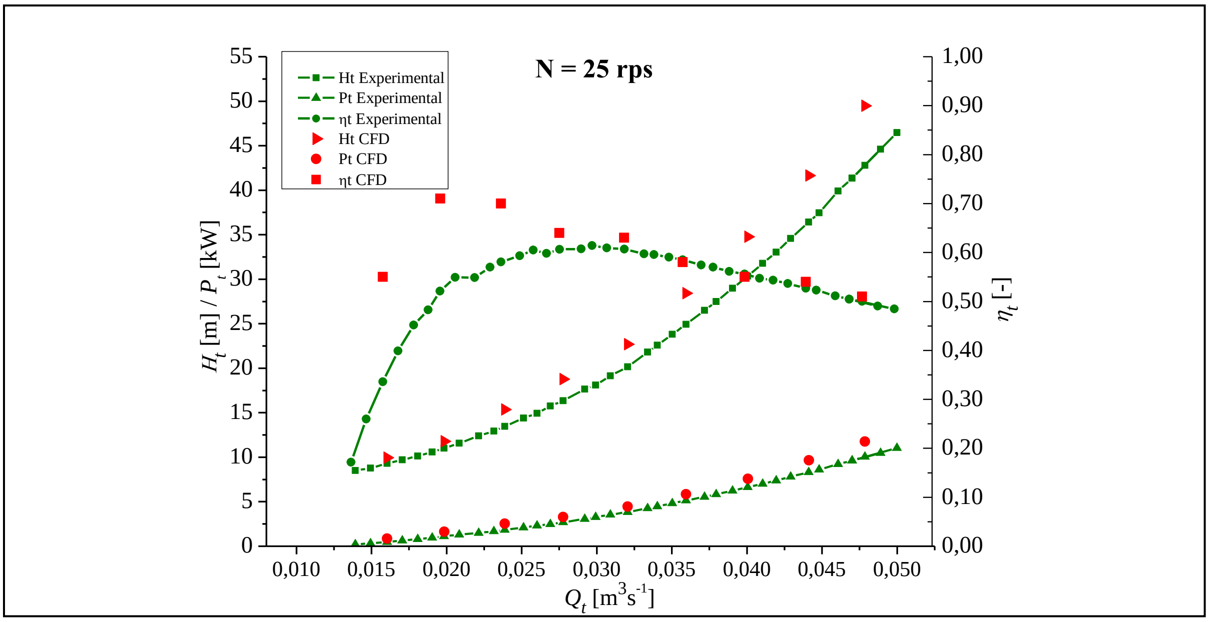

Figure 5 Experimental-numerical comparisons of $H_t(Q_t)$, $P_t(Q_t)$, $\eta_{ht}(Q_t)$ curves for N = 25 rps

CFD model overestimates the head drop H_t at increasing the flow rate Q_t, with maximum deviations in the order of 15%. For the power curve $P_t(Q_t)$ it results a relevant percentage error, especially for low flow rates, although such errors are negligible in absolute terms (in the order of tenths or hundreds of Watts). As a consequence, efficiency curve $\eta_t(Q_t)$ shows a good agreement only for flow rates $Q_t \geq 30$ l/s, with errors in the order of 5%. Because of the error on P_t at low flow rates, also efficiency was significantly overestimated for lower flows. The CFD model returned a maximum efficiency of 71.0 % for a flow rate of 20 l/s, whereas the experiments showed the BEP was achieved for a flow rate of 30 l/s and efficiency of 61%.

Conclusions

In this paper results of an experimental and numerical analysis of centrifugal PATs were analysed and discussed, aiming at investigating the performance of both Horizontal and Vertical axis centrifugal PATs, to be used in water systems for both pressure regulation and small-scale hydropower generation. About 7'400 experiments were carried out on four centrifugal PATs, with a wide range of rotational speeds and flow rates analyzed. The PATs differed for geometry, number of stages and motor class efficiency. The analysis of the Horizontal Axis Single-Stage PAT showed that the model Derakhshan and Nourbakhsh is reliable to predict the head curves, whereas, for power and efficiency curves, it returns unreliable for flow rate numbers greater than 0.40. The model of Pugliese et al. showed good agreement for all curves for flow rates numbers up to 1.50.

Similar results were observed for Vertical Axis PATs, the model of Pugliese et al. being able to predict the actual pattern of the experimental curves for head, power and efficiency curves. Nevertheless, such model underestimates the head numbers of around 20% and power numbers of about 30%. Analysis also showed the slight increase in produced power for the IE3 motor class equipped PAT, although only for high flow rate numbers (i.e. for low rotational speeds).

Models available in the literature were used to estimate the flow rate and the head drop ratios at the BEP in reverse mode. For the HA SS PAT, the Grover formulations returned errors in the order of 10%; for the VA PATs the Stepanoff, Sharma, Childs and Tan and Engeda models resulted the most reliable, with maximum errors again around 10%.

Finally, a CFD model was developed to reproduce the flow field of the HA SS PAT. The numerical model was reliable to predict the characteristic curves, especially for high flow rates. Maximum deviations in the order of 15% for the head curve and 20% for the power curve were observed for flow rates higher than the BEP. Nevertheless, a poor agreement was observed for the BEP, with a difference for the maximum efficiency around 10% and greater differences for lower flow rates.

Results showed the reliability of the CFD application to predict the performance of centrifugal PATs. Nevertheless, the CFD model requires further analysis to reduce differences with experiments. As an example, the internal geometry of the machines should be better characterized and deeply investigated both the influence of mesh resolution and volumetric, internal and motor efficiency.

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References

[1] Motwani K.H., Jain S.V. and Patel R.N. *Cost analysis of Pump As Turbine for pico hydropower plants – a case study*. Procedia Engineering 2013, 51, pp. 721-726. http://dx.doi.org/10.1016/j.proeng.2013.01.103

[2] Fontana N., Giugni M. and Portolano D. *Losses reduction and energy production in water distribution networks*. Journal of Water Resources Planning and Management 2012, 138(3), pp. 237-244. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000179

[3] Fontana N., Giugni M., Glielmo L. and Marini G. *Real time control of a prototype for pressure regulation and energy production in water distribution networks*. Journal of Water Resources Planning and Management 2016, 142(7), 04016015, pp. 1-9. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000651

[4] Carravetta A., Del Giudice G., Fecarotta O. and Ramos H.M. *Energy production in Water Distribution Networks: a PAT design strategy*. Water Resources Management 2012, 26, pp. 3947-3959. http://dx.doi.org/10.1007/s11269-012-0114-1

[5] Stepanoff A.J. Centrifugal and Axial Flow Pumps, 2nd ed., John Wiley & Sons, Inc, New York, USA, 1957, p. 276. ISBN 978-0894647239.

[6] Childs S.M. *Convert pumps to turbine and recover HP*. In: Hydrocarbon Processing and Petroleum Rejner 1962, 41(10), 173-174.

[7] Hancock J.W. *Centrifugal pump or water turbine*. Pipe Line News 1963, pp. 25-27.

[8] Grover K.M. *Conversion of Pumps to Turbines*. GSA Inter Corp, Katonah, New York, USA. 1980.

[9] Hergt P. *The influence of the volute casing on the position of the best efficiency point*. Proc. of the 11th IAHR Symposium, Amsterdam, Holland, 1982, 3, p. 69.

[10] Sharma K.R. *Small Hydroelectric Project-use of Centrifugal Pumps as Turbines*, Kirloskar Electric Co, Bangalore, India, 1985.

[11] Schmiedl E. Serien-Kreiselpumpen im Turbinenbetrieb. *Pumpentagung Karlsruhe*, A6 (in German), 1988.

[12] Alatorre-Frenk C. and Thomas T.H. The pumps as turbines approach to small hydropower. World Congress on Renewable Energy (reading), 1990.

[13] Joshi S., Gordon A., Holloway L. and Chang L. *Selecting a high specific speed pump for low head hydro-electric power generation*. Proc. of the *Canadian Conference on Electrical and Computer Engineering*, 2005. http://dx.doi.org/10.1109/CCECE.2005.1557003

[14] Derakhshan S. and Nourbakhsh A. *Experimental study of characteristic curves of centrifugal pumps working as turbines in different specific speeds*. Experimental Thermal and Fluid Science 2008, 32, pp. 800-807. http://dx.doi.org/10.1016/j.expthermflusci.2007.10.004

[15] Nautiyal H., Varun, Kumar A. and Yadav S. *Experimental investigation of centrifugal pump working as turbine for small hydropower systems*. Energy Science and Technology 2011, 1(1), pp. 79-86.

[16] Yang S-S., Derakhshan S. and Kong F-Y. *Theoretical, numerical and experimental prediction of pump as turbine performance*. Renewable Energy 2012, 48, pp. 507-513. http://dx.doi.org/10.1016/j.renene.2012.06.002

[17] Tan X. and Engeda A. *Performance of centrifugal pumps running in reverse as turbine: Part II – systematic specific speed and specific diameter based performance prediction*. Renewable Energy 2016, 99, pp. 188-197. http://dx.doi.org/10.1016/j.renene.2016.06.052

[18] Pugliese F., De Paola F., Fontana N., Giugni M. and Marini G. *Experimental characterization of two Pumps As Turbines for hydropower generation*. Renewable Energy 2016, 99, pp. 180-187. http://dx.doi.org/10.1016/j.renene.2016.06.051

[19] Stepanoff A.J. Centrifugal and Axial Flow Pumps: Theory, Design and Application, John Wiley & Sons, Inc, New York, USA, 1948. ISBN 0894647237.

[20] Fernandez J., Barrio R., Blanco E., Parrondo J. and Marcos A. *Numerical investigation of a centrifugal pump running in reverse mode*. Proceedings of the Institution of Mechanical Engineers, Part a: Journal of Power and Energy 2010, 224(3), pp. 373-381. http://dx.doi.org/10.1243/09576509JPE757

[21] Barrio R., Fernandez J., Parrondo J. and Blanco E. *Performance prediction of a centrifugal pump working in direct and reverse mode using Computational Fluid Dynamics*. Proc. of the International Conference on Renewable Energies and Power Quality ICREPQ '10, 23rd-25th March 2010, Granada, Spain

[22] Fecarotta O., Carravetta A. and Ramos H.M. *CFD and comparisons for a Pump As Turbine: mesh reliability and performance concerns*. International Journal of Energy and Environment 2011, 2(1), pp. 39-48.

[23] Tamm A., Braten A., Stoffel B. and Ludwig G. *Analysis of a standard pump in reverse operation using CFD*. Proc. of the 20th IAHR Symposium: Hydro, Technology, and the Environment for the New Century, 6th-9th August 2000, Charlotte, North Carolina, USA.

[24] International Electrotechnical Commission, *IEC 60034*, Int. Stand. 2008, 30.

[25] International Electrotechnical Commission, *IEC 60034*, Int. Stand. 2014, 30(1).

[26] Abernethy R. B., Powell B. D., Colbert D. L., Sanders D. L. and Thompson Jr. J. W. Handbook uncertainty in gas turbine measurements, 1973. USAF AEDC-TR-73-5, IS&N: 87664-483-3

[27] Buono D., Frosina E., Mazzone A., Cesaro U. and Senatore A. *Study of a Pump As Turbine for a hydraulic urban network using a tridimensional CFD modelling methodology*. Energy Procedia 2015, 82, pp. 201-208. http://dx.doi.org/10.1016/j.egypro.2015.12.020

[28] Frosina E., Buono D. and Senatore A. *A performance prediction method for Pumps As Turbines (PATs) using a Computational Fluid Dynamics (CFD) modelling approach*. Energies 2017, 10(103), pp. 1-19. http://dx.doi.org/10.3390/en10010103

[29] ANSYS. *ANSYS Fluent User's Guide*. Can be downloaded at: http://148.204.81.206/ Ansys/150/ANSYS%20Fluent%20Users%20Guide.pdf

[30] Launder B. and Spalding D.B. *The numerical computation of turbulent flow computer methods*. Computer Methods in Applied Mechanics and Engineering 1974, 3(2), pp. 269-289. http://dx.doi.org/10.1016/0045-7825(74)90029-2

[31] Patankar S.V. and Spalding D.B. *A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows*. International Journal of Heat and Mass Transfer 1972, 15(10), pp. 1787-1806. http://dx.doi.org/10.1016/0017-9310(72)90054-3

Energy and Environmental Savings in Marine Service through Successful Application of the "Affinity Law"

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Abstract

Over the period of the EEMODS conferences, diesel engines have taken increasing shares of the automobile market. The inventor credited with the first engine in 1893, Rudolf Diesel, could be proud. He made several financial fortunes; however, his greatest reward may be his name being given to the product class that has been expanded multiple times by clever engineers. It has many attributes, but leading the list would be: high efficiency and simplicity.

When we hear the term "diesel driven", most visualize the 3x2x3-foot cube in our automobiles. But that is a high-speed diesel operating above 900 RPM; diesels below 300 RPM power huge seagoing vessels such as today's container ships. This class is frequently described as a two-stroke "Marine Diesel". It is about the size of a fourteen-story apartment building in a horsepower package sometimes reaching over 100,000 at 100 RPM, 400 times greater horsepower than that automobile engine. Interestingly, like the automobile, these seagoing goliaths are favored for their high efficiency.[1]

EEMODS 15 contained a presentation on system improvement potentials for these vessels. This presentation presents an extension of potential savings and because of engine size, one can see a huge financial and environmental savings potential in optimizing auxiliary system operation.

The classic seagoing diesel system includes a cooling water loop where fresh water temperature is[2] controlled by a three-way valve in a sea water/fresh water heat exchanger. Due to engine heat loads, the seawater supply pumps are the largest pumps on the vessel. Redundancy is a fundamental marine requirement so there are typically either two 100% units or three 50% pump units that operate at full speed and maintain the fresh water temperature set point by modulating the three-way valve. For decades there have been thousands of vessels in sea going operation configured with such systems but only in 2015 was the commercial solution discussed in this presentation introduced to the industry.

Typically, systems are designed around 32°C seawater, and full power consumption is relatively constant at the point where the system curve intersects the pump curve. Vessels, however, do not operate at a constant speed, nor is seawater temperature constant. But by incorporating an electronic frequency controller with intelligent controls which apply the "Affinity Laws" for variable speed operation of this pump motor combination it can provide energy savings of as much as 80%, reduce operating loads on the pumping equipment, save fuel costs, limit CO_2 discharge and provide a platform for additional optimization of selected engine room services.[3]

This presentation provides examples, compares and identifies the system changes required, discusses the specific requirements of marine agencies, along with proposing possible future candidates for energy saving in engine room operations and vessel services. It further discusses key elements in the development of such a system and highlights the opportunity for operators to take advantage of this innovation for its financial, energy conservation and environmental benefits.

System Outline

Just like the automobile diesels, these mammoth marine two-stroke engines require a cooling system to deal with heat losses during engine operation. The difference, of course, is in sophistication and equipment size where the pump drive requirement can extend upward of 200 kWs, plus the system must be built to operate in a marine industry regulated environment. Main seawater pumps are typically single stage vertically mounted centrifugals, to conserve footprint space, and are constructed of materials for seawater service, such as naval bronze.

Sea conditions and vertically mounted pump motor units (with the future potential of variable speed operation) require special attention to vibration concerns. Such concerns also extend to electrical components, cabling and connections. Ship equipment and systems, plus production factories require "class" approval by one of several marine approval agencies such as:

- ABS (American Bureau Shipping)
- VB (Bureau Veritas)
- DNV (Det Norske Veritas)
- GL (Germanischer Lloyd)
- Intertechnics
- ISO
- KR (Korean Register of Shipping)
- Lloyd's Register
- RMR (Russian Maritime Register)

Seawater cooling systems have traditionally been designed based on agreed worst conditions; 32°C seawater, full engine speed/load, continuously running pumps at constant speed and temperature regulated by use of a large flow three-way valve with excess flow dumped to the sea. To a certain degree, this action is automated, but any abrogation is controlled by the ship's crew, who respond to the monitoring instruments and lights.

The seawater system interfaces with the fresh water system in an exchanger, and fresh water is used for the heat loads needed for engine cooling. Fresh water is used for the engine cooling so that its components can be constructed with compatible metals such as cast iron. The heat transfer occurs in the exchanger and the fresh water temperature is controlled by modulation of the three-way valve.

System Improvements

Although all of the above conditions contribute to products quite unique from ones in stationary land service, one major common feature is the performance of centrifugal pumps. Marine engines have, however, an advantage only seasonally available to stationary engines: that is, they frequently have the availability of seawater that is cooler than their design point, thus allowing a reduced quantity to capture the same engine heat load as the higher temperature fluid, lower flows and pressures reduce pump power demands.

Historically, when a system performance needed to change a valve was introduced in the system, marine seawater systems did just that, but at the expense of system efficiency. With the introduction of electronic variable frequency drives with Marine approvals, the application of variable pumping came into its own. Variable speed in centrifugal pump applications is based on the physics of pump operation known as the "Affinity Laws".[4]

- $Q_1/Q_2 = N_1/N_2$
- $H_1/H^2 = (N_1/N_2)^2$
- $BHP_1/BHP_2 = (N_1/N_2)^3$

Where Q = Flow Capacity/H = Head (pressure)/ BHP – Horsepower. In summary, flow is directly proportional to speed, pressure (head) is proportional to the square of the speed, and HP is proportional to the cube of speed.[5]

Because of the size of these engines, the potential seawater power savings through "Smart System" operation with variable speed pumps are substantial. For example, fluid handling systems on a container vessel represents approximately 25% of the vessel's electric load. Initially, smart systems entered the seawater service focused solely on the pump operation provided energy reductions in the range of 40 to 50%, but have not been extended to the broad system with capabilities to reduce energy consumption by 80%. Published articles by operators and suppliers give an insight into the savings for 300 installed systems of: [6]

- 94,327 tons of CO_2
- 34,936 tons of fuel
- 8.7 million USD
- 180,000 MWh

Transition History

Even with such savings, some owners and operators have been cautious in adoption. Initially, there were concerns about how one makes the retrofits required with a vessel fleet that is constantly in service. Secondly, equipment reliability is a primary requirement within the industry. No one wants to see their 13,000Teu containership bobbing in the sea mid-voyage. The equipment redundancy requirement of marine agencies, however, helped resolve both these issues (2/100% or 3/50% seawater units). There is also the fact that the conversion to variable speed operation could be accomplished by a hardware insertion between the power supply and the motor and not require replacements of heavy, difficult-to-access installed components. The system developer respected vessel service demands by delivering packaged conversion kits and trained their service personnel for in-voyage conversions.

[7]Of course, acceptance of reliability was an item that had to be earned, but thanks to visionary, first adopter conversions were obtained, and now one sees conversions across entire fleets. It is at this point interesting to consider the adoption cycle from the viewpoint of both the user and the developer. The pump system developer can see the advantage of variable speed operation because he knew the power of the Affinity Laws in systems with variable demands. This led to paper studies of what energy savings could be. This was followed by presentations to potential operators, and a key breakthrough was high interest by a single operator. This was so supporting that they allowed conversion of one of their in-service vessels by a team from the developer that rode the ship in its commercial operation. It was a strong learning and optimization experience by all parties.

In a parallel activity, a scaled pump test facility was constructed in the developer's plant to test the electronics, the operation, and the control philosophy. Eventually, sufficient test routines and hours were logged to convince the execution team of the viability of the program. This also was a great learning process. This phase included packaging designs, maintenance and application personnel training, marine qualified component selections, and development of software support materials.

Lessons Learned/Results

In retrospect, this always had the capability of being a successful program, but it required transition of the manufacturer from a "Flange to Flange" component supplier to a "system" supplier. That actually took management involvement from the executive down who placed very aggressive time demands on a team built with pump application skills: engineering/service/procurement/test/electronics and electrical drives. With success were added product management and customer support personnel. This now for the developer had transitioned the program from evolutionary to revolutionary.

It is hard for one to grasp the physical immensity of these engines. Consider that these engines buy their fuel oil not by the gallon, nor by the tens of gallons, but by the "ton". For sea passage, fuel typically is heavy fuel oil from the bottom of the refining barrel, also known as Residual Fuel Oil or Bunker Crude. It is not fully refined, is highly viscous, and typically contains high levels of sulfur and trace metals. This means that power reduction provides an important additional benefit in environmental savings.[(8) In a customer article, they report savings of 455000kWhrs by a two seawater pump that recovered their installation costs in less than nine months. Additionally, that is a substantial reduction in engine exhaust (approximately 230 tons of CO_2) to the atmosphere. Heavy fuel oil has long been the backbone of the shipping industry, but today there are strong environmental concerns due to the impact in Arctic shipping channels. Banning it on these routes is under consideration and[9] MEPC70-IMO sets a .5% sulfur cap on Marine fuels effective 2020. So reduction of fuel consumption is a highly sought after benefit of Smart Pumping.

In addition to cost reduction and environmental benefits, Smart Systems can extend component life and lengthen maintenance cycles. Some systems include assembly of pump operating data for planned maintenance purposes and enable reduction of operating personnel.

System Improvements

As the universe of installed units grew, it became clear that ships would likely benefit from the ability to include customizable features in addition to the universal features. An example would be the need for a single pressure requirement lower than the main line pressure, or the desire to have the system report to the main control room, or to report there in addition to reporting in the engine room.

Experience in the service has brought even greater energy reduction benefits through incorporating the full system within the Smart Pump controller. One such option allows elimination of the three-way valve, and provides the seawater loop control with a control valve on the discharge, designed to allow the pump to operate at its optimum efficiency point. As such, the system realizes energy reductions as great as 80%. An example is provided in the system schematic attached.[10] This provides much more precise control and further extends benefits.

- Maximize shipboard pumping efficiency
- Reduce operating and maintenance costs
- Minimize downtime
- Support sustainability with green vessels
- Make the best use of your crew's time

An early prediction following the seawater pump control success was that other ship services would find variable speed and computer-controlled operation attractive.

Following is a list of some of those services.

- Seawater cooling systems
- Steam condenser cooling system
- Fresh water cooling systems
- Engine room ventilation
- Cargo hold ventilation
- Pump monitoring
- Online vessels monitoring
- Customized solutions

Headwinds

The benefits of intelligent systems are occurring as the industry is dealing with a number of global economic issues. Fuel prices have seen a drastic change following the effect of lower crude prices. This seems like it should benefit the user, but efforts to ban heavy fuel would drastically change shipping economics. In fact, there likely may not be refining capacity to meet the next generation of fuel until an increased oil and gas refinery investment is made. IMO (International Maritime Organization) continues to implement environmental regulations, which require heavy capital investments by the owners (MEPC70-IMO/Sulfur Limit) (EWMC/Ballast Water Control).[11] Plus reduced global trade may be the greatest impact.

Summary / Conclusions

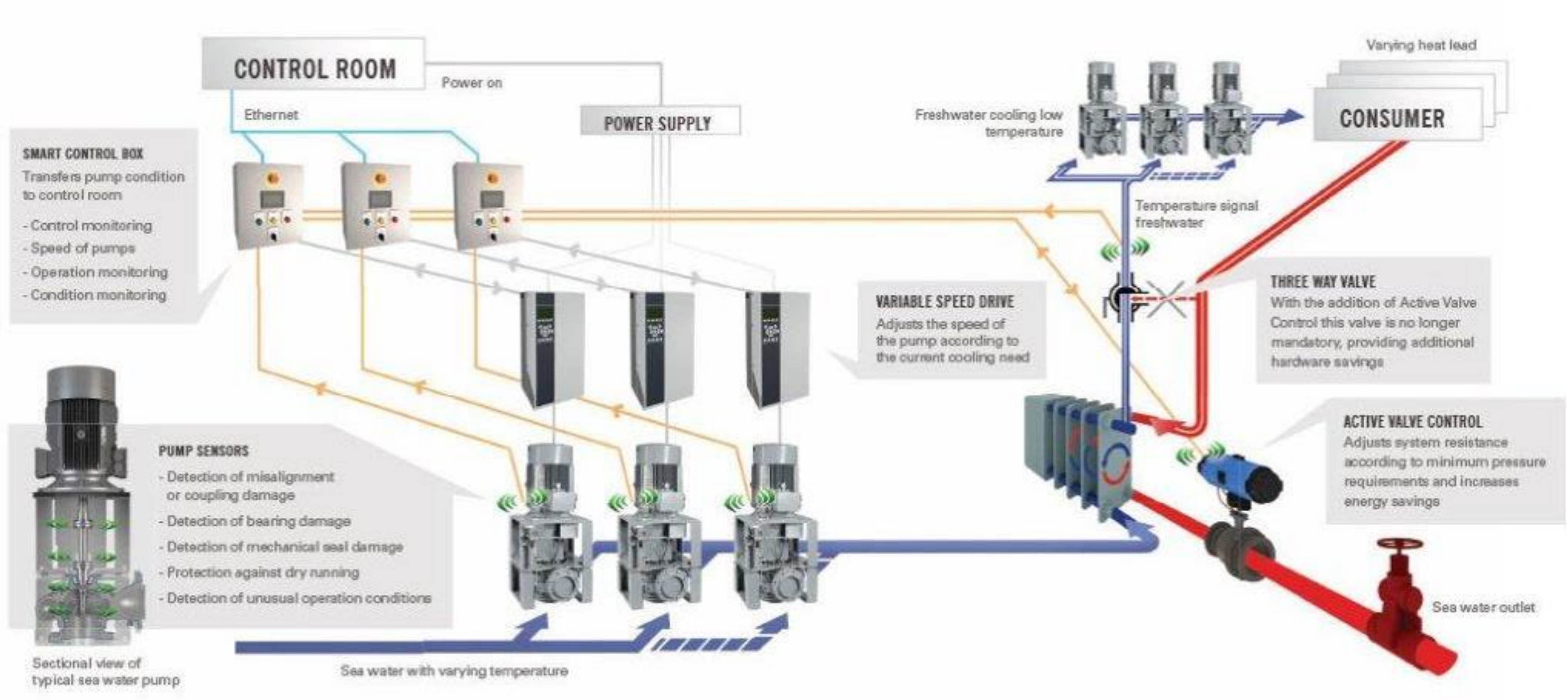
All of this creates an industry that can use the best technology available to reduce operating costs and meets regulated issues. Actually, many of the issues have approached resolution just since EEMODS 15. So an industry where innovation has focused on "bigger" may need to shift to new technologies led by a handful of visionary users and suppliers applying their knowledge to benefit their customers.

As in other industries moving from manual to automated systems can be a very major step and in the M

marine market vessel safety and operational requirements add additional cautions to such a decision. Still as additional vessels convert to intelligent control on their main sea water pumps operators will capture the benefits of "Affinity Laws" pumping and see the clear opportunity to financially improve their performance. To date, this is an opportunity that is driven by economics, which simultaneously also creates substantial environmental benefits. If economics fail to drive the market, this could then possibly be an IMO target.

The industry should thank those engineers who developed this innovation and the early adopter operators.

OPTIMIZED 3x50% SEA WATER SYSTEM SET UP



References

[1] Popular Science- Bonnier Publishing, June 2017, Page 16

[2] EEMODS 15 – Advanced Auxiliary Cooling System for Energy Efficient Ships, Mia Elg

[3] Seawater System Schematic as in Attachment to this presentation. Author.

[4] Pump Characteristics and Applications, Michael W. Volk, Marcel Dekker, Inc., 1996

Affinity Laws, Pages 97-99

[5] Variable Speed Pumping, Elsevier Publishing. Europump and Hydraulic Institute, 2004, Chapters 2 and 4.

[6] Desmi A/S, Optimizing Pump and Fan Speed to Current Conditions, Page 4

[7] Shipbuilding and Equipment, Pumps, 2016

[8] The Motorship, Speed Control of Cooling Seawater Pumps, December 2016

[9] International Maritime Organization Agrees to Stringent Sulfur Emissions Limits, Robert Wale, October 27, 2015

[10] Seawater System Schematic as in Attachment to this presentation. Author

[11] Green4Sea – March 5, 2015

Electrical energy efficiency optimization of asynchronous motors used for pump systems

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Abstract

Pumps are widely used for many domestic and industrial applications: water and waste water, food and beverage, oil and gas and many other applications. In most of cases, a pump is controlled by an asynchronous motor which converts electrical power into the mechanical power needed for the pump operation. The motor can be either connected directly to the mains (DOL) or controlled by a variable speed drive (VSD). The VSD is essential in some important case (in steady state operation out of the nominal pump operation for example) to increase the energy efficiency of the overall pump system. In fact, the VSD allows delivering all possible mechanical working points (speed, torque), and as a consequence the just needed mechanical power by the system. Furthermore, the VSD plays an important role in optimizing the electrical energy consumed by the motor in function of the mechanical energy provided to the pump. This is done by minimizing electrical energy losses (eddy current, heating losses). We propose in this paper an original method of electrical energy optimization for asynchronous motor used for pump systems. We use the hydraulic system characteristics to find the optimal motor voltage trajectory that optimize the electrical motor energy. We model the system: VSD, motor, pump and the hydraulic application. Then, we focus on the minimization of electric heating losses. Simulation and experimental results show that the motor electrical power loss can be reduced significantly by adjusting the motor voltages according to the torque versus speed characteristics of the pump system.

Introduction

Electrical energy savings with electrical motors are increasingly becoming an important topic in the last years. In fact, the electrical energy cost becomes more expensive. In addition, more stringent energy efficiency standards are required to be fulfilled by the applications using electric motors [1]. According to [2] more than 60% of the worldwide electricity is used to run electric machines. In the case of hydraulic pump systems with asynchronous motors; thanks to variable speed drives (VSDs), we can save electrical energy consumption compared to a traditional Direct-On-Line (DOL), where motors are directly connected to the mains [3]. In this paper, we focus on the motor electrical losses optimization when using a VSD to control the motor.

In the first section, we give a mathematical model of the pump and the hydraulic application and we deduce the torque versus speed characteristic. In addition, we present an original model of an asynchronous motor with a nonlinear magnetic saturation model. The consideration of saturation effects is very important to get a realistic representation of the motor system to be used for energy optimization.

In the second section, we focus on asynchronous motors controlled by VSDs. We solve the nonlinear energy optimization problem using the system model proposed in the first section in order to find the optimal trajectory of the motor voltages.

Finally, we study a hydraulic system use case and we present the results obtained with a 4 KW motor. These results illustrate the advantages of the proposed energy optimization method.

Annotations and definition

Nomenclatures

The following table gives different nomenclature for pump variables used in this paper.

Name	**Description**
H	Head [mH_2O]
Q	Flow [m^3/h]
P_w	Mechanical power [W]
ω	Mechanical speed [rpm]
T_w	Mechanical torque [Nm]: $T_w = P_w/\omega$.
H_n	Nominal Head [mH_2O]
Q_n	Nominal Flow [m^3/h]
P_{wn}	Nominal Mechanical power [W]
T_{wn}	Nominal Mechanical torque [Nm]
ω_n	Nominal speed [rpm]
H_{sys}	System head [mH_2O]
H_{s0}	Static head losses at zero flow [mH_2O]
H_{s1}	Quadratic head losses at nominal flow [mH_2O]
h	Ratio between head at current speed and nominal head (dimensionless : p.u)
q	Ratio between flow at current speed and nominal flow (dimensionless : p.u)
p_w	Ratio between mechanical power at current speed and nominal mechanical power (dimensionless : p.u)
τ_w	Ratio between mechanical torque at current speed and nominal mechanical torque (dimensionless : p.u)
x	Ratio between current speed and nominal speed (dimensionless : p.u)
h_{sys}	Ratio between the system head and nominal head (dimensionless : p.u)
h_{s0}	Ratio between the static head losses and nominal head (dimensionless : p.u)
h_{s1}	Ratio between the quadratic head losses and nominal head (dimensionless : p.u)

Motor and pump system modeling

We present in this section the mathematical model of a pump system including the pump model, the hydraulic system model and the asynchronous motor model.

Static pump curves

The static pump curves at different speeds may be represented by generic normalized equations based on the pump characteristics [4]; it is given as follows (1)-(2):

$$h = x^2 \times f_{\omega n}\left(\frac{q}{x}\right) \quad \textbf{(1)}$$

$$p_w = x^3 \times g_{\omega n}\left(\frac{q}{x}\right) \quad \textbf{(2)}$$

$where: \quad h = \frac{H}{H_n}; q = \frac{Q}{Q_n}; x = \frac{\omega}{\omega_n}.$

Hydraulic system model

The mathematical model of a hydraulic system curve can be written as follow (3):

$$h_{sys} = \underbrace{h_{s0}}_{Static\ losses} + \underbrace{h_{s1} \times q^2}_{Quadratic\ losses} \quad \textbf{(3)}$$

$where: \quad h_{sys} = \frac{H_{sys}}{H_n};\ h_{s0} = \frac{H_{s0}}{H_n}\ ; h_{s1} = \frac{H_{s1}}{H_n}.$

This curve includes all losses of the pumping system (tank, pipe, ...).

Pump load versus speed curve

The pump operation point is the intersection between the pump curve (1) and the system curve (3):

$$h = h_{sys} \quad and \quad q = q_{sys} \quad \textbf{(4)}$$

the equation (1), (3) and (4) yield:

$$\frac{h_{s0}}{x^2} + h_{s1}\left(\frac{q}{x}\right)^2 - f_{\omega n}\left(\frac{q}{x}\right) = 0 \quad \textbf{(5)}$$

the equation (5) represents the torque versus speed curve of the hydraulic pump system. The solution of the equation (5) leads to:

$$q = x \times f_2\left(h_{s1}, \frac{h_{s0}}{x^2}\right) \quad \textbf{(6)}$$

where $f_2(\ ,\ )$ is a real function depending on $f_{\omega n}()$, h_{s1}, h_{s0} $and\ x$. The equation (6) gives the relation between the hydraulic system flow and the pump speed.

The equation (2) and (6) yield:

$$p_w = x^3 \times (g_{\omega n} o f_2)\left(h_{s1}, \frac{h_{s0}}{x^2}\right) \quad \textbf{(7)}$$

hence, we get:

$$\tau_w = \frac{p_w}{x} = x^2 \times (g_{\omega n} o f_2)\left(h_{s1}, \frac{h_{s0}}{x^2}\right) \quad \textbf{(8)}$$

with

$$\tau_w = \frac{T_w}{T_{wn}}. \quad \textbf{(9)}$$

The equation (8) gives the relation between the mechanical load of the pump and the pump speed. In case of $h_{s0} = 0$ (no static losses), the relation between the pump load and speed is quadratic and the equation (8) leads to:

$$\tau_w = (g_{\omega n} o f_2)(h_{s1}, 0)x^2 = k_w x^2 \quad \textbf{(10)}$$

where $k_w = (g_{\omega n} o f_2)(h_{s1}, 0)$ is constant.

shows two possible profiles of a pump system. The left part of this figure illustrates a quadratic profile (see equation (10)) where the static losses are zero: $h_{s0} = 0$. The right part of this figure shows a quasi-quadratic profile (see equation (8)) where the static losses are considered: $h_{s0} \neq 0$.

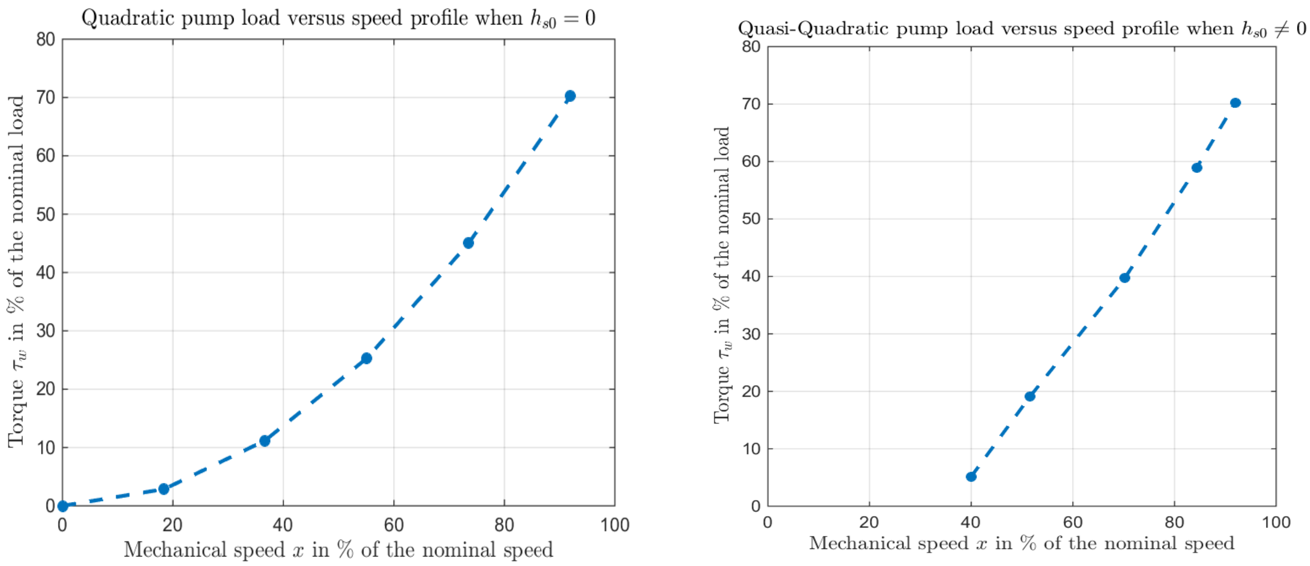


Figure 1: Load versus speed profiles of pump system

Asynchronous motor model

Standard equations

The standard equations (complex representation) of an asynchronous motor in an arbitrary rotating frame at an electrical angular frequency ω_s(d-q model) [5] are:

$$\begin{cases} \dfrac{d\phi_s}{dt} = u_s - R_s i_s - j\omega_s \phi_s \\ \dfrac{d\phi_r}{dt} = -R_r i_r - j\omega_g \phi_r \\ \dfrac{J}{n_p}\dfrac{d\omega_r}{dt} = \dfrac{3}{2} n_p \Im(\phi_s^* i_s) - \mathrm{T}_L \end{cases} \quad \textbf{(11)}$$

where:

- $j = \sqrt{-1}$ is the unitary complex number.
- ϕ_s, ϕ_r are the stator flux and the rotor flux.
- i_s, i_r are the stator current and the rotor current.
- u_s is the motor voltage.
- R_s and R_r are the stator resistance and the rotor resistance.
- ω_s is the electrical stator angular frequency.
- ω_r is rotor mechanical speed.
- $\omega_g = \omega_s - \omega_r$ is the slip angular frequency.
- T_L is the mechanical load at the shaft of the motor.
- n_p is the motor pole pair number.
- $\frac{3}{2} n_p \Im(\phi_s^* i_s) = \frac{3}{2} n_p \Im(\phi_r i_r^*)$ is the motor electromagnetic torque.
- $\Im(z)$ is the imaginary part of z and z^* is the complex conjugate of z.

Using the equation (11), at steady state the static motor equations become:

$$\begin{cases} u_s - R_s i_s - j\omega_s \phi_s = 0 \\ R_r i_r + j\omega_g \phi_r = 0 \\ \frac{3}{2} n_p \Im(\phi_s^* i_s) = \frac{3}{2} n_p \Im(\phi_r i_r^*) = \mathrm{T}_L \end{cases} \quad \textbf{(12)}$$

Magnetic model

The magnetic model of an asynchronous motor is represented by the relation between the stator flux ϕ_s, the rotor flux ϕ_r, the stator current i_s and the rotor current i_r. The Lagrangian energy formulation [6] is used to represent the magnetic coupling between fluxes and currents. The Lagragian is the co-energy of the motor.

Linear magnetic model

In case of linear magnetic model, the relations between the fluxes and the currents are linear:

$$\begin{cases} \phi_s = L_s i_s + L_m i_r = L_{fs} i_s + L_m i_m \\ \phi_r = L_m i_s + L_r i_r = L_{fr} i_r + L_m i_m \end{cases} \quad \textbf{(13)}$$

with $L_{fs} = L_s - L_m$; $L_{fr} = L_r - L_m$ and:

$$i_m = i_s + i_r \quad \textbf{(14)}$$

where

- L_s, L_r are the stator main inductance and the rotor main inductance.
- L_m is the mutual magnetization inductance.
- L_{fs}, L_{fr} are the stator leakage inductance and the rotor leakage inductance.
- i_m is the magnetizing current.

The magnetic Lagrangian for the linear magnetic model represented by the equation (13) is:

$$\begin{aligned} \mathfrak{L}(i_s, i_r, i_s^*, i_r^*) &= \frac{1}{2} L_{f_s} i_s i_s^* + \frac{1}{2} L_{fr} i_r i_r^* + \frac{1}{2} L_m (i_s + i_r)(i_s^* + i_r^*) \\ &= \frac{1}{2} L_{f_s} |i_s|^2 + \frac{1}{2} L_{fr} |i_r|^2 + L_m |i_m|^2 \end{aligned} \quad \textbf{(15)}$$

The operator $|z|$ is the module of the complex number z.

Saturation model

In practice, the relations between the fluxes and the currents are not linear because of the magnetic saturation effect [7]. We propose a magnetic model of an asynchronous motor where the magnetic saturation effect is represented by replacing the mutual inductance L_m in the Lagragian expression (15) by a nonlinear function of the total magnitude of the current $|i_m|$. Such, we propose the following Lagrangian expression $\mathfrak{L}_{sat}$:

$$\begin{aligned} \mathfrak{L}_{sat}(i_s, i_r, i_s^*, i_r^*) &= \frac{1}{2} L_{f_s} i_s i_s^* + \frac{1}{2} L_{fr} i_r i_r^* + \frac{1}{2} f_m[(i_s + i_r)(i_s^* + i_r^*)] \\ &= \frac{1}{2} L_{f_s} |i_s|^2 + \frac{1}{2} L_{fr} |i_r|^2 + \frac{1}{2} f_m(|i_m|^2) \end{aligned} \quad \textbf{(16)}$$

where f_m is a real function. The fluxes are obtained from the Lagrangian as follows:

$$\begin{cases} \phi_s = 2 \times \frac{\partial \mathfrak{L}_{\mathrm{sat}}}{\partial i_s^*} = L_{fs} i_s + f_m'(|i_m|^2) i_m = L_{fs} i_s + \mathcal{L}_m(|i_m|) i_m \\ \phi_r = 2 \times \frac{\partial \mathfrak{L}_{\mathrm{sat}}}{\partial i_r^*} = L_{fr} i_r + f_m'(|i_m|^2) i_m = L_{fr} i_r + \mathcal{L}_m(|i_m|) i_m \end{cases} \quad \textbf{(17)}$$

with $\mathcal{L}_m(|i_m|) = f'_m(|i_m|^2)$. We propose the following expression of f_m:

$$f_m(z) = \frac{2L_m}{\gamma^2}\left(\gamma\sqrt{z} - \ln\left(1 + \gamma\sqrt{z}\right)\right)$$

where $\gamma \geq 0$ is a constant positive parameter and $f_m(z) \geq 0$ is a real positive function of $z \geq 0$. The Lagrangian function in the equation (16) becomes:

$$\mathfrak{L}_{sat}(i_s, i_r, i_s^*, i_r^*) = \frac{1}{2}L_{f_s}|i_s|^2 + \frac{1}{2}L_{fr}|i_r|^2 + \frac{L_m}{\gamma^2}[\gamma|i_m| - \ln(1 + \gamma|i_m|)] \qquad \textbf{(18)}$$

the equations (17) and (18) lead to:

$$\mathcal{L}_m(|i_m|) = f'_m(|i_m|^2) = \frac{L_m}{1 + \gamma|i_m|}. \qquad \textbf{(19)}$$

When $\gamma \to 0$, we get the linear magnetic model relations:

$$\lim_{\gamma \to 0}\left(\mathcal{L}_m(|i_m|)\right) = L_m$$

$$\lim_{\gamma \to 0}\left(\mathfrak{L}_{sat}(i_s, i_r, i_s^*, i_r^*)\right) = \frac{1}{2}L_{f_s}|i_s|^2 + \frac{1}{2}L_{fr}|i_r|^2 + \frac{1}{2}L_m|i_m|^2$$

Electrical power optimization

In the previous section, we presented a mathematical model of a pump system including the pump model and the hydraulic system model. We proposed also a nonlinear magnetic saturation model of an asynchronous motor.

In this section, we focus on asynchronous motors controlled by VSDs. We find the optimal values of the motor electrical variables that minimize the total energy consumed by the motor at a given pump speed and mechanical load. Firstly, we establish the expression of the motor heating power losses in terms of the electrical and mechanical variables. Then, we formulate and we solve the nonlinear optimization problem.

Heating power losses expression

The expression of electric heating losses is:

$$P_l = \frac{3}{2}R_s|i_s|^2 + \frac{3}{2}R_r|i_r|^2. \qquad \textbf{(20)}$$

In the sequel, we express P_l in terms of the rotor flux magnitude $|\phi_r|$. To do that, we find the expression of $|i_s|$ and $|i_r|$ in function of $|\phi_r|$.

The equation (12) leads to:

$$i_r = -\frac{j\omega_g\phi_r}{R_r} \qquad \textbf{(21)}$$

and

$$\omega_g = \frac{2R_r\mathrm{T}_L}{3n_p|\phi_r|^2}. \qquad \textbf{(22)}$$

In addition, the equation (17) yields:

$$i_s = \frac{1}{\mathcal{L}_m}(\phi_r - \mathcal{L}_r i_r) \tag{23}$$

with $\mathcal{L}_r(|i_m|) = L_{fr} + \mathcal{L}_m(|i_m|)$.

The equations (21) and (23) lead to:

$$i_s = \frac{1}{\mathcal{L}_m}\left(1 + j\frac{\mathcal{L}_r}{R_r}\omega_g\right)\phi_r. \tag{24}$$

Using the equations (20), (21) and (24), we can write the expression of the heating losses as follows:

$$P_l = \frac{3}{2}R_s\left(1 + \frac{\mathcal{L}_r^2}{R_r^2}\omega_g^2\right)\frac{|\phi_r|^2}{\mathcal{L}_m^2} + \frac{3}{2}\frac{\omega_g^2}{R_r}|\phi_r|^2$$

$$P_l = \frac{3}{2}R_s\frac{|\phi_r|^2}{\mathcal{L}_m^2} + \frac{3}{2}\frac{\omega_g^2|\phi_r|^2}{R_r^2}\left(R_s\frac{\mathcal{L}_r^2}{\mathcal{L}_m^2} + R_r\right) \tag{25}$$

Replacing ω_g in the equation (25) by its expression in the equation (22), hence we get:

$$P_l(|\phi_r|) = \frac{3}{2}R_s\frac{|\phi_r|^2}{\mathcal{L}_m^2(|i_m|)} + \frac{2}{3}\frac{T_L^2}{n_p^2|\phi_r|^2}\left(R_s\frac{\mathcal{L}_r^2(|i_m|)}{\mathcal{L}_m^2(|i_m|)} + R_r\right). \tag{26}$$

The expression of the heating losses P_l in the equation (26) depends on the rotor flux magnitude $|\phi_r|$ and the current magnitude $|i_m|$. We need to find the relation between the current $|i_m|$ and the flux $|\phi_r|$ to find the explicit expression of P_l in function of $|\phi_r|$. The equations (17) and (21) lead to:

$$|\phi_r|^2 = \frac{\mathcal{L}_m^2(|i_m|)|i_m|^2}{1 + L_{fr}^2\frac{\omega_g^2}{R_r^2}} \tag{27}$$

hence

$$|\phi_r|^2 + L_{fr}^2\frac{\omega_g^2|\phi_r|^2}{R_r^2} = \mathcal{L}_m^2(|i_m|)|i_m|^2. \tag{28}$$

Replacing ω_g in the equation (28) by its expression in the equation (22), we get:

$$|\phi_r|^2 + \frac{4L_{fr}^2T_L^2}{9n_p^2|\phi_r|^2} = \mathcal{L}_m^2(|i_m|)|i_m|^2 \tag{29}$$

using the equation (19), the equation (29) yields:

$$\frac{L_m^2|i_m|^2}{(1+\gamma|i_m|)^2} = |\phi_r|^2 + \frac{4L_{fr}^2T_L^2}{9n_p^2|\phi_r|^2} = \mathrm{g_r}(|\phi_r|). \tag{30}$$

Finally, the expression of $|i_m|$ is obtained from the equation (30) as follows:

$$|i_m| = \mathcal{I}_m(|\phi_r|) = \frac{\sqrt{\mathrm{g_r}(|\phi_r|)}}{L_m - \gamma\sqrt{\mathrm{g_r}(|\phi_r|)}} \tag{31}$$

The equations (26) and (31) give the expression of the power losses P_l in function of the rotor flux magnitude $|\phi_r|$. In the next part of this section, we find the optimal $|\phi_r|$ that minimize these power losses.

Optimization problem

The goal of this optimization problem is to find the amplitude of the flux $|\phi_r| = \bar{\phi}$ that minimize the heating losses at constant load torque ($T_L = \bar{T}_L = constant$):

$$\bar{\phi} = ArgMin[P_l(|\phi_r|)]|_{T_L=\bar{T}_L} \quad \textbf{(32)}$$

This optimization problem is defined under the constraints of the hydraulic demand (speed ω_r and load T_L). The solution of this problem (32) changes with the variation of the hydraulic demands.

The solution of the optimization problem (32) is obtained by solving the equation (33):

$$P_l'(\bar{\phi}) = 0. \quad \textbf{(33)}$$

In the sequel, we give the solution of the equation (33) in case of linear magnetic model and in case of magnetic saturation model.

Case of linear magnetic model

In case of linear magnetic model $\mathcal{L}_m = L_m \ and \ \mathcal{L}_r = L_r$, hence the equation (33) leads to:

$$\frac{3R_s\bar{\phi}}{L_m^2} - \frac{4\bar{T}_L^2}{3n_p^2\bar{\phi}^3}\left(R_s\frac{L_r^2}{L_m^2} + R_r\right) = 0 \quad \textbf{(34)}$$

the solution of the equation (34) is:

$$\bar{\phi} = \sqrt{\frac{2\bar{T}_L}{3n_p}\sqrt{L_r^2 + \frac{R_r}{R_s}L_m^2}} \quad \textbf{(35)}$$

Case of magnetic saturation model

In this case, from the equations (19), (26) and (31) we get:

$$P_l(|\phi_r|) = \frac{3R_s}{2L_m^2}[1 + \gamma \times \mathcal{I}_m(|\phi_r|)]^2|\phi_r|^2 + \frac{2\bar{T}_L^2}{3n_p^2|\phi_r|^2}\left(R_s\frac{\left[L_r + \gamma L_{fr}\mathcal{I}_m(|\phi_r|)\right]^2}{L_m^2} + R_r\right) \quad \textbf{(36)}$$

then, the equation (36) and (33) read:

$$\frac{3R_s\bar{\phi}}{L_m^2}[1 + \gamma \times \mathcal{I}_m(\bar{\phi})]^2 - \frac{4\bar{T}_L^2}{3n_p^2\bar{\phi}^3}\left(R_s\frac{\left[L_r + \gamma L_{fr}\mathcal{I}_m(\bar{\phi})\right]^2}{L_m^2} + R_r\right) + \frac{3\gamma R_s}{2L_m^2}\mathcal{I}_m'(\bar{\phi})\left(1 + \gamma \times \mathcal{I}_m(\bar{\phi})\right)\bar{\phi}^2 + \frac{4\gamma R_s L_{fr}\bar{T}_L^2}{3n_p^2L_m^2\bar{\phi}^2}\mathcal{I}_m'(\bar{\phi})\left(L_r + \gamma L_{fr}\mathcal{I}_m(\bar{\phi})\right) = 0 \quad \textbf{(37)}$$

with

$$\mathcal{I}_m'(\bar{\phi}) = \left(2\bar{\phi} - \frac{8L_{fr}^2\bar{T}_L^2}{9n_p^2\bar{\phi}^3}\right)\frac{L_m}{2\sqrt{\mathrm{g_r}(\bar{\phi})}\left(L_m - \gamma\sqrt{\mathrm{g_r}(\bar{\phi})}\right)^2} \quad \textbf{(38)}$$

It is not possible to find an explicit solution of the equation (37) but we find a numeric solution analytically. The analytical solution is obtained using the motor parameters. These parameters are obtained using a special tuning process of the motor.

UF VSD control

We consider the case on a pump running a mechanical load $T_w = \bar{T}_w$ at a given speed $\omega = \varpi$. At steady state we have:

$$\omega_r = n_p\varpi \quad and \quad T_L = \bar{T}_L = \bar{T}_w \tag{39}$$

Consider this operation point, we want to find the optimal values of the stator voltage u_s and the electrical stator angular frequency ω_s that minimize the motor electrical power in these conditions.

The electrical power consumed by the motor P_e is the sum of the mechanical power P_m and the heating power losses P_l:

$$P_e = P_m + P_l$$

At steady state, the mechanical power is given by:

$$P_m = \frac{\omega_r}{n_p}T_L = \varpi \times \bar{T}_w = cst.$$

The mechanical power is constant at this operation point. Thus, to minimize P_e, we minimize P_l at this point. Therefore the minimization of P_e is done by solving the optimization problem defined in the equation (32).

Solution of motor equations

There are 10 electrical and mechanical motor scalar variables: i_s, ϕ_s, i_r, ϕ_r, ω_r and T_L. In addition, we have 3 input scalar variables: u_s and ω_s. In total, we have 13 variables. The operation point gives 2 scalar relations $\omega_r = n_p\varpi$ *and* $T_L = \bar{T}_w$. The motor equations (12) and (17) provide 9 scalar relations between the motor variables. Hence, we have 11 relations and 13 variables. Thus, we have two independent variables that can be chosen arbitrarily.

Firstly, we set the imaginary part of the rotor flux to zero: $\phi_r = \phi_r^* = |\phi_r|$ (the rotor flux is always positive). In fact, the proposed magnetic saturation model is invariant by the rotation of the flux ϕ_r as shown in the equation (31), this can explain that we replace the flux by its magnitude. Then, it remains 11 relations for 12 variables. In the sequel, we express 11 variables in function of ϕ_r using these 11 relations.

The equation (22) and (39) lead to:

$$\omega_g = \bar{\omega}_g = \frac{2R_r\bar{T}_w}{3n_p\phi_r^2} \tag{40}$$

then

$$\omega_s = \bar{\omega}_s = n_p\varpi + \bar{\omega}_g \tag{41}$$

The rotor current i_r is obtained using the equation (21) and (41):

$$i_r = \bar{\imath}_r = -j\frac{\bar{\omega}_g\phi_r}{R_r}. \tag{42}$$

The stator current is get from the equation (23) and (42) as follows:

$$i_s = \bar{\imath}_s = \frac{\phi_r}{\mathcal{L}_m(\mathcal{I}_m(\phi_r))} + j\frac{\bar{T}_w}{\left(\frac{3}{2}n_p\phi_r\right)} \times \frac{\mathcal{L}_r(\mathcal{I}_m(\phi_r))}{\mathcal{L}_m(\mathcal{I}_m(\phi_r))}$$
$$= \mathcal{I}_d(\phi_r) + j\mathcal{I}_q(\phi_r) \quad \textbf{(43)}$$

with $\mathcal{I}_d(\phi_r) = \frac{\phi_r}{\mathcal{L}_m(\mathcal{I}_m(\phi_r))}$ *and* $\mathcal{I}_q(\phi_r) = \frac{\bar{T}_w}{\left(\frac{3}{2}n_p\phi_r\right)} \times \frac{\mathcal{L}_r(\mathcal{I}_m(\phi_r))}{\mathcal{L}_m(\mathcal{I}_m(\phi_r))}$. Using (40) we note:

$$\bar{\omega}_g = \frac{R_r\mathcal{I}_q(\phi_r)}{\mathcal{L}_r(\mathcal{I}_m(\phi_r))\mathcal{I}_d(\phi_r)}. \quad \textbf{(44)}$$

The stator flux is calculated using the equation (17) and (43)

$$\phi_s = \bar{\phi}_s = L_{fs}\bar{\imath}_s + \mathcal{L}_m(\mathcal{I}_m(\phi_r))\mathcal{I}_m(\phi_r)$$
$$= L_{fs}\mathcal{I}_d(\phi_r) + \Phi_M(\phi_r) + jL_{fs}\mathcal{I}_q(\phi_r) \quad \textbf{(45)}$$

with $\Phi_M(\phi_r) = \mathcal{L}_m(\mathcal{I}_m(\phi_r))\mathcal{I}_m(\phi_r)$.

Finally, from the equations (12), (41), (43) and (45) the stator voltage expression reads:

$$u_s = \bar{u}_s = R_s\bar{\imath}_s + j\,\bar{\omega}_s\bar{\phi}_s$$
$$= R_s\mathcal{I}_d(\phi_r) - L_{fs}\bar{\omega}_s\mathcal{I}_q(\phi_r) + j\bar{\omega}_s\left(\frac{R_s\mathcal{I}_q(\phi_r)}{\bar{\omega}_s} + L_{fs}\mathcal{I}_d(\phi_r) + \Phi_M(\phi_r)\right) \quad \textbf{(46)}$$

The expressions of the electrical stator angular frequency $\boldsymbol{\omega_s} = \boldsymbol{\bar{\omega}_s}$ and the stator voltages $\boldsymbol{u_s} = \boldsymbol{\bar{u}_s}$ are given in the equations (41) and (46) in function of the mechanical speed $\boldsymbol{\bar{\omega}}$, the mechanical load torque $\boldsymbol{\bar{T}_w}$, the motor electrical and magnetic parameters $(\boldsymbol{R_s}, \boldsymbol{R_r}, \boldsymbol{L_m}, \boldsymbol{\gamma}, \boldsymbol{L_{fs}}, \boldsymbol{L_{fr}}, \boldsymbol{n_p})$ and the rotor flux $\boldsymbol{\phi_r}$.

Optimal UF control law

Consider a UF control defined as follows:

$$\begin{cases} \omega_s = \omega_{ref} \\ u_s = U_0 + j\omega_{ref}\phi_{ref} \end{cases} \quad \textbf{(47)}$$

where U_0, ω_{ref} and ϕ_{ref} are the parameters of the control law.

Using the equation (41), **(44)**, (46) and (47), the control law parameters can be expressed as follows:

$$\begin{cases} \omega_{ref} = n_p\bar{\omega} + \dfrac{R_r\mathcal{I}_q(\bar{\phi})}{\mathcal{L}_r\left(\mathcal{I}_m(\bar{\phi})\right)\mathcal{I}_d(\bar{\phi})} \\ U_0 = R_s\mathcal{I}_d(\bar{\phi}) - L_{fs}\omega_{ref}\mathcal{I}_q(\bar{\phi}) \\ \phi_{ref} = \Phi_M(\bar{\phi}) + \dfrac{R_s\mathcal{I}_q(\bar{\phi})}{\omega_{ref}} + L_{fs}\mathcal{I}_d(\bar{\phi}) \end{cases} \quad \textbf{(48)}$$

The value of $\bar{\phi}$ is chosen such that the power loss P_l is minimized. The numeric solution of the equation (37) provides the value of the rotor flux $\bar{\phi}$:

$$\phi_r = \bar{\phi}. \quad \textbf{(49)}$$

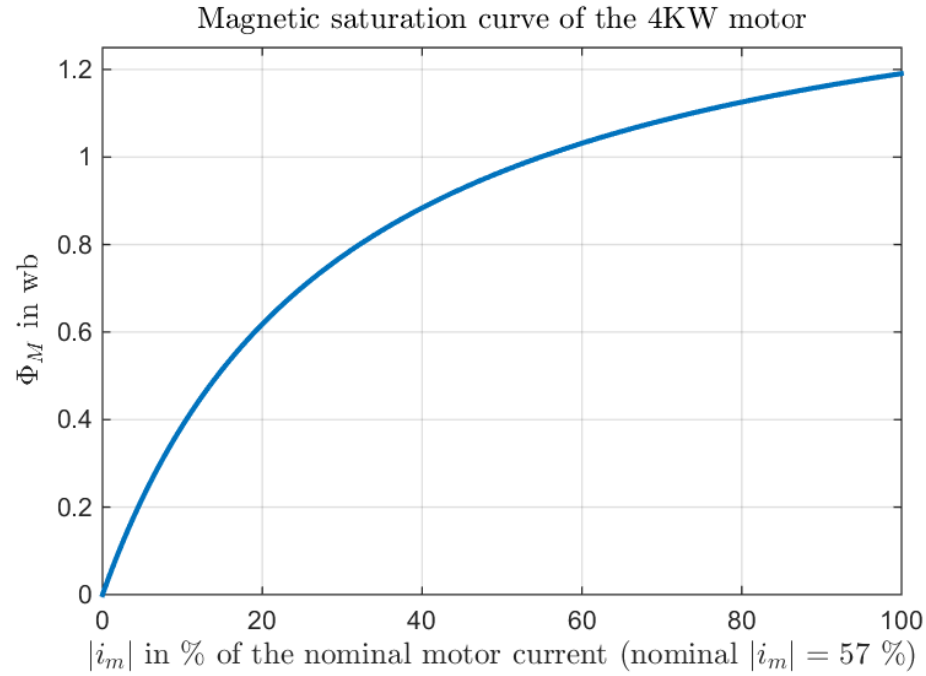
The voltage value must be feasible regarding the constraints of the drive power electronics capabilities (voltage and current).

Experimental and simulation results

We validated the proposed power optimization method on a 4 KW / 400 V asynchronous motor. We used the pump load versus speed profile as described in the equation (8). The input voltages and electrical frequency are applied to the motor as described in the equation (47).

Magnetic saturation curve

The magnetic saturation parameters of the motor are fitted experimentally. Figure 2 shows the magnetic saturation curve $\Phi_M(|i_m|)$ of the tested motor. In the sequel, this saturation curve is used to optimize the electrical power losses of the motor.



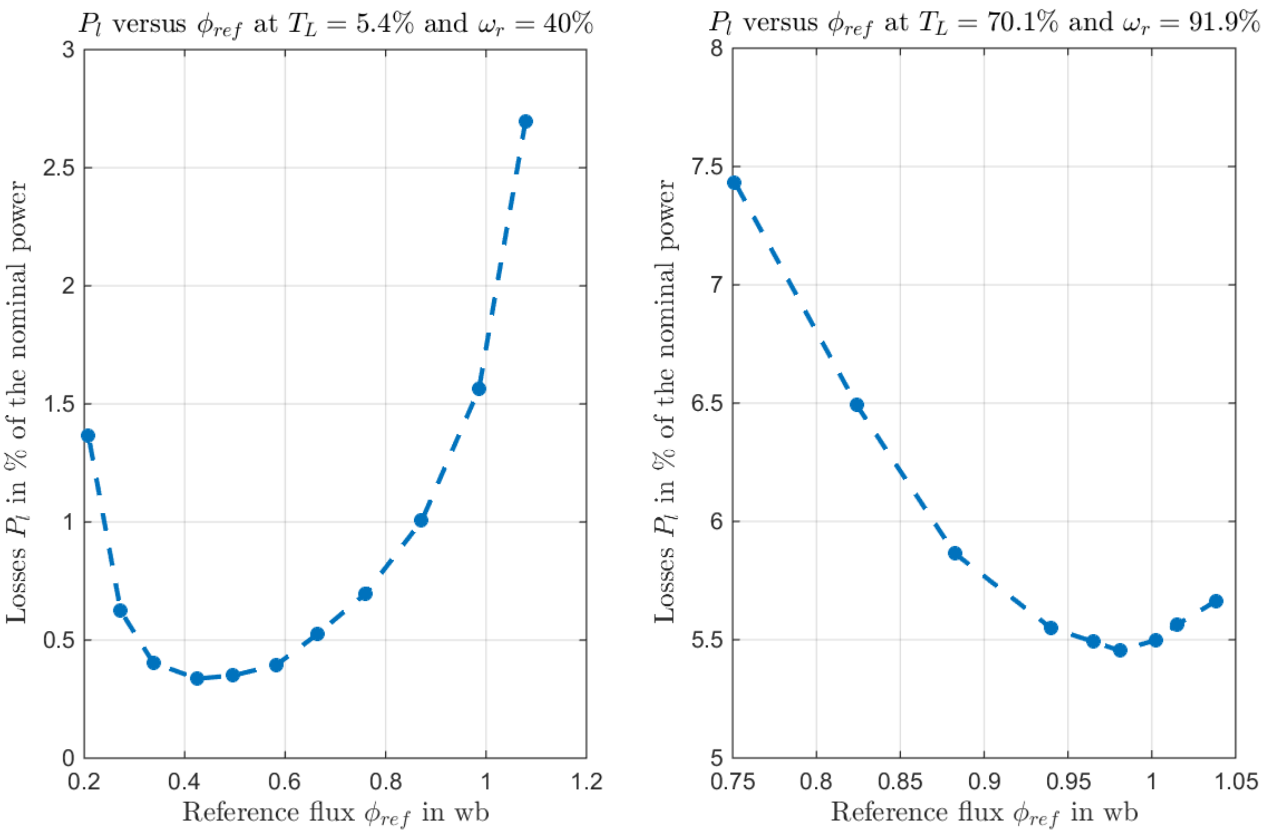


Figure 2: Φ_M versus $|i_m|$ characteristic for the tested 4 KW motor

Figure 3: Experimental curves of the power losses P_l versus the reference flux ϕ_{ref}

Power losses versus flux

Given a mechanical point (speed and load), the reference flux ϕ_{ref} is varied from a minimum value to a maximum value in order to find the optimal flux that minimize the heating power losses P_l.

Figure 3 shows experimental results of the power losses optimization on two different mechanical operation points. This figure shows that, for each point, the value power loss P_l has a minimum value that it is reached at an optimal flux value. This results validates the existence of an optimal solution as proposed in the equation (48).

Optimal operation for the complete speed range

In this part, we consider the quadratic and the quasi-quadratic load versus speed profiles shown in the Figure 1. We find the optimal solution of the electrical power loss optimization problem for each profile.

Figure 4 shows the optimal flux ϕ_{ref} trajectories in function of the stator electrical frequency ω_s for each profile. Figure 5 shows the motor electrical power and electrical efficiency in function of the pump mechanical speed. These figures show that the experimental data fit very well the model simulation data. These results validate the energy optimization procedure proposed in the previous section.

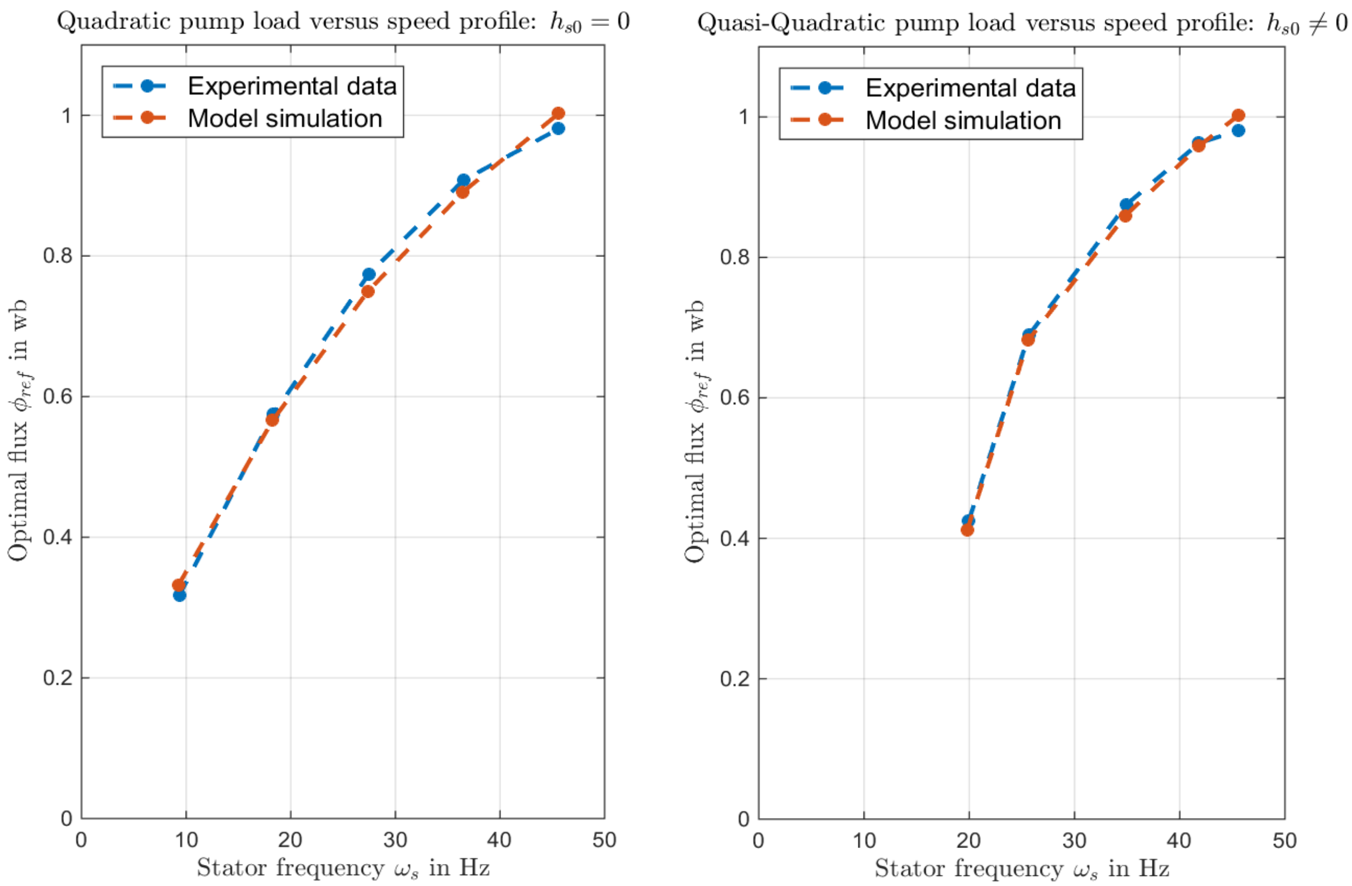


Figure 4: Experimental and simulation results: optimal flux ϕ_{ref} versus the stator frequency

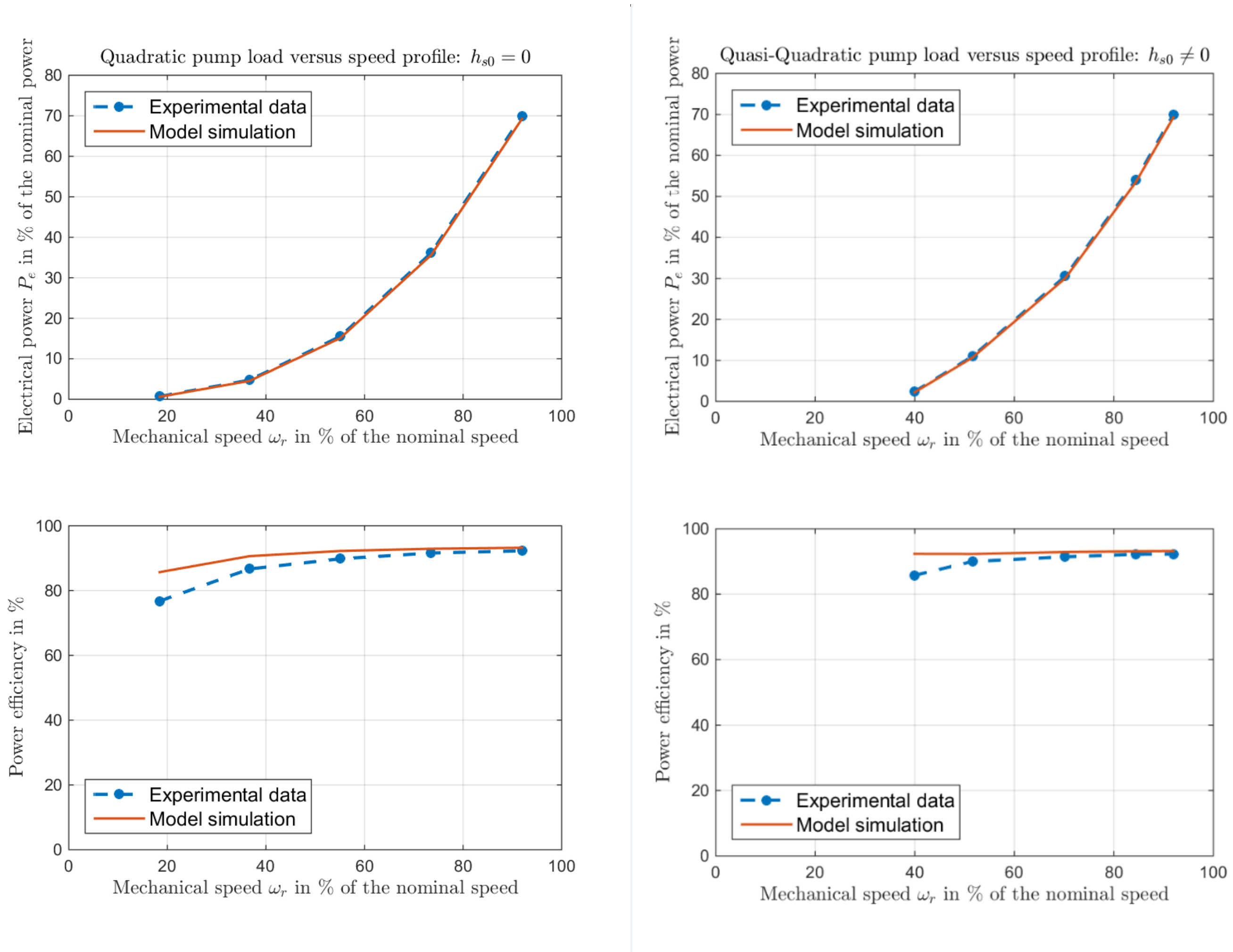


Figure 5: Experimental and simulation results: motor electrical power and electrical efficiency in function of the mechanical speed ω_r.

Conclusion

We propose in this paper an original way of the electrical energy optimization for asynchronous motors used in pumping applications. We present pump and hydraulic system static equations and we deduce the load versus speed characteristic of a pump system. We propose a nonlinear magnetic saturation model of an asynchronous motor based on Lagrangian formulation. Using this saturation model, we establish the static equations of an asynchronous motor. Then, using the expression of the electrical heating power loss, we find the optimal solution that minimize the motor electrical power at a given mechanical speed and load.

A UF VSD control is used to validate this optimization procedure. Simulation and experimental tests results show that, for each mechanical operation point, the motor electrical power loss is minimized (to maximize the electrical motor efficiency) by adjusting the reference flux ϕ_{ref} used for motor voltage generation. Finally, for each load versus speed pump system profile, we obtain a corresponding reference flux versus electrical speed curve. Experimental data validate the solution of the optimization problem obtained by using the proposed theoretical optimization approach. A perspective of this study is to add a comparison of energy performances for different drive options:

direct online (DOL), VSD with standard drive control and the proposed energy optimization strategy in this paper.

References

[1] A. T. de Almeida, F. J. T. E. Ferreira and G. Baoming, "*Beyond Induction Motors - Technology Trends to Move Up Efficiency*" in IEEE Transactions on Industry Applications, vol. 50, no. 3, pp. 2103-2114, May-June 2014.

[2] S.-K. Sul, "*Control of Electric Machine Drive Systems*". Wiley-IEEE Press, February 2011.

[3] J. C. Cone, "*PUMP ENERGY CONSERVATION TECHNIQUES*", Wilmington, Delaware.

[4] F. Malrait and K. Ejjabraoui, "*Best efficiency point of a multiple. VSD pumps' equipment*". EEMODS'15 Conference. Energy efficiency in motor driven systems. Helsinki 15 -17 September 2015.

[5] F. Jadot, F. Malrait, J. Moreno-Valenzuela and R. Sepulchre, "*Adaptive Regulation of Vector*-Controlled *Induction Motors*" in IEEE Transactions on Control Systems Technology, vol. 17, no. 3, pp. 646-657, May 2009.

[6] D. Basic, F. Malrait and P. Rouchon, "*Euler-Lagrange Models With Complex Currents of Three-Phase Electrical Machines and Observability Issues*" in IEEE Transactions on Automatic Control, vol. 55, no. 1, pp. 212-217, Jan. 2010.

[7] E. Levi, "*Magnetic saturation in rotor flux oriented induction motor drives: Operating regimes consequences and open-loop compensation*", Eur. Trans. Elect. Power ETEP, vol. 4, no. 4, pp. 277-286, 1994.

Energy management in a multiple VSD pumps system – pumps with different characteristics

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Abstract

Multiple pumps systems are widely used in many Water & Waste Water applications. They can be controlled with different equipment's: VSD's (Variable Speed Drives), DOL's (Direct-on-line), SST's (Soft-Starter) or a mixed of them. In most of cases, pumps have different characteristics, i.e. we can have for instance mixed states of pumps with different aging, with different impeller sizes, with different power sizes and with different technology. Moreover, the energy management of global pumping system becomes very important to reduce energy bill of installations and to optimize maintenance cost, for instance by increasing the lifetime of equipment's. It is known that the best way to optimize energy consumption in a multiple VSD pumps system with the same pump characteristic is to share evenly the process contribution between pumps, i.e. same speed. This paper will address the energy management on multiple pumps systems with different characteristics, in particular different impeller sizes. First, we demonstrate with a theoretical approach how the process demand must be shared between pumps, how to choose the right number of pumps and their speeds, in order to optimize energy consumption of a global pumping system. Secondly, we generalize this approach by adapting our theoretical formulation of energy consumption optimization problem depending on application context. A theoretical model that considers a multiple VSD pumps system as a single "equivalent" VSD pump is used. Finally, to support and validate our theoretical demonstration, we show simulation and experimental results on a boosting station application.

Keywords: Energy management, Multiple pumps system, Pump characteristics, Optimization, Analytics.

Introduction

The energy management in multiple pumps systems is becoming increasingly crucial to minimize energy consumption and to save maintenance cost. We have to consider the global system which includes the electrical actuators (variable speed drives), motors, pumps and process when we need to optimize the global consumed energy. It is known that to minimize energy consumption in a multiple pump system with pumps having identical characteristics is to share evenly the system demand between pumps, which mean pumps should run at the same speed [14]. However, in the most of Water & Waste Water applications, the multiple pumps systems are not always composed by pumps with identical characteristics. That's why we need to define what the system best working point is, in terms of energy consumption by taking into account multiple pumps systems with different pump characteristics and whatever the process constraint (volume control, pressure control and many more, etc.). In this paper, we focus on the hydraulic equipment: centrifugal pump and system without taking into electrical losses.

The aim of this paper is to define the **S**ystem **B**est **E**fficiency **P**oint (**S-BEP**) for Water & Waste Water applications with multiple pumps equipment (pumps with different characteristics) and whatever the system constraint (open system without constraints on process variables, system with pressure control, system with volume control). First, we will provide an overview about pump characteristics. We will describe the impact of the specific speed, impeller diameter changes and aging on the characteristic of a centrifugal pump. We will see on a particular use case of pump with different characteristics by a theoretical demonstration how the energy consumption could be optimized and managed by acting on the pump speeds and number of pumps to run in case of a multiple pumps system. Simulation-based results will support the theoretical demonstration. Finally, experimental results will be presented.

Annotations and definition

Nomenclatures

The following table gives different nomenclature used in this paper.

(a) Name	(b) Description
(c) H	(d) Head [mH_2O]
(e) Q	(f) Flow [m^3/h]
(g) P_w	(h) Mechanical power [W]
(i) ω	(j) Mechanical speed [rpm]
(k) η	(l) Efficiency [%]
(m) H_n	(n) Nominal Head* [mH_2O]
(o) Q_n	(p) Nominal Flow* [m^3/h]
(q) P_{wn}	(r) Nominal Mechanical power* [W]
(s) ω_n	(t) Nominal speed [rpm]
(u) η_n	(v) Nominal efficiency* [%]
(w) H_{sys}	(x) System head [mH_2O]
(y) H_{s0}	(z) Static head losses at zero flow [mH_2O]
(aa) H_{s1}	(bb) Quadratic head losses at nominal flow [mH_2O]
(cc) h	(dd) Ratio between head at current speed and nominal head (dimensionless : p.u)
(ee) q	(ff) Ratio between flow at current speed and nominal flow (dimensionless : p.u)
(gg) p_w	(hh) Ratio between mechanical power at current speed and nominal mechanical power (dimensionless : p.u)
(ii) x	(jj) Ratio between current speed and nominal speed (dimensionless : p.u)
(kk) h_{sys}	(ll) Ratio between the system head and nominal head (dimensionless : p.u)
(mm) h_{s0}	(nn) Ratio between the static head losses and nominal head (dimensionless : p.u)

(oo) h_{s1}	(pp) Ratio between the quadratic head losses and nominal head (dimensionless : p.u)
P-BEP	(qq) **P**ump **B**est **E**fficiency **P**oint
S-BEP	(rr)**S**ystem **B**est **E**fficiency **P**oint
P-BEC	(ss) **P**ump **B**est **E**fficiency **C**urve
k	(tt) Coefficient to calculate pump efficiency from physical unit
N	(uu) Number of pumps

*: Corresponds to the Pump Best Efficiency Point (P-BEP).

Single pump system

Generally, the characteristics of centrifugal pumps are given by the pump manufacturers in one only motor quadrant where the speed and torque are positive. That's means, the pump will operate in their normal operating range (positive head and positive flow). In the case of transient studies, it is possible to leave this normal operating range: reflux, more pressure at the inlet than at the outlet, negative speed: it is therefore possible to simulate these phases to extend the pump characteristics known outside the normal operating range. To have a good understanding of the behavior of the centrifugal pump in the 4 quadrants of the motor, several methods of organizing the data have been proposed [1] [2] [3] [5], and each has certain advantages.

It exists another method which called the Karman circle diagram [4], the principle is to show the complete characteristics as a four-quadrant contour plot of surfaces representing head and torque with speed and flow rate as base. Because the head and torque tend to infinity in two zones of operation, another diagram would be required to show the complete pump characteristics. Other examples may be found in [6] [7] [10] [11].

In other literature, according to the dimensional similarity principle, Marshal, Flesh and Suter [8] [9] developed the complete characteristic curves of pump, which includes only two functions (WH(y) for the head and WB(y) for the torque) where the variable y represents the localization in the flow rate and speed plane and can represent the pump's complete characteristics at various rotate speed. The Suter's formulation is written as follow:

$$\begin{cases} y = \pi + tan^{-1}\dfrac{q}{x} \\ WH(y) = \dfrac{h}{x^2+q^2} \\ WB(y) = \dfrac{\beta}{x^2+q^2} \end{cases} \qquad (1)$$

The variables are $h = H/H_n$,$q = Q/Q_n$, $\beta = T/T_n$, and $x = \omega/\omega_n$, wherein H, Q, M and ω represent instantaneous values of head, flow rate, torque, and speed respectively and the subscript n refers to the rated values at pump best efficiency operating point.

In Suter formulation, $WH(y)$ is the function describing the head evolution; $WB(y)$ is the function describing the torque evolution. $y = \pi + tan^{-1}\frac{q}{x}$ is the independent variable in the domain $(0,2\pi)$. The two curves established by the equations (1) represent all unstable characteristics of pump, so it named complete characteristic curves of pump. According to the x and q, pump's operation is divided into four pattern zones. When $0 < y < \pi/2$ we have $(x < 0,\ q \leq 0)$ and the pump operate in turbine zone (1st zone); In the area $\pi/2 < y < \pi$ we have $(x \geq 0,\ q < 0)$ and the pump is in the dissipative zone (2nd zone); In the area $\pi < y < 3\pi/2$ we have $(x \geq 0,\ q \geq 0)$ and is the normal zone of the pump (3rd zone); At the end in the area $3\pi/2 < y < 2\pi$ we have $(x < 0,\ q > 0)$ and the pump is in the converse dissipative zone (4th zone).

The Suter curves are given according to a specific speed which defined different rotor geometry of pump. The specific speed is used to classify the pumps, and to estimate the shape of the performance curves of centrifugal pump [12]. Several definitions of specific speed exist in the literature; the most commonly used is defined as follow:

$$N_q = N_R \cdot \frac{\sqrt{Q_R}}{{H_R}^{3/4}} \tag{2}$$

Where N_R in tr/min, Q_R in m^3/s and H_R in m.

Otherwise, based on affinity laws, the pump curves in the normal operating zone are expressed as follow:

$$\begin{cases} h = x^2 \cdot f\left(\frac{q}{x}\right) \\ p_w = x^3 \cdot g\left(\frac{q}{x}\right) \quad where:\ h = \frac{H}{H_n}; q = \frac{Q}{Q_n}; x = \frac{\omega}{\omega_n} \\ \eta = k \cdot \frac{h.q}{p_w} \end{cases} \tag{3}$$

From equations (1) and (3), we can formulate the function f and g according to Suter curves (WH(y) for the head and WB(y) for the torque) as described by the following system:

$$\begin{cases} \frac{h}{x^2} = f\left(\frac{q}{x}\right) = \left(1 + \frac{q^2}{x^2}\right) \cdot WH\left(\pi + tan^{-1}\left(\frac{q}{x}\right)\right) \\ \frac{p_w}{x^3} = g\left(\frac{q}{x}\right) = \left(1 + \frac{q^2}{x^2}\right) \cdot WB\left(\pi + tan^{-1}\left(\frac{q}{x}\right)\right) \end{cases} \tag{4}$$

Thus, from the literature we can find examples of WH and WB curves for different specific speeds. Here are the curves extracted from [8] [9].

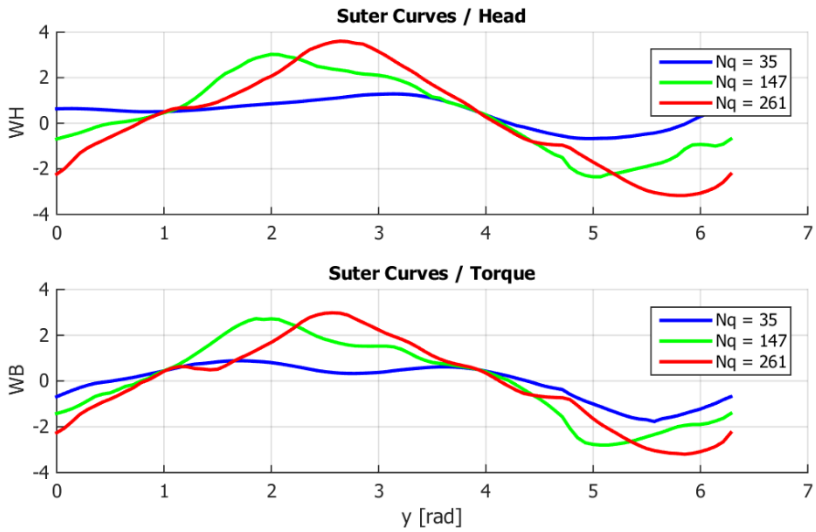


Figure 1 : Suter curves (Head : WH(y) and Torque : WB(y))

Nq = 35 (solid blue line); Nq = 147 (solid green line); Nq = 261 (solid red line)

According to the equation (4) and from the presented Suter curves in the figure 1, we can represent the pump curves in the plan (Head vs Flow) and (Power vs. Flow) as shown in the figure 2:

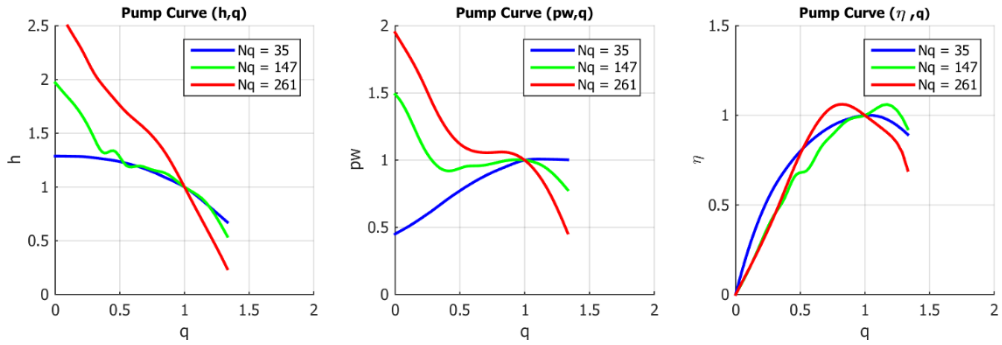


Figure 2 : Pump curves (Head vs Flow ; Power vs Flow and Efficiency vs Flow)

Nq = 35 (solid blue line); Nq = 147 (solid green line); Nq = 261 (solid red line)

The specific speed has a truly impact on pump characteristics shape due to different geometry of the pump rotor. However, other factors can also change the pump curves characteristics which are impeller diameter reduction for the same pump rotor geometry which mean the same specific speed. And another one which is the pump aging due to the operating conditions of the pump, the wear of the mechanical part of the pump (Blades, impellers …) due in most cases to the cavitation phenomena.

Many pump manufacturers provide pump performance curves that indicate how various models will perform with different impeller diameters or trims. The impeller should not be trimmed any smaller than the minimum diameter shown on the curve. Figure 3 shows the impact of impeller reduction or trimming on the performances of centrifugal pump.

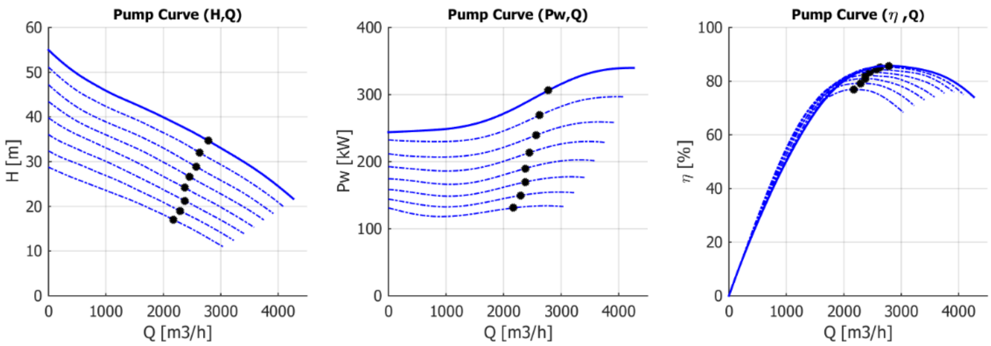


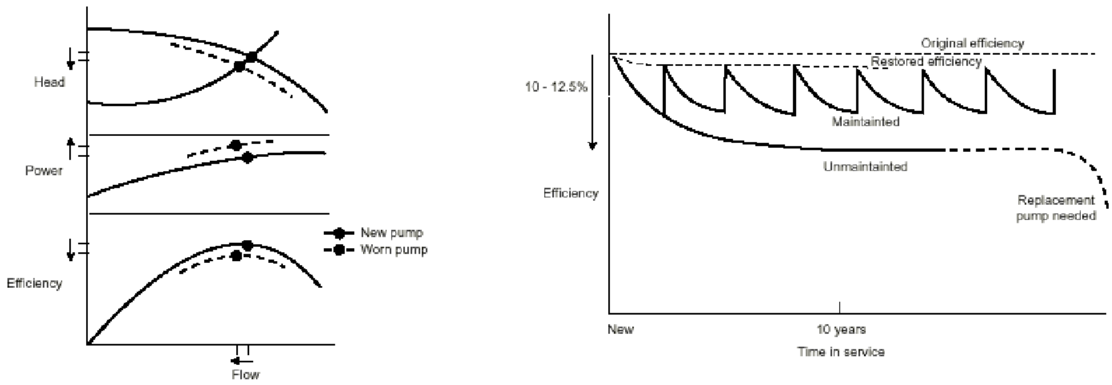
Figure 3: Impact of diameter reduction on pump performances.

Trimming reduces the impeller's tip speed, which in turn reduces the amount of energy imparted to the pumped fluid; as a result, the pump's flow rate and pressure both decrease. A smaller or trimmed impeller can thus be used efficiently in applications in which the current impeller is producing excessive head. Pump and system curves can provide the efficiency or shaft power for a trimmed impeller. If these curves are not available, affinity laws can be used to predict the variations in pumping performance with changes in the impeller diameter:

$$\begin{cases} Q_{DN_i} = \left(\frac{DN_i}{DN_n}\right)^1 \times Q_{DN_n} \\ H_{DN_i} = \left(\frac{DN_i}{DN_n}\right)^2 \times H_{DN_n} \\ Pw_{DN_i} = \left(\frac{DN_i}{DN_n}\right)^3 \times Pw_{DN_n} \end{cases} \quad (5)$$

However, the affinity laws predict the result of impeller diameter reducing, but they are not as accurate as we would like them to be, especially if we are making more than a 10% reduction in impeller diameter.

The pump characteristics are changing also due the bad utilization of pumps and some phenomena which can be appear inside the pump as cavitation and turbulence. The impact on pump performances can be different according to the problem. In the literature [12] [13], we find some information about how the pump curves characteristics change during time as shown in the figure 4 below:



(a) **(b)**

Figure 4: Pump aging and impact on pump curve characteristics

(vv) Effect of wear on pump characteristics;

(ww) Average wear trends for maintained and unmaintained pumps

Multiple pumps system

A multiple pumps system can be considered from process point of view as a single "equivalent" pump, with a degree of freedom based on how the flow demand is shared between pumps. It's known that, when pump characteristics are identical, the best way to optimize energy consumption for an operating system point $(\bar{h},\bar{q})$ is that pump run at the same speed, which means that the required flow must be shared evenly between pumps [14].

The problematic in a multiple pumps system is that the pumps haven't the same characteristics in the most of cases, for instance we can have multiple pump system with mixed states of pumps with different aging, with different impeller sizes, with different power sizes and with different technology. For that, we have to address the optimization of energy consumption taken into account this criteria of different characteristics of pumps.

System Best Efficiency Point with Multiple Pumps Equipment

Problem description

The problem of optimization in case of different pumps characteristics is to find the right distribution of flow between the pumps to satisfy the system demand $(\bar{q},\bar{h})$ while minimizing the total power consumption. Otherwise, the problem of the optimization can be expressed by another manner which is to find the right distribution of speeds of pumps that minimizes the total power consumption.

Theoretical demonstration

The objective of this part is to give a theoretical demonstration to get the best efficiency operating point in multiple pumps system by considering the constraints on the process defined by the system operating point $(\bar{q},\bar{h})$.

For N pumps, let's considering the following system of equations:

$$\begin{cases} \bar{h} = {x_i}^2 \cdot f_i\left(\frac{q_i}{x_i}\right) \\ \bar{q} = \sum_{i=1}^{N\ pumps} q_i \\ p_{w_T} = \sum_{i=1}^{N\ pumps} p_{w_i} = \sum_{i=1}^{N\ pumps} {x_i}^3 \cdot g_i\left(\frac{q_i}{x_i}\right) \end{cases} \quad (6)$$

Where:

- p_{w_i} ratio between the mechanical power of the i^th^ pump and the nominal mechanical power
- q_i ratio between the flow of the i^{th} pump and the nominal flow
- x_i ratio between the speed of the i^{th} pump and the nominal speed
- $\bar{h}$ is the current operating system head
- $\bar{q}$ is the current operating system flow
- p_{w_T} is the total mechanical power

Let's define the variables q_i from 1 to N-1 as independent variables of the system. The relation between the flow of each pump and the global system flow is given by the following equation:

$$q_1 + q_2 + \cdots + q_{N-1} + q_N = \bar{q} \quad (7)$$

The relation (7) allows expressing the flow q_N as a function of the other N-1 flows. The optimization problem can be expressed by finding the flows distribution $(q_1, q_2, \cdots, q_{N-1}, q_N)$ that cancel the N-1 partial derivative relations:

$$\begin{cases} \frac{\partial p_{w_{sys}}}{\partial q_1} = \sum_{i=1}^{N\ pumps} \frac{\partial p_{w_i}}{\partial q_1} = 0 \\ \frac{\partial p_{w_{sys}}}{\partial q_2} = \sum_{i=1}^{N\ pumps} \frac{\partial p_{w_i}}{\partial q_2} = 0 \\ \vdots \\ \frac{\partial p_{w_{sys}}}{\partial q_{N-1}} = \sum_{i=1}^{N\ pumps} \frac{\partial p_{w_i}}{\partial q_{N-1}} = 0 \end{cases}$$

Then, for j = 1 to N-1 we have the following general equation:

$$\frac{\partial p_{w_{sys}}}{\partial q_j} = \sum_{i=1}^{N\ pumps} \frac{\partial p_{w_i}}{\partial q_j} = \frac{\partial p_{w_j}}{\partial q_j} + \frac{\partial p_{w_N}}{\partial q_j} = \frac{\partial p_{w_j}}{\partial q_j} + \frac{\partial q_N}{\partial q_j} \cdot \frac{\partial p_{w_N}}{\partial q_N} \quad (8)$$

With the following constraint on the differential flows given from equation (9):

$$0 = \frac{\partial \bar{\boldsymbol{q}}}{\partial q_j} = \sum_{i=1}^{N\ pumps} \frac{\partial q_i}{\partial q_j} = 1 + \frac{\partial q_N}{\partial q_j} \quad \text{where } j = 1 \text{ to } N-1 \quad (9)$$

According to the equations (8) and (9), the solution of the problem should verify the following condition:

$$\frac{\partial p_{w_j}}{\partial q_j} = \frac{\partial p_{w_N}}{\partial q_N} \quad \text{where } j = 1 \text{ to } N-1 \quad (10)$$

Let’s define a new pump function which can be called MPE (Multiple Pump Efficiency) as follow:

$$C_i(q_i) = \frac{\partial p_{w_i}}{\partial q_i} \quad \text{where } i = 1 \text{ to } N \quad (11)$$

Thanks to this new function, the optimization problem becomes to find the flows q_i which verify the constraint defined on the equation (7) and the constraint defined by the new pump function MPE which is:

$$C_1(q_1) = C_2(q_2) = \cdots = C_{N-1}(q_{N-1}) = C_N(q_N) = \bar{C} \quad (12)$$

Then, this new MPE function is calculated as follow:

$$C_i(q_i) = \frac{\partial p_{w_i}}{\partial q_i} = \left(3{x_i}^2 \cdot g_i\left(\frac{q_i}{x_i}\right) - x_i \cdot q_i \cdot {g_i}'\left(\frac{q_i}{x_i}\right)\right) \cdot \frac{\partial x_i}{\partial q_i} + {x_i}^2 \cdot {g_i}'\left(\frac{q_i}{x_i}\right) \qquad where\ i = 1\ to\ N \quad (13)$$

From the equation (6), by doing a partial derivative on the system head $\bar{h}$ according to each flow q_i we obtain the following formula:

$$\frac{\partial \bar{h}}{\partial q_i} = \frac{\partial}{\partial q_i}\left(x_i^2 \cdot f_i\left(\frac{q_i}{x_i}\right)\right) = 2x_i \cdot \frac{\partial x_i}{\partial q_i} \cdot f_i\left(\frac{q_i}{x_i}\right) + x_i^2 \cdot \frac{x_i - q_i \cdot \frac{\partial x_i}{\partial q_i}}{x_i^2} \cdot f_i'\left(\frac{q_i}{x_i}\right) = 0$$

It yields to the following expression:

$$\frac{\partial x_i}{\partial q_i} = \frac{x_i \cdot f_i'\left(\frac{q_i}{x_i}\right)}{q_i \cdot f_i'\left(\frac{q_i}{x_i}\right) - 2x_i \cdot f_i\left(\frac{q_i}{x_i}\right)} \qquad where\ i = 1\ to\ N \qquad (14)$$

Then replacing with the expression $\frac{\partial x_i}{\partial q_i}$ obtained from (14) in the equation (13), the function C() is expressed as follow:

$$C_i(q_i) = \frac{\bar{h}}{f_i\left(\frac{q_i}{x_i}\right)} \cdot \frac{3 \cdot g_i\left(\frac{q_i}{x_i}\right) \cdot f_i'\left(\frac{q_i}{x_i}\right) - 2 \cdot f_i\left(\frac{q_i}{x_i}\right) \cdot g_i'\left(\frac{q_i}{x_i}\right)}{\frac{q_i}{x_i} \cdot f_i'\left(\frac{q_i}{x_i}\right) - 2x_i \cdot f_i\left(\frac{q_i}{x_i}\right)} \qquad where\ i = 1\ to\ N \qquad (15)$$

with x_i a function of system head, and i[th] pump flow: $\bar{h} = x_i^2 \cdot f_i\left(\frac{q_i}{x_i}\right)$.

On the flow range where the functions Ci may be reversed, the optimization problem becomes, from (7), finding the variable $\bar{C}$ such as

$$\sum_{i=1}^{N\ pumps} C_i^{-1}(\bar{C}) = \bar{q} \qquad (16)$$

Each flow is deduced from equation (16).

Simulations results

After demonstrating by a theoretical approach how we can get the best efficiency point in a multiple pumps system by sharing the right flows on pumps to satisfy the process demand while minimizing the total power consumption. We will show in this part simulation results got on a multiple pumps system with different pumps characteristics. The process constraint will be defined by the operating system point $(\bar{q}, \bar{h})$.

Now let's take an example with three pumps with different characteristics. Figure 5 shows the characteristics (h vs. q; pw vs. q and eta vs. q) of each pump.

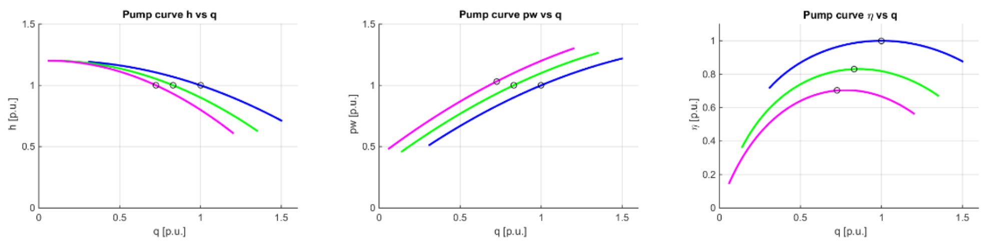


Figure 5: Pump curves – nominal speeds

Pump N°1 curves (Solid blue lines); Pump N°2 curves (Solid green lines); Pump N°3 curves (Solid magenta lines);Best Efficiency point (black circles).

For a multiple pumps system, if we consider that each pump operates at a given speed. Then, the equivalent pump curve (h_{eq}, q_{eq}) is obtaining by adding the flow rates q_i for a given pressure h. The curve (q_{eq}, pw_{eq}) is obtained by adding the powers of each pump for its flow rate at the given pressure. Figure 6 shows the characteristics of the equivalent pump curve for the pump working at the same nominal speed.

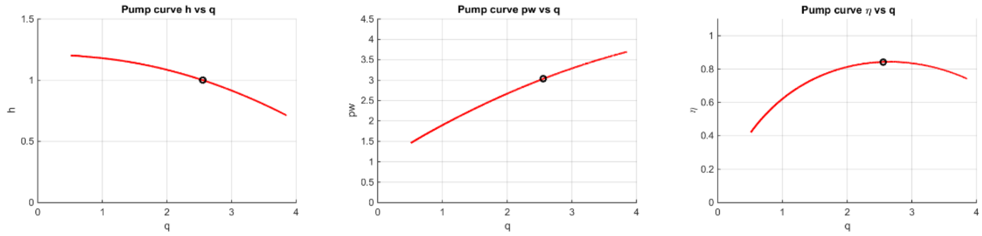


Figure 6: Pump curves – nominal-speeds

Equivalent pump curves (Solid red lines);Best Efficiency point (black circles).

Let's now consider the operating system working point by a flow of 2. [p.u.] for a head of 0.9 [p;u.]. According to

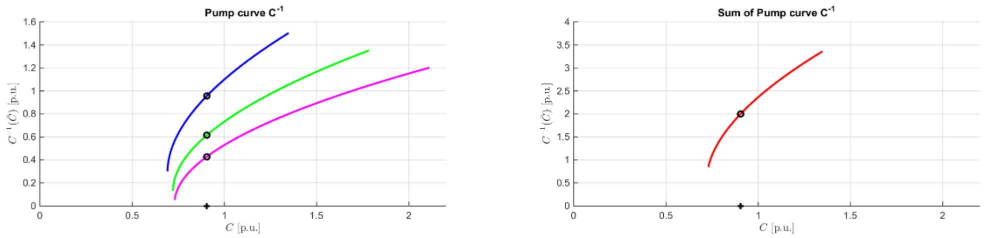


Figure 7: Pump curves – C^{-1} curves for system head

Pump N°1 curves (Solid blue lines); Pump N°2 curves (Solid green lines); Pump N°3 curves (Solid magenta lines); Sum of curves (Solid red lines); Operating working point (black circles).

We deduce that pump 1, respectively pump 2, pump3 is providing 0.957 [p.u], respectively 0.615 [p.u], 0.428 [p.u], with a global mechanical power consumption of 2.160 [p.u]

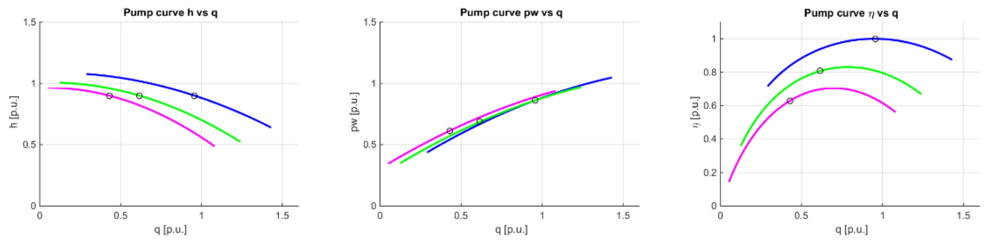


Figure 8: Pump curves – working point

Pump N°1 curves (Solid blue lines) 95.0% nominal speed; Pump N°2 curves (Solid green lines) 91.5% nominal speed; Pump N°3 curves (Solid magenta lines) 89.6% nominal speed; Operating working point (black circles).

Once the speed of each pump is founded, from the curves (q, pw) we can easily deduce the power consumed by each pump, respectively (pw_1 = 0.861, pw_2 = 0.686 and pw_3 = 0.613) and a total power consumption about 2.160 [p.u].

With pumps running at the same speed ($x_1 = x_2 = x_3 = 0.921$), the total power consumption will be 2.177. the gain provided by the optimization with MPE curve is estimated at 0.78%.

Experimentation results

Experimental test bench description

To consolidate the theoretical demonstration done, some experimentations were made on a real test bench. The objective is to validate the optimization results about speed sharing between pumps compared to the strategy where we have pumps are running at the same speed. Two tests have been made, the first one with two pumps and the second one with 3 pumps at the system constraint which is to make a constant pressure.

Figure 9 gives an overview about the hydraulic installation where tests have been made.

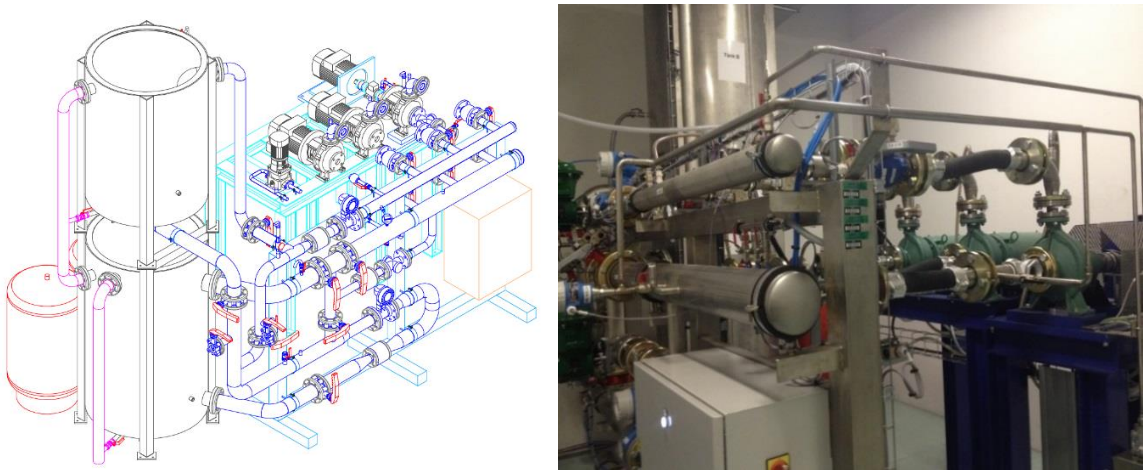


Figure 9: Experimental test bench

The test bench was realized in order to test a large configuration of hydraulic systems (closed hydraulic system, open hydraulic system, system with high head losses, pressure control at different points on the hydraulic system, flow control, level control …). It composed with three pumps within the following theoretical datasheet characteristics (Q_{BEP} = 32.2 m^3/h, H_{BEP} = 38.94 m, Pw_{BEP} = 5.47 kW and N = 2900 rpm, $\eta = 62.46\,\%$), two tanks for suction and discharge pressure, pipes with different dimensions and material to have different pressures losses at different level of the hydraulic system, manual valves used to configure the hydraulic system according to the test to be done and the control function to validate and finally automatic valves to manage controlled system curve. The control part of this system is implemented to manage pumps with fixed speeds (Direct-on-line, soft-starter) or variable speeds.

The test of the new control strategy based on MPE curve approach was done on rapid prototyping to have an overview about optimization results before implement the function on a real control board. The outputs of this function (speeds and run order of each pump) is provided to the variable speed drive which is used only as an actuator.

Pump curves characteristics definition

Before making test of the control function, a new characterization of the test bench pumps was done to identify the new characteristics of each pump compare it with the datasheet characteristics as shown in the following figure:

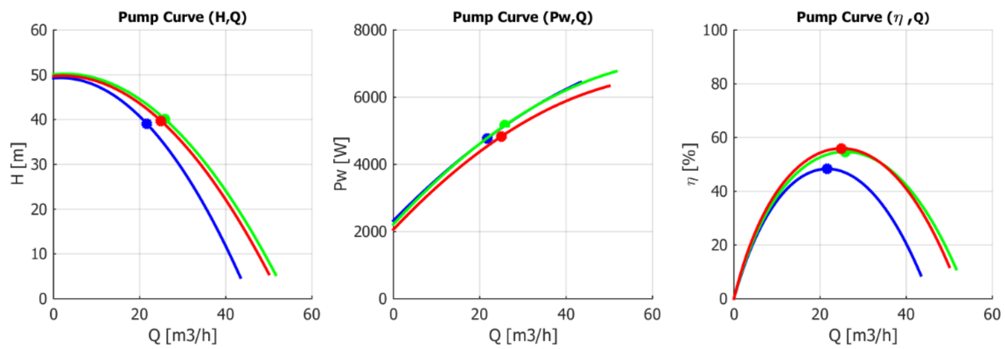


Figure 10: Pump curves characteristics

Pump 1 (solid blue lines) ; Pump 2 (solid green lines) ; Pump 3 (solid red lines)

The following table give the Best efficiency points of each pump:

Pumps BEP (Best Efficiency Point)

	Pump N°1	**Pump N° 2**	**Pump N° 3**
$Q_{BEP}\ [m^3/h]$	21.7	25.8	25
$H_{BEP}\ [m]$	39.05	40.16	39.68
$Pw_{BEP}\ [W]$	4777.83	5161.48	4831.78
$\eta\ [\%]$	48.33	54.70	55.95
Performance degradation from original BEP	**-23%**	**-13%**	**-11%**

Experimental results

On the real test bench, we select the operating point (0.9*Pump3.BEP.Hn = 35.7m; 3*Pump3.BEP.Qn = 75 m^3/h), we get the optimal speeds as follow

Pump 1 speed: 0.953 [p.u.]; Pump 2 speed: 0.9696 [p.u.]; Pump 3 speed: 0.9813 [p.u.]

The total mechanical power is equal to 13 787 W.

On the same working point, with a strategy to control the pumps at the same speed (0.9684), the total mechanical power is equal to 13 804 W. The gain with the proposed algorithm allows an energy savings of 0.1% of consumption.

Conclusion

In the first section, we have provided an overview on centrifugal pump characteristics and how these characteristics will be changing according to the specific speed, the impeller diameter and the aging. We have presented a new formulation of the pump curve which is called "Suter" curves. The objective of this section was to give the different causes impacting the pump curve characteristics in multiple pumps systems.

In the second section, by using theoretical demonstration and simulation-based results we have demonstrated that the system best efficiency point (S-BEP) in multiple pumps systems with pumps having different characteristics is not to share the same speed between pumps. According to this demonstration, we have developed a new control strategy to manage system with pumps having different characteristics by selecting the right speed for each pump and to choice the right number of pump to run, to satisfy an operating point while minimizing energy consumption.

In the Third section, simulation and experimental results was done with rapid prototyping to validate the new control strategy on a real test bench.

References

[1] W. Wan, W. Huang "Investigation on complete characteristics and hydraulic transient of centrifugal pump", Journal of Mechanical Science and Technology 25 (10) (2011) 2583~2590.

[2] M. A. El-Naggar "A One-Dimensional Flow Analysis for the Prediction of Centrifugal Pump Performance Characteristics", International Journal of Rotating Machinery,Volume 2013, Article ID 473512, pages 19

[3] E. Ayder, A.N. Ilikan, M. Şen, C. Özgür, L. Kavurmacıoğlu, K. Kirkkopru "Experimental investigation of the complete characteristics of rotodynamic pumps". Proceedings of the ASME 2009 Fluids Engineering Division Summer Meeting, August 2-6, 2009, Vail, Colorado USA.

[4] Knapp, R. T."Complete Characteristics of Centrifugal Pumps and Their Use in the Prediction of Transient Behavior."Trans. ASME 59:683, 1937;60:676, 1938

[5] S. Derakhshan and A. Nourbakhsh, Experimental study of characteristic curves of centrifugal pumps working as turbines in different specific speeds, Experimental Thermal and Fluid Science,32 (8) (2008) 800-807.

[6] S. Derakhshan and A. Nourbakhsh, Theoretical, numerical and experimental investigation of centrifugal pumps in reverse operation, Experimental Thermal and Fluid Science, 32 (8) (2008) 1620-1627

[7] J. S. Anagnostopoulos, "Numerical Calculation of the Flow in a Centrifugal Pump Impeller Using Cartesian Grid". Proceedings of the 2nd WSEAS Int. Conference on Applied and Theoretical Mechanics, Venice, Italy, November 20-22, 2006

[8] Peter K. Dörfler "Improved Suter Transform for Pump-Turbine Characteristics" International Journal of Fluid Machinery and Systems. Vol. 3, No. 4, October-December 2010

[9] X B Zheng, P C Guo, H Z Tong, X Q Luo "Improved Suter-transformation for complete characteristic curves of pump-turbine" 26th IAHR Symposium on Hydraulic Machinery and Systems 2012.

[10] M. Gölcü, Y. Pancar, H. Sevil Ergür, Esrah Ö. Göral, "Prediction of head, efficiency, and power characteristics in a semi-open impeller". Mathematical and Computational Applications, Vol. 15, No. 1, pp. 137-147, 2010.

[11] Y. M. Lahssuny,W. Jędral "Universal correlations for predicting complete pump performance characteristics", Institute of Heat Engineering, Nr89/90. 2004

[12] Igor J. Karassik, Joseph P. Messina, Paul Cooper, Charles C. Heald "Pump Handbook" Fourth Edition, by McGRAW-HILL companies, 2008.

[13] CETIM (France), David T. Reeves (United Kingdom), NESA (Denmark), Technical University Darmstadt (Germany) "Study on improving the energy efficiency of pumps", European Commission. February 2001

[14] F.Malrait, K.Ejjabraoui, "Best efficiency point of a multiple VSD pumps' equipment", EEMODS'15 Conference, Energy Efficiency in Motor Driven Systems. Helsinki 15 – 17 September 2015.

Performance of a wastewater submersible pump under mechanical wear

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Abstract

In the paper, the influence of pump wear on the electro-mechanical efficiency of the wastewater submersible pumps is analysed. The presence of solids in the water and the related mechanical wear could reduce the pump performance and the overall efficiency of the pumping system. This study is relevant for the optimal management of drainage networks and for the setup of new standards.

Pump wear on a wastewater submersible pump have been artificially simulated and the performance curves have been experimentally determined for different rotational speed of the pump. The effects of the pump performance variations on the mechanical wear has been evaluated with reference to classic pump working conditions of constant flow or variable flow. In the first case, the pump operates at fixed speed, while, in the second case a variable frequency driver is used.

With reference to pumping system with storage capacity, a numerical model has been set up to predict the optimal daily distribution of on/off operation at constant flow and of motor speed in variable flow conditions. Then, the energy required for wastewater pumping has been determined for a brand new or an aged pump and the results have been compared. Results refer to the working conditions of a system equipped with a single pump.

Keywords: Wastewater pump, energy efficiency, mechanical wear, industrial standards, pump test

Nomenclature

D	tank diameter
H	head
N	rotational speed (rpm)
P	power
Q	flow rate

Greek Symbols

η	efficiency (-)

Subscripts

BEP	at Best Efficiency Point

Abbreviations

BEP	Best Efficiency Point	VFD	Variable Frequency Driver
PAT	Pump as Turbine	WSS	Water Supply Systems
PRV	Pressure Reducing Valve		

Introduction

One of the main challenges in EC policy is to increase the efficiency of the energy related and energy using products. Directives 2005/32/EC and 2009/125/EC promote technical changes in the industrial design of water pumps and introduce the concept of eco-design. New efficiency indexes have been introduced or are under study accounting for the overall efficiency of pumping units under real working conditions.

Among the different pump types, submersible pumps used for wastewater are probably the most critical for the quality of the pumped fluid and for the intermittency of working conditions. Submersible pumps are designed to handle solids of different sizes and in some cases to cut or grind incoming solids to reduce their sizes. Pump efficiency is therefore only one of the aspect to be considered in the design, for the importance of obtaining a global plant effectiveness.

The presence of solids in the water and the related mechanical wear could have a dramatic effect on the pump performance. Depending on the pump type, the wear is mainly located on specific components of the pumps. Only occasionally, in presence of high sediment concentration mechanical wear lead to pump failure. In the other cases, a progressive reduction of pump performances is observed.

Water energy nexus is a challenging research topic and a number of recent studies can be found in literature exploring the possibility of energy recovery in water supply systems. Different aspects are considered, like the reduction of water leakages by optimal pressure control with pressure reduction valves (PRVs) [1-2] or with PATs [3-5], the evaluation of pump performances in typical operating conditions [6-7], the optimal operation of pumping systems [8], the location of pump as turbines (PATs) for producing electricity instead of merely dissipating the hydraulic energy in the PRVs [9-11], the introduction of energy performance indexes of the network to facilitate the energy assessment [12]. All these studies have been applied to water distribution for drinking use or for irrigation. The results of such studies cannot be easily extended to drainage systems due to the peculiarities of the waterworks used for the displacement of meteoric and wastewater. The pumping systems are equipped with storage tanks and a sequence of ON/OFF is used to operate the pump depending on the water level within the tank. Only recently, variable frequency drivers (VFD) have been introduced and variable flow conditions have been considered as an operation option [13-14].

In the present paper, we discuss the effect of pump mechanical wear in wastewater transport. The basic idea is to compare the cost of pumping in presence of a storage capacity for a pump brand new or for a pump with a decay in the hydraulic performances. An optimization model has been set up to find the optimal running speed of the pump and the optimal ON/OFF sequence to obtain the minimum required energy. The first application is made on pumping system quipped with a single grinder pump presenting low to high wear.

Pump performances in presence of mechanical wear

Pump testing rig

Specific tests have been performed in the new Hydro Energy Laboratory (HELab) of Federico II University. HELab was specifically created to perform the test included in the new standard EN16480, according to the specification of ISO 9906.

In Figure 1 the test rig used for submersed wastewater pumps is schematically shown. The pump is connected to the rig by a fast joint. The automatic measuring system acquires temperature and water level in the tank, pressure and flow rate in the delivery pipeline, adsorbed power and electric parameters.

All measurements are acquired by an automatic system and test report are created. Measurement errors are evaluated based on instrument accuracy (Level 1 of ISO 9906).

Wastewater pump under test

A Caprari grinder pump, model K, has been tested, Figure 2. The pump was regulated by a Santerno Variable Frequency Driver (VFD), model IRIS BLUE 11kW. Preliminary experiments were performed to assess the VFD efficiency a full speed N_{max}=3000 rpm. Average VFD efficiency was found to be 98%, and 97% at pump BEP.

Pump characteristic and efficiency curves, for varying rotational speed are shown in Figure 3. Grinder pumps are equipped with a cutting mechanism that macerates waste and grinds items that are could be found in sewage. For the presence of this mechanism the efficiency for this type of pumps is in general much lower than in the fresh water pumps. The BEP efficiency of the pumping group (pump+motor+VFD) at full speed was found to be lower than 25%. Measured BEP efficiency at lower rotational speed reduced significantly.

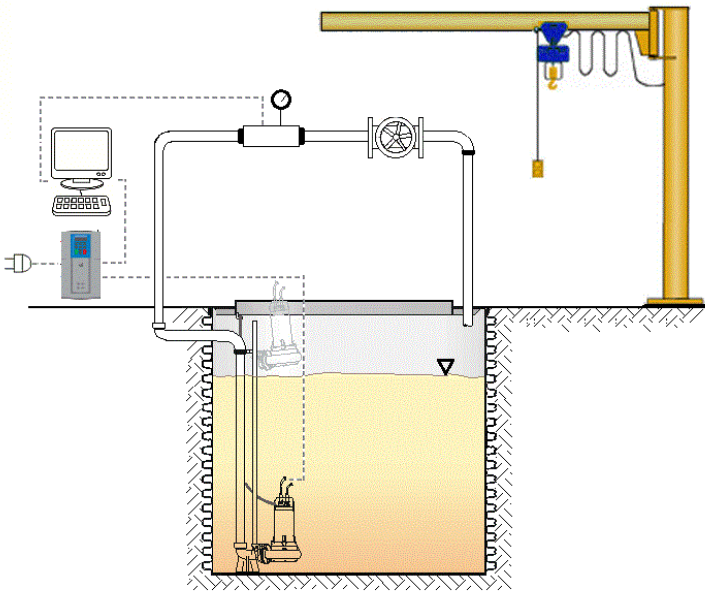


Figure 1 – Test rig used for submersed wastewater pumps

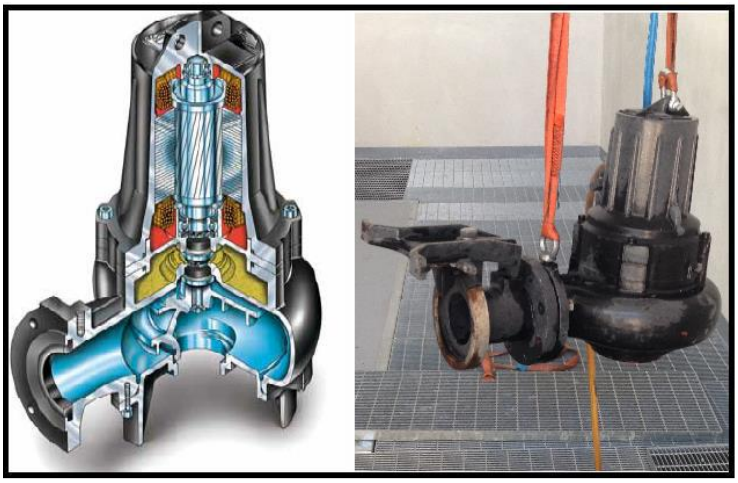


Figure 2 – Grinder pump used in the study

Then, the pump mechanical wear has been simulated. In Figure 4 a magnified view of the pump section is given. The bottom of the pump is fixed to the body by three screws. The inner part of an aged bottom plate is shown in Figure 5: a number of concentric circular slots, 2 mm depth, is present to inhibit the sediment particles to stick between the open impeller and the bottom. As an effect of sediment motion, these pumps exhibit a progressive wear, with a reduction of the crests between tie circular slots. This effect has been replicated by introducing calibrated thicknesses under the fixing screws of the plate, preventing the complete tightening. Hence, the distance between the runner vane and the runner was increased of the high of the thicknesses. Two different stages of mechanical wear were simulated using elements of 1 mm and 2 mm thickness, as representative of an intermediate and high wear, the last case corresponding to the total abrasion of the crests.

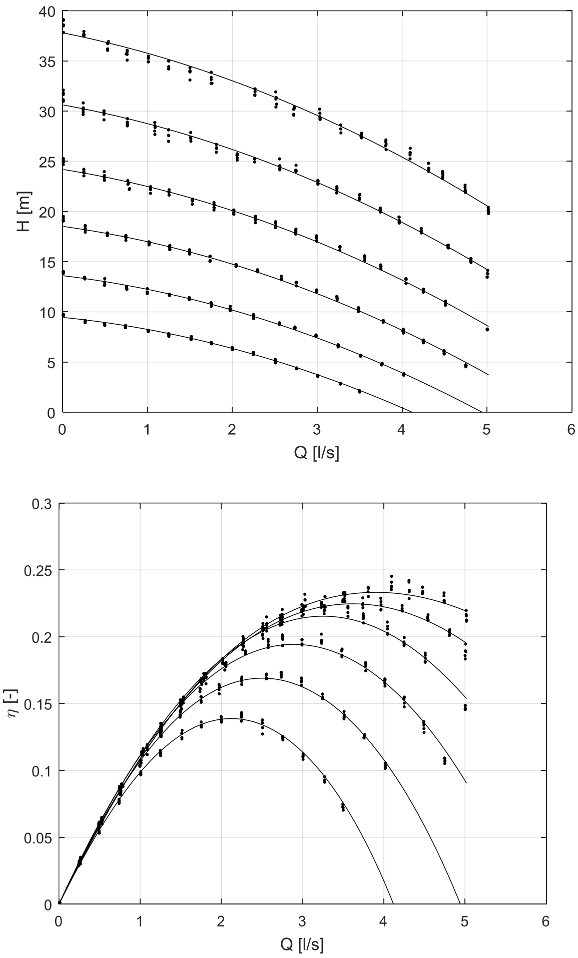
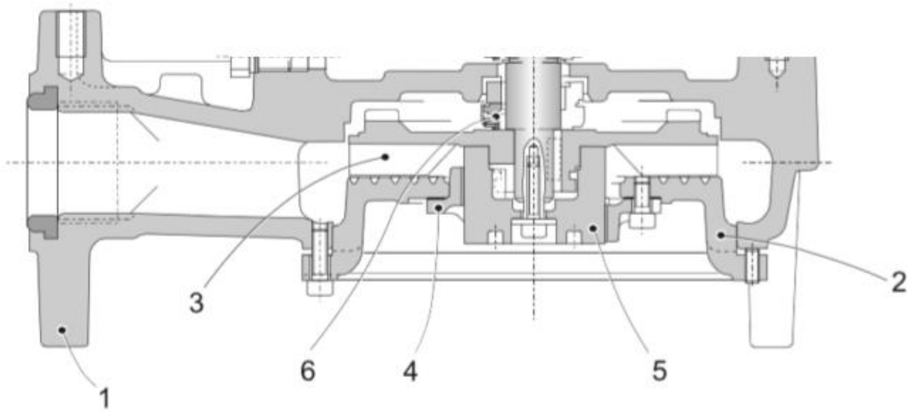


Figure 3 – Pump characteristic and efficiency curves



1	Outlet
2	Bottom Plate
3	Impeller
4	Stationary Grinder
5	Rotating Grinder
6	Mechanical Seal

Figure 4 – Magnified view of the pump section

Figure 5 – Inner part of an aged bottom plate

Test were repeated with the two stages of wear. The pump characteristic and efficiency curves for different rotational speed were obtained, as reported in figures 6 and 7. The effect of the mechanical wear on the pump efficiency and on the full speed characteristic curve is evident. The full speed characteristic curve moves downward for an aged pump and the efficiency reduces too. In figure 8, the efficiency curves of the aged pumps are compared with the performance of the new pump: the differences in pump efficiency between a new or an aged pump are smaller for the lower pump speeds.

Storage capacity model

Tank design

The design of the pumping system has performed based on best practice criteria. A circular tank of D=2 m diameter was considered equipped with a single pump model K as tested. The pumping time T_1 for the water level in the tank to move from the maximum to the minimum level is:

$$T_1 = \mathrm{W}/(Q_m - Q) \tag{1}$$

where W is storage capacity of the tank and Q_m is the average pumping flow rate and Q is the inlet flow rate. The most unfavourable case is when the inlet flow rate is equal to the peak value of the hydrograph: $Q=Q_p$.

The time occurring to the inflow stream to fill the storage tank in absence of pumping is:

$$T_2 = \mathrm{W}/Q \tag{2}$$

Therefore, the time occurring between two following starts of the pump is given by the expression:

$$T = T_1 + T_2 = \mathrm{W}/(Q_m - Q) + \mathrm{W}/Q = \mathrm{W}Q_m/[Q(Q_m - Q)] \tag{3}$$

The number of starts in one hour is:

$$\mathrm{Z} = 3600(Q_m - Q)/(W - Q_m) \tag{4}$$

By deriving eq (4) with respect to Q, the maximum number of starts, Z_{max}, is obtained for Q_p being the half of Q_{BEP}. Therefore, the storage volume can be obtained assuming Z_{max}= 8, corresponding to a water level excursion of about 0.45 m.

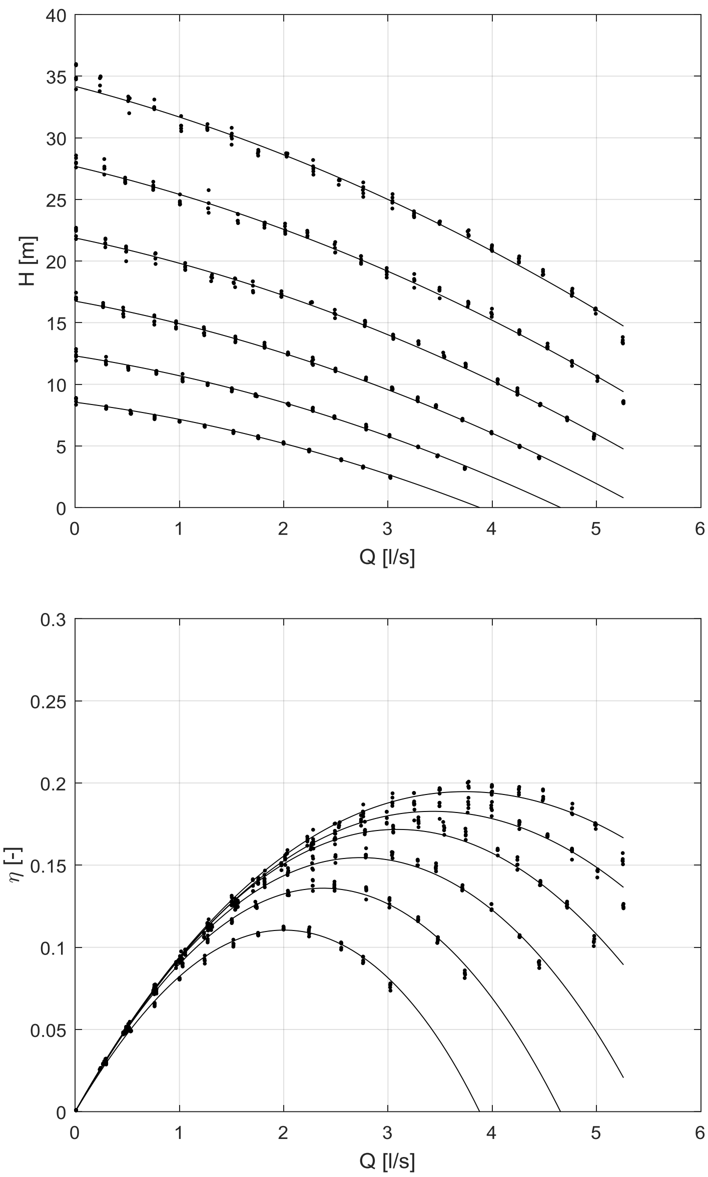


Figure 6 – Pump characteristic and efficiency curves for medium wear

A real sewer hydrograph, measured in the drainage network of Naples (Italy), was scaled to obtain a peak discharge Q_p being the half of Q_{BEP}. Such hydrograph is shown in Figure 9. In order to compute the pumping head, a plant with a 100 m long and 56 mm diameter cast iron pipe was considered. Darcy formula was used to compute the friction loss and the required head at the BEP discharge was set equal to the head at the BEP of the pump. The resulting difference in elevation between the pumping tank and the end of the pipe is less the one half of the total head. The plant curves is plotted in figure 8.

Based on the hydrograph and on the pump characteristic curves at full speed, for the different stages of wear, the working condition of the pumping station were computed. This working mode is called *constant flow*, because the low rate has only a small variation around the BEP on the full speed characteristic curve. The daily trend of pump flow rate is plotted in Figure 10. The Figure shows that, for increasing wear, the pumped flow reduces: this happens because the working point of the machine in constant flow is the intersection between the head curve of the pump and the plant curve (see Figure 8), with small variations due to the changing of the water level in the tank.

Variable flow conditions

A modern technology for the reduction of energy use is based on the control of the pump motor by a VFD during operation. This working mode is called *variable flow*, because, as an effect of the variation of the running speed, the flow rate changes much more than in constant flow conditions.

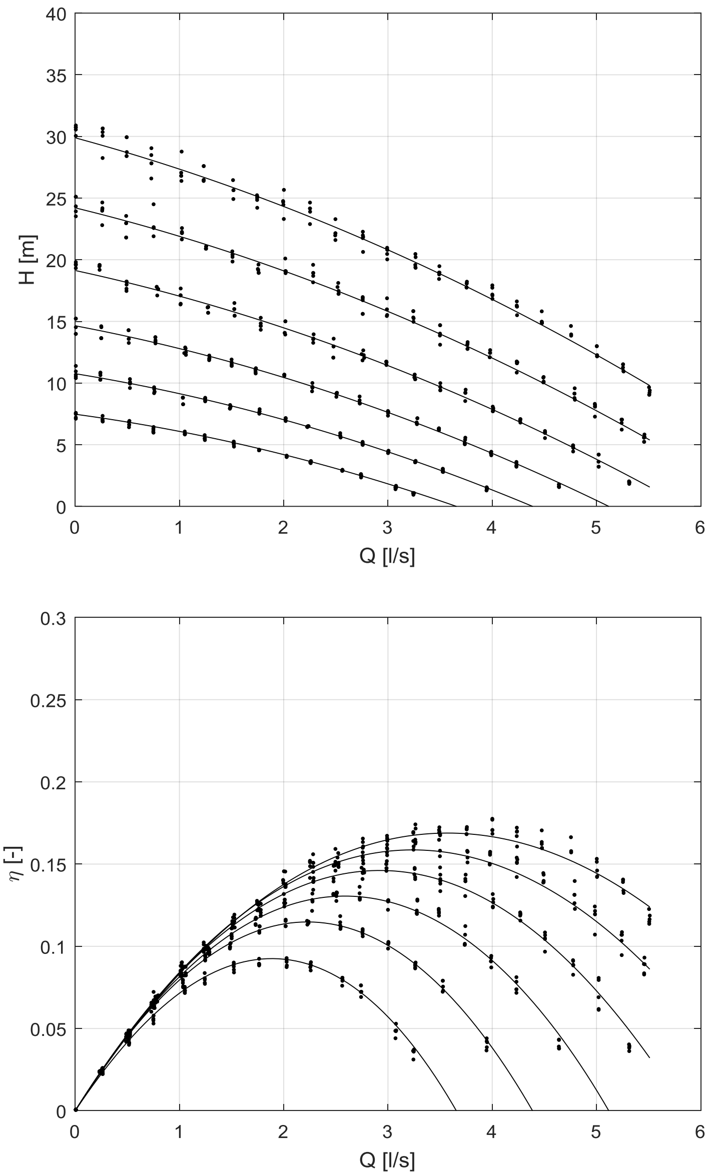


Figure 7 – Pump characteristic and efficiency curves for high wear

During operation, the rotating speed of the impeller can be set in order to minimize the energy consumption. In this case, the pump is always on, in order to reduce the mechanical stress on the motor.

This optimization process has been performed on the hydrograph of Figure 9, based on the tank design dimensions and on the performances of the pump.

The optimization problem can be expressed as:

$$\begin{cases} \underset{N(t)}{\text{minimize}} & E_{day} = \sum_{t \in day} \frac{\gamma Q_p(N(t)) H_p(N(t))}{\eta_p(N(t))} \Delta t \\ \textit{subject to} & \begin{array}{c} H_T \geq H_{min} \\ H_T \leq H_{max} \\ N_{min} \leq N \leq N_{max} \end{array} \end{cases} \tag{5}$$

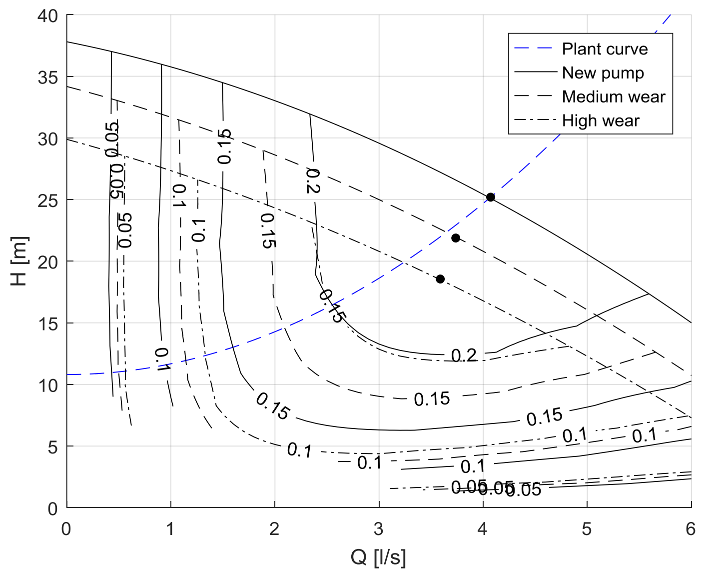


Figure 8 – Effect of wear on full speed characteristic curves and on pump efficiency

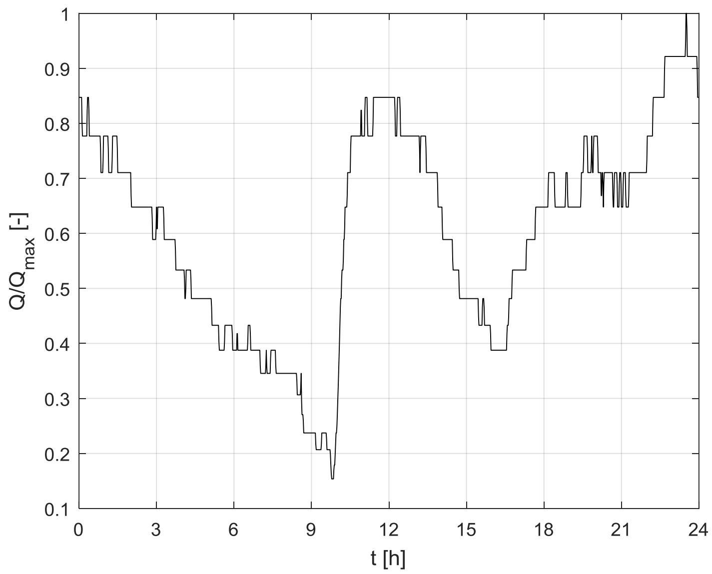


Figure 9 – Design hydrograph

where E_{day} is the total energy requested during the day, t is the generic timestep whose length is Δt, γ is the water specific weight, Q_p, H_p and η_p are the pumped discharge, the pumping head and the pump efficiency respectively at N rotational speed. The daily energy is optimized by searching the optimal values of N for each timestep under the following constraints:

- The water level H_T within the tank should be ranged between H_{min} and H_{max}. H_{min} has been set to 0 as system reference and H_{max} is related to the ratio W/S, where S is the section of the tank.
- The rotational speed should be ranged between a minimum N_{min} and a maximum N_{max} values, respectively equal to 1500 and 3000 rpm

For the optimization, a continuous non-linear algorithm has been used [15]. A timestep of 3 minutes has been set. Figure 11 shows the operating points on the hill chart (a), the water level in the tank compared with the solution obtained for the constant flow condition (b) and the daily pattern of the inflow and the outflow (c), calculated for the new pump. Figure 11c shows that the outflow is very close to the inflow, so that the water level within the tank (Figure 11b) is fairly constant. Only between 9 am and 10 am the inflow and the outflow are significantly different and in this case the water level modifies and reaches a minimum value. Figure 11a shows that the operating points lie in a region of the hill chart where the efficiency of the pump is quite low. The plots obtained for the two other stage of wear are similar to the given ones.

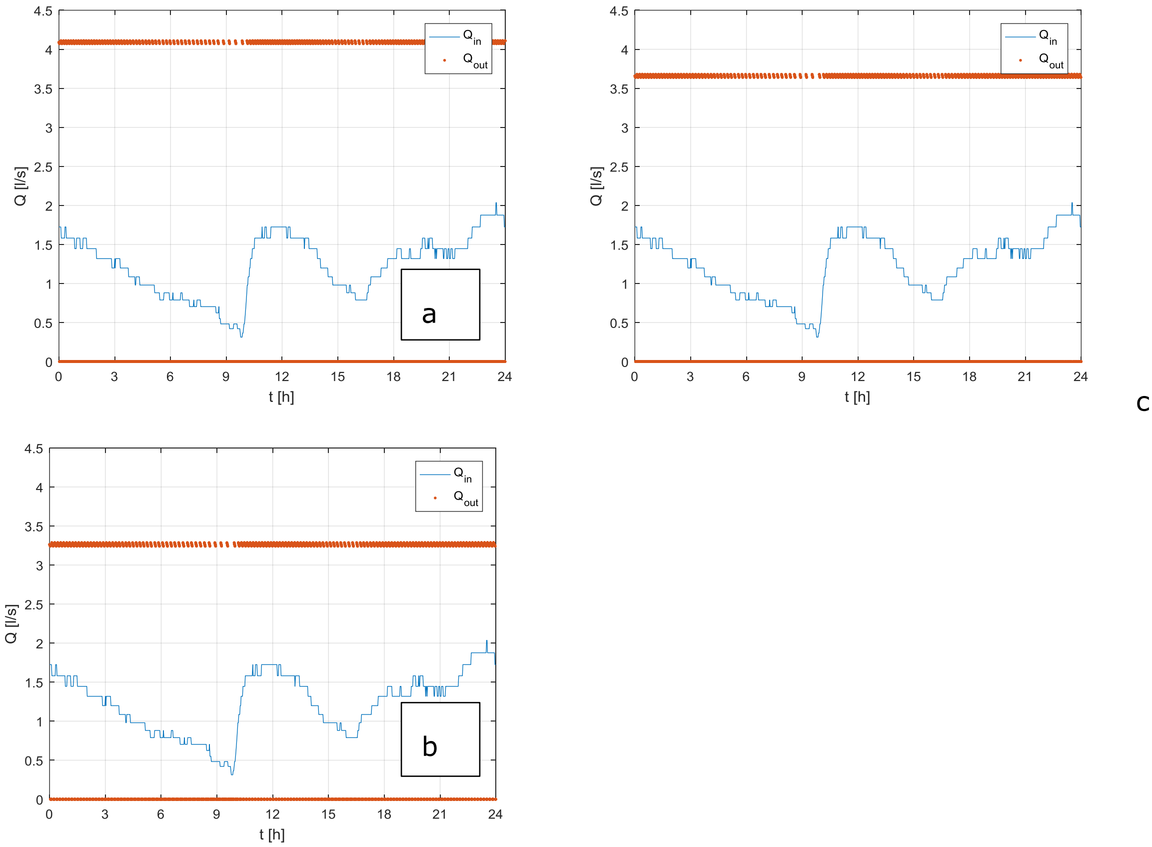


Figure 10 –Flow rate of the pumping station in constant flow at different stages of pump wear (a – new pump, b – medium wear, c – high wear).

Comparisons

In order to discuss the results of the optimization, Table 1 reports the required energy per day (E) for the two working conditions (constant flow vs variable flow) and the three stage of wear. For constant flow, the maximum rate of starts (Z), the minimum time span between two following starts (T) and of pumping are reported as well.

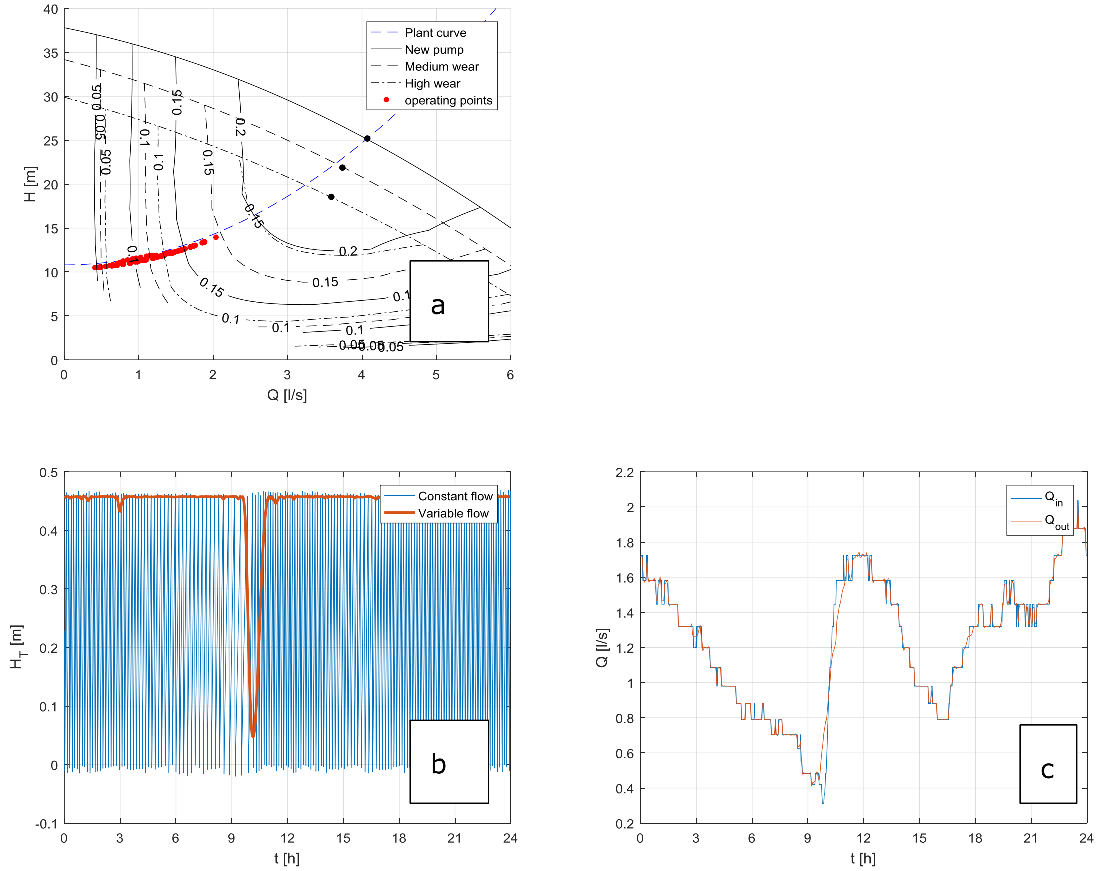


Figure 11 – Operating points (a), water level in the tank for both constant and variable flow (b) and inlet and pumped discharge for variable flow (c) for the new pump

Figure 11a shows that in variable flow, the required hydraulic power is less, because the machine operates at lower discharges where the friction losses are minimized. Nevertheless, the machine operates in the low efficiency zone. Thus, the application of the variable flow strategy gives a significant benefit in terms of energy reduction (about 10%) in case of a new pump, while the energy consumption is comparable in case of a pump with medium wear. In the case of high wear, the constant flow strategy is more convenient due to the high reduction of efficiency in the variable flow condition. Figure 12 shows the daily pattern of the efficiency of the machine in variable flow for the three stages of wear.

The mechanical stress on the machine can be considered high in both cases: in constant flow the frequent start-and-stops of the machine accelerate the ageing of the motor, while in variable flow the machine always works in operating points that are far from the BEP and this can affect the mechanical reliability [16].

In Figure 13, the frequency distribution of the rotating speed of the pump is plotted for the three wear conditions. The figure shows that the speed values are always far from the maximum allowed speed and the average rotating speed increases with the wear of the machine. The range of operating speed is of about 500 rpm for each of the three cases.

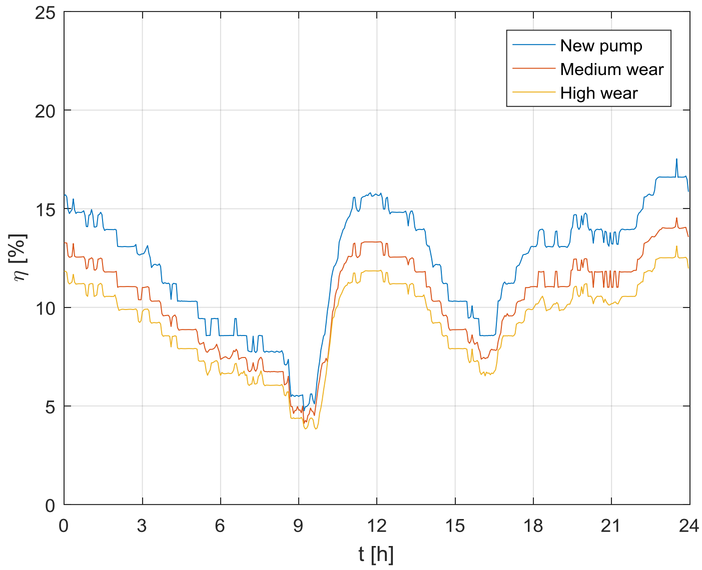


Figure 12 – Efficiency of the pump during the day for the variable flow working conditions at different stage of wear

Table 1 – Comparison of constant and variable flow for different stages of wear.

Wear	**Constant flow**			**Variable flow**
	max(Z) [-]	**min(T) [s]**	**E [kWh]**	**E [kWh]**
New	8	108	31.13	27.90
Medium	8	126	33.29	32.73
High	7	156	34.24	36.61

Final considerations

The results of a model for the optimal management of wastewater pumps in plant with storage capacity have been presented.

The model can be used, both in constant flow or in variable flow conditions, and use as input data the pump performance curves, the WSN curve, the tank volume, and an experimental hydrograph measured in the sewage system of Naples, Italy.

In constant flow conditions, the on/off sequence is found depending on the water level in the tank. In variable flow conditions, a VFD modifies the impeller speed and the optimal sequence of rotational velocity is determined to minimize the energy consumption.

Based on the performance curves of a wastewater submersible grinder pump, constant and variable flow conditions have been compared for different stage of the mechanical wear of the pump.

The benefit in terms of energy savings coming from the introduction of VFD is close to 10% when a new pump is operating. This benefit reduces with the pump age, and the use of a VFD could be negative at a high stage of mechanical wear.

The study will be extended to other pump types, like vortex and channel pumps, and to naturally aged pumps.

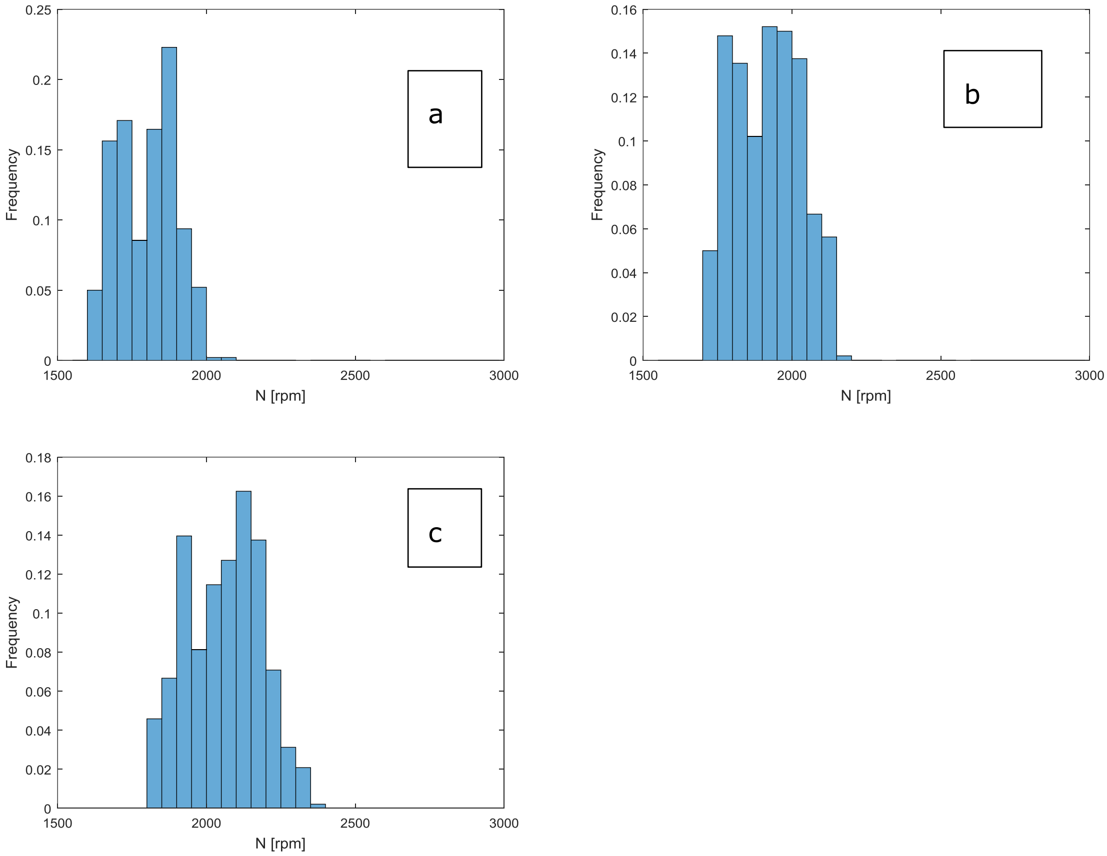


Figure 13 – Frequency distribution of rotational speed at different stages of pump wear (a – new pump, b – medium wear, c – high wear) and for low (1) and high (2) friction loss plant

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Conflict of interest

The authors declare no conflict of interest.

References

[1] Nicolini, M., & Zovatto, L. (2009). Optimal location and control of pressure reducing valves in water networks. Journal of water resources planning and management, 135(3), 178-187.

[2] Ulanicki, B., AbdelMeguid, H., Bounds, P., & Patel, R. (2008). Pressure control in district metering areas with boundary and internal pressure reducing valves. In Water Distribution Systems Analysis 2008 (pp. 1-13).

[3] Carravetta, A., Fecarotta, O., Del Giudice, G., & Ramos, H. (2014). Energy recovery in water systems by PATs: A comparisons among the different installation schemes. Procedia Engineering, 70, 275-284.

[4] Carravetta, A., Fecarotta, O., & Ramos, H. (2011, June). Numerical simulation on Pump As Turbine: mesh reliability and performance concerns. In Clean Electrical Power (ICCEP), 2011 International Conference on (pp. 169-174). IEEE.

[5] Carravetta, A., Antipodi, L., Golia, U., & Fecarotta, O. (2017). Energy Saving in a Water Supply Network by Coupling a Pump and a Pump As Turbine (PAT) in a Turbopump. Water, 9(1), 62.

[6] Kishor, N., Saini, R. P., & Singh, S. P. (2007). A review on hydropower plant models and control. Renewable and Sustainable Energy Reviews, 11(5), 776-796.

[7] Ma, Z., & Wang, S. (2009). Energy efficient control of variable speed pumps in complex building central air-conditioning systems. Energy and Buildings, 41(2), 197-205.

[8] Brion, L. M., & Mays, L. W. (1991). Methodology for optimal operation of pumping stations in water distribution systems. Journal of Hydraulic Engineering, 117(11), 1551-1569.

[9] Fecarotta, O., Aricò, C., Carravetta, A., Martino, R., & Ramos, H. M. (2015). Hydropower potential in water distribution networks: Pressure control by PATs. Water Resources Management, 29(3), 699-714.

[10] Giugni, M., Fontana, N., & Ranucci, A. (2013). Optimal location of PRVs and turbines in water distribution systems. Journal of Water Resources Planning and Management, 140(9), 06014004.

[11] Corcoran, L., McNabola, A., & Coughlan, P. (2015). Optimization of water distribution networks for combined hydropower energy recovery and leakage reduction. Journal of Water Resources Planning and Management, 142(2), 04015045.

[12] Carravetta, A., Del Giudice, G., Fecarotta, O., & Ramos, H. M. (2013). Pump as turbine (PAT) design in water distribution network by system effectiveness. Water, 5(3), 1211-1225.

[13] Fecarotta, O., Carravetta, A., Ramos, H. M., & Martino, R. (2016). An improved affinity model to enhance variable operating strategy for pumps used as turbines. Journal of Hydraulic Research, 54(3), 332-341.

[14] Carravetta, A., Fecarotta, O., Martino, R., & Antipodi, L. (2014). PAT efficiency variation with design parameters. Procedia Engineering, 70, 285-291.

[15] Byrd, R. H., Hribar, M. E., & Nocedal, J. (1999). An interior point algorithm for large-scale nonlinear programming. SIAM Journal on Optimization, 9(4), 877-900.

[16] Carravetta, A., Del Giudice, G., Fecarotta, O., & Ramos, H. M. (2013). Pump as turbine (PAT) design in water distribution network by system effectiveness. Water, 5(3), 1211-1225.

Reliable Protection Relay for Pumps

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Pumps in critical applications need to be protected. Standard solutions from factory automation are not necessarily a desirable choice for pump installations because pumps are used in a wide variety of different situations, often in harsh environments and require installations to have easy connections and high electromagnetic compatibility (EMC). This paper describes possibilities of electronic pump protection: severe failures in pumps are explained and sensors to detect these failures are presented. The paper also describes technical solutions to mount electronic circuits directly into or close to a pump and communicate data out of the pump for remote monitoring with a smartphone or using the Internet.

Introduction

Pumps are used in many critical processes like water supply, wastewater treatment or (chemical) processes, which have a high impact on our safety and life. A damaged or failed pump in these applications can cause severe problems. Due to that, pumps often need to be monitored and protected against damage or failure.

Typical failures in a pump are:

- Leakage
- Dry running
- Overload
- Overheating of the motor due to under-voltage, high switching cycles, locked rotor…
- Excessive temperature in bearings
- Fluid temperature too high
- Clogging in the pump due to particles, fibers or dirt [1]

Such failures should be avoided, as they can damage the pump and can cause high replacement costs. Moreover, water supply and wastewater treatment and many other applications using pumps are important for our life and health. In those applications, the financial damage due to a pump failure might be significantly higher than the value of the pump itself. Hence, pump-protection often means protection for the process itself. [2]

Targets of pump protection

Due to this, pump protection becomes more and more important. Pump protection is basically aimed at three main targets:

a. The basic target is to protect the pump from being damaged. Under-voltage in the grid, for example, can increase the electrical current in the pump motor significantly, resulting in over-temperature of the windings, which can destroy the motor. In many cases, when under-voltage or phase loss occur, the temporary switching off of the pump is necessary.

b. A second target of pump protection is often to schedule preventive maintenance. For example, an increasing bearing temperature can be a warning of a deteriorating bearing in the pump before the pump fails. Maintenance or replacement can be scheduled and an unexpected damage can be avoided if such a case is detected in time.

c. it is also desirable to increase the availability of a pump: improvements in control algorithms, based on data sent by the pump to the controller, can help to reduce down-time or prevent failure before they occur. This could be achieved for example, if a pump is reverse working with changed direction of rotation as soon as a sensor detects dirt or fibers in the pump which could finally block the pump. Many pumps allow such a self-cleaning procedure and this can automatically avoid critical conditions.

Sensors in pump protection

The determination of the parameters and sensors which can be used to detect dangerous situations for the pump is necessary to reach one or more of these targets. Starting from the typical failures which should be protected (see above), sensors need to be selected to measure reasonable values and an electronic system needs to be defined to generate warning and failure messages from the measured values. If dry running is a critical failure and needs to be protected, in some applications a current sensor might be the best solution because the electrical current changes with the torque of the motor and the torque depends on viscosity of the fluid (gas or liquid). In other pumps or applications, a conductivity sensor in the suction line or the pump inlet might be the best solution to see if the pump is sucking water or air (dry running).

The sensors and electronic circuits used in the pump protection system need to withstand the harsh environment the pump is used in (e.g. vibration, ambient temperature or EMC). Many components which are designed to be used in a switching cabinet, might have a shorten life expectancy due to the harsh environment.

Typical parameters and sensors for a monitoring system are [3]:

Electrical current of the motor (to detect overload, dry running or dirt in the pump)

Relationship between operating point of the pump and electrical current can depends on the kind of the pump, but in many cases, the electrical current increases in case of an overload situation. This can happen if e.g. a valve at the outlet of the pump is closed and the fluid is not moving. The pump is building up pressure but not delivering fluid.

The electrical current can also be an indicator for dry-running. In this case, the pump is sucking gas instead of liquid. This can be dangerous because in many pumps the liquid is expected to cool down the pump. In addition, mechanical seals or stuffing boxes can deteriorate if they are allowed to become dry.

The electrical current can also be influenced if fibers, dirt or particles accumulate in the pump or the pipes. Depending on the location, the necessary torque to move the pump can increase. It is also possible that these fibers or dirt reduce the dimeter of a pipe (inlet or outlet) and have also an influence on the electrical current. Measurements and tests needs to validate the situation for a specific type of a pump. In such case, a self-cleaning of the pump, by a temporary reversing of the rotation, can be an option [4].

Conductivity (to detect leaks)

Most pumps have parts of the housing or the body, which are not allowed to be in contact with water or other pumped fluids. Typically, all electrical parts are strictly separated from the liquid part of the pump to avoid short circuits. In addition, parts of the pump can be filled with oil for lubrication or force transmission. If water leaks into this oil the oil will degrade and loose its properties. Especially in those applications where the pumped fluid is water, conductivity can be a good indicator for leaks. A typical setup is to measure the conductivity between an isolated electrode and the metal pump housing. The electrode and the housing are connected to the pump protection relay and a very small AC voltage is applied to both electrodes. If this voltage can drive an electrical current this will be an indicator for conductivity between the originally isolated electrodes which typically means water is present in the contact area.

Winding temperature (to detect overload of the motor or a closed pump outlet)

Winding temperature is a major indicator for the condition of an electrical motor. The magnet wire in an electrical motor has a temperature class which must not be exceeded. The limit is typically between 155°C and 180°C. If the limit of the temperature class is exceeded, lifetime of the motor is reduced significantly. Due to this, motor protection relays or bimetal switches sense the temperature in the winding and switch off the motor in case of over-temperature. Typical reasons for increased winding temperatures can be a locked rotor in the motor, grid failures (see below), overload or local short circuits in the magnet wire winding [5]. Electronic motor protection relays have significant advantages compared to mechanical bimetal switches: hysteresis (time to switch on a motor after a motor stop) is much more reliable than mechanical action of a bimetal. Also, trends in temperature, slow or fast increase of temperature, can be monitored, providing more information and not only a black-and-white decision. This is valuable information to help establish predictive maintenance with a pump.

Bearing temperature (to detect beginning wear and deterioration)

Bearing temperature is also a very important parameter. A bearing in a mechanical system like a pump is used to allow rotating movement with low friction. In case friction is increasing, or there is a misalignment between rotating components, the temperature of the bearing will increase and the remaining lifetime of the mechanical system can be significantly reduced. Due to this, increasing bearing temperature can be an indicator for necessary maintenance. Sometimes, bearings are cooled by the fluid, so an increasing bearing temperature can also be an in indicator for a fluid problem [6].

Grid monitoring including under- and overvoltage, phase sequence and phase asymmetry

A pump driven by an electrical motor also depends on the quality of the grid. In case a phase is lost (motor is just running with two remaining phases) or the grid voltage is too high or too low, the motor windings can become too hot because of an increased electrical current. This over-temperature will reduce the lifetime of the motor. But grid failures can have more issues: the torque of the motor can be reduced in case of grid problems and also the direction of rotation will be changed if the phase sequence is wrong. Hence the mechanical properties of a pump are very much related to a reliable grid and grid voltage in an acceptable tolerance.

Sensor requirements

All these parameters can today be measured with sensors inside the pump. In many cases, three to four sensors are connected to a pump. Most of these sensors need to be inside or near to the pump. Electronic preprocessing of the data needs to be done to eliminate influences of EMC, which can deteriorate the signals significantly. Those sensors, electronic circuits and protection relays also need to work reliable at high and low ambient temperature, vibration and high humidity.

In this paper, two new options are presented to connect sensor signals directly inside or near the pump, do some preprocessing of the measured signals directly inside the pump with a very robust electronic circuit and to transmit these signals digitally. Such a digital interface enables a connection to the pump controller. If the pump controller has the information about electrical current, winding and fluid temperature, grid voltage or conductivity it is possible to e.g. start a reverse cycle in case dirt, fibers or particles start to accumulate inside the pump. Due to this, a self-cleaning process can be started in many cases. Another option could be to increase the frequency of the inverter and the speed of the pump to avoid pipes blocked by dirt. Dirt and fibers can be a significant problem in wastewater pumps if the speed of the pump and the flow of water are low for some time. This happens nowadays more and more often due to demographic changes and our efforts to save water [1]. For all those actions to avoid failures in a pump, it is necessary to have data out of the pump available in a control system.

Pump-protection systems

Figure 1 is a block diagram showing a first approach: the technical functionality is split between the two modules (one in the pump and one in the switching cabinet). Typically, pump protection modules are mounted in the switching cabinet and all sensors are connected by long wires from the pump to the switching cabinet. In many situations, sensor signals are disturbed by EMC. EMC influence can be reduced if a current based signal and not a voltage level based signal is used. A current based digital signal also allows a wide distance between the modules, up to 100 meters. Using checksums can identify accuracy of the transmitted data. Reduction of necessary wires to four makes installation very easy compared to transmission of each individual analog sensor signal though its own cable. Existing drawbacks can be solved by this new approach to split overall functionality into two parts and to use a digital and current based interface between both elements instead of simple analog voltage based sensor connection.

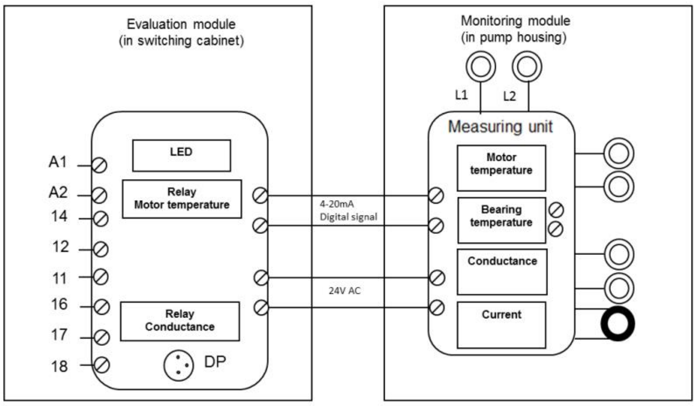

Figure 1 block diagram of the two-module pump protection system

The module on the left side of Figure 1 will be mounted inside the switching cabinet (see also Figure 2). The connections on the left side of this module (A1, A2, 11 – 18) are power connection to the grid and the contacts of internal relays. The evaluation module contains two relays to generate two different alarms (e.g. conductivity alarm and motor temperature alarm) or to generate a warning and an alarm. The key component is a three pins circular connector in this module (DP). With this interface, the whole pump protection system (both modules) can be programmed and status messages or failure lists can be shown in a dashboard (smartphone APP). This interface can also be used to connect a gateway and transmit data from the pump via Modbus or the internet. The data transmitted can be runningtime and switching-frequency of the pump, temperatures, electrical current, failure list and other operational data. With the data available in the switching cabinet, the pump can be integrated in an IoT (Internet of Things) environment.

Figure 2: Module for the switching cabinet

The right side of Figure 1 shows a schematic of the sensor module which installs directly into the pump. The different blocks inside the schematic indicate different sensors, hardware and software for data pre-processing, AD conversion and storage of data in a non-volatile memory. This module needs to withstand high vibration levels and shock levels (in case of cavitation) and high ambient temperature because it is designed to be mounted close to the pump motor. The size of the disk (Figure 3) is only 6 cm diameter with a height of 1,5 cm.

Figure 3: Sensor module to be mounted inside the pump

A second option is shown in Figure 4: on the left side of the module, several sensors can be connected. Important for an Internet of Things (IoT) approach is the right side: next to the relays (*fault* and *warning*), also a data interface is implemented. A constant stream of data is sent via this interface. Sensor data are digitally transmitted but also statistical data about the pump like running time or switching frequency are sent via this interface. Such a module can be mounted close to the pump or up to 30m from the pump.

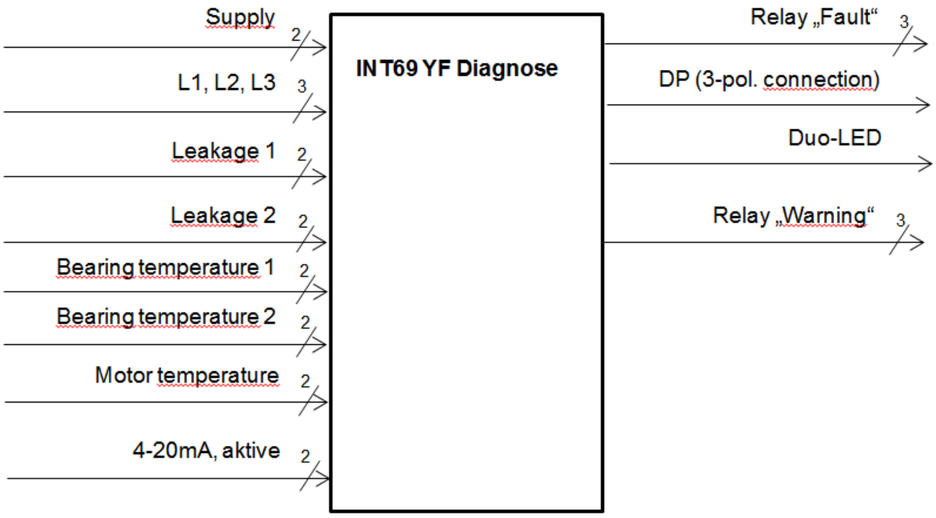

Figure 4: Internet of Things (IoT) module for pump protection

The modules shown in Figure 2, 3 and 4 are part of a R&D program at the moment. Tests are done with various pump systems and installations. Pump manufacturers in Italy and Germany are involved and are testing those modules.

Measurements and results

First tests and measurements have been done to proof the concept. Special focus was on EMC because this topic is known to be root-cause for many issues of existing pump protection relays in the field. For an increased level of confidence, the test specification for the DUT (device under test) was more difficult to pass than defined for standard electronic equipment:

Surge

In a surge test fast, short duration voltage spikes with high energy have been transferred into the power lines of the DUT. In this specific test, spikes up to 4000V have been used. A surge impulse has typically a length of 100µs. Surge impulses give an indication how sensitive a DUT is to effects due to lightning and also switching-off of large inductive loads.

Burst

In a burst test, transient, high frequency impulses have been applied to all sensor inputs. Connection has been done both, galvanically coupled, and by capacitive coupling. A burst impulse has a typical length of 100ns (1000 times shorter than a surge impulse). This test simulates effects of sparks in a switching relay or switch. In this test, burst impulses up to 4400V have been transferred into the DUT.

Results

In first tests, the DUT failed and additional improvement was necessary. Especially the input circuits of the sensor module needed to be improved. These failures were very similar to the reports about failing pump monitors from the field: sensor signals were deteriorated, spurious trips of the protection relay happened and communication was interrupted. After some changes in the layout and schematic diagram the new DUT has passed the tests. The tests have been proven since many years to define a reliable EMC level for HVAC/R equipment. Hence the new pump monitor is also expected to work reliable in this environment.

Internet of things (IoT) environment

With data like temperature, current or a failure list accessible in the switching cabinet, it is possible to use a smartphone in the field to make maintenance of the pump easier. The smartphone is simply connected with a USB- or Bluetooth-gateway to the 3-pin interface at the evaluation module (left side of Figure 1 or Figure 2 and 4). Data can be downloaded and evaluated through a smartphone APP at the switching cabinet location without removing the pump from its location. The reason and timing of a pump stoppage can be seen easily on the screen and helps to reduce the time for troubleshooting the root cause. But there are more possibilities: if a pump is connected to Modbus or the internet, it is also possible to integrate pump data into a controller (via Modbus) or to have remote monitoring access and email or text-message alerts for critical situations. Such a system also gives the opportunity to observe trends of data and measured signals. For example, a bearing temperature increasing day by day can be seen indicating a possible growing deterioration, or if the electrical current goes down every day at the same time might indicate a repeating dry running condition. Also trends and changes in running time and switching frequency can indicate a change in the process. The operating point of the pump might have changed and the controller is working in a different point in the operating envelope.

Next to data transmission also cyber security is a very important topic in an IoT setup. Pumps are often used in critical applications like water supply, where a cyber-attack could cause severe damage. Due to this, it is necessary to make sure that a pump cannot be subject to a malware attack. A special demand is also that such a vulnerability should not occur during the lifetime of a pump that can easily be 10, 20 and more years and updates and patches can often not be installed at those electronic circuits because the pumps are located remotely in the field [7]. It can be a very reliable solution to allow changes in parameters of the pump protection system only via USB when an authorized person is standing directly next to the protection relay. Remotely it is only possible to read data via Modbus or the internet but it is not possible to change any parameters (no remote write access to the module). In this approach, security is not only based on IT algorithms like encryption or VPN but also on security equipment of the perimeter like a fence, a wall or a locked door. It is necessary to walk physically to the electronic system to change the protection algorithm but it is possible to read data from every location in the world.

Conclusion

Pump protection is a vital topic to ensure pumps are running reliable for a long time. In this paper, most typical failures of pumps are listed and a correlation between those failures and possible sensor signals is given. Integrating sensors and data processing electronics into a pump is a challenging task because of limited space in the pump, high ambient temperature and severe vibration and shocks. An approach to solve those issues with a pump protection module divided into two separate parts is also explained. Digital communication between both modules gives high EMC protection and makes it possible to integrate a pump into IoT or a local fieldbus network.

References

[1] Thamsen, P. U.; Wulff, S.: „Abwasserpumpen fit für die Zukunft" PuK-Prozesstechnik und Komponenten, Dr. Harnisch Verlags GmbH, S.10-13, Nürnberg

[2] Ellwein, C.: *Electronic Pump Protection*; Pump Summit Conference; 30. Nov. 2016; Düsseldorf

[3] Toliyad Hamid A., Nandi, S., Choi, S., Meshgin-Kelk, H. 2013. 2013. Electric Machines – modeling, condition monitoring and fault diagnosis. CRC Press. 9-16

[4] Thamsen, P.U.: *Digitalisierung von Fluidsystemen: Fortschritte und Hemmnisse*; VDI-Fachkonferenz Pumpensysteme 4.0; Sindelfingen, 07-08.12.2016

[5] Hundy, G.F., Trott, A.R., Welch, T.C. 2008. Refrigeration and Air-Conditioning. Elsevier, 51-52

[6] Merkle, Thomas. 2012. Schäden an Pumpen und Pumpensystemen. Expert Verlag, 29-30

[7] Ellwein, C.: IT Independent Security Concept for Internet of Things; VDE Congress, Mannheim; 8. November 2016

Pumps as turbines – Analysis on their applicability to flow control and economic feasibility

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Abstract

Efficient Energy Use (EFEU) is a Finnish cross-disciplinary research program with an aim to develop new system level solutions for energy efficiency in fluid handling systems. For systems where it is necessary both to produce and locally lower the pressure, a novel method for pressure reduction has been studied. The throttling that otherwise would be done with a control valve, could also be done with a variable-speed pump used as a turbine. Pumps as turbines have been traditionally used for hydraulic energy recovery in, for example, small-scale hydropower, osmotic systems and in fertilizer manufacturing plants, but their applicability as control valve replacement has not been studied in detail.

The focus of this article is to study the replacement of the control valve with a variable-speed-driven pump as turbine (PaT) and the economic feasibility of the energy recovery with a PaT system. Experimental research on operating pumps as turbines has been conducted on multiple devices, but this article focuses on the experimental results for an integrated pump-motor device also developed in EFEU research program. The turbine mode performance is shown and the performance is referenced to the characteristics of typical flow control valves. Economic feasibility is studied by using different sized pumps, for which prices were inquired from two pump manufacturers.

Introduction

Centrifugal pumps are the most common type of pumps used in industrial applications. Pumping consumes around 10 % of global electricity consumption, and recently EU has set stricter regulations for pump efficiencies, such as classification by Energy Efficiency Index (EEI) for circulator pumps and Minimum Efficiency Index (MEI) for water pumps [1]. These efficiency requirements only take into account the efficiency of individual components, whereas the system level energy efficiency should also be increased when possible. One solution for this is the energy recovery by using a pump as turbine (PaT) as a part of the system.

Application of variable-speed drives in the pumping system usually provides the best solution to increase the energy efficiency, but use of them may not always be feasible or wanted. For instance, water distribution systems may require local decreasing of pressure, which is normally realized by throttling. As illustrated in [2], this is very poor way of controlling the water flow: if the nominal operating point has a relative power consumption of 100 %, speed control at 20 % reduced flow rate has a power consumption of 65 %, throttle control power consumption of 94 % and bypass control power consumption of 110 %. In such cases, the pressure decrease with PaT system can extract a part of the hydraulic power, meaning that the overall system power consumption would be below 94 % in the example introduced above.

Pumps as turbines are already used for energy recovery in drinking water distribution system in Germany, for small scale hydropower applications especially in developing countries and in nitrogen based fertilizer manufacturing, where a large energy recovery potential exists due to the need of local pressure decreasing [3]−[5]. The main benefit of using PaT instead of regular turbine is their lower cost, made possible by large manufacturing volumes and simple construction. On the other hand, PaT systems lack the flow control device that make them sensitive to the change of flow conditions [5].

With variable-speed drives also PaT systems can be operated efficiently at different flow conditions.

In an application where the flow is throttled with a control valve, a PaT system could be used to replace the control valve and to recover hydraulic energy from the application. However, as PaTs are not primarily designed for good controllability of the passing flow, their properties should be studied against typical control valves applied in the pumping systems. Besides studies on their technical feasibility and prediction of PaT characteristics [6], also the economics of PaT systems should be studied to see their potential for replacing simple control valves.

The focus of this article is to study the replacement of the control valve with a variable-speed-driven pump as turbine and to study the economic feasibility of the energy recovery with a PaT. Experimental research on pumps as turbines has been done on multiple devices, but this article focuses on the experimental results for an integrated pump-motor device also developed in Efficient Energy Use research program. The turbine mode performance is shown and the performance is referenced to the characteristics of control valves. Economic feasibility is studied by using different sized pumps, for which prices have been inquired from two pump manufacturers.

Integrated pump-motor concept device

When a control valve is meant to be replaced with a PaT system, it should be as simple as possible for its convenient installation. In addition, a PaT system benefits on having a variable-speed drive that is able to estimate the system operating state without any additional measurement sensors.

To answer these objectives with an aim to make a material and energy efficient industrial pump, an integrated pump-motor device has been realized in EFEU research program [7]. This concept device comprises an ABB 5.5 kW high output synchronous reluctance motor integrated with a Sulzer Ahlstar series end-suction centrifugal by using a common shaft in the device. Nominal values of the device are as follows; 14.3 l/s and 14.2 m at 1455 rpm, resulting in 70.3 % pump efficiency. For experimental results presented in this paper, the concept device has been operated with a four-quadrant ABB ACS880 variable-speed drive (VSD) that also allows sensorless estimation of PaT operating state.

Fig. 1. Integrated pump-motor concept device.

Turbine characteristics of the concept device

The turbine inherent valve characteristics can be created based on the turbine map that is similar representation for PaT as characteristic curves are for centrifugal pumps. Fig. 1 illustrates the measured turbine map for the concept device. The blue line represents the runaway (i.e. free rotational speed) curve of the turbine, while the red is the resistance (i.e. zero rotational speed) curve. The lines between them represent the fitted constant speed lines that are based on the results of laboratory test measurements for the concept device [8]. The dots represent individual measurement points. The black contours are the turbine efficiency curves that now reach the maximum of 71 %. The practical turbine operation area is limited between runaway and resistance curve, as outside this region (quadrant) PaT consumes power [9].

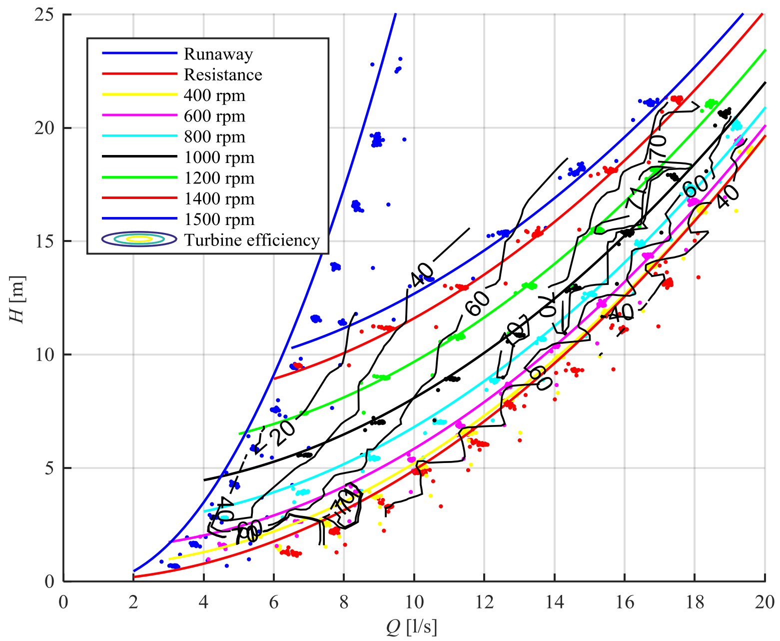


Fig. 1. Turbine map for the concept device with efficiency contours. Note that with PaT the system curve is a decreasing parabola, as turbine curves are increasing ones.

Turbine as valve replacement

Fig. 2 illustrates the different opening characteristics of typical control valves. These inherent valve characteristics are created by keeping the pressure difference over the valve constant, while the relative valve opening *h* is changed. Control valves can be divided to three groups based on their opening characteristics; quick-opening, linear and equal percentage valves. Equal percentage valves are the most common type of control valves because when combined with pipeline characteristics, the resulting behavior from valve opening to flow rate is usually nearly linear. This is a wanted property in flow control applications, because it makes the flow control system easier to tune and use [10].

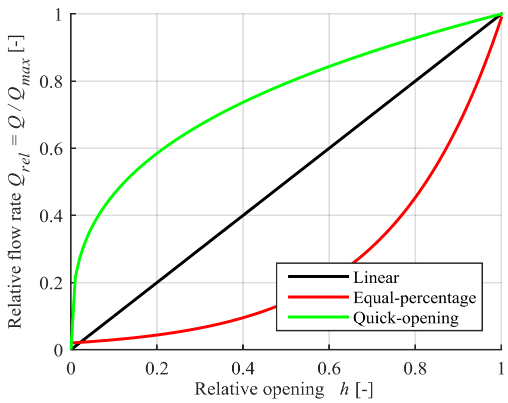
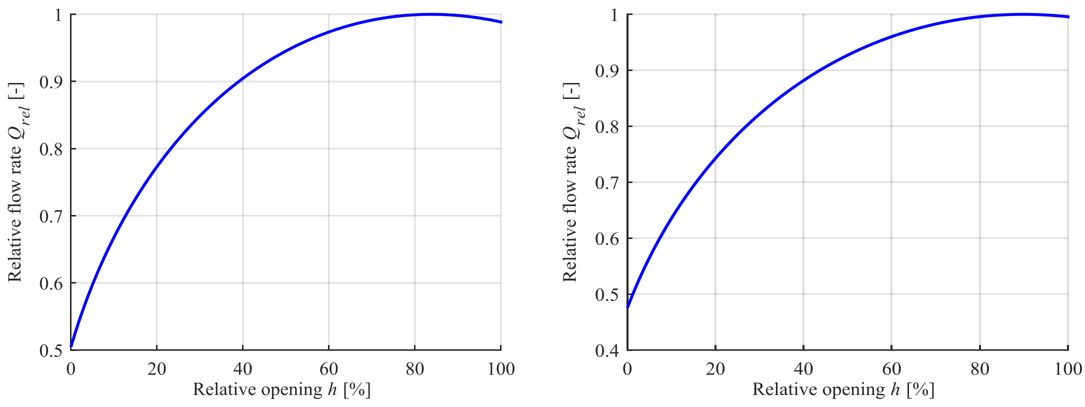


Fig. 2. Different valve opening characteristics [10].

PaT's inherent characteristics can be described with a similar figure as for control valves. Fig. 3 illustrates the inherent valve characteristics for two different Sulzer centrifugal pumps operating as a turbine. The inherent valve characteristics for PaT are based on polynomial turbine models for head and power described in [8], which is fitted to the measurement data. As the original measurements have been conducted at various rotational speeds, their relation with the relative opening *h* applied in valve characteristics is now represented with

$$n = n_{\mathrm{ra}}\left(1 - \frac{h}{100}\right), \tag{1}$$

where n_{ra} is the runaway speed that is applied to reach the minimum relative flow of PaT still with hydraulic power recovery capability.



a) b)

Fig 3. Inherent valve characteristics for a) Sulzer A22-80 and b) A11-50 (concept device).

When the resulting characteristics are compared with Fig. 3, clear differences arise, as zero flow rate cannot be reached with PaT. This would require going to an operation area where power is consumed to maintain that operating point. In addition, the characteristics of both pumps resemble the fast opening valve characteristics shown in Fig. 3. In addition, the usable area for flow control is quite narrow for both devices, from around 50 to 100 % of the maximum flow rate. Based on these findings, a PaT system can be considered more suitable for static pressure decrease than for replacing equal-percentage valves in flow control applications.

As the turbine inherent valve characteristics in Fig. 4 are based on generic polynomial models for turbine head and power as a function of rotational speed and flow rate, their correctness was verified by separate measurements for Sulzer Ahlstar A22-80. As the results in Fig. 5 show, the turbine inherent valve characteristics based on the polynomial turbine models are quite accurate and comparable to the characteristics obtained with separate measurements.

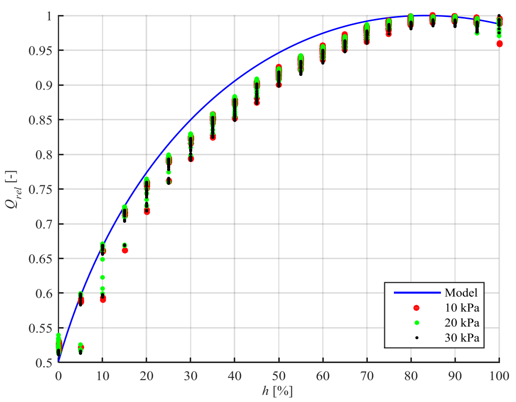
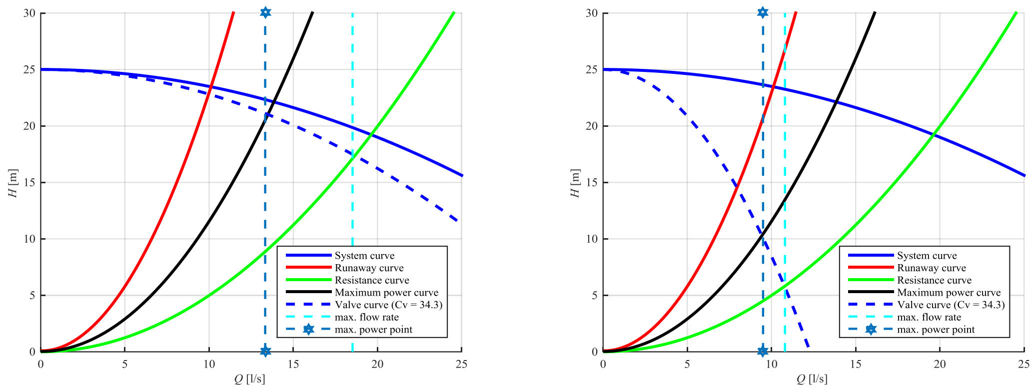


Fig. 4. Measured and modelled turbine inherent characteristics for Sulzer Ahlstar A22-80.

Flow control with combined use of PaT and control valve

To reach a wider flow control area with desired flow control properties discussed above, a PaT can be combined with a control valve in series. With this approach the whole flow control area can be achieved and energy recovery with PaT operation near the turbine maximum power point (MPP) would also be possible. The working principle of this setup is described in Fig. , where also the maximum power curve for PaT is introduced.

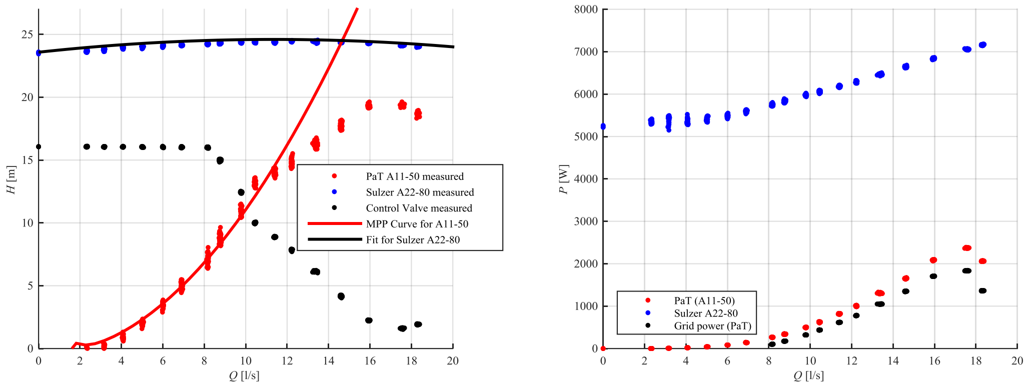
Firstly, the highest flow rate is found from the system without throttling as with normal pumping systems. If a lower flow rate is required, it can be reached either by varying the turbine rotational speed or shape of the system curve with valve control. The throttling of the valve is subtracted from the system curve, and the operating point of the turbine is found from the intersection of this curve and the turbine curve that can be set with VSD to correspond with the required flow rate (see Fig. 6a). With the combined use of variable-speed operation and valve control, the turbine operating point can be set to the intersection of maximum power curve and required flow rate also at very low flows (i.e. near the zero flow rate) that would be otherwise unreachable as shown in Fig. 6b.



a) b)

Fig. 5. Concept device operation with a) fully open control valve b) 50 % open control valve.

The flow control with this method was tested in the pump laboratory to determine its practical operation and economic feasibility. The required PaT rotational speed and the control valve opening to reach the turbine MPP were solved for each flow rate, and the system operation was done with an open loop control with the solved control signals. The tested system consisted of a pressure producing fixed-speed pump (Ahlstar A22-80), a PaT (Ahlstar A11-50) driven with four-quadrant VSD and a valve installed in series. Measured head of the system components are illustrated in **Fig.** a together with the MPP reference curve applied in the test run. The resulting power of turbine and the pump are illustrated in Fig. 7b, which were determined with the measurement of pump shaft power, read-out of VSD estimates for PaT shaft power and measurement of electric power supplied to the grid by the four-quadrant VSD.



a) b)

Fig. 6. a) The head of the system components as a function of flow rate. b) The power of the pump and the turbine as a function of flow rate.

Results in Fig. 7a indicate that the open loop control has resulted in the desired PaT operation at its MPP at flow rates below 11 l/s. The deviation of turbine head from the maximum power point at higher flow rates is caused by the limited maximum rotational speed of the concept device, meaning that with unlimited PaT rotational speed even higher power recovery would have been possible at flow rates up to 16 l/s.

More generally, the obtained results in Fig. 7b introduce the overall capability of PaT system recover a part of the hydraulic energy that would be otherwise consumed with the control valve. Although shaft (mechanic) power recovery begins already at 5 l/s, PaT system starts to provide electricity to the grid at 8 l/s due to internal losses in four-quadrant VSD. The PaT shaft power reaches a maximum value of 2370 W at 17.6 l/s. The maximum electric power to the grid is then 1840 W with the resulting drivetrain efficiency of 78 %. The pressure producing pump, A22-80 had a measured shaft power of 7050 W at the same point. With an electric motor efficiency of 90 %, the pumping system electric power consumption from grid is around 7830 W, and therefore the overall (from grid back to the grid with a four-quadrant VSD) energy recovery percentage with the PaT can be approximated to be around 23.5 % with the electric power consumed by the pump in this operating point.

Fig. illustrates the applied control signals for the turbine rotational speed and control valve opening as a function of the flow rate. At 16 l/s flow rate the control valve is fully open, and the turbine speed needs to be reduced to increase the flow rate. The operation can be therefore split in to two areas: At small flow rates, the flow rate is controlled both with turbine rotational speed and the valve opening to keep the turbine operation point at the maximum power point curve. The second operation area is operation at high flow rates when the valve is fully open and the turbine speed is adjusted to change the flow rate. Similar operation areas for PaT systems has been described by Van Antwerpen for constant pressure applications in [11].

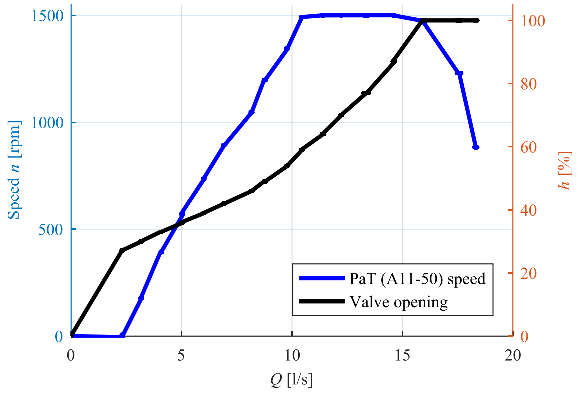


Fig. 7. Control signals of the test setup.

ECONOMIC FEASIBILITY

The feasibility of hydraulic energy recovery with a PaT was studied with inquired price information for 14 different sized pumps, for which turbine operation points were estimated, and payback periods at different capacity factors were calculated. The pumps are selected so that their nominal speed is 1500 rpm and the turbine operating point is estimated also for 1500 rpm. Due to higher power available from the same pump casing, pumps operating at 3000 rpm would be more cost-effective alternatives, but because too high runaway speeds should be avoided in turbine operation [5], 1500 rpm pumps were selected for this evaluation. The calculation is based on the average electricity price of Finnish industrial electricity consumer, which was 0.071 €/kWh in 2015 [12].

Table 1. Pump nominal operating points for part of the inquired pumps.

	CASE A (0.3 kW)	CASE B (200 kW)	CASE C (620 kW)	CASE D (3 kW)
n	1455	1485	1490	1455
H_p (m)	7.94	93.44	44.1	14.24
Q_p (l/s)	2.94	107.28	941.86	14.28
n_q	16.7	16.2	84.5	23.7
η_p (-)	0.42	0.69	0.92	0.71

The turbine mode nominal operation points for these pumps were calculated with correlations provided by Chapallaz [6], as described in [13]. First the pump mode nominal operating point at 1500 rpm was calculated with affinity laws. The efficiency at the turbine mode nominal operating point is assumed to be the same as it is in pump mode nominal operation point, as this is usually an accurate assumption [6]. The electric motor efficiency is also assumed to be the same in the generating mode as it is in the motoring mode. The exemplary turbine mode nominal operating points are illustrated in **Table** . The coefficients C_Q and C_H are used to change the pump nominal flow rate and head to turbine nominal point values with the method presented by Chapallaz. Coefficient values depend on the efficiency and the specific speed of the pump.

Table 2. Turbine mode operating points for part of the inquired pumps.

	CASE A (0.30 kW)	CASE B (200 kW)	CASE C (620 kW)	CASE D (3 kW)	CASE E (11 kW)
n	1500	1500	1500	1500	1500
C_Q	1.67	1.6	1.25	1.4	1.27
C_H	2.05	1.85	1.35	1.55	1.4
H_t (m)	17.30	176.37	60.34	23.46	31.27
Q_t (l/s)	5.06	173.38	1185.23	20.60	49.75
η_t	0.42	0.69	0.92	0.71	0.78
P_t (kW)	0.36	205.74	644.48	3.35	11.89
P_e (kW)	0.30	197.10	622.56	3.00	10.96

Because the turbine mode best efficiency point (BEP) has a higher power than the pump mode does, the electric motors should be selected based on the turbine mode operating point. This would mean selecting one size higher output motor in many cases. This has not taken into account in these calculations, because the price data was provided for pumps with an induction motor dimensioned for the pump operation.

Fig. 8 illustrates the specific prices of the PaT as function of turbine mode nominal electric power. These prices also include the price of single variable-speed drive. The three different colors illustrate different manufacturers and different price inquiries.

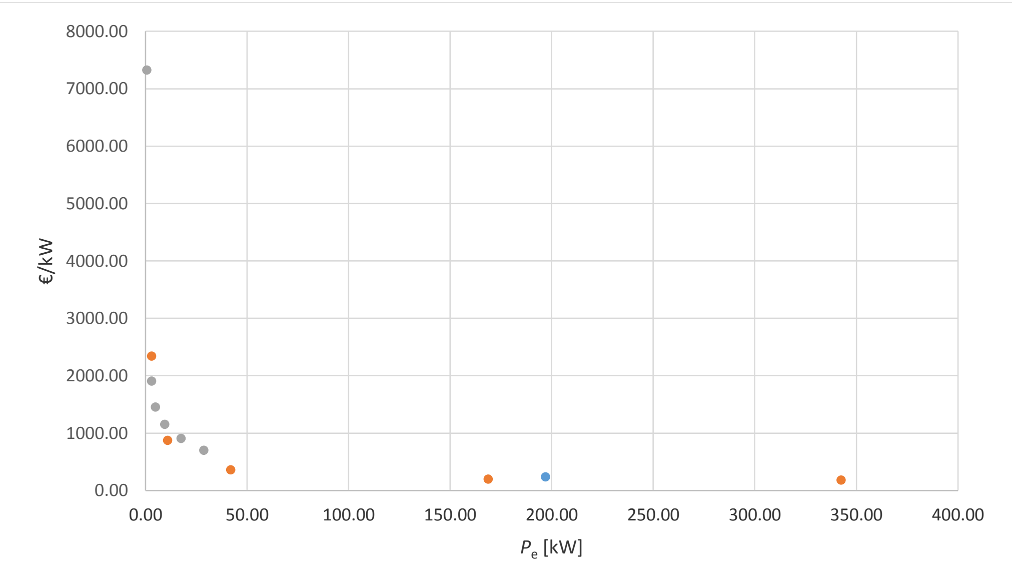


Fig. 8. PaT system unit prices as a function of turbine mode nominal electric power.

The turbine mode nominal operation points, illustrated in **Table 2**, and annual capacity factor C_f (i.e. time ratio of PaT operation at its nominal point) were used to calculate the payback period for the PaT's based on the inquired prices that include the installation baseplate, pump, motor, coupling, pump and a single variable-speed drive[69]. If a regenerative four-quadrant VSD is needed for PaT system, it has an increasing effect on the payback period (mainly being in the range of months).

As can be seen from Fig. , if the limit for economic feasibility is set at 2 year payback period with a 50 % capacity factor operation, PaT systems able to reach this have an electrical power of 42 kW, 200 kW, 340 kW and 170 kW. Also Case N with 29 kW is near this limit, indicating around 20 kW as the smallest possible size range for economically feasible PaT systems.

It needs to be noted that this figure does not either consider the cost of installation or the annual maintenance costs, which can be assumed to be similar with normal pump and valve systems. However, significantly more important factor in the economic evaluation is the applied electricity price level, and hence PaT systems are more feasible in other European countries, as Finnish electricity prices are clearly below average EU-28 level that is around 0.12 €/kWh.

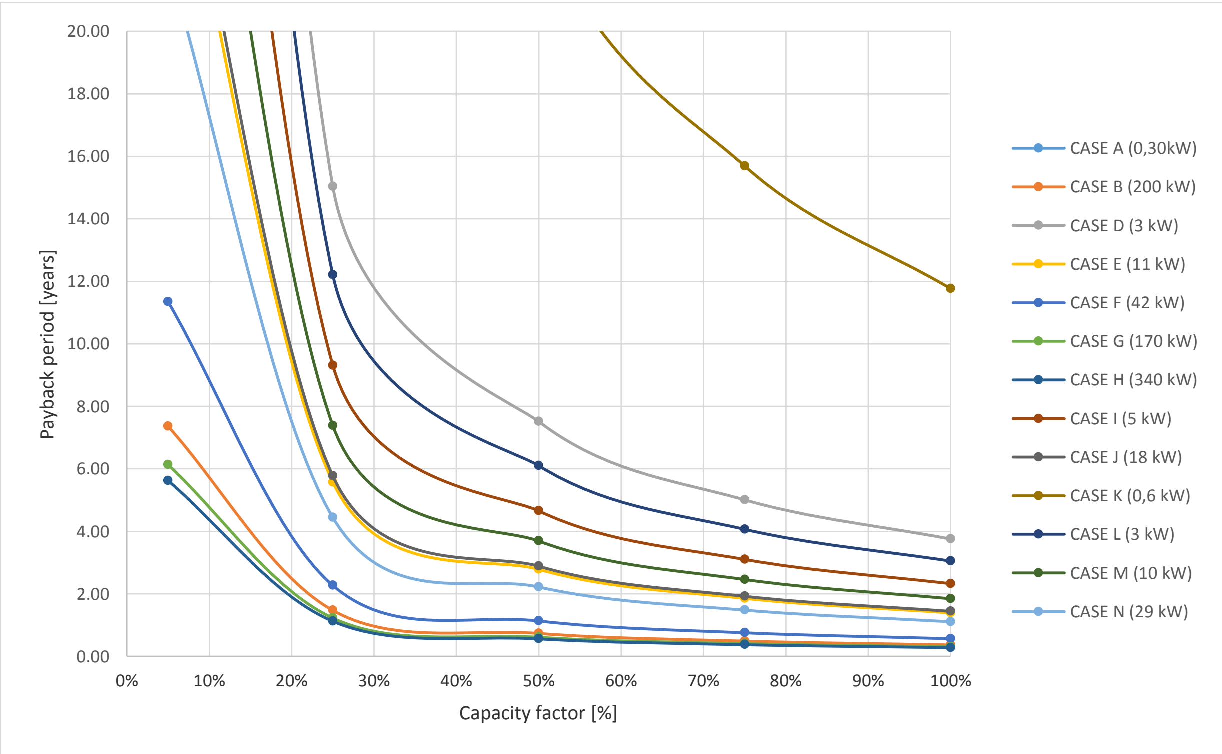


Fig. 9. Payback period for the inquired pumping systems.

CONCLUSIONS

The suitability of PaT system to flow control as control valve replacement was studied and the economic feasibility of hydraulic energy recovery with PaT system was analyzed. Centrifugal pump working as turbine has a narrow operation area when compared to a control valve. With PaT system it is possible to control the flow from approximately half to the maximum flow rate, but when system characteristics are taken into account, the control area is even narrower. The opening characteristics of PaT resemble those of quick-opening control valves that are not typically used in precise control applications. Based on these findings, a PaT system can be considered more suitable for static pressure decrease than for replacing the equal-percentage valves in flow control applications.

[69] Here it is assumed that the generated electricity can be supplied to another variable-speed drive by connecting their DC link intermediate circuits with each other.

To overcome this issue, a PaT and a control valve can be used in series to obtain wider flow control area, but still make the hydraulic energy recovery possible. This setup was tested with open loop control scheme and the maximum energy recovery was around 24 % in this test setup from supplied to the recovered electric power. Also a control area from nearly zero flow rate to maximum flow rate through the PaT was possible with PaT recovering energy to the grid, when the flow rate was over 8 l/s.

Economic feasibility of PaT systems was studied by inquiring prices of 14 pumping systems from two different manufacturers. The turbine mode BEP was estimated using a method described by Chapallaz, and the payback period as a function of capacity factor was calculated using Finnish electricity prices. If a 2 year payback period with a 50 % capacity factor is desired, economic scale seems to be around 20–30 kW_e of turbine mode BEP. As electricity prices in Finland are one of the lowest in Europe, the results indicate the economic potential of PaT systems especially in static pressure decreasing applications.

References

[1] Stoffel B. *Assessing the Energy Efficiency of Pumps and Pump Units*, 2015. ISBN 978-0-08-100597-2.

[2] Grundfos Management A/S. *Pump Handbook*, 2004. Can be downloaded at: http://net.grundfos.com/doc/webnet/mining/_downloads/pump-handbook.pdf

[3] Orchard B. and Klos S. *Pumps as Turbines for Water Industry*. World Pumps. August 2009, pp. 22-23.

[4] Sulzer. *Your Partner for Hydraulic Power Recovery*, 2014. Can be downloaded at: http://www.sulzer.com/mr/-/media/Documents/ProductsAndServices/Pumps_and_Systems/Power_Recovery/Brochures/YourPartnerForHydraulicPowerRecovery_en_E10141_6_2014_WEB.pdf

[5] Alatorre-Frenk B. *Cost Minimisation in Micro-Hydro Systems Using Pumps-as-Turbines*, 1994. Can be downloaded at: http://wrap.warwick.ac.uk/36099/

[6] Chapallaz J.-M., Eichenberger P. and Fischer G. *Manual on Pumps used as Turbines*, 1992. ISBN 3-528-02069-5.

[7] Ahonen T. *Putting It All Together: Energy Efficiency Opportunities at System Levels*, 2016. Can be downloaded at: https://www.slideshare.net/CLIC_Innovation/efeu-flexe-ahonen-tero-energy-efficiency-opportunities-at-system-levels

[8] Hyypiä J. *Hydraulic Energy Recovery by Replacing a Control Valve with a Centrifugal Pump Used as a Turbine*, 2016. Can be downloaded at: http://urn.fi/URN:NBN:fi-fe2016111528541

[9] Gülich J.F. *Centrifugal Pumps*, 2014. ISBN 978-3-642-40113-8.

[10] Kirmanen J., Niemelä I., Pyötsiä J. et al. *Flow Control Manual*, 2011. ISBN 952-9773-12-9. Can be downloaded at: http://valveproducts.metso.com/documents/softwarepackages/nelprof/FlowControl_manual.pdf

[11] Van Antwerpen H.J. and Greyvenstein, G.P. *Use of Turbines for Simultaneous Pressure Regulation and Recovery in Secondary Cooling Water Systems in Deep Mines*. Energy Conversion and Management. March 2005, pp. 563-575.

[12] Eurostat. *Electricity Price Statistics*, 2016. Can be downloaded at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics

[13] Nygren L. *Hydraulic Energy Harvesting with Variable-Speed-Driven Centrifugal Pump as Turbine*, 2017. Can be downloaded at: http://urn.fi/URN:NBN:fi-fe201702281885

Optimizing the speed of centrifugal pumps

Troy Leyden

Fitzroy River Water

Abstract

Specific energy is the quantity of energy required to pump a given volume and is a useful indicator of energy efficiency. Specific energy is pump and system dependent and varies with flow rate, but does not necessarily decrease as flow rate is reduced. The ability to determine the minimum specific energy that meets the process requirements while being within the pump, motor and drive's range of application will identify the best energy efficiency available. A synergy of equations specifically developed for systems with a static head component is presented which will allow the specific energy to be determined for most combinations of system, centrifugal pump and flow rate, using information available on most pump curves and a system curve. Along with the specific energy, other pump performance information such as speed, power and efficiency can also be calculated across a range of flow rates for a detailed system analysis. The effect on speed, power, efficiency and specific energy from the proportion of static head in the design duty is illustrated as a function of flow rate and demonstrates the importance of understanding the effect the system has on pump performance. Finally, the methodology is utilized to develop a specific energy contour line graph that has regions of similar specific energy displayed in the same manner as elevation contour lines on a map. The contour line graph allows the specific energy to be estimated for any applicable flow rate and pressure head without the need for further calculations. The methodology presented is intended as a tool for pump professionals when performing a pumping system review.

Introduction

There are a number of considerations when a pump package is chosen. One of the most important is its suitability to pump at a specific flow rate and pressure head known as the design duty. The design duty for a municipal pump station for example, may include allowances for anticipated future connections, seasonal fluctuations or similar contingencies. Therefore, the design duty is not required for most of the life of the pump.

Often, pumps are operated at a fixed speed but "in almost all situations, a pump and associated variable speed drive will be substantially more efficient and more reliable than a constant speed pump with a discharge control valve" [1]. A Variable Speed Drive (VSD) allows the speed of a pump to be changed to modify the flow rate, and this removes the need to restrict the discharge. Then, as the pump power required is less than if the discharge was restricted to achieve the same flow rate the efficiency is improved.

Not all applications benefit from the inclusion of a VSD, "…variable speed pumping can save a tremendous amount of energy and sometimes actually increase the energy consumption" [2]. A VSD can increase energy consumption in comparison to full speed operation if the reduction in speed affects the flow rate more than the power. The only systems that the power reduction can be used as an indicator of efficiency gains are systems with no static head component. For all other systems the flow rate must be considered in conjunction with power to allow a relevant comparison.

Specific energy (Es) is the amount of energy required to pump a given volume and allows meaningful comparison between various system, process and pump arrangements. Es is expressed as power by time per unit volume and can take a variety of forms. Kilowatt hours per cubic meter (kWh/m^3) is a common representation but, the units used throughout this paper have been chosen to be relevant to municipal water providers that is, kilowatt hours per Mega Liter (kWh/ML).

Analyzing the Es across a range of flow rates for numerous pump and system combinations has shown that the decrease in pump efficiency at lower flow rates is often offset by the decrease in total pressure required, the net result being a decrease in Es. Importantly, there is typically a limitation to the benefit from decreasing the flow rate and any further reduction results in an increase in the Es or the pump package operating outside its range of application.

Lindstedt et al. [3] and Xylem 2013 [4] demonstrate the Es limitation associated with various systems for a specific pump. However, the ability to determine the pump speed or flow rate that correlates to the minimum Es for a given pump and system is not readily available.

The utilization of a process control program such as a Supervisory Control and Data Acquisition (SCADA) package will allow the actual Es to be observed. By trending an algorithm of the instantaneous power consumed in kilowatts (kW) divided by the flow rate in Mega Liters per hour (ML/h), the Es in kWh/ML can be displayed in almost real time. Then, changes to the rate of pumping on energy consumption can be trended. This will allow the energy consumption of the entire pump package to be reviewed and the most efficient operation identified.

However, observing the Es trend does not allow changes to the pump or system to be evaluated. To overcome this, a mathematical methodology has been developed that uses a synergy of equations to allow the Es to be calculated using the information commonly provided on a pump curve. The process involved in developing the methodology along with the resultant formulas allows any centrifugal pump and system to be analyzed, including systems with a static head component. Along with Es, other pump performance data including speed, power and efficiency is determined for a range of flow rates to allow trends to be observed and provide a detailed system analysis.

Results produced from a theoretical pump and an array of system curves are presented in the applications section along with a contour line graph. The contour line graph has regions of similar Es identified in a similar manner to elevation contour lines on a map, and can be used to estimate Es for any applicable flow rate and pressure head without the need for further calculations.

This paper is intended to communicate a methodology for assessing the energy efficiency and pump performance across a range of flow rates for existing and proposed pumps and systems. Through the detailed presentation of the methodology and examples, it is hoped that sufficient detail has been provided to allow pump professionals to apply the methodology.

Methodology

To determine the Es across a range of flow rates rather than for a given duty there are a number of steps required. Once pump specific equations are developed and entered into a spreadsheet package such as Microsoft Excel they can be manipulated to suit various scenarios.

Care must be taken to ensure the results are relevant. The calculated Es does not account for an array of other factors that need to be considered when assessing the suitability of a pump to perform a specific duty including the manufacturer’s recommended range of application for the pump, motor and drive as well as the effect on efficiency from the motor and VSD at different speeds and loads.

Step 1 – Pump speed

Regardless of motor speed, use the data available from the *full-speed* pump curve to develop a quadratic (second degree) polynomial of the portion of the pump curve that interacts with the system curve. Several models may be required to generate results for the entire system curve. However, a single quadratic is often sufficient for an Es review and will be the form utilized for demonstration.

$$H_{Pump} = a.Q_{Pump}^2 + b.Q_{Pump} + c$$

Where:

- H_{Pump} = Pressure Head developed in meters (m)
- Q_{Pump} = Flow rate in Liters per second (L/s)
- *a, b, c* = Dimensionless constants specific to each pump

Utilizing the pump affinity laws [1][5] for a specific centrifugal pump allows estimation of pump behavior at different speeds.

$$\frac{Q_1}{Q_2} = \left(\frac{n_1}{n_2}\right)$$

$$\frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2$$

Where:

- Q = Flow rate
- H = Pressure Head
- n = Rotational speed of pump

It can be seen that:

$\left(\frac{n_1}{n_2}\right)$ =Dimensionless ratio of rotational speeds

To demonstrate, if n_1 = 2980rpm = *full-speed* and n_2 = 1788rpm = 60% of *full-speed*, this could be written correctly as any of the following:

$$\left(\frac{n_1}{n_2}\right) = \left(\frac{2980rpm}{1788rpm}\right) = \left(\frac{100\% \times 2980rpm}{60\% \times 2980rpm}\right) = \left(\frac{100\%}{60\%}\right) = \left(\frac{1}{0.6}\right)$$

Regardless of the unit used to define *full-speed*, n_2 is a proportion of n_1. Using n_1=*full-speed*=100%=1, the affinity laws can be rearranged to form:

$$Q_1 = \frac{Q_2}{n_2}$$

$$H_1 = \frac{H_2}{n_2^2}$$

Where:

- n_2 = Relative proportion of the nominated *full-speed* of the pump

These expressions are then substituted into the quadratic produced to describe the pump curve such that Q_{Pump} = Q_1 and H_{Pump} = H_1 to give.

$$\frac{H_2}{n_2^2} = a\left(\frac{Q_2}{n_2}\right)^2 + b\left(\frac{Q_2}{n_2}\right) + c$$

$$0 = (c)n_2^2 + (b.Q_2)n_2 + \left(a.Q_2^2 - H_2\right)$$

This can now be solved to find n_2 [6], the relative pump speed required to deliver flow rate Q_2 at pressure head H_2. This allows n_2 to be determined for any point on the system curve.

"In any consistent units of measure" [1]

$$n_2 = \frac{-b.Q_2 \pm \sqrt{(b.Q_2)^2 - 4.c(a.Q_2^2 - H_2)}}{2.c}$$

(Typically the positive version produces the correct result.)

Where:

- Q_2 = Flow rate in L/s
- H_2 = Pressure Head in m

Step 2 – Pump power

For the pump power curve the polynomial can be any degree and the steps demonstrated can be adapted to suit. However, a quadratic has again been utilized as it is typically a good fit for centrifugal pump power curves.

$$P_{Pump} = d.Q_{Pump}^2 + e.Q_{Pump} + f$$

Where:

- P_{Pump} = Pump Power in kW
- Q_{Pump} = Flow rate in L/s
- *d, e, f* = Dimensionless constants specific to each pump

As with Step 1, utilization of the affinity laws [1][5] for a specific centrifugal pump where n_1=*full-speed*=100%=1.

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3$$

$$P_2 = P_1.n_2^3$$

Where:

- P = Pump Power
- n_2 = Relative proportion of the nominated *full-speed* of the pump

Substituting this into the equation developed for the pump power curve where $P_{Pump}=P_1$ along with the term developed for $Q_{Pump}=Q_1$ developed previously gives:

$$P_2 = \left\{ d\left(\frac{Q_2}{n_2}\right)^2 + e\left(\frac{Q_2}{n_2}\right) + f \right\} n_2^3$$

Where:

- P_2 = Pump Power in kW

"In any consistent units of measure" [1]

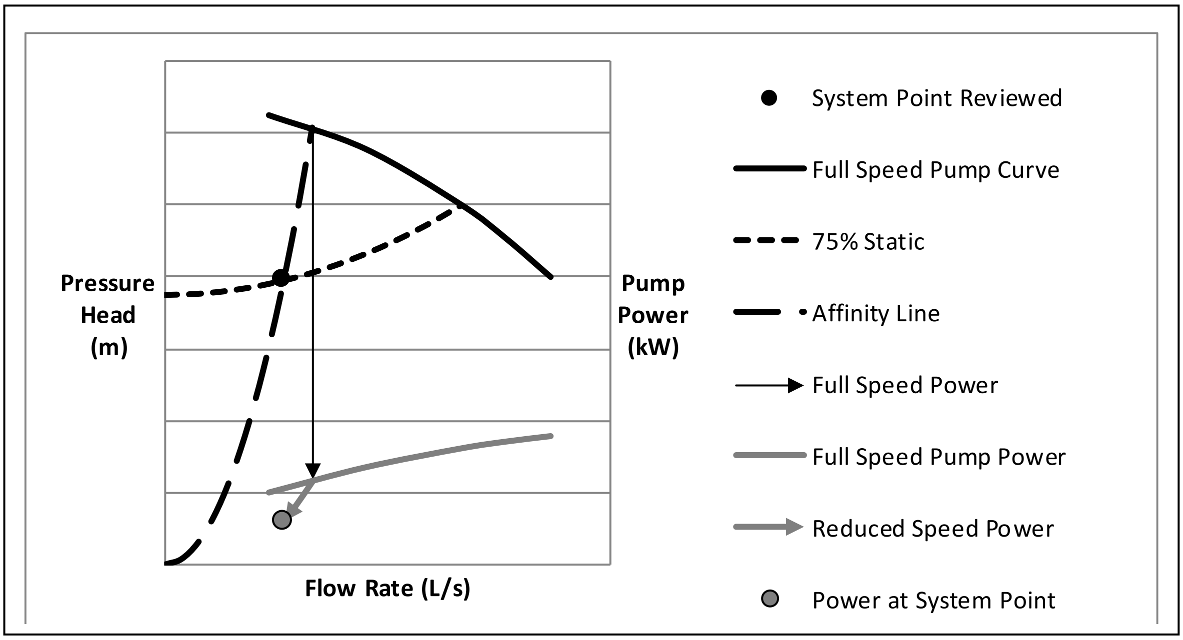


Figure 1 – Illustration of determination of pump power for system with high static head.

The equation for power uses the speed determined in step 1 to find the flow at *full-speed* for the affinity line that passes through the system point being reviewed. The polynomial developed for power can then be used to determine the *full-speed* power, which in turn is manipulated back to the power relevant for the system point using the affinity laws. Figure 1 is an illustration of the process undertaken.

Step 3 – Pump efficiency

As the pump power required at each point on the system curve can be determined it is good practice to determine the pump efficiency at each point on the system curve. This allows the application range to be confirmed to ensure the pump is suitable for delivering the duty. The equation to determine pump efficiency [1] is:

$$\eta = \frac{Q_2.H_2.g}{1000.P_2} \times 100\%$$

Where:

- η = Pump efficiency in percent (%)
- g = The gravitational constant in meters per second squared (m/s^2)

Step 4 – Specific energy

The Es can be determined across the range of the system curve by calculating the pump power for each flow rate to be analyzed. Additionally, as the units required for Es in the presented examples are kWh/ML, the flow rate needs to be changed from L/s to ML/h.

$$Es = \frac{P_2}{Q_2}\left(\frac{1}{3600}\right)\left(\frac{10^6}{1}\right)$$

Where:

- Es = Specific energy in kWh/ML

Applications

Whenever a pump, system or process is being reviewed there is potential benefit from reviewing the Es. The outputs from a range of systems with varying proportions of static head have been compared along with the outputs from a system using throttling as the flow control method. Then a Es contour line graph is presented that demonstrated that the Es is pump specific, and it is the flow rate and pressure head from the system curve that causes different systems to have different Es trends.

Model Development

From the *full-speed* pump curve, a range of data points for flow, head and power are used to determine the dimensionless constants *a, b, c, d, e* and *f*. If the data points are able to coincide with minimum flow rate, pump Best Efficiency Point (BEP) and maximum flow rate, the efficiency can also be recorded and used as a guide for when the pump is outside its range of application.

Table 1 shows the data points from pump curve which will be used for the succeeding demonstrations. The pump BEP has been designed to be 100 L/s at 100m Head. This has been done to allow demonstrations to represent proportions of the design duty

Table 1 - Data Points from Pump Curve developed for demonstration

Q_{Pump}(L/s)	H_{Pump}(m)	P_{Pump}(kW)	η
35	125	71.5	60%
100	100	115.4	85%
130	80	127.5	80%

Q_{Pump} =Pump Flow rate, H_{Pump} =Pump Pressure Head, P_{Pump} =Pump Power, η =Pump efficiency

Using the above information the pump specific dimensionless constants can be determined using a number of methods, one such example follows:

(Equation 1) $125 = a(35)^2 + b(35) + c$

(Equation 2) $100 = a(100)^2 + b(100) + c$

(Equation 3) $80 = a(130)^2 + b(130) + c$

(Equation 4 = Equation 1 x-100) $-12500 = -122500a - 3500b - 100c$

(Equation 5 = Equation 2 x 35) $3500 = 350000a + 3500b + 35c$

(Equation 6 = Equation 4 + Equation 5) $-9000 = 227500a - 65c$

(Rearrange to form an expression for ‘c’) $c = 3500a + 138.46$

(Sub expression for ‘c’ into Equation 3) $20400a = -130b - 58.46$

(Rearrange to form an expression for ‘a’) $a = -6.37*10^{-3}b - 2.87*10^{-3}$

(Substitute expressions for ‘a’ and ‘c’ into Equation 2 to find value for ‘b’)

$$100 = (-6.37*10^{-3}b - 2.87*10^{-3})(100)^2 + 100b + 3500(-6.37*10^{-3}b - 2.87*10^{-3}) + 138.46$$

$$100 = -63.7b - 28.7 + 100b - 22.33b - 10.04 + 138.46$$

$$100 = 13.97b + 99.72$$

$$b = 0.02$$

(Use value for 'b' to solve 'a' and 'c')

$a = -0.003$

$c = 128$

This process is then repeated to find *d, e, and f*. Using a spread sheeting program such as Microsoft Excel allows the calculations to be performed without rounding, improving the accuracy of the final results. The results taken from the Excel spreadsheet rounded to 4 significant digits are:

- a =-2.967x10^{-3}
- b =1.1619x10^{-2}
- c =128.1
- d =-2.859x10^{-3}
- e =1.062
- f =37.85

VSD pump performance results for design duty with 75% static head

A system curve that has 75% static component and a design duty that coincides with the pump BEP will be analyzed. Table 2 shows the results from application of the methodology in 10 L/s increments from no flow to the design duty. If greater accuracy were required the increments could be smaller and if the results beyond the design duty were required the same methodology is still applicable.

Table 2 – Results of VSD flow control calculations for 75% static head system

Q_2(L/s)	H_2(m)	n_2	P_2(kW)	η	ED(kWh/ML)
0	75.0	76.5%	17.0	n/a	n/a
10	75.3	76.7%	23.1	31.9%	642.7
20	76.0	77.5%	29.5	50.5%	409.6
30	77.3	78.8%	36.3	62.6%	335.9
40	79.0	80.6%	43.7	70.8%	303.7
50	81.3	82.9%	52.1	76.4%	289.5
60	84.0	85.6%	61.6	80.2%	285.2
70	87.3	88.7%	72.5	82.6%	287.6
80	91.0	92.2%	84.9	84.0%	294.9
90	95.3	95.9%	99.2	84.7%	306.1
100	100.0	100.0%	115.4	84.9%	320.6

Q_2 =Flow rate, H_2 =Pressure Head, n_2= Relative proportion of the nominated full-speed of the pump, P_2 =Pump power, η =Pump efficiency, Es=Specific energy

Using a set of system data points from Table 2, Q=40 L/s and H=79 m, the following can be calculated

$$n_2 = \frac{-(1.619*10^{-2} \times 40) + \sqrt{\left(1.619*10^{-2} \times 40\right)^2 - 4 \times 128.1 \times \left(-2.967*10^{-3} \times 40^2 - 79\right)}}{2 \times 128.1} \times 100\%$$

n_2 =80.6% (The negative version of the equation returns -81.1%)

$$P_2 = \left\{-2.859*10^{-3} \times \left(\frac{40}{0.806}\right)^2 + 1.062 \times \left(\frac{40}{0.806}\right) + 37.85\right\} \times 0.806^3$$

P_2 =43.73 kW

$$\eta = \frac{40 \times 79 \times 9.8}{1000 \times 43.73} \times 100\%$$

η =70.8%

$$ED = \frac{43.73}{40} \times \left(\frac{1}{3600}\right) \times \left(\frac{10^6}{1}\right)$$

ED=303.7 kWh/ML

Likewise, the other data points can be used to determine the same data across a range of flow rates.

Reviewing the data in Table 2 reveals:

- Below 60% efficiency the results may not be accurate as it is outside the region of pump curve and power curve used to determine the dimensionless constants,
- Based on an efficiency of 60% being the manufacturer's minimum recommended flow rate, the pump should not be operated at less than approximately 78.8% of full speed or 30L/s,
- Despite the pump power continuing to reduce as the speed is reduced the Es reaches its minimum at 60% of the design flow rate. Therefore, unless the process specifically requires a slower flow rate, the speed should not be reduced below 85.6% of full speed or 60 L/s, as at this speed the Es is at its minimum, and
- For this example, the energy consumed at the minimum Es is 11% less than at full speed.

Effect of static head on pump performance

The design pressure head consists of static pressure head, dynamic pressure head, or a combination of the two. Understanding the effect the system has on pump performance when variable speed pumping will allow insight into the most efficient operation of the pump arrangement.

For example, for a system with a high proportion of static head there is only a small benefit from running the pump at a flow rate below the design duty. Additionally, the increased loss from the VSD may even make its inclusion detrimental to energy efficiency. However, as can be seen in Figure 2, there is generally a benefit from using a VSD to control the flow rate in comparison to a control valve.

It is important to note that the results presented in both Table 2 and Figure 2 are specific to the theoretical pump used to determine the dimensionless constants. The illustrations should not be incorrectly interpreted as being relevant for all systems with similar static head characteristics.

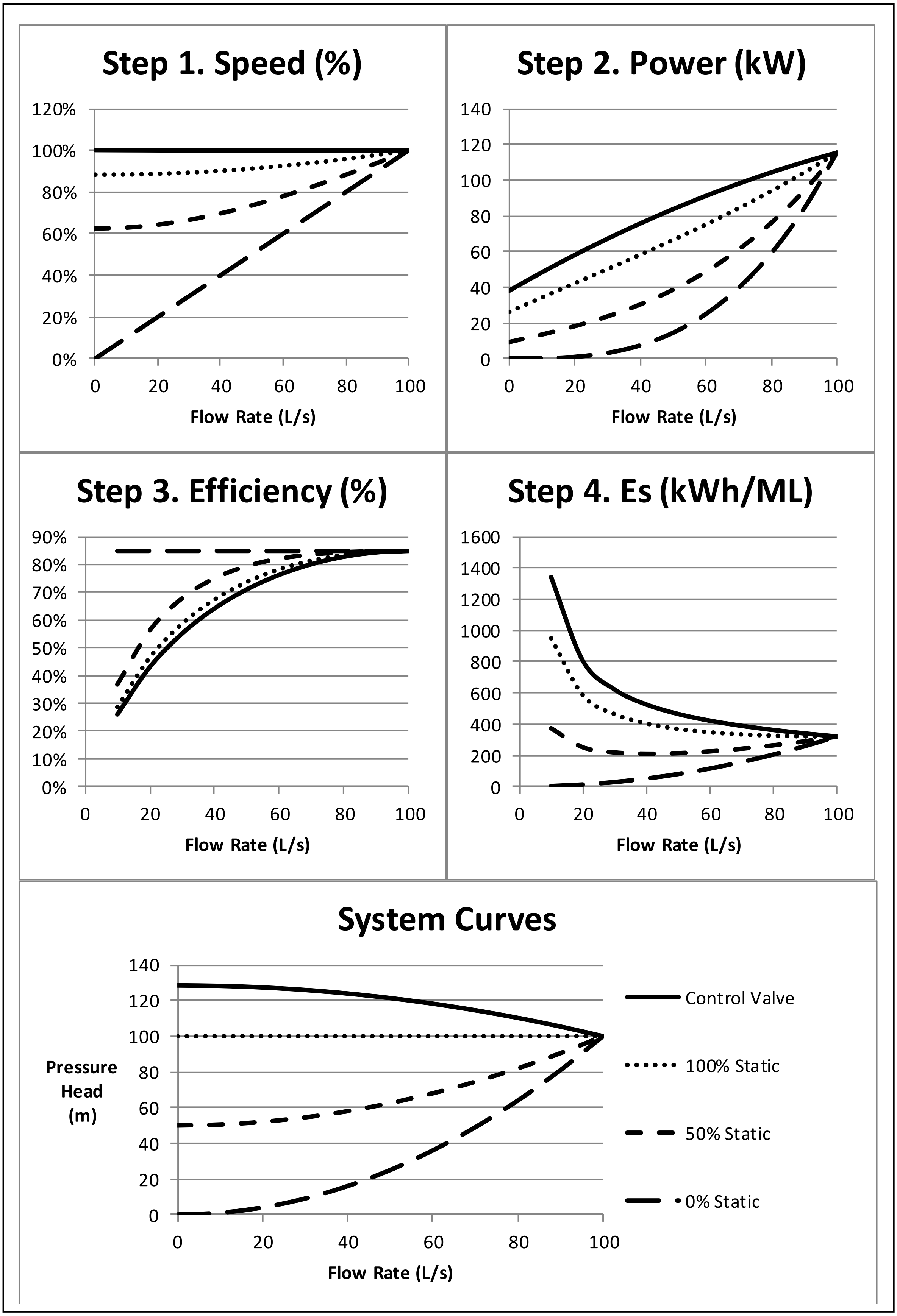


Figure 2 – Comparative effect of the static head proportion on pump performance using VSD as flow control including effective system from using control valve as flow control method.

Specific energy contour lines

Using the methodology presented the Es can be determined for any flow rate and pressure head. A three dimensional graph of the Es can be generated with contour lines used to identify regions of similar Es. This output with the original pump curve overlaid can be used to approximate the Es, including the minimum Es for a given system, without the need for further calculations.

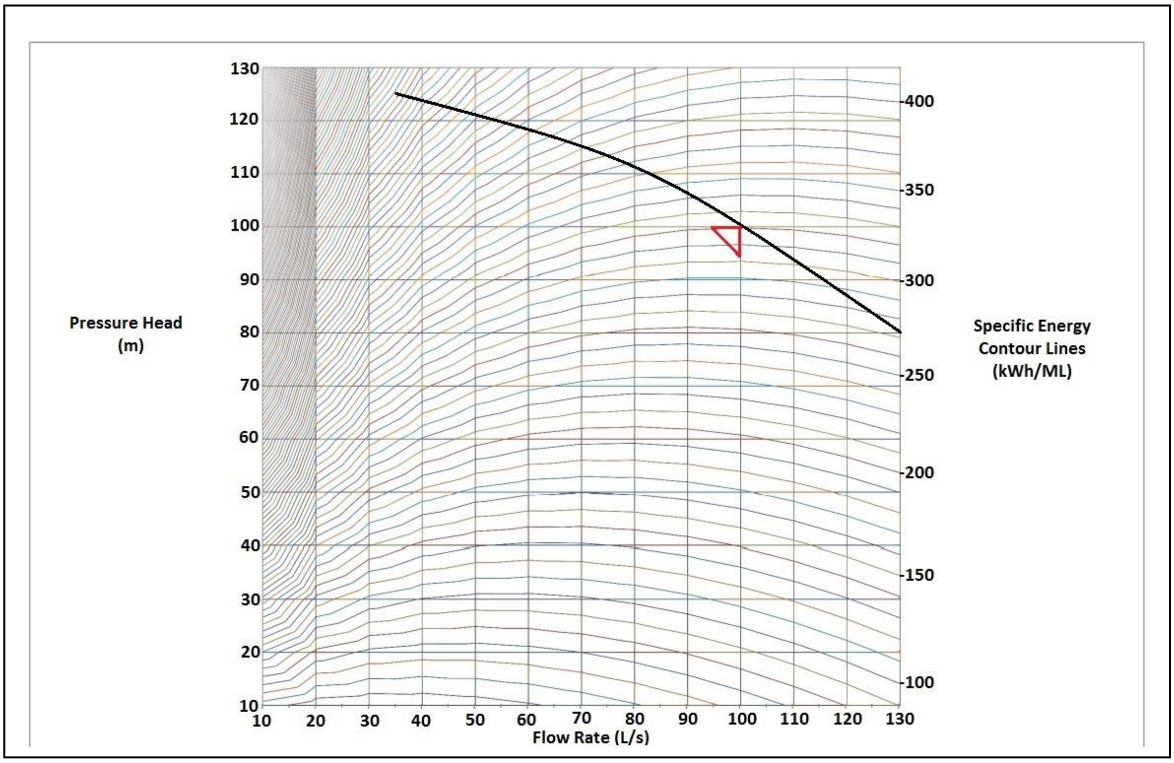


Figure 3 – Specific Energy contour lines with pump curve including BEP overlaid.

Using Figure 3 it can be seen that the BEP of the full speed pump curve coincides with a Es of 320 kWh/ML, and the duty point 40 L/s at 79m has a Es of 305 kWh/ML, both of which are relatively good approximations of the findings in Table 2.

Care needs to be taken to ensure the duty identified is suitable for long term operation, but is useful nonetheless for a very quick energy efficiency analysis. The graph could also have regions outside the application area of the pump, motor and VSD marked on it to allow users to quickly identify if the pump is being used incorrectly.

Conclusion

The methodology presented can be applied to most fluid systems specific to centrifugal pumps. The examples presented provide an insight on how the tool can be used on existing or proposed pumps to allow the pump performance and energy efficiency to be calculated across a range of flow rates. Although the focus of the tool is on pump power, it is hoped that an avenue for further investigations and refinement has been provided. The inclusion of variable frequency variable voltage drives, generalized as VSD's, and their effect on motor performance across the range of loads and speeds will produce a more robust methodology that will provide improved insight into optimizing the efficiency of centrifugal pumps.

References

[1] Karassik I.J., Messina J.P., Cooper, P. and Heald C.C. *The Pump Handbook.* 2008. 4th Ed. ISBN: 978-0-07-146044-6. P. 2.11, p. 2.155 and p9.129

[2] Hovstadius G., Tutterow V. and Bolles S. *Getting it Right, Applying a Systems Approach to Variable Speed Pumping.* Proc. of the EEMODS 2005. Can be downloaded at http://www.pumpsystemsmatter.org/uploadedFiles/PumpSystemsMatter/Education_and_Tools/Free_Downloads/Systems%20Approach%20to%20Variable%20Speed%20Pumping.pdf

[3] Lindstedt M., Ahonen T. and Tolvanen J. *Progress in Energy Efficiency of Fluid Handling System*. Proc. of the EEMODS 2015. Can be downloaded at http://www.eemods15.info/midcom-serveattachmentguid-1e55df342aa58d25df311e5970043007ec61b5d1b5d/fluid_systems1_tero_ahonen.pdf

[4] Xylem. *Variable Speed Wastewater Pumping*. November 2013. Can be downloaded at http://www.wioa.org.au/operator_resources/documents/XylemVariableSpeedPumping.pdf

[5] Munson B.R., Young D.F., Okiishi T.H and Huebsch W.W. *Fundamentals of Fluid Mechanics*. 2009. 6th Ed. ISBN: 978-0470-26284-9. p. 669.

[6] Croft A. and Davison R. *Mathematics for Engineers*. 2008. 3rd Ed. ISBN: 978-0-13-205156-9. p. 213.

A Cost model for Pumps as Turbines and a comparison of design strategies for their use as energy recovery devices in Water Supply Systems

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Abstract

Pressure Reducing Valves are an essential component in Water Supply Systems for the control of leakage and pipe failures, but their reduction of pressure in the network is wasteful of the energy within the system. Such valves may be replaced by a Micro-Hydropower (MHP) turbine which can control pressure by converting its excess to electricity. A fit and promising technology for such in-pipe hydropower schemes are Pumps as Turbines (PATs), which are cost-effective and reliable machines with many advantages with respect to conventional MHP turbines. The two major shortcomings of PATs application are the lack of a systematic model for prediction of purchase price and the uncertainties occurring in the design phase while choosing a suitable PAT for a given site.

In the first part of the present research, data from 324 commercially available centrifugal pumps were compared in order to obtain mathematical formulations estimating the PAT cost. The results showed that PAT unit costs ranged from 115 to 5,600 €/kW according to their rated power.

In the second part, the Variable Operating Strategy (VOS) design method which aims at maximization of energy yield was compared with an alternative method based on minimization of investment payback time based on data from an existing water network. The results from both methods suggest that when such a machine operates as an in-pipe energy recovery device the presence of an automated flow by-pass fosters an increase of the possible energy yield by nearly 60%, as well as enhancing system reliability.

Keywords: Cost analysis, Energy Recovery, Hydropower, Pump as Turbine (PAT), Variable Operating Strategy (VOS), Water Supply Systems (WSS)

Nomenclature

D	impeller diameter
d	day
H	head
h	head non-dimensional coefficient
N	rotational speed (rpm)
$N_{s,p}$	specific speed based on power (-)
$N_{s,q}$	specific speed based on flow for PATs in turbine mode (-)
P	power
pp	number of magnetic pole pairs
Q	flow rate
q	flow non-dimensional coefficient
R^2	coefficient of determination

Greek Symbols

η	efficiency (-)
η_p	overall plant efficiency (-)

Subscripts

t	turbine
p	pump
BEP	at Best Efficiency Point

Abbreviations

BEP	Best Efficiency Point
ER	Electric Regulation
HR	Hydraulic Regulation
MHP	Micro-Hydropower
PAT	Pump as Turbine
PRV	Pressure Reducing Valve
SPBT	Simple Payback Time
VOS	Variable Operating Strategy
WSS	Water Supply Systems
FIT	Feed-In tariff
O&M	Operations and Maintenance

Micro-hydropower in Water industry

Hydropower is a well-known renewable energy technology exploiting the potential contained in free falling water to produce electricity. Micro-Hydropower (MHP) is defined as a subset of hydropower installations having nominal capacity ranging between 5 and 100 kW [1]. Such a range includes schemes either connected to a grid or feeding stand-alone consumers which commonly operate without the need of a large water reservoir [2].

On the other hand, water utilities are large energy consumers as a result of the process of extracting, purifying, transporting and again treating water. As an example, it has been estimated that the amount of energy consumed by water pumping in the U.S. accounts for 3 to 4% of the total yearly energy demand throughout the whole nation [3]. Due to increasingly stringent water quality standards, demographic expansion and the ageing of water infrastructures, the energy demand of the water sector in developed countries has increased substantially during the past decades [4]. An opportunity to increase the sustainability of the water industry is the application of MHP to recover wasted energy potential existing in most Water Supply Systems (WSS). Indeed, the generation of certain amounts of electricity from water networks has the potential to partially off-balance the impact of water pumping under both economic and environmental terms [5, 6].

As a result of the efforts made by water utilities to supply clean water in a reliable way and at a sufficient pressure, at certain nodal points within distribution networks an excessive pressure may develop with respect to the desired level. Such systematically occurring overpressures are an area of great concern for water companies since they are symptomatic of inefficient energy use, they are among the primary causes of pipe bursts and they increase leakage rate and pressure-related water consumption. As a result, in the long run overpressures may signify a significant waste of resources as well as decreasing the reliability and increasing the maintenance needs of a network [7]. A common strategy to address these is to install a Pressure Reducing Valve (PRV) specifically designed to bring down the pressure in a pipe to the optimal value [8, 9]. Pumps as Turbines have been pointed out by many authors as devices capable of effectively replacing or complementing PRVs, thus recovering certain amounts of energy from water instead of merely dissipating it [10, 8, 11, 12].

Pumps as Turbines technology

Generalities and applications

Pumps as Turbines (PAT) are a family of unconventional reaction water turbines hydraulically similar to Francis turbines. Unlike conventional water turbines, water pumps are mass manufactured are available off-the-shelf in a large variety of sizes and types. When operated in reverse mode they can extract energy from pressurized water and produce useful electricity through a connected generator which usually is of asynchronous induction type [13]. Other advantages of PAT usage include their long life span, reduced investment cost, compact dimensions, easy installation and maintenance with respect to conventional hydro turbines [14, 15, 16]. In spite of the cited advantages, PATs application has been found to be limited by two factors:

1. characteristic curves of pumps running as turbines are commonly not available from the producers, thus their operating point must be estimated prior to installation. The available methods to predict pump performances are based either on analytical procedures or on Computational Fluid Mechanics and may lead to significant errors when applied to a determined machine [17, 18];

2. the absence of flow regulation devices in PATs commonly leads to low part-load efficiency and may turn the device unsuitable to accommodate seasonal of hourly variations of flow and head without causing system disruptions. This is particularly significant in WSS which are characterized by high demand fluctuations [19, 20].

PATs have proven to be effective to power MHP plants and as in-pipe energy recovery devices [21]. Among the many commercially available pump types which can be used as turbines are the centrifugal, mixed flows or axial units as well as multistage and double-flow pumps [18].

Many successful examples of PAT application in water networks are to be found in literature, among them are the 300 kW Breech pressure reduction station [22] and the 16 kW Beliche hydropower station [23, 24]. Several authors have investigated the opportunity and challenges around installing PATs of even smaller sizes as pressure control devices within urban water distribution networks, showing promising financial payback times (2-6 years) and demonstrating that small PATs may effectively replace PRVs [14, 9, 25, 8, 26, 20]. Besides the revenues expected from the electricity sales, water utilities may also benefit economically from the reduction of pressure-induced leakage [8, 27].

PAT cost in literature

In order to evaluate the feasibility of a PAT scheme in a WSS an updated cost model is needed to estimate the amount of investment cost required by the acquisition of a generating set (turbine and generator). However, a systematic and updated cost model covering the possible PAT sizes and types range is not available in the literature. Ramos et al. [28] in 2009 suggested that PAT cost per nominal installed power may vary from

400 €/kW for smallest units to 200 €/kW for 40kW-units thanks to economies of scale. Other researches instead suggested constant unit prices equal to 2,000 €/kW for the assembled PAT and generator unit according to De Marchis et al. [26] and 230 €/kW for a turbine alone according to Carravetta et al. [29].

Despite being the most complete cost model available, the one proposed by Ramos et al. [28] was published almost a decade ago and considered only one specific PAT type (centrifugal, single stage) and a limited range of nominal powers. As for the other mentioned studies, instead, the use of a constant equipment cost is an evident over-simplification of reality and may be applicable only to a narrow range of PAT sizes. Additionally, all the mentioned papers considered the equipment unit cost as invariant with respect to nominal head and flow values. However, other studies which investigated the cost of hydraulic equipment found such factors to have a significant impact on purchase cost [30, 31].

VOS design strategy

Given the cited absence of flow regulation devices the efficiency of a PAT usually declines sharply outside the surroundings of its Best Efficiency Point (BEP), while conventional water turbines can maintain a high efficiency over a large interval of flow rates [18, 20]. Besides this, the implementation of PATs as PRV replacements in water networks where a prescribed downstream pressure must be maintain independently from the flow rate poses additional design challenges since a PAT alone lacks in-built regulation devices. In order to account for such issues, Carravetta et al. [6, 29, 32] proposed a design procedure called Variable Operating Strategy (VOS) enabling the choice of machinery which maximize the ratio of energy yield from a determined site over the potentially available energy, calculated as:

$$\eta_p = \frac{\sum_{i=1}^{n} \quad 9.8\, \eta_i\, Q_{t,i}\, H_{t,i}\, \Delta t_i}{\sum_{i=1}^{n} \quad 9.8\, Q_i\, H_i\, \Delta t_i} \qquad (1)$$

where "n" refers to the number of sampling points available to the designer. Besides, the authors proposed two alternative plant configurations adopting PAT technology featuring pressure control functionalities similar to those offered by a PRV. In particular, those are:

1. Hydraulic Regulation (HR), consisting of a PAT in series with a PRV and an automatically regulated by-pass circuit;
2. Electric Regulation (ER), where a PAT unit totally replaces a PRV and its turbine characteristic curve can be modified by varying the shaft rotational speed N by means of a speed drive.

Within the cited studies [6, 29, 32] a comparison between HR and ER layouts was carried out evaluating the performance of a family of geometrically similar PATs (i.e. having identical specific speed Ns) whose impeller diameter D and shaft speed N was varied from a prototype model according to turbomachinery affinity laws. Within the chosen daily flow and head pattern obtained from an existing PRV installation, a PAT designed according to HR principles proved to offer higher energy yield, higher flexibility and lower payback time with respect to ER configuration.

A significant limitation of the described method is that the design of a hydropower scheme based on solely technical parameters (i.e. energy yield maximization) may lead to the selection of plant parameters lying away from an "optimal" configuration from an economic point of view. Since the economic viability of any hydro project is a fundamental prerequisite to its implementation, it would be appropriate to perform also an optimization based on economic parameters (e.g. payback time minimization or net present value maximization). Secondly, another limitation of the presented studies consists of having the whole analysis based on a unique PAT model. Instead, considering different PAT families having other values of Ns could lead to more universal results.

Research targets

The present research was aimed at improving and complementing the literature regarding PAT application as pressure control devices in WSS. In particular, two research targets have been addressed:

1. the generation of a rigorous PAT cost model including end-suction radial units in single or multistage configuration;

2. building on the VOS design strategy, a procedure will be established to determine the characteristics of a PAT installation in terms of Ns, N and D leading to the project payback time minimization. The results obtained were compared with those arising from the VOS procedure across a first scenario featuring the installation of a PAT without any pressure or flow control devices and a second scenario regarding the installation of a PAT with HR capabilities.

PAT cost model

Data source and quality

The analysis was based on the 2016 price list (excl. VAT) of 324 centrifugal pumps associated with asynchronous motor/generator units. All considered end-suction pumps featured a stainless steel shaft, cast iron impeller case and a generator unit having 1, 2 or 3 pairs of magnetic poles (pp). Besides, for each pump information was gathered from manufacturer's manuals about their parameters $\eta_{p,BEP}$, $Q_{p,BEP}$, $H_{p,BEP}$ and $N_{s,q}$ in pump mode. In order to estimate a pumps' nominal head and discharge in turbine mode two non-dimensional coefficients are commonly utilized to relate the location of BEP between the two operating modes [17]:

$$h = \frac{H_{t,BEP}}{H_{p,BEP}} \qquad q = \frac{Q_{t,BEP}}{Q_{p,BEP}} \tag{2}$$

Several methods have been proposed to obtain values of head and discharge ratios based on machine maximum efficiency or specific speed [33, 34], however no one-dimensional mathematical correlation available in literature can accurately calculate h and q for any pump [17]. Yang et al. in 2012 proposed two semi-empirical correlations to calculate head and flow ratios from a pump's maximum efficiency, showing that such equations produced more accurate results when compared with existing methods (namely, those proposed by Stepanoff and Sharma) against a large database of PATs having $N_{s,q}$ in pump mode between 8 and 95 [35]. The formulae for h and q as proposed by Yang et al. correspond to:

$$h = \frac{1.2}{(\eta_{p,BEP})^{1.1}} \qquad q = \frac{1.2}{(\eta_{p,BEP})^{0.55}} \tag{3}$$

In the process of establishing the PAT cost model, those equations have been employed to estimate the working point of analysed pumps given the absence of information from manufacturer. Even though it has been proven that the use of 1-D BEP prediction methods may produce incorrect results for a specific PAT [18], it was supposed that the impact of such likely-to-occur scattered errors on the final cost figures will be small given the large number of considered units.

As an additional consideration, the maximum efficiency of each pump when running in reverse mode was considered equal to the one given by the manufacturer in pump mode in agreement with the results of previous comparative studies [36, 37].

Results

PAT unit cost

The PAT+generator cost per unit of nominal power was found to vary from 115 €/kW for units larger than 200 kW up to 5,600 €/kW for a 200 W turbine following a decreasing trend with size increase indicating realistic economies of scale. Values of machinery cost for PATs having capacity lower than 30 kW is shown in Figure 1.

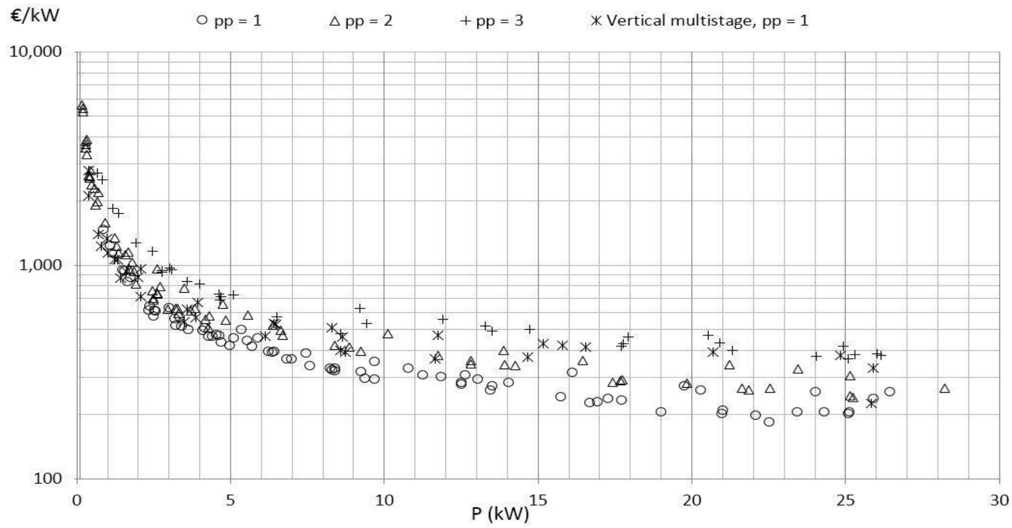

Figure 1 – PAT and generator assembly cost per kW at nominal power

The obtained cost figure shows the influence of rotational speed choice on the equipment cost, since a high rotational speed with respect to a lower one allows for the selection of a smaller PAT and a less sophisticated generator having a lower number of pole pairs (pp).

PAT cost determination

Couper et al. [31] proposed analytical formulae to estimate the purchase price of centrifugal pumps for industrial applications as a linear function of the parameter $Q\sqrt{(H)}$. Following such a concept, four linear correlations relating the $Q_{t,BEP}$ (m^3/s) and $H_{t,BEP}$ (m) to the purchase price of each PAT+generator unit were obtained as shown in Figure 2.

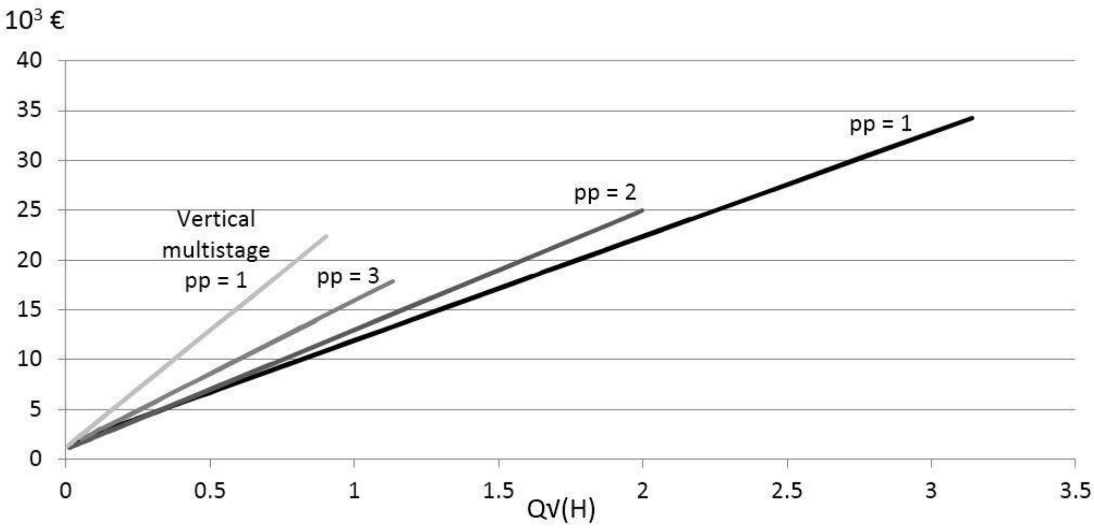

Figure 2 – Linear correlations providing estimates of centrifugal PAT purchase price according to machine type (single stage or multistage) and generator characteristics

PRVs substitution with PATs

Methodology

In order to test different PAT design strategies against a realistic operating environment, daily profiles of flow rate and head drop across an existing PRV valve in a water network in the US were obtained. Along a typical 24-h period the valve produced a mean pressure reduction of 77 m, while processing an average flow rate of 25 l/s [38]. Assuming an efficiency range of 60-70%, the power output of a PAT in such environment would be approximately equal to 12-13 kW. Two different scenarios have been compared:

1. PRV substitution with a PAT without flow or head control capabilities;
2. addition of a PAT in series to the PRV and with an automated flow by-pass allowing for Hydraulic Regulation (HR).

The first scenario would be feasible only if a reservoir is placed downstream of the PAT or if the admissible band of downstream pressure is large enough to accommodate all head drop values generated by the unregulated PAT at different flow rates [10]. In all other cases flow and head control capabilities are needed, which may be designed according to HR or ER principles. Given the overall superiority of HR mode over ER as stated by Carravetta et al. [6, 29, 32], the latter was disregarded.

The analysis was conducted in a way to obtain for each scenario the characteristic of a PAT installation in terms of N and D which would lead to the overall plant efficiency (η_p) maximization as described in Equation 1. Such results were compared to those obtained seeking for the minimization of Simple Pay Back Time (SPBT) as defined in Equation 4.

$$SPBT = \frac{I}{R - O\&M} \tag{4}$$

Where:

SPBT (d): Simple Pay Back Time

I (€): initial investment

R (€/d): daily revenues

O&M (€/d): daily cash outflow for Operation and Maintenance

Parameters for I, R and O&M were calculated through the PAT cost figures presented in the previous section and considering a Feed In Tariff equal to 0.153 €/kWh, a grid connection fee of 500 €, a 3000 € cost figure for the by-pass and valves needed in HR control mode and a yearly maintenance cost equal to the 2.5% of the initial PAT purchase price. The optimal values of N and D were obtained by applying the affinity laws to twelve centrifugal, single stage PATs experimentally tested **[17, 39, 40, 41]** whose main characteristic are summarised in Table 1.

Table 1 – BEP values of a set of experimentally tested pumps as presented in literature

	Ns,q	η_{BEP}	D (mm)	N (rpm)	$H_{t,BEP}$ (m)	$Q_{t,BEP}$ (m^3/s)
PAT 1	18.5	0.73	225	1520	26.5	0.020
PAT 2	18.6	0.77	258	1520	48.6	0.051
PAT 3	28.1	0.81	206	1520	21.2	0.033
PAT 4	30.1	0.72	174	1520	15.8	0.025
PAT 5	35.7	0.84	264	1520	30.5	0.093
PAT 6	41.1	0.80	200	1520	16.2	0.048
PAT 7	38.1	0.76	139	1520	9.6	0.019
PAT 8	57.6	0.74	165	1520	10.2	0.047
PAT 9	70.1	0.76	224	1520	16.1	0.137
PAT 10	9.9	0.46	176	1520	21.6	0.004
PAT 11	20.9	0.61	125	1020	4.1	0.003
PAT 12	50.4	0.88	518	760	23.2	0.485

Source [17, 39, 40, 41]

Affinity laws are commonly utilised in turbomachinery sizing since they can conveniently relate the operation point of two geometrically similar pumps or turbines (i.e. having identical N_s) by means of the ratios between impeller diameters D or shaft speeds N:

$$\frac{Q'}{Q} = \frac{N'}{N} \left(\frac{D'}{D}\right)^3 \quad (5)$$

$$\frac{H'}{H} = \left(\frac{N'}{N}\right)^2 \left(\frac{D'}{D}\right)^2 \quad (6)$$

$$\frac{P'}{P} = \left(\frac{N'}{N}\right)^3 \left(\frac{D'}{D}\right)^5 \quad (7)$$

Equation 7 assumes the maximum efficiency of PATs to be always constant for a given Ns, which is contradicted by the real behaviour of turbomachinery [42]. In order to overcome such limitation, in addition to the use of Equations 5-6 the value of maximum efficiency for each PAT was estimated through the inverse distance weighting interpolation technique based on nominal head and flow values in turbine mode of the same 324 pumps considered in the cost analysis section. Such additional information helped reducing the errors associated with Equation 7.

Finally, the full characteristic curves for each PAT were calculated from the available data at BEP following the second and third order polynomials empirically determined by Derakhshan and Nourbakhsh [37]:

$$\frac{H_t}{H_{t,BEP}} = 1.0283\left(\frac{Q_t}{Q_{t,BEP}}\right)^2 - 0.5468\left(\frac{Q_t}{Q_{t,BEP}}\right) + 0.5314 \tag{8}$$

$$\frac{P_t}{P_{t,BEP}} = -0.3092\left(\frac{Q_t}{Q_{t,BEP}}\right)^3 + 2.1472\left(\frac{Q_t}{Q_{t,BEP}}\right)^2 - 0.8865\left(\frac{Q_t}{Q_{t,BEP}}\right) + 0.0452 \tag{9}$$

Results

For each of the two investigated scenarios (absence of regulation and HR) the PATs were considered as rotating at 1510 or 3020 rpm which corresponded to the approximate stationary speed of most commonly found asynchronous generators having pp equal to 2 and 1 respectively.

Absence of regulation

In Figure 3 the influence of the choice of impeller diameter size D and rotational speed N on the resulting overall plant efficiency and SPBT is represented. Results show that, in the absence of flow and head regulation devices, a PAT working as substitute for the selected PRV could attain a maximum plant efficiency in the range of 31-38% which is slightly higher when rotating at 3020 rpm. Conversely, the values of optimal payback time under either N regime correspond to about 200 days. However, such promising values may be misleading since in practical applications it would be advisable to undersize the PAT since given the absence of a flow by-pass even a slight increase of flow rate above the design value could generate an excessive pressure drop across the turbine leading to service disruptions.

Additionally, it must be pointed out that for both values of N the optimal D values which minimize SPBT are slightly lower than those leading to η_p maximization.

Hydraulic Regulation (HR)

Similarly to the previous Figure 3, Figure 4 shows the profiles of η_p and SPBT against impeller diameter for a PAT operated in HR mode installed as an alternative to the analysed PRV. Even though the values of minimum payback time (220-237 days) are similar to those attainable by an unregulated PAT because of the additional investment required, the maximum possible η_p is increased by 23 and 18 percentage points for N equal to 1510 and 3020 rpm respectively. With respect to the previous scenario, the introduction of a flow by-pass in HR mode makes it possible to design a PAT scheme set to achieve highest possible energy yield or economic attractiveness without risks of compromising the network’s functionality.

At any given N, the minimum values of SPBT occur for impeller diameters lower than a factor of around 50 mm with respect to the values of D maximizing the overall plant efficiency.

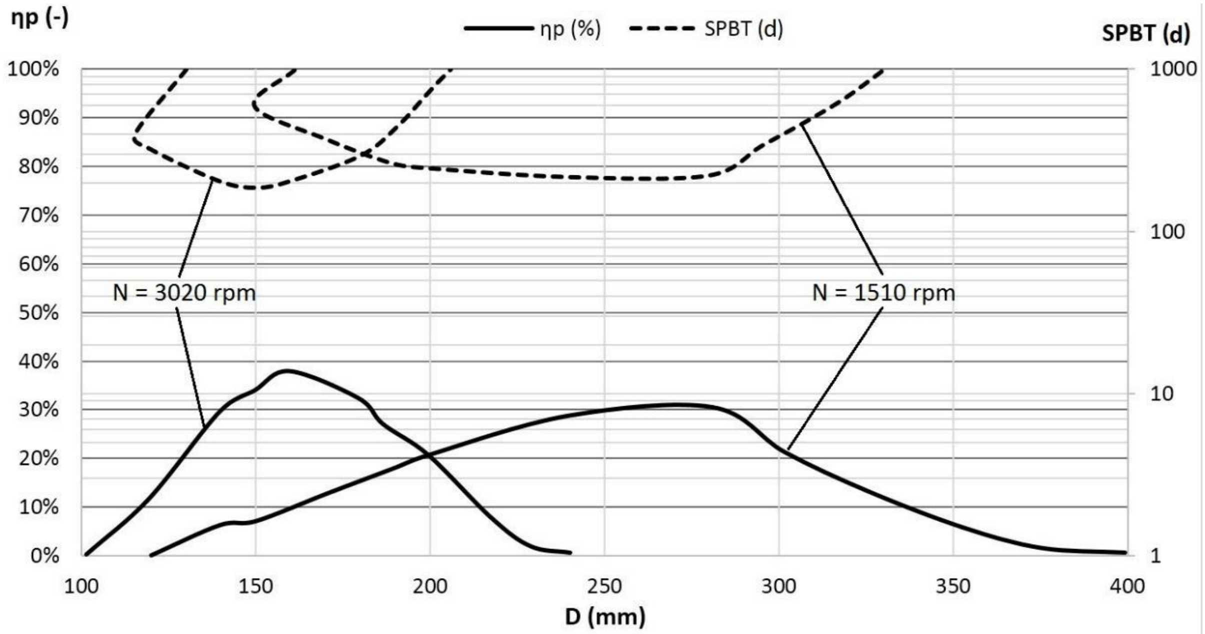

Figure 3 - η_p and SPBT versus impeller diameter in absence of PAT regulation devices

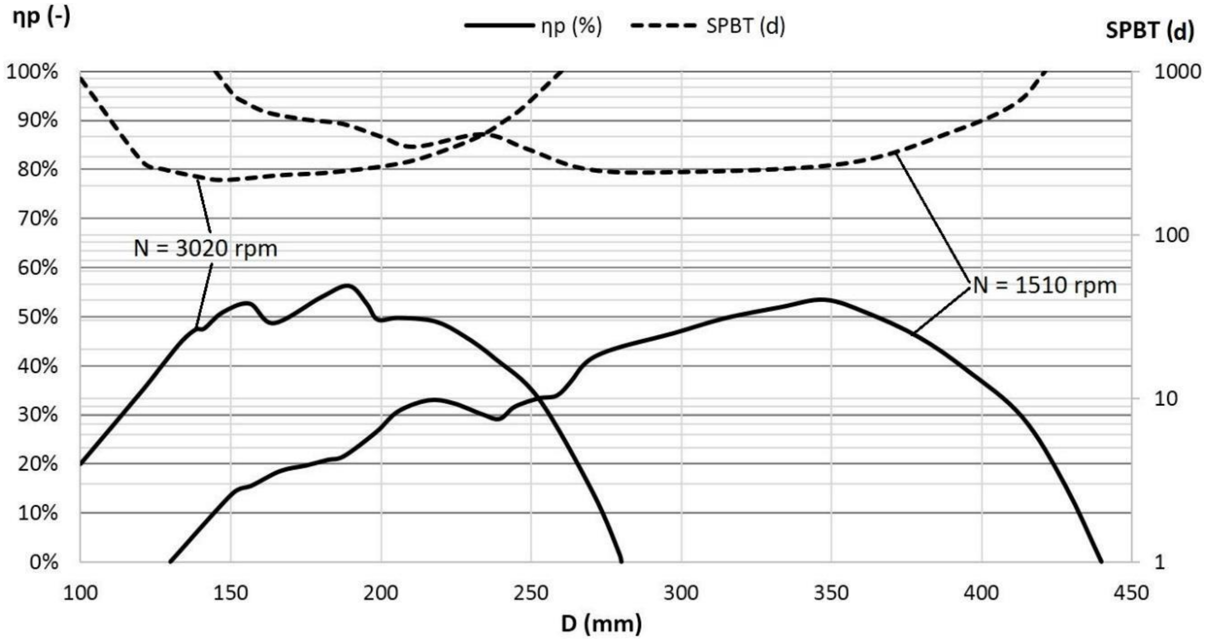

Figure 4 - η_p and SPBT versus impeller diameter for a PAT operated in HR mode

Final considerations

PAT cost model

The calculated PAT+generator unit cost compares favourably with previously published data on conventional MHP turbines [30]. In addition, four linear correlations were found which can be applied to estimate the total purchase price of a PAT as function of nominal flow rate and head drop across it.

The main inaccuracies involved in the PAT cost model determination are linked to the assumption of equal maximum efficiency between pump and turbine mode and to the use of the Yang et al. empirical equations for the prediction of the turbine working point coordinates.

PRVs substitution with PATs

The results of the study are in good agreement with the referenced literature, showing that several advantages occur if a PAT inserted within a WSS is fitted with control devices enabling HR. Namely:

1. higher possible energy yield, enabling a maximum plant efficiency η_p in the range 54-56% with a significant increase over the 31-38% achievable by an unregulated PAT;

2. despite the higher investment cost brought by the by-pass and associated valves, the SPBT in HR mode is comparable to the one achievable in absence of regulation devices.

Besides, in HR configuration the PRV in series to the turbines allows the network operator to maintain at any given time the desired backpressure while the automated by-pass ensures that the prerequisites of flexibility and reliability of the network are met even under non-ordinary situations (e.g. sudden flow rate increase to feed fire hoses).

Even though the calculated payback time achievable by installing a PAT as complement or replacement of the analysed PRV fell in a promising range between 180 and 240 days, in reality such values could turn to be overoptimistic. Indeed, actual projects could require for additional financial efforts (e.g. site-specific civil works, manpower, capital costs, purchase of sensors and electric cabinets) which haven't been accounted for in the present research.

Additionally, since the results of PAT sizing according to η_p maximization and SPBT minimization shown in Figures 3-4 did not lead to equal results it would be advisable to design a determined PAT scheme according to economic parameters with priority over merely technical parameters and eventually compare the two outcomes.

The optimal size of PAT impellers in HR mode is larger than the one calculated in the scenario with an unregulated PAT. The reason for it is that in absence of a bypass the turbine must be undersized in order not to generate unacceptably high head drop at large flow rates.

As a limitation of the performed analysis, the even partial application of affinity laws to modify the impeller size of sampled PATs could be a potential source of error. This shall be limited in the future by selecting a database of PATs with a range of impeller diameters close to that shown in the results of the analysis

Acknowledgements

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Conflict of interest

The authors declare no conflict of interest.

References

[1] IRENA, "Renewable energy technologies: cost analysis series - Hydropower," 2012.

[2] O. Paish, "Micro-hydropower: status and prospects," in Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2002.

[3] EPA, "Water and Energy Efficiency at Utilities and in the Home," 2017. [Online]. Available: https://www.epa.gov/sustainable-water-infrastructure/water-and-energy-efficiency-utilities-and-home. [Accessed 12 February 2017].

[4] S. Pabi and al., "Electricity use and management in the municipal water supply and wastewater industries," Electric Power Research Institute & Water Research Foundation, 2013.

[5] A. McNabola, P. Coughlan, L. Corcoran, C. Power, A. P. Williams, I. Harris, J. Gallagher and D. Styles, "Energy recovery in the water industry using micro-hydropower: an opportunity to improve sustainability," Water Policy, vol. I, no. 16, pp. 168-183, 2014.

[6] A. Carravetta, G. Del Giudice, O. Fecarotta and H. M. Ramos, "Energy production in water distribution networks: A PAT design strategy," Water resources management, vol. 26, no. 13, pp. 3947-3959, 2012.

[7] P. Mistry, "Pressure management to reduce water demand & leakage," Wide Bay Water Corporation, Australia, 2011.

[8] M. Giugni, N. Fontana and D. Portolano, "Energy saving policy in water distribution networks," Renewable Energy Power Qual., vol. J, no. 7, pp. 1-6, 2009.

[9] H. M. Ramos, D. Covas and L. Araujo, "Válvulas Redutoras de Pressão e Produção de Energia," in 7º Congresso da Água, LNEC, Lisbon, 2004.

[10] H. M. Ramos, D. Covas, L. Araujo and M. Mello, "Available energy assessment in water supply systems," in XXXI IAHR Congress, Seoul, Korea, 2005.

[11] T. Gaius-obaseki, "Hydropower opportunities in the water industry," International Journal of Environmental Sciences, vol. 1, pp. 392-402, 2010.

[12] H. M. Ramos, M. Mello and P. K. De, "Clean power in water supply systems as a sustainable solution: from planning to practical implementation," Water science and technology: water supply, vol. 10, pp. 39-49, 2010.

[13] A. Williams, "Pumps as turbines: a user's guide," Intermediate Technology Development Group (ITDG), London, 1995.

[14] A. Williams, "Pumps as turbines for low cost micro hydro power," Renewable Energy, vol. I, no. 9, pp. 1227-1234, 1996.

[15] J.-M. Chapallaz, P. Eichenberger and G. Fischer, Manual on pumps used as turbines, Vieweg, 1992.

[16] G. A. Caxaria, D. d. M. Sousa and H. M. Ramos, "Small scale hydropower: generator analysis and optimization for water supply systems," Hydropower Applications, vol. 6, p. 1386, 2011.

[17] P. Singh, "Optimization of internal hydraulics and of system design for PUMPS AS TURBINES with field implementation and evaluation," Diss. Institut für Wasserwirtschaft und Kulturtechnik, Universität Karlsruhe (TH), 2005.

[18] C. Alatorre-Frenk, "Cost minimisation in micro-hydro systems using pumps-as-turbines," PhD Diss., University of Warwick, 1994.

[19] L. Corcoran, A. McNabola and P. Coughlan, "Energy recovery potential of the Dublin region water supply network," in Water Congress on Water, Climate and Energy, Dublin, 2012.

[20] T. Lydon, P. Coughlan and A. McNabola, "Pump-as-turbine: Characterization as an energy recovery device for the water distribution network," Journal of Hydraulic Engineering, vol. 43.8, pp. 1 – 10, 2017.

[21] A. A. Lahimer, M. A. Alghoul, K. Sopian, N. Amin, N. Asim and M. I. Fadhel, "Research and development aspects of pico-hydro power," Renewable and Sustainable Energy Reviews, vol. 16.8, pp. 5861-5878, 2012.

[22] KSB, "Electricity recovery system Breech – Scope of supply and project details," 2008.

[23] H. M. Ramos, I. Samora, T. Salqueiro, N. Carriço, D. Covas and A. Monteiro, "Intervention concepts for energy saving, recovery and generation from the urban water system," Lisbon, 2014.

[24] J. M. Livramento, "Central micro-hídrica incorporada em adutora, M.Sc. Thesis for Renewable Energies and Energy Management," Faculdade de Ciências e Tecnologia, Universidade do Algarve, Faro (PT), 2013.

[25] H. M. Ramos and A. Borga, "Pumps as turbines: an unconventional solution to energy production," Urban Water, vol. 1, no. 3, pp. 261-263, 1999.

[26] M. De Marchis, C. M. Fontanazza, G. Freni, A. Messineo, B. Milici, E. Napoli, V. Notaro, V. Puleo and A. Scopa, "Energy recovery in water distribution networks. Implementation of pumps as turbine in a dynamic numerical model," in Procedia Engineering, 2014.

[27] O. Fecarotta, C. Aricò, A. Carravetta, R. Martino and H. M. Ramos, "Hydropower potential in water distribution networks: Pressure control by PATs," Water Resources Management, vol. 29, no. 3, pp. 699-714, 2015.

[28] H. M. Ramos, A. Borga and M. Simão, "New design solutions for low-power energy production in water pipe systems," Water Science and Engineering, vol. 2, no. 4, pp. 69-84, 2009.

[29] A. Carravetta, G. Del Giudice, O. Fecarotta and H. M. Ramos, "PAT design strategy for energy recovery in water distribution networks by electrical regulation," Energies, vol. 6, no. 1, pp. 411-424, 2013.

[30] B. Ogayar and P. G. Vidal, "Cost determination of the electro-mechanical equipment of a small hydro-power plant," Renewable Energy, vol. 34, no. 1, pp. 6-13, 2009.

[31] J. R. Couper, W. R. Penney and J. R. Fair, Chemical process equipment: selection and design, Gulf Professional Publishing, 2009.

[32] A. Carravetta, G. Del Giudice, O. Fecarotta and H. M. Ramos, "Pump as turbine (PAT) design in water distribution network by system effectiveness," Water, vol. 5, no. 3, pp. 1211-1225, 2013.

[33] T. Agarwal, "Review of pump as turbine (PAT) for micro-hydropower," International Journal of Emerging Technology and Advanced Engineering, no. 2.11, pp. 163-168, 2012.

[34] H. Nautiyal, V. Varun, A. Kumar and S. Y. S. Yadav, "Experimental investigation of centrifugal pump working as turbine for small hydropower systems. , 1(1), 79-86.," Energy Science and Technology, vol. 1, no. 1, pp. 79-86, 2011.

[35] S. S. Yang, S. Derakhshan and F. Y. Kong, "Theoretical, numerical and experimental prediction of pump as turbine performance," Renewable Energy, no. 48, pp. 507-513, 2012.

[36] P. N. Garay, "Using pumps as hydro turbines," Hydro Review, no. 9.5, pp. 52-61, 1990.

[37] S. Derakhshan and A. Nourbakhsh, "Experimental study of characteristic curves of centrifugal pumps working as turbines in different specific speeds," Experimental thermal and fluid science, vol. 3, no. 32, pp. 800-807, 2008.

[38] Rentricity Inc., [Online]. Available: rentricity.com.

[39] B. H. Teuteberg, "Design of a Pump-As-Turbine Microhydro System for an Abalone Farm," Department of Mechanical and Mechatronic Engineering, Stellenbosch University, 2010.

[40] T. V. R. Calado, Diss. Microprodução de energia, Caso de Loures, Lisbon: Instituto Superior Técnico, 2014.

[41] S. Scafa, Diss. Characteristic curves towards micro-generation applications, Lisbon: Instituto Superior Técnico, 2014.

[42] A. R. Simpson and A. Marchi, "Evaluating the approximation of the affinity laws and improving the efficiency estimate for variable speed pumps," Journal of Hydraulic Engineering, vol. 139, no. 12, pp. 1314-1317, 2013.

7 OTHER APPLICATIONS

Two New Metrics for Fan System Efficiency: Fan Energy Index and Fan Electrical Power

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Abstract

Two new metrics have been developed by the Air Movement and Control Association (AMCA) International and its member companies to support fan efficiency codes, standards, regulations, and rebate programs. Fan energy index (FEI) and fan electrical power (FEP) are wire-to-air, design-point metrics that emphasize compliant fan selections based on operating points. This drives better fan selections for fan type and size. The alternative metric used in U.S. energy codes, fan efficiency grade (FEG), is based on the peak total fan efficiency and considers the fan without a motor or drive. It was used in codes and standards that set minimum FEG levels.

FEI and FEP are metrics that emerged from a U.S. Department of Energy (DOE) rulemaking, which has not been completed. These metrics also are being considered by the State of California in the preliminary stages of its appliance energy efficiency code.[70] AMCA currently is in an advanced stage of publishing a calculation standard that defines FEI and FEP, which, when complete, will be submitted for consideration to ISO for use in its fan efficiency standard.

This paper describes FEI and FEP and how these metrics may be used in regulations and rebate programs.

Introduction

Fan efficiency is particularly sensitive to operating conditions, which often leads to fans wasting energy due to design and installation problems. Energy waste can happen for several reasons, including poor inlet and outlet conditions (known as system effect); poor distribution system design or installation practice, such as too many elbows, elevation changes, or air leaks; inappropriate fan size; mismatch of fan type to the application; or a mix of these.

Equipment-level energy standards, such as those imposed by federal and state regulations, would focus on the fan itself at the point of manufacture and labeling. Codes and standards for buildings and energy can regulate design-phase fan sizing and selection. Rebates can add an additional level of efficiency for new construction and retrofits. Requirements for commissioning can help resolve some design-phase and construction-phase issues.

What FEI and FEP provide are metrics that drive better design-phase and procurement decisions by factoring in intended operating points and motor and drive efficiencies as part of the equipment-level metric. Moreover, the metrics are numerically simple, enabling labeling that could facilitate easier code enforcement and commissioning.

FEI and FEP are not currently used in any published regulation or standard; in fact, AMCA International is still completing a consensus-based calculation standard that can be referenced in codes, standards, and regulations. The current complete draft of AMCA Standard 208 currently is in its approval stage.

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[70] Note: California is not considering including this in its building energy code.

Two fan efficiency equipment regulations are currently underway. The DOE initiated a rulemaking[71] in 2010, which currently is stalled without having published a draft test/labeling standard or a draft efficiency standard. The DOE rulemaking did progress to the point where it identified FEI and FEP as the recommended metrics for fan efficiency representation.

Based largely on the DOE work to date, the State of California is actively developing an equipment-level regulation for fans. Additionally, the ASHRAE Special Standing Project Committee (SSPC) 90.1 Mechanical Subcommittee and the ASHRAE Technical Committee 5.1 for Fans also have begun collaborating on updating the ASHRAE Standard 90.1 fan efficiency provision. ASHRAE also is considering FEI and FEP as the foundation for fan efficiency representation, which would mean abandoning the FEG metric that first appeared in ASHRAE 90.1 in 2013.

Since the FEG rating standard, AMCA Standard 205, was first published by AMCA International in 2010 [1], the fan engineering community has substantially advanced its understanding and treatment of fan efficiency, leading to the development of FEI and FEP. The DOE provided the motivation for much of the development when they released a rulemaking framework document in February 2013 [2]. In this framework document, the DOE indicated a preference for a metric based on electrical power consumption. This was a departure from FEG. FEG is an efficiency representation closely tied to what could be described as the base fan unit, commonly called a bare fan. A bare fan typically consists of the fan impeller, a drive shaft, and a fan housing (if present) but does not include motors and drives [3]. FEG is incomplete with respect to "extended product" approaches taken for other motor-driven loads (i.e., clean water pumps) in the U.S. and Europe [4][6]. FEG on its own is not capable of estimating electrical input power to the fan system. The concept of FEG was extended to a wire-to-air metric with the introduction of the fan motor efficiency grade (FMEG) described in ISO Standard 12759 in 2010 [7]. ISO Standard 12759 is employed in European fan-efficiency regulations effective January 2012 [4]. Although FMEG is a wire-to-air metric, it remains a first-generation metric based on a fan system's capability to operate efficiently. Differences between the FEG and FMEG metrics and how these metrics are applied in U.S. and European fan efficiency regulations are described in a paper presented at CIBSE/ASHRAE Technical Symposium in Dublin, Ireland, in 2014 [5].

During the DOE rulemaking process, a fan working group was established consisting of more than 20 stakeholders under the direction of the Appliance Standards and Rulemaking Federal Advisory Committee (ASRAC). The effort was completed with the publication of a term sheet [8]. The term sheet embodies the consensus-based stakeholder recommendations to the DOE of what the DOE regulation should contain.

In the course of the rulemaking, DOE also published three "Notice of Data Availability" (NODA) packages containing analytical reports and spreadsheets. The term sheet and three NODAs led to hundreds of comments being posted to the public docket, adding considerable technical information and industry points of view to the record. However, more than six years after the rulemaking was initiated, the DOE has yet to publish a notice of proposed rule (NOPR) for the test procedure, labeling requirements, or efficiency standard requirements. Therefore, the ASRAC term sheet provides the best indication of the direction the DOE was taking for an equipment-level fan efficiency regulation.

Key recommendations of the term sheet are the test procedure basis (which is AMCA Standard 210) and the FEP and FEI metrics [9].

Because the DOE has not yet published a test standard that would formalize the definitions and calculation procedures for FEI and FEP, AMCA initiated the standard-development process for these tasks, which will take the form of AMCA Standard 208. This standard will be used in conjunction with the AMCA Standard 210 test standard for

[71] The rulemaking is being administered by the Appliance and Equipment Standards Program within the Office of Energy Efficiency and Renewable Energy.

commercial and industrial fan rebate programs [10]. Because AMCA Standard 210 is harmonized with ISO 5801 [11], ISO 5801 can be used to calculate FEI and FEP. Furthermore, AMCA has recently published a standard that enables calculation of FEP and FEI using measured and default values for motors, variable speed drives, and belt drives. AMCA Standard 207, *Fan System Efficiency and Fan System Input Power Calculation* [12], is a rating standard that provides a method to estimate the input power and overall efficiency of an extended fan system. AMCA Standard 208 is being drafted with a target publication date in the winter of 2017.

Characteristics of FEI and FEP

When the DOE initiated the commercial and industrial fans rulemaking in 2011, the U.S. had already settled on the FEG metric and its reference standard, AMCA Standard 205, for fan efficiency provisions in model energy codes and standards for energy efficiency and green construction [1][3], namely the *International Green Construction Code* [13], ASHRAE 90.1 [14], ASHRAE 189.1 [15], and the *International Energy Conservation Code* [16]. The FEG provision remains in the subsequent editions of each of these publications and is slowly making its way into state energy codes. To date, 11 states in the U.S. are known to have FEG-based fan efficiency provisions adopted in model codes and standards.[72]

The DOE initiated the rulemaking for commercial and industrial blowers in June 2011 [17], well after the path had been set for FEG in model codes and standards. The framework document signaled the DOE's preference for a wire-to-air metric based on electrical input power consistent with recent regulatory approaches toward electrically driven pumps.

A significant shortcoming of FEG is that the metric alone is not sufficient to establish energy-saving regulations or code provisions. By design, FEG ratings remain constant across different sizes of the same geometrically similar model even though fan efficiency varies, sometimes radically, for a given operating point (Figure 1). For example, a manufacturer's hypothetical fan Model #123 may be geometrically similar across all fan sizes offered and have an FEG rating of 67 across all its sizes. Thus, when an engineer is selecting a fan for a given application, the sizing/selection software could provide an array of sizes to select from, say, 18-inch (460 mm) diameter to 36-inch (920 mm) diameter (Table 1) [18]. These results, however, can result in sizes that have an identical FEG rating yet consume significantly different amounts of power and have correspondingly different efficiency values at the operating point or point of rating.

[72] FEG uptake into state energy codes is coming through gradual adoption of the 2015 edition of *International Energy Conservation Code* and ASHRAE 90.1-2013. AMCA looked at the state-by-state adoption record of these editions at the Building Codes Assistance Project website (http://bcapcodes.org/code-status/state/) and examined the published state codes to ensure the FEG provision carried through the adoption process.

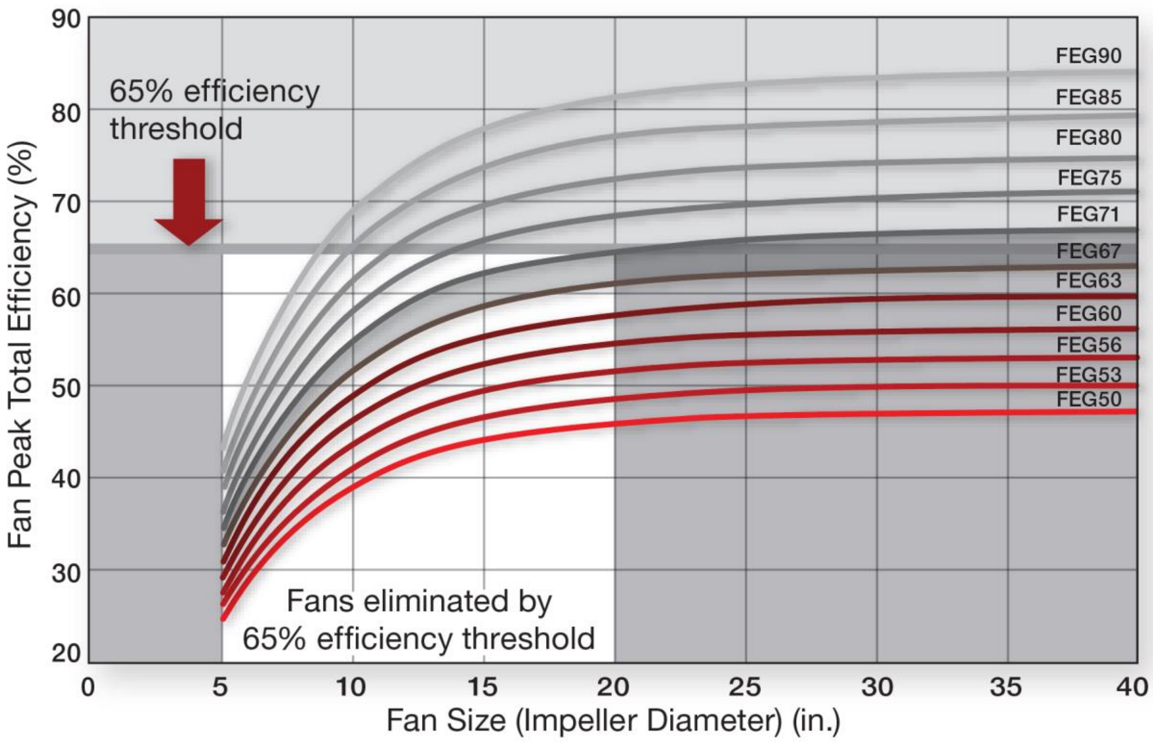

Figure 1: FEG ratings with sizing/selection window used to limit fan selections to larger sizes. FEG curves were developed from numerical analysis of fan data from manufacturers around the world. The 65 percent efficiency threshold was a starting point for energy standards but was removed because it eliminated fan selections below 20-inch diameter.

A unique characteristic of fans is that those of similar geometric design but different sizes (based on impeller diameter) can operate at a similar duty point, with a duty point defined as a fan delivering a specified flow and pressure. Figure 2 below demonstrates this phenomenon. Although only one fan size consumes the minimum power, other sizes of fan can deliver an identical flow-pressure operating condition. These fans, in theory, would have identical FEG ratings. Yet when they are applied, they consume vastly different amounts of energy.

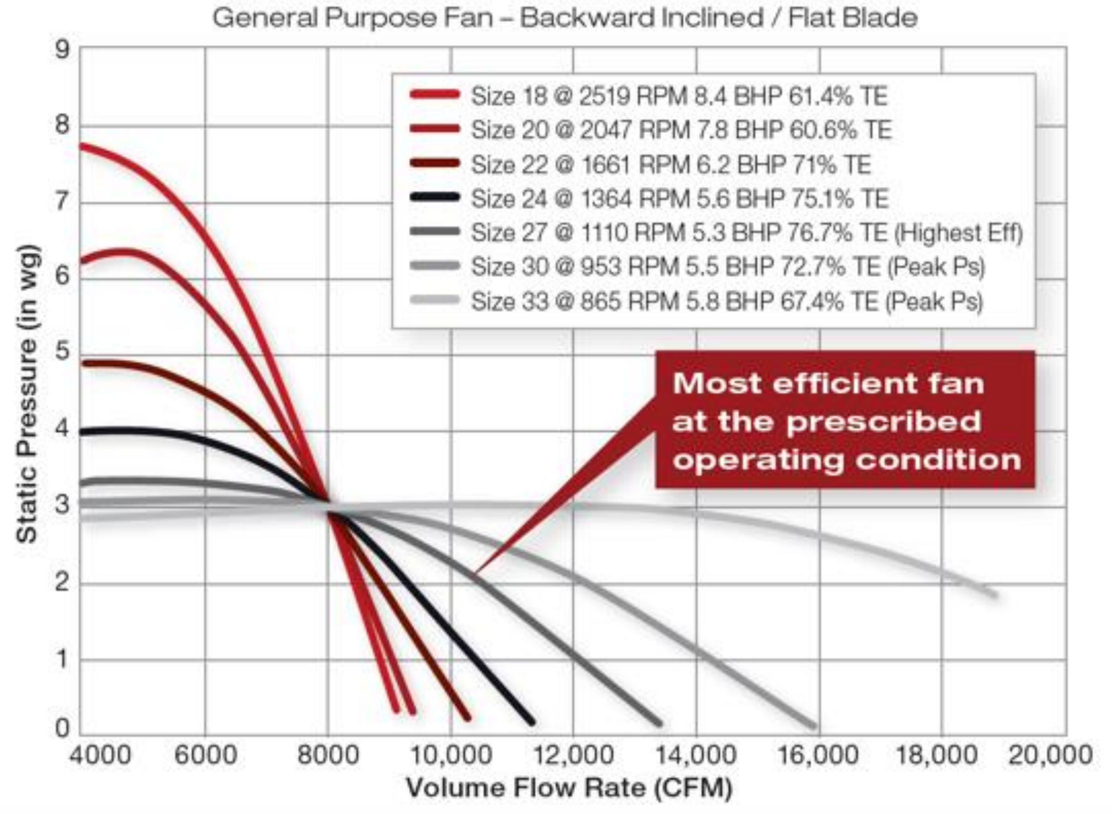

Figure 2. Variety of fans of similar geometric design operating at an identical duty point. Source: New York Blower Co.

This condition is similarly displayed in Table 1. Table 1 displays the output of a manufacturer's sizing/selection program for a double-width, double-inlet fan sized/selected for 80,000 cfm (37,755 l/s) at three-inch (747 pa) static pressure. The operating costs are based on a run time of 16 hours per day, 250 days per year, and an electricity cost of $0.10 per kWh.

Table 1: Impact of Fan Size on Annual Power Consumption and Operating Cost

Diameter (in.) [mm]	FEG Rating	Total Efficiency (%)	Operating Power (hp) [kW]	Price ($)	Operating Cost Per Year ($)	Weight (lbs) [kg]
36 [920]	85	56	114 [85]	21,200	37,797	2,330 [1,056]
40 [1016]	85	62	90 [67]	16,100	29,939	2,850 [1,293]
44 [1118]	85	68	74 [55]	16,900	24,402	3,570 [1,619]
49 [1245]	85	77	60 [45]	17,600	19,926	4,170 [1,891]
54 [1372]	85	78	56 [42]	20,300	18,401	5,200 [2,359]
60 [1524]	85	81	51 [38]	23,800	16,976	6,310 [2,862]

Data courtesy of Greenheck Fan Corp.

As can be seen, the fans of smaller diameter operate less efficiently and, as a result, consume more energy than fans of larger diameters to meet the airflow requirements at a given pressure. An investment of the $7,700 price differential for the larger fan could pay for itself in less than one year from reduced electrical costs of approximately $12,960 per year.

To encourage engineers to select fans closer to their optimum energy efficiency capability as applied, FEG-based code provisions needed to include a clause to limit fan operating points to be "within 15 percentage points of the fan's peak total efficiency" (Figure 3) [3][15][16][17]. This clause results in FEG-based provisions being difficult to enforce because labels alone cannot be used for compliance. Code officials must refer to engineering submittals to verify compliance with the sizing/selection requirements.

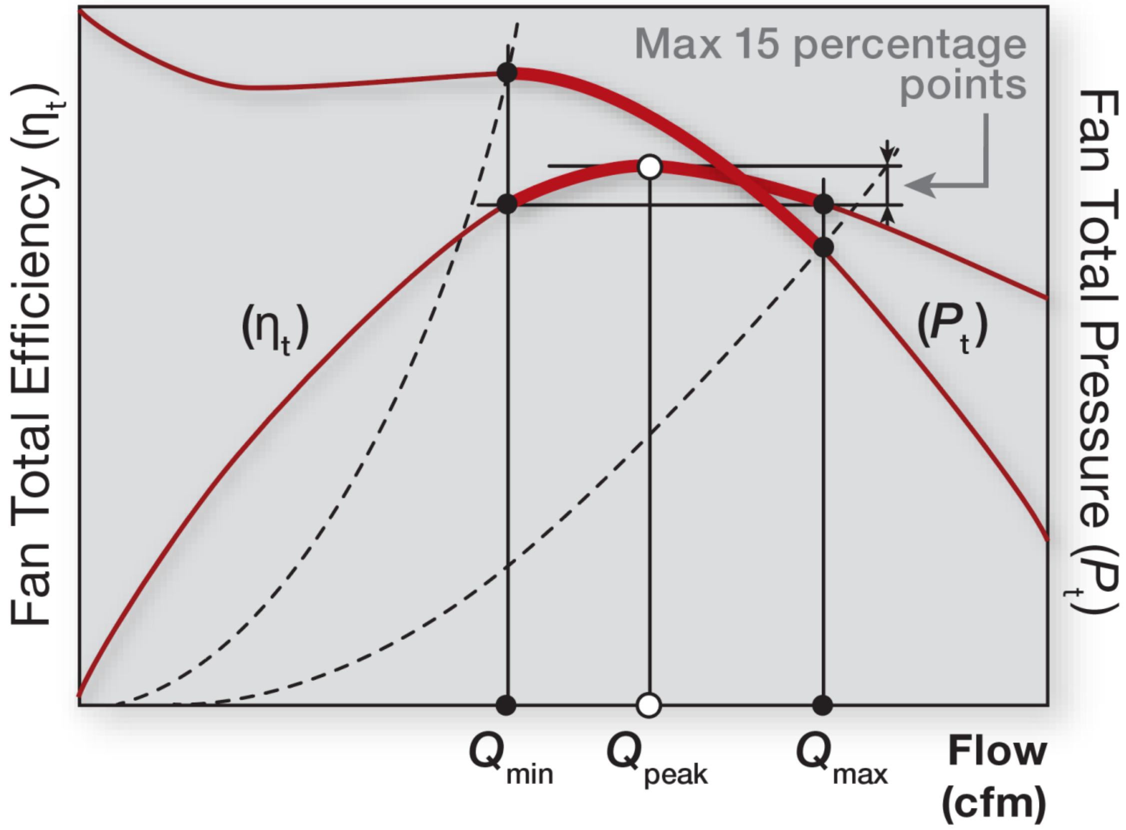

Figure 3. Typical fan curve showing total efficiency vs airflow vs total pressure. The sizing/selection window of 15 percentage points also is showing, which is applied during the design phase to lead toward higher efficiency fan selections.

FEI, however, as will be shown later, has the operating point characteristics incorporated in the calculation, so compliance officials for any program, code, or regulation need only check the FEI rating on the label to ensure compliance [9]. Table 2 exemplifies the advantage of FEI over FEG for compliance purposes. In Table 2, a baseline FEP rating has been assumed to compute an FEI value. Fan sizing/selection data are displayed for a design point of 10,000 cfm (4,719 l/s) at 3.0 inches (747 pascal) total pressure.

Table 2: Data Comparing FEG with FEI for Multiple Sizes of the Same Fan Model

Fan Size [in.] (mm)	**Fan Speed (rpm)**	**Fan Power (bhp) [kW]**	**Actual Total Efficiency (%)**	**Baseline Power**	**FEG**	**FEI**
18 (460)	3,238	11.8 [8.8]	40.1	7.96	85	0.67
20 (510)	2,561	9.6 [7.2]	49.5	7.96	85	0.83
22 (560)	1,983	8.0 [6.0]	59.0	7.96	85	0.99
24 (610)	1,579	6.8 [5.0]	69.1	7.96	85	1.16
27 (685)	1,289	6.2 [4.6]	75.8	7.96	85	1.28
30 (770)	1,033	5.7 [4.3]	82.5	7.96	85	1.39
36 (920)	778	6.0 [4.5]	78.7	7.96	85	1.32

Data courtesy of Greenheck Fan Corp.

Table 2 clearly shows fans of similar geometric design, thus carrying a similar FEG rating, having their respective energy consumption values and efficiencies communicated through FEI values.

FEP and FEI are wire-to-air metrics consistent with the regulatory approaches being taken for other motor-driven loads, such as pumps and air compressors. AMCA considers FEP and FEI as second-generation metrics because they employ duty-point ("sizing and selection") specifications in the metric in a manner acceptable to the DOE. ("Acceptable" is based on the DOE carrying them into the most recent NODA [19]). With these basic conditions in place, FEP and FEI stand to introduce novel ways efficiency programs can be developed, and they stand to completely change how fans are sized, selected, and specified by practitioners.

As referenced in the ASRAC term sheet [8], FEI is calculated as the ratio of the actual fan system efficiency to a baseline fan system efficiency (Equation 1), both calculated at a given airflow and pressure point. The phrase "fan system" is used to imply the incorporation of motors, transmission systems, and controls in the efficiency calculation. The baseline used in the equation is defined in AMCA 208 within the definition for a reference fans as, "A conceptual fan used to relate all fans to a common baseline. The reference fan is one capable of producing the required airflow and fan pressure at a specified shaft input power, uses a V-belt transmission, has a motor efficiency based on a 4 pole, 60 Hz, IE3 motor, and does not include a speed control."

Because the actual and baseline efficiencies are calculated at the same airflow and pressure, FEI is also defined as the ratio of the baseline electrical power to the actual electrical power of a fan (Equation 2) [8].

$$FEI = \frac{Fan\ \text{System}\ Efficiency}{Baseline\ Fan\ \text{System}\ Efficiency} \qquad \text{Eq. 1}$$

$$FEI = \frac{Baseline\ Fan\ Electrical\ Input\ Power}{Electrical\ Input\ Power} \quad \text{Eq. 2}$$

Equation 2 is equivalent to Equation 1, but because the goal of mandatory and voluntary programs is to reduce energy consumption, Equation 2 is preferred. Reducing electrical power consumption and the corresponding calculation of energy savings has more relevancy and value to regulatory bodies than merely increasing energy efficiency. Equation 2 also is easier to apply and has the added benefit of working along the entire fan curve.

Equation 2 implies an intermediary calculation leading to FEI—the measurement or calculation of FEP. FEP is obtained either by directly measuring fan electrical input power during rating tests, or it is calculated by measuring fan shaft power and incorporating default values for motors, drives, and controls [8]. The default values are defined in AMCA Standard 207 [12]. Fan rating tests can be conducted using AMCA Standard 210 [10], which the ASRAC fan working group agreed to as being the basis of the DOE test standard per the ASRAC term sheet [8].

Once the FEP rating of a fan system is calculated, it is compared against a baseline FEP, called FEP_{std}, as shown in Equation 3. Note FEP has engineering units of kW corresponding to electrical input power [8]. Also note FEI is a unitless ratio.

$$FEI = \frac{FEP_{std}}{FEP\ rating} \quad \text{Eq. 3}$$

FEI and FEP are technology neutral in that they inherently lead to a fan selection that requires the least amount of power consumption for the duty point.

Table 3 displays possible applications of FEI for regulations and voluntary incentive programs [9].

Table 3: How FEI can be applied in regulatory and voluntary programs.

Fan Regulatory or Voluntary Program Body	**Possible FEI Requirement**
U.S. Department of Energy	FEI ≥ 1.0 at Design Point
ASHRAE 90.1 or International Energy Conservation Code	FEI ≥ 1.0 at Design Point
ASHRAE 189.1	FEI ≥ 1.1 at Design Point
Utility Incentive Programs	FEI ≥ 1.1 at Design Point

A useful characteristic of FEI is that for FEI ratings greater than one, the amount of energy savings over the baseline can be directly calculated. Subtracting 1 from the FEI rating results in a percentage reduction in energy consumption. For example, a fan rated FEI = 1.1 uses 10 percent less energy than the baseline requirement. This makes FEI useful for calculating relative energy savings between any two fans or between a fan and the FEI threshold in a fan code/standard/regulation provision.

Applying the FEI Metric

Instead of specifying a minimum peak efficiency level for the each of the various fan types, the FEI establishes a baseline efficiency and resulting baseline power that varies with both airflow and pressure that can be universally applied to all fan categories [20]. FEI defines a compliant range of operation, not a single compliant efficiency threshold.

For a single speed fan curve, the compliant range is a subsection of the total fan curve. This is shown graphically in Figure 4 below [21].

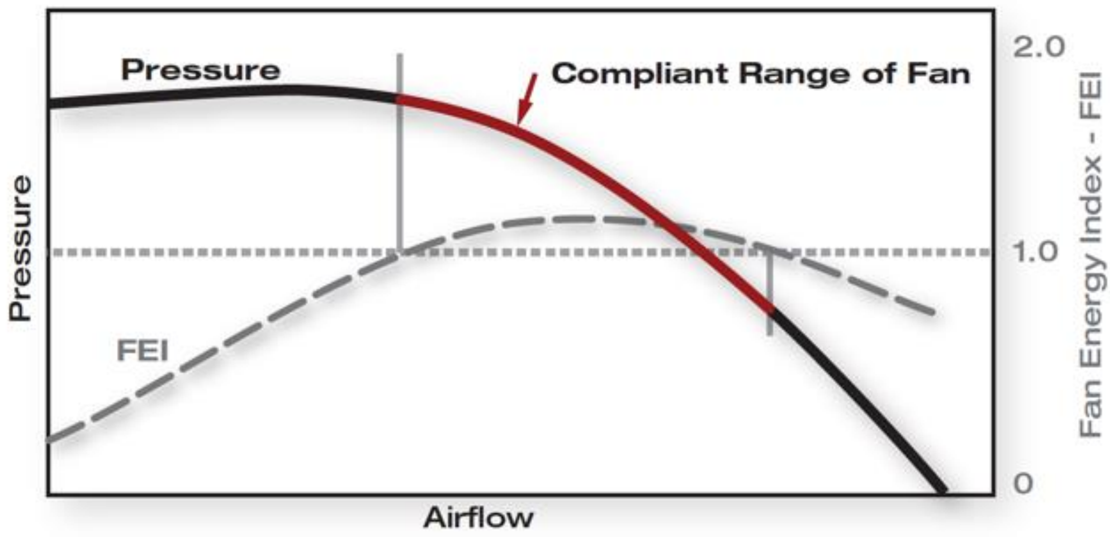

Figure 4. Compliant range of operation for a fan operating at a single speed.

When fan curves are created at multiple speeds, as would be the case when operated with a variable frequency drive (VFD), these compliant zones take on the appearance of bubbles, with the size of the bubble being proportional to fan efficiency. Generally, the more efficient the fan, the larger the compliance bubble. In some cases, however, fans can be very efficient over a small operating range. The shaded regions in Figure 5 show the FEI 1.0 bubble [20]. Assuming an FEI value of 1.0 indicates compliance, the shaded regions indicate fan operating conditions that would be in compliance.

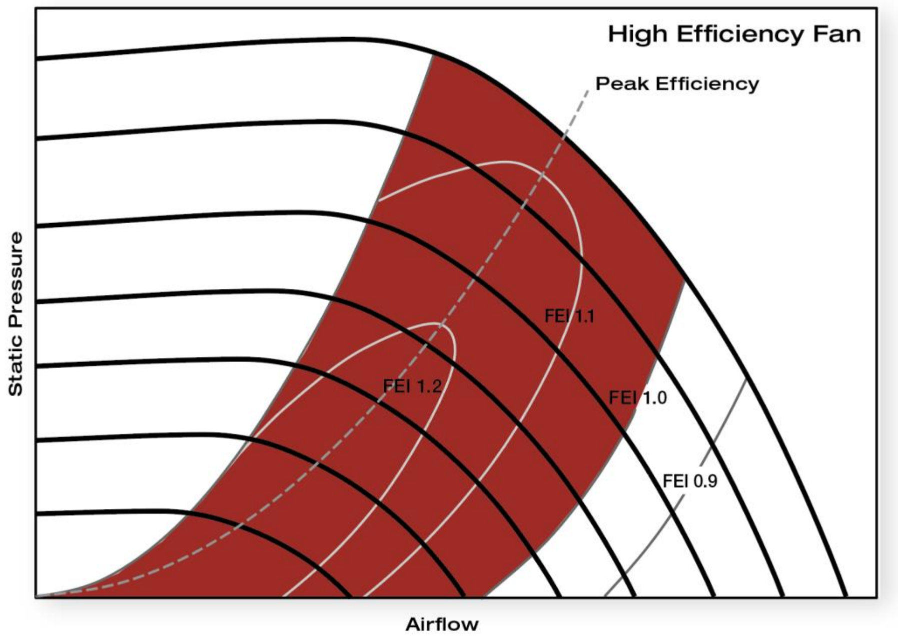

Figure 5. Compliance bubble for a high-efficiency fan operating at multiple speeds, such as those using a variable-speed drive. The colored region shows FEI 1.0 and higher with the larger FEI levels having smaller bubble regions. The high-efficiency fan has a larger FEI compliance bubble than lower-efficiency fans.

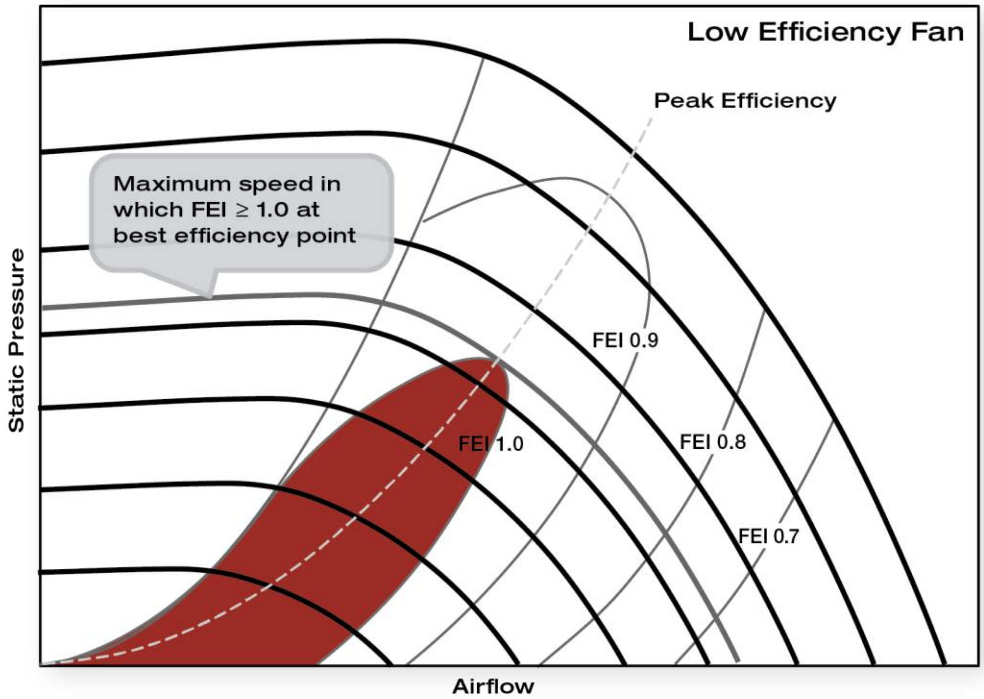

Figure 6. Compliance bubble for a low-efficiency fan operating at multiple speeds, such as with a variable speed drive. Note the smaller compliance region FEI = 1.0 compared to the higher-efficiency fan in Figure 5.

In Figure 6, a label for fan speed indicates the maximum speed at which the fan can be operated and comply. This gives operators and engineers an opportunity to set up variable speed drives and belts to restrict fan speed. Manufacturers would include such diagrams or their tabular equivalents in product literature and sizing/selection software.

The ratio of fan power to this baseline power at design conditions is used to package the metric and make it easier to use for customers, owners, regulatory bodies, and utility rebate programs.

Selection of the baseline value for the calculation of FEP_{std} is an important component of the approach and the corresponding calculation of FEI [8]. FEP_{std} will need to be specified to represent a reasonable efficiency. Regulations can be written around FEP_{std} as documented in the ASRAC term sheet [8]. However, a regulation or program written around a FEI of 1.0 could serve as an optimal FEI requirement, for example, for most types of fans. Exceptions for an FEI value less than 1.0 could include fans used for variable air volume (VAV) systems to encourage more use of VAV systems [20]; fans used infrequently, such as emergency fans; or fans used for material handling.

Table 3 also implies high-performance building standards (such as ASHRAE 189.1) or utility rebate programs could set FEI requirements to be greater than the baseline requirement. In the current fan efficiency provision in ASHRAE 189.1, additional stringency is added to the corresponding ASHRAE 90.1 provision by making the sizing/selection window smaller—from 15 percentage points to 10 [15]. This is because more energy is saved by further restricting fan selections to operate close to their peak efficiency capabilities rather than increasing the FEG rating from 67 to the next level up, FEG 71. The approach taken by ASHRAE 189.1 further validates the utility of having sizing/selection criteria incorporated into a metric.

Regulators determine baselines for energy conservation standards by balancing goals for energy savings, the benefit to consumers, and the impact on stakeholders. Different regulatory entities may have different imperatives and cost-benefit analysis processes, as well as diverse stakeholders promoting a variety of advocacy positions. The FEI metric also supports expected increases in codes and regulations over time as fan technology improves. The baseline FEI can be changed, for example, from 1.0 to 1.1. This would nudge requirements higher while also preserving the integrity of fans labeled with FEI ratings set previously. A fan's label showing FEI 1.0, indicating compliance with a current requirement of FEI 1.0, would be valid in the future if the requirement was raised to a higher FEI value. A building owner replacing the fan under the future regulation could replace the FEI 1.0 fan with a FEI 1.2 fan.

AMCA Standards

AMCA remains committed to increasing fan efficiency and reducing energy consumption independent of regulatory activities. AMCA promotes bringing FEP and FEI into the market through the development of two new rating standards, AMCA Standard 207 and AMCA Standard 208, that work with data taken from tests performed in accordance with AMCA Standard 210 (or ISO 5801) to enable calculation of wire-to-air fan system energy.

AMCA Standard 207 provides a method to estimate the input power and overall efficiency of an extended fan system. As mentioned earlier, FEP can be directly measured, and while direct measurement of fan system performance may be preferred, the large number of fan system configurations possible from assembling commodity components makes testing impractical. It is reasonable to assume a hypothetical fan manufacturer could have one fan model consisting of five sizes with five options of motors and five options of drive packages. The number of testable configurations would be 53, or 75, tests. It is also reasonable to assume this manufacturer offers dozens of models with dozens of motor and drive options across the different sizes. Testing costs quickly escalate into the hundreds of thousands of dollars, if not millions.

AMCA Standard 207 offers a standardized method to estimate fan system performance by modeling commonly used components [12]. Calculations reported in accordance with this standard offer fan users a tool to compare alternative fan system configurations in a consistent and uniform manner. The scope of AMCA Standard 207 includes all electric-motor-driven fan systems that utilize a specific combination of components as defined below:

- Fan airflow performance tested in accordance with
    - ANSI/AMCA Standard 210, *Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating*,
    - ISO Standard 5801, *Industrial fans—Performance Testing Using Standardized Airways*, or
    - Otherwise rated in accordance with AMCA Publication 211, *Certified Ratings Program—Product Rating Manual for Fan Air Performance*
- Polyphase induction motors within the scope of
    - EISA-2007 (*Code of Federal Regulations* Title 10, Chapter II, Subchapter D, Part 431, Subpart B),
    - IEC 60034-30 *Rotating electrical machines—Part 30-1: Efficiency classes of line operated AC motors*, or
    - GB 18613, *Minimum Allowable Values of Energy Efficiency and Energy Efficiency Grades for Small and Medium Three-Phase Asynchronous Motors*

(Other types of motors are explicitly excluded)

- Pulse-width modulated VFD for use with single motors
- Mechanical power transmissions that utilize V-belts

(Note: Single VFDs that service multiple parallel fan motors are excluded)

AMCA has been working with ISO to incorporate AMCA Standard 207 into ISO Standard 12759. ISO standards have a presence in some countries where AMCA standards do not.

As a result, AMCA has collaborated with ISO during the revision cycle for 12759 in an effort to create a broader range of applications for fan energy efficiency ratings. AMCA Standard 207 has been approved by the AMCA Board of Directors and is now undergoing accreditation by ANSI as the final step leading to publication. Publication is expected in the summer of 2017.

AMCA Standard 208 is currently being drafted by an AMCA committee and will use the ASRAC term sheet as a basis to rigorously define FEP and FEI and provide examples for how they can be applied

Rebate Programs

AMCA has been involved with the Extended Motor Product Label Initiative (EMPLI) program since its inception. EMPLI is a "collaborative effort involving over two dozen representatives from the motor-drive equipment manufacturing sector, trade organizations, utilities, energy efficiency program administrators, and energy efficiency nongovernmental organizations" [22].

Absent a draft or final DOE labeling requirement, Figure 7 shows a label mocked up by Twin City Fan Companies for consideration in a rebate program being developed for motor-driven loads [9].

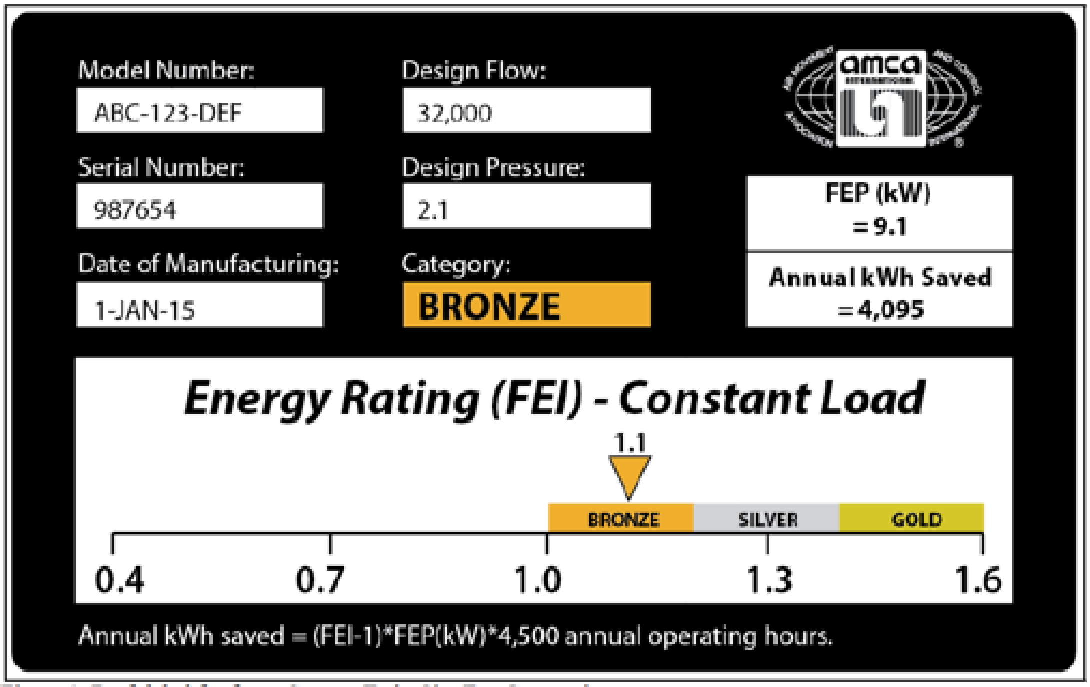

Figure 7. Draft of a possible label supporting fan rebate programs.

The Fine Points and Future of FEI

FEI is calculated as a ratio of the baseline electrical input power compared to the fan system's actual electrical input power—either measured or estimated. The calculation method of AMCA Standard 207 and the measurement method of AMCA Standard 210 are available to establish FEI as a wire-to-air metric. While code authorities and the DOE will establish minimum FEI (or maximum fan power) levels as they deem appropriate, fan suppliers and users have the freedom to meet these requirements in any manner they choose. A fan user can utilize any combination of fan, transmission, and motor and speed control if the combined FEI level meets the minimum requirement [8].

Even though FEI was developed to focus on fan energy as applied, it can also be used as an application-independent metric when the design operating point is not known [9]. This would be true for fans sold off the shelf without a motor. In this case, FEI is evaluated at the best efficiency point at the maximum published fan speed. If the fan on the shelf has a motor and drive, the distributor has the information to compute the FEI bubble. By considering this single point, the metric establishes a restricted speed range while remaining consistent with its use at the design point of operation. As shown in Figure 5, the "restricted speed size" is the maximum speed at which the fan can be operated to remain at FEI = 1.0 or greater.

While driving significant energy savings and technological improvements, FEI also encourages improved fan selection. Everywhere a consumer makes a fan selection decision, including performance tables, fan curves, or electronic selection software, the value of FEI for that selection will be shown. Consumers will know immediately how fan selections compare to the maximum baseline fan electrical input power. They will also know how the energy consumption of one product compared to another, regardless of product type, category, size, or drive method.

As with the adoption of any new metric, complications exist in the adoption of FEI. Potential barriers include the inertia of investment in fan energy efficiency metrics, the need to educate stakeholders regarding the value of the metric, generating advocacy momentum among interested parties, and gaining exposure to rulemaking processes. Code officials have communicated limitations on both time and budget for regulatory activities.

Another complication is how to administer compliance assurance using an operating-point metric. Compliance checking FEI ratings against mandatory thresholds in regulations, code provisions, and incentive programs is simple "in the field." A fan rated at an FEI level lower than the requirement is noncompliant. But, there are questions being resolved around labeling, whether non-compliant operating points will be made visible to users of fan sizing/selection software outputs, and how compliance of fans can be assured when operating points are not known at time of manufacturer (for example, fans that are stocked for off-the-shelf purchase).

Also, one valuable aspect of FEI may work against it at the same time: the metric takes into account the consumer approach toward energy consumption, complicating the metric in the process. The consumer desired a metric that specified flow and pressure and reflected energy consumed to deliver specified requirements. While this would be a beneficial change from previous metrics, which focused on a product's performance at a peak operating condition, such a step forward cannot be made without increasing complexities in the metric itself. Education and clear communication of the application of the metric will be the key to a successful adoption of FEI.

Summary

Consider these benefits to FEP and FEI:

- Supports wire-to-air, extended-product consideration of motors and drives
- Incorporates sizing/selection criteria within the metric, thus establishing entirely new ways of regulating or incentivizing energy efficiency
- Supports calculations for energy savings based on comparing fans against minimum requirements and against other fans
- Simplifies compliance checking
- Covers unducted fans, which are exempted from FEG-based code provisions due to impracticalities
- Guides practitioners to reduce wasted fan energy just by using the metric
- Enables engineers to protect specifications against post-design value engineering, resulting in lower-cost, lower-efficiency fans
- Is backward-compatible with incremental increases in regulatory or voluntary thresholds

Conclusion

FEI is a metric that allows many different types of fans to be compared on equal footing, and it does so by concentrating on the energy consumed by a fan as it is applied. It can be used by regulators and purchasers alike to make a price-sensitive market favor reduced energy consumption, helping consumers see how a fan can be affordable and efficient at the same time. Additionally, FEI can provide manufacturers with assurance they are creating energy-saving products that will appeal to their customers. It is an all-encompassing, high level solution to a complex problem.

FEI was selected by the DOE, AMCA, and other industry stakeholders to be the metric around which a federal efficiency standard would be developed. It is expected FEI will replace FEG where used in existing energy codes and standards, and it can be applied in rebate programs for commercial and industrial fans. The long, hard work that has gone into the development of this sophisticated and effective metric and supporting regulatory framework deserves to be brought to conclusion.

References

[1] AMCA. ANSI/AMCA Standard 205, *Energy Efficiency Classification for Fans*. Arlington Hts., IL: AMCA, 2012.

[2] DOE. "Energy Efficiency Program for Commercial and Industrial Equipment: Public Meeting and Availability of the Framework Document for Commercial and Industrial Fans and Blowers." Federal Register 78-FR-7306. Washington, DC: DOE, 2013

[3] Cermak J., and Ivanovich M. "Fan Efficiency Requirements For Standard 90.1-2013." ASHRAE Journal, April 2013: 24–30.

[4] EC (European Commission). "Commission Regulation (EU) No 327/2011 of 30 March 2011." Official Journal of the European Union, L90/8, 2011.

[5] Ivanovich M., and Jones N. "A Comparison of U.S. and European Approaches to Regulating Fan Efficiency." Arlington Hts., IL: AMCA, 2014.

[6] DOE. *Energy Conservation Program: Energy Conservation Standards for Pumps*; Final rule. 2016-01-26 Federal Register, 81 FR, 4368, 2016. www.regulations.gov/document?D=EERE-2011-BT-STD-0031-0060.

[7] ISO (International Standards Organization). ISO Standard 12759 *Fans—Energy efficiency classification for fans*. Geneva, Switzerland: ISO, 2010.

[8] DOE. "Term Sheet of the Commercial and Industrial Fans and Blowers Working Group." Washington, DC: DOE, 2015.

[9] Persful T., Ivanovich M., Rogers E., and Wickes G. "Look at the Extended Product Motor Labelling Initiatives for Fans." Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC: ACEEE, 2016.

[10] AMCA. ANSI/AMCA Standard 210–ANSI/ASHRAE 51, *Laboratory Methods of Testing Fans for Aerodynamic Performance Rating*. Arlington Hts., IL: AMCA, 2016.

[11] ISO. ISO Standard 5801 *Industrial fans — Performance testing using standardized airways*. Geneva, Switzerland: ISO, 2007.

[12] AMCA. ANSI/AMCA Standard 207. Arlington Hts., IL: AMCA, 2017.

[13] ICC. *International Green Construction Code*. Washington, DC: ICC, 2013.

[14] ASHRAE. ANSI/ASHRAE/IES Standard 90.1, *Laboratory Methods of Testing Fans for Aerodynamic Performance Rating*. Atlanta: ASHRAE, 2016.

[15] AMCA. ANSI/ASHRAE/IES Standard 189.1, *Laboratory Methods of Testing Fans for Aerodynamic Performance Rating*. Atlanta: ASHRAE, 2014.

[16] ICC (International Code Council). *International Energy Conservation Code*. Washington, DC: ICC, 2015.

[17] DOE. "Energy Conservation Program for Consumer Products and Certain Commercial and Industrial Equipment: Preliminary Determination of Commercial and Industrial Fans, Blowers, and Fume Hoods as Covered Equipment." Federal Register 76 FR 37678. Washington, DC: DOE, 2011.

[18] Rizzo A., and Wolf M. "Update on U.S. Fan Energy-Efficiency Regulation." HPAC Engineering, 2016. www.hpac.com/iaq-ventilation/update-us-fan-energy-efficiency-regulation.

[19] DOE (U.S. Department of Energy). *Energy Conservation Standards for Commercial and Industrial Fans and Blowers: Availability of Provisional Analysis Tools*. Washington, DC: DOE, 2017.

[20] AMCA. "Introducing the Fan Energy Index." Arlington Hts., IL: AMCA, 2017.

[21] Mathson T. "Update on the Impending U.S. Fan Efficiency Regulation." Arlington Hts., IL: AMCA, 2016.

[22] Rogers E. "Development of a New Extended Motor Product Label for Inclusion in Energy Efficiency Programs." Washington, DC: ACEEE, 2014.

Designing an energy efficient motor system from the viewpoint of an installation system within a liberal energy market

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Abstract

The costs of energy are determined by two aspects – consumption and energy prices. The consumption of a motor system can be optimized by properly fitting the components of the system and their duty profiles to the requirements of the application. The Extended Product Approach specified in EN 50598-1 and IEC 61800-9-1 can be used as a guideline for these considerations.

The cost per MWh is a matter of predictive contracting within a liberal energy market. A different demand of energy can result in tremendously higher costs due to trading on the energy stock exchange. This leads to an increasing requirement for an accurate forecast of energy consumption. This forecast is related to 15-min-periods for next week and partly to next month and even years. Therefore the observation of consumption and a well-adapted load management of each branch are a must for the future. The recently introduced standard IEC 60364-8-1 concerning energy efficiency of installation systems considers such requirements and introduces a set of criteria for an efficient installation system.

This paper discusses how to address both future requirements, namely

- using a consistent system approach taking into account the duty profile, installation and processing equipment, via motor control up to the power supply,
- implementing the different efficiency aspects of an electrical installation mainly focused of load monitoring and load management aspects.

Introduction

Depending on the industry sector (product and technology), the cost of energy accounts for about 4% (automotive, machine-building, electrical industry) to about 15%-20% (food and beverage, chemistry) up to about 30% (paper, metal producing, cement) of total production costs [1]. So energy costs play an important role within the value creation process. Of course in general, the cost of energy relates to the simple formula of price per MWh multiplied by the amount of electrical energy. However today, the price per MWh is a matter of predictive contracting within a liberal energy market, so there is not a linear correlation of energy consumption to total cost of energy. In fact it is more a matter of a correct amount of consumption within a previous planned time slot and also a question of energy quality and some other variables. In worst case conditions, a saving on energy demand is not a saving in money, but paradoxically must be paid for due to trading on the energy stock exchange.

Managing the costs of energy is a very complex matter and depends (at least) on the following influences:

- Investment in efficient infrastructure and machines (i.e. high efficiency motors)
- Usage of power factor correction, electricity storage and on-site generation of electricity
- Average consumption of energy (i.e. low base load, efficient processes and equipment)

- Load management (i.e. knowledge of load profiles / consumption, avoiding peak loads)
- Predictive contract management (knowledge about correct time-dependent consumption, contracting on the futures market and handling the spot market).

As this very simplified list already shows, everything is closely related, but three main issues can be derived:

- knowledge of load profiles,
- efficient / low consuming machinery,
- knowledge about a time-resolved consumption profile.

This paper contours existing and future needs in procurement of energy within a liberal energy market. It also shows possibilities to install and operate an efficient electrical installation system by the use of recently published standards for installation systems (IEC 60364-8-1) and for the Extended Product Approach specified in EN 50598-1 and IEC 61800-9-1.

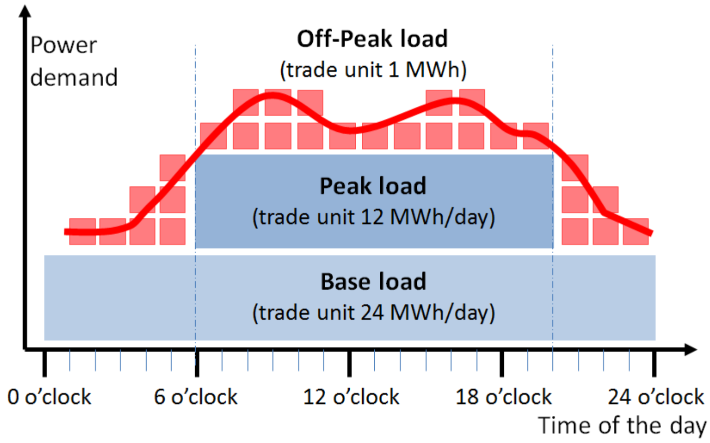

Figure 1 Contract quantities within liberal energy market

Energy contract management

Since 1996 when EU directive 96/92/EG came into force, a transparent and a competitive energy market has been established. This liberal energy market has been achieved by an unbundling approach. The generation, distribution and sales of energy are now managed by different entities. A consumer is now able to choose his electricity provider on a free market. This results in a physical and an economic layer in the delivering of energy. The balance of supply and demand is controlled by ramping up and down of power plants on the physical side. The economic side is adjusted by trading energy quantities on the stock exchange.

Industrial consumers are buying (via their electricity provider) their electricity on the futures market, namely base load (trade unit 24 MWh/day) and peak load (trade unit 12 MWh/day). The third kind - the off-peak load (trade unit 1 MWh) will be traded (sold and purchased) at spot market prices (Figure).

While base and peak load is contracted years or month ahead, off-peak load can be adjusted one day ahead and not later than 45 minutes before delivering.

Of course, base load is usually the cheapest quantity (currently about 35 EUR/MWh). Peak load is about 1/3 more expensive (currently about 45 EUR/MWh).

All additional off-peak loads (too much or too little) can be taken as a kind of uncertainty about the forecast energy demand. Unfortunately the prices on the spot market are not predictable, so a high risk of too high energy prices exist (currently about 40 EUR/MWh as a long term average value, with at least +/- 20 EUR/MWh price fluctuations). These fluctuations are mainly influenced by the current balance of supply and demand as a result of all stakeholders, and also increasingly from the amount of renewable energy provided (presence of feed-in of renewables, influence of weather conditions). Trading these off-peak load is not only a matter of eventually elevated prices during purchase; it is also a matter of selling residual energy for much lower prices than purchased, and even the risk of paying an additional fee to give energy back.

In turn off-peak load should be avoided, which means there is a need for precise forecast of energy consumption for buying only base and peak load. This forecast has to be time-resolved for every quarter of an hour for each day. This is certainly a huge challenge, taking into account all possible influences like future production quantities, exception effects or weather conditions. The knowledge of the time-resolved load profile of all bigger loads and the effect of lower or higher utilization of this load can be taken as a minimum requirement.

Beside this dependency on the quantity of energy, some other parameters are influencing prices, especially maximum peak power, uniformity of demand, duration of demand or the quality of energy (power factor, harmonics). All these quantities can really be influenced by a proper system approach.

Energy efficient installation

It is a matter of fact that the total cost of energy can be influenced in the same manner by well-established and powerful energy management as by savings in energy consumption. The observation of energy use by measurement, monitoring and control is creating a basis for a cost-effective and efficient installation and operation as well as for value-adding energy contracting.

From this background the recently released standard "Electrical energy efficiency within low-voltage electrical installations" (IEC 60364-8-1) defines requirements and guidelines for the design or refurbishing of an electrical installation with regards to electrical energy efficiency. It proposes a set of various electrical energy efficiency measures in all low voltage electrical installations, as given in the scope of IEC 60364, from the origin of the installation including power supply, distribution and transmission of energy, up to each load (motor) branch, including the observation of energy use and quality. It also addresses measures for on-site generation of renewable energy, primarily used as an add-on source for base load demand, but also increasingly used as a buffer to cut down peak load demand (see Figure).

Moreover, this standard is intended to provide requirements and recommendations for the electrical part of the energy management system addressed by ISO 50001 [2, 3].

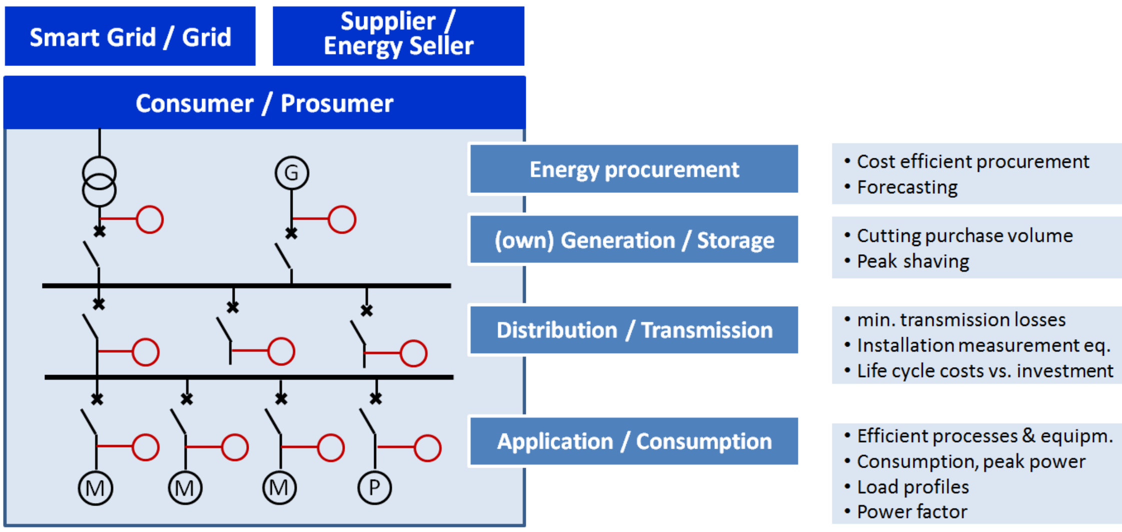

Figure 2 Focus of the standard: Energy efficiency measures for low-voltage electrical

The IEC 60384-8-1 standard applies to residential and commercial buildings, industrial facilities and infrastructural institutions, but considers their different needs and requirements. For each of these areas a set of Efficiency Measures (EM) is defined. Then again, five, subsequently more sophisticated Energy Efficiency Performance Levels (EEPL) are defined for each efficiency measure. Reaching the requirements of such an EEPL gives a certain number of points (from 0 to 4). The sum of all points of all Efficiency Measures leads to a certain Electrical Installation Efficiency Class (EIEC); see Figure 3 in case for industrial facilities.

As can be derived from Figure 3:

- The knowledge about the energy consuming application is the basis for energy optimization
- Therefore it is of fundamental importance to measure the different electrical quantities on each feeder or even on each (larger) load or motor
- This data logging enables the monitoring of performance and benchmarking of consumption pattern, the identification of energy use and any changes of consumption pattern and a power quality survey.
- This kind of transparency is in turn leading to load profiles, forecast of energy consumption, load management and to other optimization possibilities.

As stated in various publications, most users do not really know in which way their motor system is loaded (idle times or just lightly loaded, kind of cycles, needed peak power, possibilities to flatten power demand a.s.o.). The proposed analysis within this standard will support the improvement of motor control and the proper selection of motor power. Consideration shall be given to the use of motor starters, or other motor control devices such as variable speed drives when appropriate, to achieve higher energy efficiency, particularly for efficient management of energy for intensive consumption applications [2]. To achieve the highest EEPL it is necessary to analyze and optimize 90% of installed (rated) motor power for instance in case of motor loads.

Category	Efficiency Measures (EM)	EEPL (0 .. 4) (points)
Determination	Load profile	
	Location of main substation	
Required optimization analysis for	Motors	
	Lighting	
	HVAC	
	Transformers	
	Wiring system	
	Power factor correction	
Requirements to measure	Power factor measurement	
	Energy and power measurement	
	Voltage measurement	
	Harmonics and inter-harmonics measurement	
	Renewable energy	
Minimum Requirements	Assignment of annual consumption to loads	
	Reducing reactive power	
	Transformer efficiency	
	Total number of points	xxx

Efficiency class1	# of points	26	36	48	58	64
very low efficiency installation		EIEC 0				
low efficiency installation			EIEC 1			
reference efficiency installation				EIEC 2		
advanced efficiency installation					EIEC 3	
optimized efficiency installation						EIEC 4

Figure 3 Efficiency measures and resulting efficiency class for electrical installations

Energy efficient load branch

Significant energy savings for motor-driven applications are only obtained when considering the whole chain of the application. The optimization should start with the process itself, next with the processing machinery and afterwards with the selection of the motor and the kind of motor control.

It is about matching the requirements of the application with the proper equipment (motor system and mechanical systems) in an optimal way [4]. Unfortunately, there are only a few publications and little research about this overarching engineering approach. The previously discussed standard for the efficiency of electrical installations IEC 60364-8-1 will support building up better knowledge of existing installations by recording load profiles at least. This should serve as a starting point for the description and optimization of the application process. It is of major importance to subdivide all process steps, and to define their (often mechanical) requirements. It can be shown in many technical applications, that there is just a kind of a flow rate and a state quantity for different quasi-stationary operation points. For instance in the case of pump applications, that is the required flow rate Q_{sys}, and the geodetic head H_{geo} for maybe different time intervals t_i. Similarly, for conveyor applications, the flow rate Q_{sys} is the amount of material which has to be transported. Friction or truly differences in height H represent the state quantity, again maybe separated in different time intervals t_i (Figure). From the energy perspective, high flow rates, large state differences and heavy differences of these quantities between time intervals should be avoided. Especially the latter issue can often be optimized. This would decrease the peak power (often due to acceleration needs) and in the very end the size and duration of part load. Both effects tremendously influence the selection of components, the control approach and energy efficiency. For improving energy efficiency, the task must therefore be: How can the flow rate be evened out?

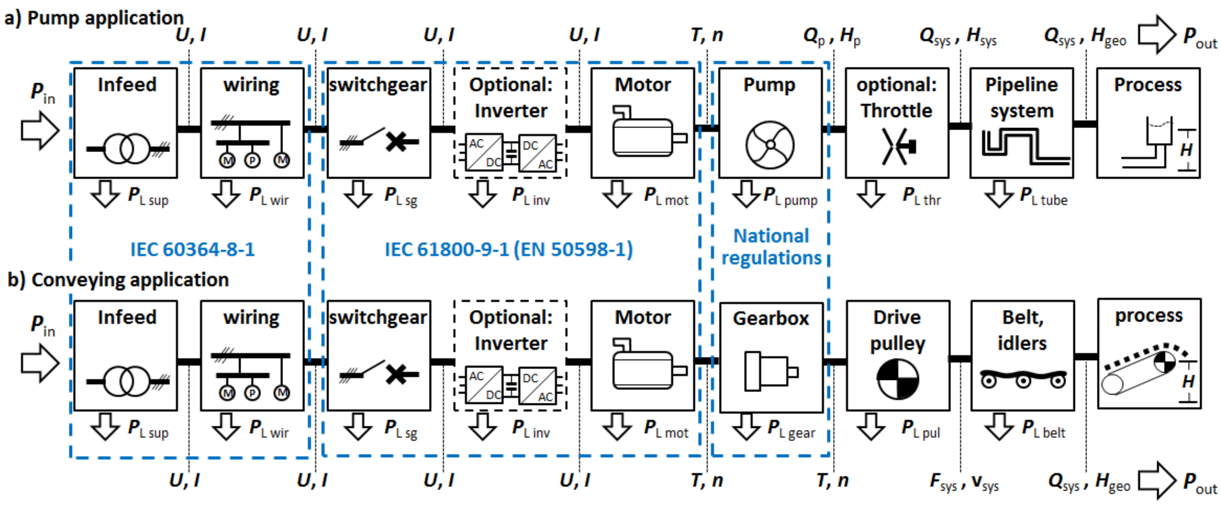

Figure 4 Complete system consideration of a pump and a conveyor application

Beside these process requirements, an often underestimated influence is the selection or design of the transportation systems (e.g. pipe system, belts, gears). In the battle between investment and life time costs, all subsequent costs of larger equipment and their additional losses should be considered. A flow within a pipe creates frictional losses, which increase quadratic with the flow rate and a power of three with pipe diameter, so the power demand is increasing accordingly [5]. This dramatic increase of frictional losses by relatively thin pipes and/or a lot of pipe curvatures requires larger pumps, motors, drives, switchgear and so on *without* any advantage for the end-user. It is just consuming more energy. And in case of a lower demanded flow rate Q_{sys}, all equipment additionally tends to lower efficiency, independently of the motor control strategy!

Transferred to electrical installation systems, the same issue of optimized "transportation systems" is addressed in the standard IEC 60364-8-1 for wiring systems, the location of transformers and the main substation relative to the loads mentioned before.

An additional focus should be made on the working machines. Their efficiency is low compared to gearboxes, motors, drives or other motor controller (contactors, soft-starter). Equipment with the highest available efficiency should be chosen and any oversizing shall be avoided. Most equipment is designed to manage a certain overload, at least for short periods of time. For a few working machines, namely pumps or fans, certain efficiency standards have been established by the European regulation.

Having the load profile or duty cycle of the working machine (that is torque, speed, periods of time), the Extended Product Approach (EPA) described in EN 50598-1 (or IEC 61800-9-1) is the most relevant approach for designing the electrical and motor control part of the drive train (see also Figure). Some examples of such load profiles and the effect of energy consumption as a result of different control strategies can be taken from some sources, e.g. [6,7].

As part of a system approach to realize significant energy savings the electrical installation should meet the following requirements:

- Motors shall typically be sized so that the maximum process demand represents at least 80% or 90% of the motor rated power. Keep also in mind that motors are designed to withstand an overload condition, for example 150% for less than two minutes. Thus there is no need to size motors for short or exceptional power peaks, rather to size for long-lasting "high" load time intervals.
- The control system (motor starter or variable speed drive) should be well matched to the requirements of the application. As a guideline:
  - If the application really requires modulating the speed of the motor, variable speed drives are often the most appropriate solution since they allow controlling speed and torque independently.
  - Otherwise, fixed-speed installations controlled by motor starters (contactors, star-delta starters, soft starters) are often a more efficient solution because they consume less power. Direct on line motors dynamically adapt to the variations of the power demand of the application by self-adjusting the motor torque and, of course, their power consumption. In this case, no further control mechanism is necessary. Even in part load situations down to about 30% rated load, the system efficiency (motor + switchgear device) is really high, about of the level of full load efficiency.
  - In case of huge load differences, especially when combined with long time intervals at low and high load, cascaded systems or two-speed-systems are an efficient alternative. In addition multi motor systems are also favorable to lower down transportation losses, e.g. stacked booster pumps or distributed drive unit for long conveying sections.
- The power losses of all possibly needed accessories, like auxiliary supply, filters and especially cooling devices, have to be taken into account too since they may be significant.

The EN 50598-1 and the IEC 61800-9-1 standards give guidance on how to calculate the interaction of all components within the (electrical) motor system.

The above-mentioned IEC 60364-8-1 closely ties up with this analytical procedure by defining some rules for the installation (see also Figure), this means there is a standardized approach to all electrical equipment from infeed (grid, transformer) up to the motor.

For example, the barycenter method is used for defining the most energy efficient location of the transformers and switchboards with respect to the loads / consumers in a production plant. The objective of this method is to install the transformer and switchboard at a location based on a relative weighting due to the energy consumption of the loads, so that the distance to a higher energy consumption load is less than the distance to a lower energy consumption load. The barycenter enables the equipment location to be defined in order to minimize as much as possible the lengths and cross-sectional areas of conductors [2]. For decades now, another quite simple rule is used for designing the cross section of cables considering the length and current to carry. Here a maximum voltage drop is allowed (IEC 60364-5-52). This ensures certain efficiency on the one hand, and on the other hand also guarantees the functionality of all the downstream equipment.

Another topic addressed by IEC 60364-8-1 is using all the data acquisition of voltage, current, power factor for power factor correction, especially for reducing the reactive power. In general, it is more efficient to compensate for each (bigger) individual load / motor, rather than a group of loads within certain zones or even the whole installation with only a central compensation. All compensation units should be controlled depending on current load and power factor situation, as indicated by the mentioned data acquisition.

More sophisticated aspects like load shedding are also addressed by IEC 60364-8-1. Such energy management methods will be used more and more and are also supported by certain standards and equipment, like PROFIenergy [8].

Conclusion

In any case, energy efficiency is not about assembling the most efficient devices together. It is about matching the requirements of the application with an optimal drive train structure (type of mechanical and electrical system) combined with the use of well-selected equipment (high efficiency rate, no oversizing).

It shows that knowledge of the duty profile is of crucial importance for three major aspects of total cost of ownership:

- designing an energy efficient installation,
- consuming the lowest possible amount of energy,
- deriving a precise forecast of consumption for best possible energy procurement.

The last aspect in particular is becoming more and more important within a liberal energy market. End users are essentially interested in low total costs, mainly comprising the costs of installation and equipment, the costs of operation and maintenance, the consumption of energy and the price for this energy, which is determined by good trading on the stock market. Energy efficiency is therefore an important point, but not the only issue.

With the publication of IEC 60364-8-1 – Energy Efficiency within low-voltage electrical installations – a further cornerstone was established to achieve customer’s goal of lowering the total cost of ownership. This standard supports optimized electrical installation design and requests measurement of relevant data to observe and to manage the application. This data is also a key for energy procurement.

Getting consumption or load profiles of each single motor helps to understand and to improve the system and serves as a starting point for a redesign or a new build of the drive system for such applications. This will certainly help to overcome the most prevalent problems within the requested system approach.

References

[1] Energie-Info: Industriestrompreise; Bundesverband der Energie- und Wasserwirtschaft bdew; 2015; https://www.bdew.de/internet.nsf/id/23AB0D60851F2923C1257E88002EFA3E/$file/BDEW_Energie-Info_Industriestrompreise_160715_final_ohne_AP.pdf

[2] IEC 60364-8-1:2014, *Low-voltage electrical installations – Part 8-1: Energy efficiency*

[3] ISO 50001, *Energy management systems– Requirements with guidance for use*

[4] Kraetzschmar A. & Leprettre B.; *Impact of IE3/IE4 Motors on Switchgear Standards, Manufacturers and Customers;* EEMODS 2015 conference, Helsinki, 2015.

[5] Wagner W., *Strömung und Druckverlust*, Vogel Fachbuch, 2001.

[6] Leprettre B. & Kraetzschmar A.; *Selecting the most efficient motor control system for a given application: the Extended Product Approach in prEN 50598 series of standards;* EEMODS 2013 conference, Rio de Janeiro, 2013.

[7] CAPIEL; *Electric motor system efficiency*; white paper, 2012; http://www.capiel.eu/data/Journal_capiel-EN-BAT091110.pdf

[8] The PROFIenergy *Profile: Increasing the Energy Efficiency of Automation Systems using Smart Energy Management over PROFINET*, PI White paper, 2010, http://www.appliedc.com/Downloads/PI_PROFIenergy_White_Paper_01.pdf

Development of an industrial centrifugal fan for increased efficiency at high volume flow rates

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Abstract

Increasing awareness and legislation regarding the vast energy costs of running fans has led to increased emphasis on design changes to increase efficiency. This paper outlines how these issues were addressed for a particular industrial fan. A theoretical approach was adopted, backed by intensive experimental testing to accurately measure fan performance. A one-dimensional model based on the method of losses was used as the primary tool. Previous models of this type have essentially used experimentally determined loss factors to describe performance, meaning changes in the losses for new designs are difficult to predict. This model links fan components to well-known loss factors for pipes and fittings to overcome this weakness. Predicted results are close to measured, within limits that are equal to or lower than those from more complex analysis such as Computational Fluid Dynamics (CFD). Accuracy is very good at high flow rates, less so at low flow rates below the normal operational range where two-dimensional effects such as reverse flow are likely to be more significant. The model allows the basic fan components and their interaction to be optimised. This provides a base for more detailed optimisation of individual components using CFD and experimental flow visualisation.

Keywords: Experimental; Mathematical-modelling; Optimisation; Turbomachinery

Nomenclature

Formulae

α: Flow coefficient

A: Cross-sectional area (m)

β: Blade angle (°)

δ: Orifice to duct diameter ratio

D: Diameter (m)

ε: Expansibility factor

$\dot{m}$: Mass flow rate (kg·s−1)

η: Total efficiency (%)

Ω: Datalogging error band (%)

Δp: Pressure rise or loss (Pa)

P: Power (kW)

R: Radius from centre-point (mm)

Re: Reynold's number

ρ: Air density (kg·m−3)

r: Pressure ratio

t: Temperature (°C)

τ: Torque (Nm)

v Velocity (m·s−1)

$\dot{V}$: Volume flow rate (m3·s−1)

ω: Angular velocity (rad·s−1)

Z: Constant used to define compressibility coefficient

Subscripts

0: Inlet cone throat

1: Blade inlet

2: Blade outlet

3: Volute

a: Atmospheric

b: Bearing

d: Dynamic

f: Radial (flow) direction

i: Impeller

id: In-duct

L: Leakage

NS: No-shock condition

o: Orifice plate

out: Fan outlet

r: Relative to blade

s: Static

sh: Shaft

t: Total

sk: Shock

sh: Shaft

w: Circumferential (whirl) direction

Acronyms

CAD: Computer-aided design

CAM: Computer-aided manufacturing

CFD: Computational fluid dynamics

FEA: Finite element analysis

FMEA: Failure mode and effects analysis

FSO: Full scale output

NDT: Non-destructive testing

Introduction

There are numerous articles which explore the development and optimisation of centrifugal fans. Most recently, there have been several key theoretical and experimental studies.

Huang et al. [1] improved the performance of a fan by optimising the volute design. They obtained good experimental results to validate their numerical studies which utilised algorithms such as the Levenberg-Marquardt Method. Lin et al. [2] established an integrated aerodynamic, acoustic and electro-mechanical evaluation scheme for centrifugal fans used in computers. They successfully enhanced fan performance via numerical calculation, including SIMPLE, PISO and LES mathematical models. Xiao et al. [3] found that flow instability in a centrifugal fan could be analysed using energy gradient theory. They concluded that this complex flow phenomenon is particularly developed in the regions of impeller outlet and volute cut-off.

Zhao et al. [4] performed experimental and numerical studies on a forward-curved centrifugal fan. They determined the effect of the volute design on performance. They related noise and flow characteristics to the openness distribution. Lei et al. [5] performed numerical simulation of rotating stall within a centrifugal fan. They developed a new method of inhibiting stall by blowing air into the impeller passages. Zhang et al. [6] recently analysed the unsteady aerodynamics and aero-acoustics of a backward curved centrifugal fan. They found good agreement between their CFD and experimental results, showing that unsteady behaviour and noise mainly occurred in the volute.

Lee et al. [7] show a 2D blade profile optimization scheme utilizing CFD code and a genetic algorithm to achieve an increase of over 1% in impeller efficiency. Van den Braembussche [8] also demonstrates a genetic algorithm along with a database and artificial neural network to optimise radial impellers.

Qiu et al. [9] present an automated design system centred on 3D geometry which results in efficient impeller optimisation. This involves 1D meanline design, 2D and 3D CFD as well as FEA and CAM. Pauer et al. [10] present the code TUVEST which optimises impeller blade geometry and loading by changing the mean streamline. Singh et al. [11] apply the Taguchi method, based on orthogonal array experiments, to significantly improve blower performance.

Based on CFD studies, Gasparovic et al. [12] propose a new casing design which produces more homogenous outlet flows. Sharma et al. [13] optimised the location of splitter vanes, placed on impeller and diffuser, resulting in improved static pressure recovery. Using CFD analysis, Karanth et al. [14] found the optimal radial gap between impeller and diffuser, leading to maximum fan efficiency.

Singh et al. [15] and Chunxi et al. [16] investigated impeller geometry, such as number of blades and enlarged diameter respectively. Both studies show trends and laws that can be used to tune the performance of a centrifugal fan.

Various literatures are available which focus upon the numerical analysis of flow interaction and losses that occur in centrifugal turbomachinery.

Perhaps one of the most detailed studies is by Purnell [17] whose program for predicting centrifugal fan performance encompasses all losses in the fan, such as expansion at the impeller inlet and leakage paths. This is rigorously evaluated against experimental results. Myles [18] also comprehensively analysed fan losses and presents a method of assessing performance using diffusion factors supported by empirical studies. Thin et al. [19] analysed a centrifugal pump design based on the Berman Method, providing formulae for impeller geometry as well as calculations for friction and recirculation losses.

The works of Gonzalez et al. [20] and Ballasteros-Tajadura et al. [21] concentrate on simulating the flow within the volute. Both looked at the pressure fluctuations, specifically around the tongue or cut-off and the relationships with blade passing frequency. Similarly Meakhail et al. [22] and Pavesi [23] simulated impeller-diffuser-volute interaction and highlighted unsteady phenomena such as vortex shedding, recirculation zones, swirl flow and rotating stall.

CFD studies by Pathak et al. [24] and Corsini et al. [25] utilise ANSYS and OpenFOAM codes respectively and provide accurate representations of various pressure fields within the fan. Leonard et al. [26] also present a CFD based simulation tool but in a quasi-one dimensional form that is for rapid assessment of turbomachinery, utilising some empirical information.

Lastly, Lee [27] investigated the gap between inlet cone and impeller and found that if it is not correctly set up then passage-flow separation and volute flow losses can reduce fan efficiency by 2-5 %.

Despite the work cited, there remains a distinct lack of development of industrial fans which are used all over the world in key applications such as blast furnaces, dust ventilation, landfill gas extraction and food production. Fan motor systems consume approximately 20% of all electricity in the European Union [28]. Some of these fan designs have been left unchanged for over 40 years and these must be adapted quickly to comply with recent efficiency-targeted legislation such as the Energy-related Products (ErP) Directive 2009/125/EC. The overall objective of this study is to produce a more efficient, energy-saving fan. This will meet future efficiency regulations, as well as manufacturing and cost targets. The design process utilises a one-dimensional model based on the method of losses. Full-scale experimental prototyping and testing was used to validate and assist the study.

Materials and Methods

Specification and Geometry

The original fan used in this study, see Fig. 2, is typical of those in the industrial sector. Constructed from sheet metal, focus is placed upon simplicity and robustness. The flat, backward-sloping blades are designed to eradicate particle build-up. The thick blades and inter-shroud are able to withstand large centrifugal loads, exposure to high temperatures and harsh chemical/dirt based environments. The wide volute, dimensions given in Table 1, provides a high ratio of volume flow rate to total pressure.

Table 1 Specifications of the original 550BSZ100 centrifugal fan

Exit flange width	556 mm
Exit flange height	588 mm
Cut-off depth from flange	167 mm
Cut-off clearance	95 mm
Motor shaft clearance gap	3 mm
Volute / scroll casing overall height	1032 mm
Volute / scroll casing overall length	978 mm
Material thickness	3-4 mm
IE2 three-phase AC electric motor size	30 kW
Test rotational speed	2100 rpm

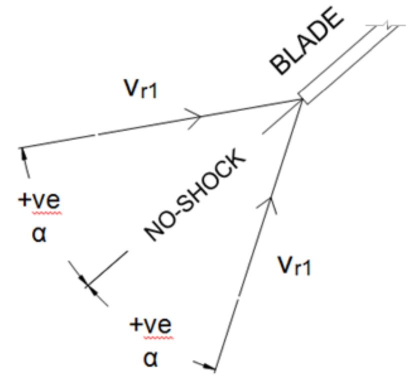


Fig. 1. Shock loss Δp(iii)

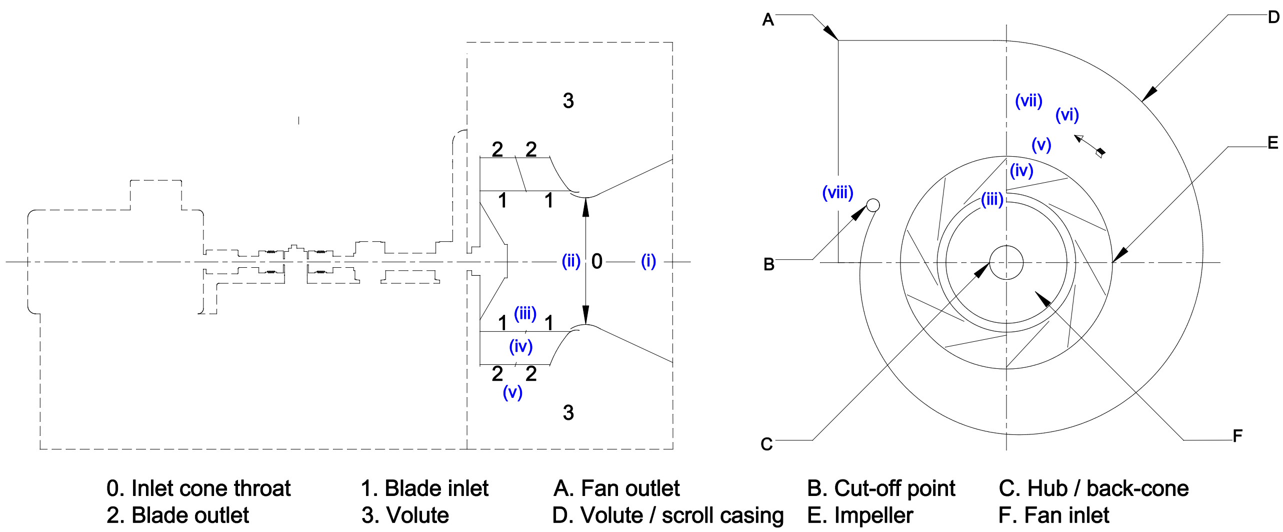


Fig. 2. Key positions in fan for losses (0 - 3), fan components (A - F) and positions of losses ((i) – (viii))

One-Dimensional Modelling

The model bridges the gap between the very detailed CFD analysis and basic one-dimensional modelling which uses empirical loss factors to estimate fan performance. The CFD models suffer from sensitivity to grid/mesh design and the need to input a number of turbulence modelling parameters that are not known for the complex and varying types of flow found within a centrifugal fan. The one-dimensional models use known loss factors that fit theory to measured results. Their disadvantage is that design alterations change the loss factors in an unknown way and, therefore, their effects cannot be predicted.

The model uses known data for pipe systems coupled with a simple mixing model in the staged exit volute to predict overall fan performance. In some cases, the analogy between the fan and the pipe system equivalent loss is tenuous, but, surprisingly, results indicate very good agreement between the model and measured performance without the need to introduce adjusting factors.

The performance is predicted based on the Euler theoretical performance, with slip loss allowed for using the Wiesner model [29]. A series of further pressure losses is then predicted for the various fan components at the chosen flow rate, see Fig. 2. These are shown below:

Table 2 Pressure losses for fan components

$\Delta\mathrm{p}(i)$	Loss for the contraction at the entrance to the inlet cone [30].
$\Delta\mathrm{p}(ii)$	Loss for the expansion between the minimum area and the inlet to the blades [31] [32].
$\Delta\mathrm{p}(iii)$	Shock loss at the blade inlet, according to Eck [33] *.
$\Delta\mathrm{p}(iv)$	Frictional loss as the flow passes through the blade passages [30].
$\Delta\mathrm{p}(v)$	Loss at the sudden expansion where the flow passes from the blade outlet into the much larger volute [30].
$\Delta\mathrm{p}(vi)$	Loss in the volute due to the circular motion [30].
$\Delta\mathrm{p}(vii)$	Loss in the volute due to the area expansion [31] [32].
$\Delta\mathrm{p}(viii)$	Loss at the pipe exit expansion after the cut-off point [31] [32].

* Note: $\Delta\mathrm{p}(iii)$ shock loss, see Fig. 1 occurs due to the angle of incidence (attack), α, of the inlet velocity relative to the blade. At a particular flow the relative velocity is in-line with the blade direction, the angle of incidence is zero and there is no shock loss. At flows above and below the 'no-shock' flow, the flow impinges on the blade and has to be rapidly re-orientated in the blade direction. This turbulence causes the shock loss, which increases away from the no-shock flow.

The volute is treated in 12 30° sections, with a calculated proportion of the flow being re-circulated around the volute rather than passing out of the exit. A simple model to describe the mixing between the fluid passing around the volute and that exiting the blades is used for each section. The 2 volute losses, Δp(vi) and Δp(vii) are simply added together. All the losses Δp(i) – Δp(viii) are summed and the total taken from the pressure rise calculated using the Euler model adjusted for slip.

The net pressure rise developed:

$$\Delta p_{net} = \Delta p_{Euler} - \Delta p_{slip} - \sum_{n=(i)}^{(viii)} \Delta p_n \qquad (1)$$

where Δp_{Euler} is calculated from the rate of change of angular momentum. Δp_{slip} arises from the reverse circulation between successive blades at the impeller outlet and is calculated using the Wiesner model [29]. Δp_n refers to the individual losses referred to in Table 2. Leakage takes place at the inlet between the rotating impeller and the inlet cone, and between the back-plate and the driveshaft. The pressure rise at the fan outlet, Δp_{net} is used to estimate the leakage flow using simple nozzle theory. The estimated leakage flow is then used to adjust losses Δp(iii), Δp(iv) and Δp(v), and a new outlet pressure rise calculated. This is used to re-calculate the leakage flow and the process iterated until a stable result is obtained.

The flow through the fan is assumed one-dimensional with full impeller symmetry and steady conditions at a fixed rotational speed of 2100 rpm. Thus, the velocity distribution at any point is assumed uniform. The analysis applies to incompressible flows. A series of different flows between zero and sensible maximum are tackled which allows a predicted pressure rise versus flow characteristic to be plotted.

The power and efficiency characteristic curves require a power prediction to be made. The power is predicted by taking:

$$P = (\Delta p_{Euler} - \Delta p_{slip} - \Delta p(iii) - \Delta p(iv))(\dot{V} + \dot{V}_L) \qquad (2)$$

where $\dot{V}$ = volume flow rate and subscript L refers to leakage. The proposition is that slip, losses (iii) and (iv) do not have to be provided by the motor to the fan.

The calculations are realised in a spreadsheet where the significant fan dimensions are input, the various losses, pressure rise and power calculated at each flow and the results viewed graphically, see Fig. 4. Several geometry modifications can be tried and results compared to measured data where it is available.

Details of the calculation of each of the losses (i) – (viii) follow.

(i) Loss for the contraction at the entrance to the inlet cone

For this fan, the inlet cone involves a very gradual contraction so that it can be taken that the radius of the contraction cone, r is large and r/D0 > 0.15, so that the loss coefficient is given by $K(i)$ = 0.04.

The corresponding pressure loss is then calculated:

$$\Delta p(i) = K(i)\frac{\rho}{2}v_0^2 = K(i)\frac{\rho}{2}\frac{\dot{V}^2}{A_0^2} \qquad (3)$$

where v = velocity; A = cross-sectional area; ρ = density and subscript 0 refers to the position of the inlet cone minimum area, see
Fig. 2. Other arrangements could have much higher loss coefficients. For instance, a sharp edged abrupt entrance would have $K(i)$ = 0.5.

(ii) Loss for the expansion between the minimum area and the inlet to the blades

Although the flow turns through a right angle while expanding, the calculation is based upon standard factors for expansions with no allowance for the right-angle. Some texts suggest that this produces acceptable results.

$$\Delta p(ii) = \frac{\rho}{2} K(ii)(v_{0}-v_{1})^{2} \quad (4)$$

where the subscript 1 refers to the position at the blade inlet. The loss factor $K(ii)$ is given by:

$$K(ii) = 2.6 \sin\left(\frac{\theta}{2}\right) \quad (5)$$

where the effective half-angle of the expansion, $\frac{\theta}{2}$ is calculated from the mean free path of a fluid streamline at the centre of the blade L, the radius at position 0, R_0 and the effective radius at position 1, R_1:

$$\tan\left(\frac{\theta}{2}\right) = \frac{(R_1 - R_0)}{L} \quad (6)$$

The effective radius R_1 is estimated from:

$$\frac{R_1}{R_0} = \sqrt{\frac{A_1}{A_0}} \quad (7)$$

Where A is cross-sectional area and 1 denotes impeller inlet, 0 denotes inlet cone throat.

(iii) Shock loss at the blade inlet, according to Eck [33]

For multi-bladed fans, the fluid path relative to the blade has to be along the blade. At the inlet, approaching the blade, the fluid path relative to the blade is determined by the relative values of the velocity in the flow direction (radial) and the blade velocity (circumferential). The radial velocity is proportional to the flow rate, but the blade velocity is constant. Therefore, there is only one flow rate at which the flow passes smoothly through the blades. At a smaller flow, the fluid passes angular momentum to the blade; at a larger flow, the blade must transfer additional angular momentum to the fluid. The additional velocity given to fluid, v_{sk} is given by:

$$v_{sk} = \left(\frac{v_{f1}}{v_{f1NS}} - 1\right)\omega R_1 \quad (8)$$

where ω is the angular velocity; subscript f denotes radial velocity (flow direction) and subscript NS denotes the no-shock condition.

Using momentum theory, the transfer of energy results in an additional pressure loss given by:

$$\Delta p(iii) = \mu \frac{1}{2} \rho v_{sk}^{2} \quad (9)$$

The factor μ is less than 1 and is included because there are finite passages between blades and the fluid at the centre of the passages is not subject to as much momentum change as the fluid close to the blades. For the particular fans analysed, a value of μ = 0.37 is used, based on Eck [33]:

$$\mu = 0.3 + 0.6\frac{\beta_1}{90} \quad (10)$$

where β_1 = inlet blade angle.

(iv) Frictional loss as the flow passes through the blade passages

The frictional pressure loss as the fluid passes through the blades can be determined by treating the blade passages as pipes, in the case of the fan analysed, straight pipes as the blades are flat. In some cases, there may be a significant expansion of the flow, but for the fan analysed there is a small difference between blade inlet and outlet areas.

The relevant velocity is the velocity of the fluid relative to the blades, v_r which increases significantly from the inlet to the outlet. The equation used is:

$$\Delta p(iv) = \frac{fL}{D}\frac{1}{2}\rho\overline{v_r^2} \quad (11)$$

where f is the fully turbulent friction factor determined from the relative roughness; L blade length; D the average value of the effective diameter calculated from $D = \frac{4A}{P}$; A is cross-sectional area and P perimeter. The average value of the fluid velocity relative to blade $\overline{v_r{}^2}$ can be determined as follows:

$$\overline{v_r{}^2} = \frac{1}{2}(v_{r1}^2 + v_{r2}^2) \quad (12)$$

$$v_{r1}^2 = \omega^2 R_1{}^2 + v_{f1}^2 \quad (13)$$

$$v_{r2}^2 = (\omega R_2 - v_{w2})^2 + v_{f2}^2 \quad (14)$$

where subscript 2 denotes the blade outlet and subscript w denotes whirl.

(v) Loss at the sudden expansion where the flow passes from the blade outlet into the much larger volute

The fluid leaves the blade at its highest velocity, v_2 and passes immediately into the volute which is much wider and of much higher cross-sectional area than the blade passages. The velocity in the volute, v_3 is much lower than v_2. The process is modelled as a sudden expansion, with an associated pressure loss:

$$\Delta p(v) = \frac{1}{2}\rho(v_2 - v_3)^2 \quad (15)$$

The volute is divided into 12 segments, v_2 being equal for all segments, but v_3 varies between segments. v_2 can be calculated from:

$$v_2^2 = v_{w2}^2 + v_{f2}^2 \quad (16)$$

where v_{w2} represents the Euler outlet whirl (circumferential) velocity adjusted for slip. As v_{w2} tends to decrease as flow rate increases so does v_2, whilst v_3 increases. The loss $\Delta p(v)$ thus decreases as the flow increases, making this loss of totally different character to the other losses which all tend to increase with flow rate. Hence, this loss is the main loss at low flow rates.

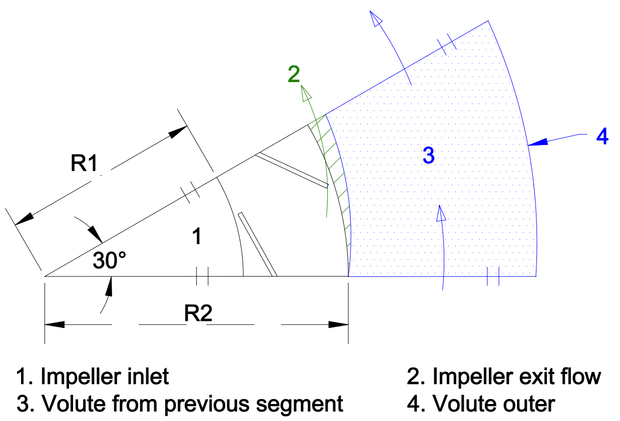


Fig. 3. A segment of the volute

The calculation of v_3 is dependent on the volute model. The volute is divided into 12 x 30° segments, starting from the cut-off point, see Fig. 3. The cross-sectional area available to the flow in the volute increases with the distance from the cut-off point. A quantity of fluid which leaves the final segment re-circulates around the volute, rather than leaving at the duct exit. This is determined by the angle α2 of the absolute velocity leaving the impeller, v_2. This fixes the flow rate and velocity into the 1st segment of the volute. It is assumed that this flow continues to occupy the same area as it leaves the segment. Therefore, the increase of volute cross-sectional area across the segment is available to the fluid leaving the impeller. The velocity of the fluid leaving the impeller when slowed as it expands into the volute, v_3, is calculated from the volume flow rate leaving the impeller divided by the increase in area. Each segment is then dealt with in a similar way. The loss $\Delta p(v)$ is then averaged for the 12 segments.

(vi) Loss in the volute due to the circular motion

This is modelled as a series of pipe bends, each segment representing one bend. The total loss is the sum of the losses for all segments. A loss coefficient KB can be calculated from the angle turned through (30°) and the ratio of the radius of the volute centre-line to the effective diameter.

$$\Delta p(vi) = K(vi)\frac{1}{2}\rho\overline{v_3}^2 \qquad (17)$$

The average velocity, $\overline{v_3}$ for a segment is calculated from the mean of the inlet and exit.

(vii) Loss in the volute due to the area expansion

This is dealt with in a similar way to loss (ii).

(viii) Loss at the pipe exit expansion after the cut-off point

This is dealt with in a similar way to loss (v).

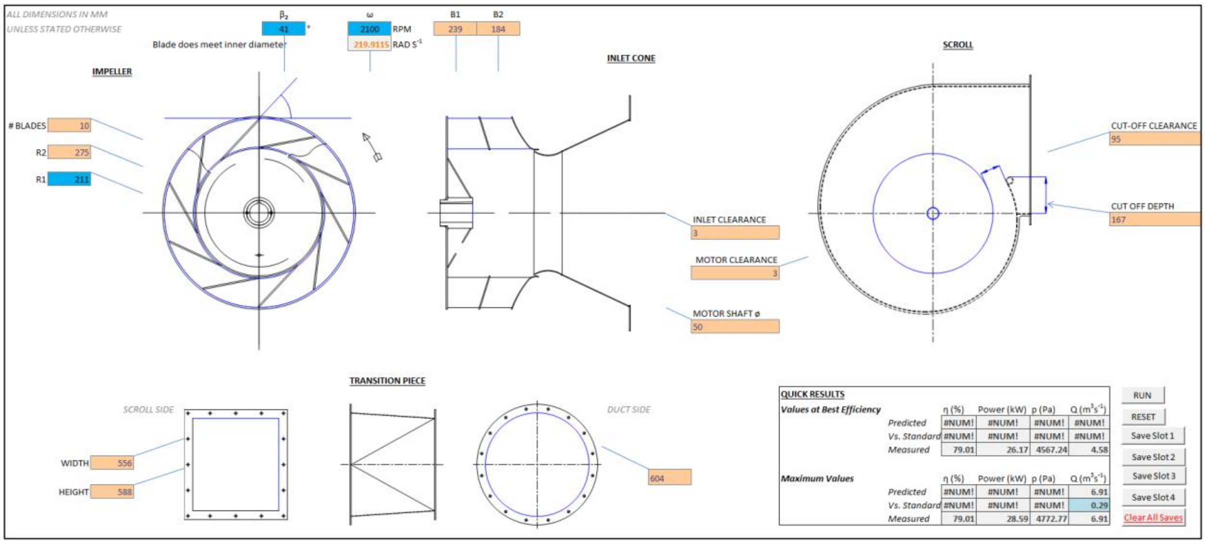


Fig. 4. Screenshot of one-dimensional fan theory model (inputs).

Table 3 Specifications of the different impeller configurations

Type	Inlet radius R1 (mm)	Outlet radius R2 (mm)	Shroud inner radius (mm)	Inter-shroud outer radius (mm)	Blade length l (mm)	Blade width b1 (mm)	Blade width b2 (mm)	Inlet angle β1 (°)	Outlet angle β2 (°)	No. blades Z
Standard (Original)	187	275	183	275	165	239	184	11	47	10
V2-5 (New)	207	275	200	241	143	232	191	10	41	10

Prototyping

Various fan modifications and designs were carried out during this study. Table 3 details the specifications of the relevant impeller configurations.

One particular improvement was the reduction of the inter-shroud which is an intermediate disc supporting the centre of the blades during high centrifugal loading. Originally, this spanned the full width of the blades. Detailed FEA analysis and the use of high-strength steel allowed for the reduction of the outer diameter of the inter-shroud. This simplified manufacture, changing from a two-piece to a single-piece blade which is slotted to receive the stiffener ring, shown in Fig. 5. In turn, this smaller inter-shroud reduces losses within the impeller, most notably friction in the blade passages where the flow reaches high velocities.

A simple, notched plate was utilised as a jig to constrain the blades during welding. After construction, measurements were taken using a Renishaw probe arm attached to a lathe. The blade angles were found to vary by a maximum of ±0.4° which is a tight tolerance for a hand-made item.

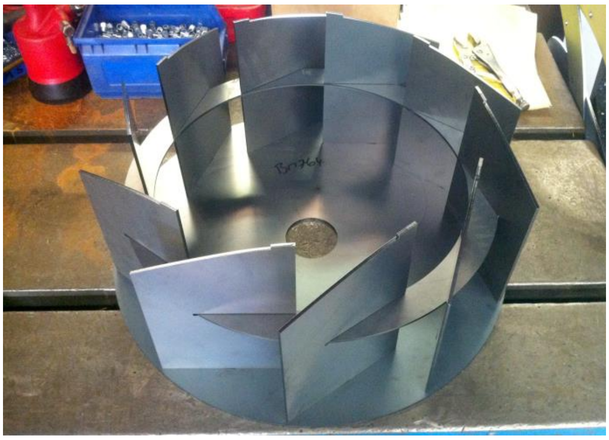


Fig. 5. V2-5 impeller construction with single-piece blade and ring type inter-shroud.

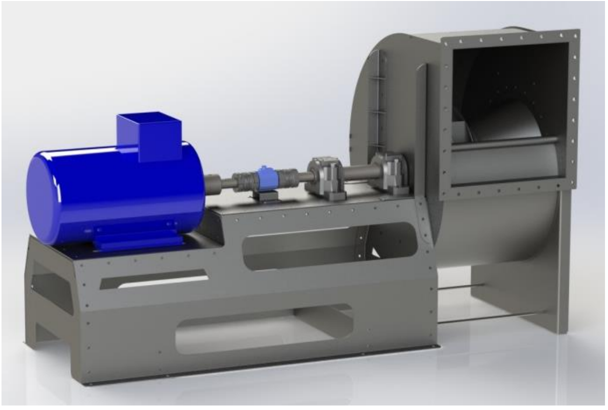


Fig. 6. Test fan setup with motor and torque transducer (highlighted in blue).

Experimental Setup

Fan performance testing of full scale machines was carried out in accordance with British Standard BS848-1: Industrial fans – Performance testing using standardized airways, now known as BS EN ISO 5801. Standardised test method with outlet side ducts: Type B was used, as shown in Fig. 7. This involves measuring the flow using an in-duct orifice plate with wall tappings at D and 0,5D. The orifice plate is governed by ISO 5167-1 and it was laser cut from stainless steel to meet the tolerances of the standard. The ratio of orifice plate diameter to ducting diameter, δ is 0.7, designed to maintain a sufficient pressure drop but also give a good range of flow points.

A bespoke rig shown in Fig. 6 was designed to accommodate the use of a brushless, rotary torque transducer for power measurement. The torque transducer was calibrated using a 19 kg weight on a 0.3 m lever arm, reporting a 0.03% error.

The prime mover is a 30kW AC motor manufactured by Weg; 3-phase; 50Hz; 400-415 volts; IE2 efficiency class. The transmission system comprised of a stub-shaft, bellows couplings and plummer block bearing units. All of which were laser-aligned to reduce misalignment. Power used in the transmission was measured regularly by running the rig without the impeller attached. This way, losses in the transmission were accounted for.

A data-logger was used to take pressure rise and torque measurements at set intervals of a minute long; these were then time-averaged. Measurements from the transducers were taken before each test to establish zero readings.

Tests were performed at 2100 rpm using a variable speed drive. Electrical noise was kept to a minimum using single-point grounding, shielded cables and differential inputs on the data-logger.

Experimental Calculations

The following equations are used to analyse the experimental results. These are taken from BS848-1, section 28: standardized test methods with outlet side test ducts: type B.

Total pressure rise is calculated as follows:

$$\Delta p_t = \Delta p_s + (1 + \zeta)\Delta p_d \qquad (18)$$

where Δp_s is the directly measured static pressure rise; ζ is the conventional friction coefficient and Δp_d is the dynamic pressure rise:

$$\zeta = 0.015 + 1.26\mathrm{Re}^{-0.3} + 0.95\mathrm{Re}^{-0.12} \qquad (19)$$

$$\Delta p_d = \frac{\dot{m}^2}{2\rho_{id}{A_{id}}^2} \tag{20}$$

Where Re is Reynold's number in the outlet duct; A_{id} is in-duct cross sectional area; ρ_{id} is in-duct density and $\dot{m}$ is mass flow rate:

$$Re = \frac{\rho_{id} v_{id} D_{id}}{\mu_{id}} \tag{21}$$

$$\rho_{id} = \rho_a \left(\frac{\Delta p_a + \Delta p_s}{\Delta p_a}\right)\left(\frac{273 + t_a}{273 + t_{id}}\right) \tag{22}$$

$$\dot{m} = \alpha\varepsilon \frac{\pi {D_o}^2}{4}\sqrt{2\rho_{id}\Delta p_o} \tag{23}$$

Where D_{id} is the duct diameter; t is temperature, subscript a denoting atmospheric; Δp_o is the measured differential pressure across the orifice plate; D_o is orifice diameter; α is flow coefficient; ε is the expansibility factor and δ is the orifice to duct diameter ratio:

$$\alpha = (1-\delta^4)^{-0.5}\left[0.5899 + 0.05\delta^2 - 0.08\delta^6 + (0.0037\delta^{1.25} + 0.011\delta^8)\left(\frac{10^6}{Re}\right)^{0.5}\right] \tag{24}$$

$$\varepsilon = 1 - (0.41 + 0.35\delta^4)\frac{\Delta p_o}{1.4(\Delta p_a + \Delta p_s)} \tag{25}$$

$$\delta = \frac{D_o}{D_{id}} \tag{26}$$

Total efficiency is calculated as follows:

$$\eta_t = k_p\left(\frac{\dot{V}\Delta p_t}{P_i}\right) \tag{27}$$

where k_p is the compressibility coefficient and P_i is the impeller power, calculated as follows:

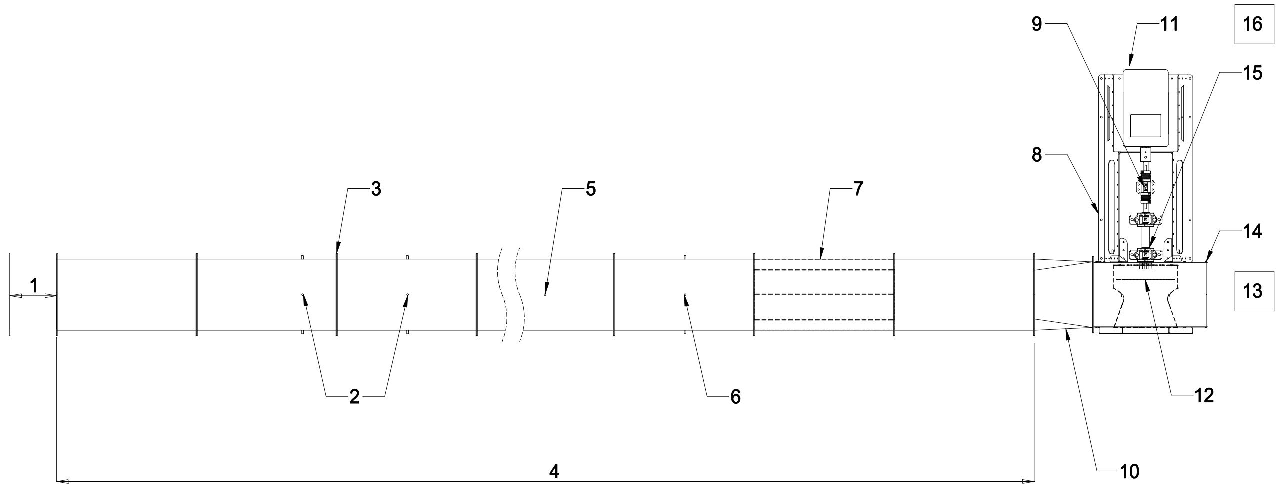
$$k_p = \frac{Z\log_{10} r}{\log_{10}[1 + Z(r-1)]} \tag{28}$$

$$P_i = \tau_{sh}\omega_{sh} - \tau_b\omega_b \tag{29}$$

where subscripts sh and b denote shaft and bearing measurements respectively; Z is a constant used to define the compressibility coefficient and r is the pressure ratio:

$$Z = \frac{0.4\rho_a P_i}{1.4\dot{m}\Delta p_t} \tag{30}$$

$$r = \frac{\Delta p_a + \Delta p_t}{\Delta p_a} \tag{31}$$



1. Exit flow controlled with damper plate 2. Flow measurement tappings (8 no.) connected to differential pressure transducer 3. Orifice plate; 0.422 m ID
4. Smooth bore ducting; 0.6 m ID x 12 m long 5. Thermocouple 6. Average static pressure tappings (4 no.) connected to gauge pressure transducer
7. Star straightener vanes (8 no.) 8. Pedestal 9. Torque transducer 10. Transition piece 11. Motor 12. Inlet flow into cone & impeller
13. Barometer 14. Volute / scroll casing 15. Transmission 16. Tachometer

Fig. 7. Test rig and measuring devices layout.

Table 4 Apparatus

Measurement	**Measuring Device**	**Error Band (±%)**
Static pressure	Honeywell SSC differential pressure sensor; 1 psi rating; temperature compensated strain gauges; amplified 5V FSO. 1 side exposed to atmosphere.	2
Flow (via static pressures)	Honeywell SSC differential pressure sensor; 1 psi rating; temperature compensated strain gauges; amplified 5V FSO. Connected either side of orifice plate.	2
Atmospheric pressure	Barometer; 23-31 “Hg.	0.1
Atmospheric & in-duct temperatures	BEHA 93402 digital thermometer with type K thermocouple.	0.05
Torque	Kistler 4520A rotary torque sensor; brushless; 100Nm rating; temperature compensated strain gauges; amplified 10V FSO.	0.5
Rotational speed	COMPACT CT6 Tachometer.	0.01
(Datalogging)	Microlink 751 analog to digital convertor	0.05
(Power supply)	Farnell E30-2BT dual 30V 2A DC	-

Results and Discussion

Uncertainty Analysis

The results in Fig. 8 to Fig. 19 have been plotted with error bars. These are based on the error band values in Table 4. For values of total pressure, impeller power and total efficiency, the associated error band values have been summed in RMS fashion. For example, total pressure error band, $\pm\Delta p_t$ is calculated as:

$$\pm\Delta p_t = \sqrt{\pm\Delta {p_s}^2 + \pm\dot{V}^2 + \pm\Delta {p_a}^2 + \pm{t_a}^2 + \pm{t_{id}}^2 + \pm\Omega^2}$$

$$\pm\Delta p_t = \sqrt{2^2 + 2^2 + 0.1^2 + 0.05^2 + 0.05^2 + 0.05^2} \qquad (32)$$

Total pressure error band, $\pm\Delta p_t = \pm 2.83\ \%$

Where Ω denotes the error band of the datalogging apparatus.

Absorbed power error band, $\pm P = \pm 2.07\ \%$ (33)

Total efficiency error band, $\pm\eta_t = \pm 2.88\ \%$ (34)

These values are then multiplied by the full scale output (FSO) value of the associated dataset. For example, in Figre 8 a fixed error is plotted according to:

$$\text{Fixed } \pm \Delta p_t = \pm 2.83\ \% \times 2312\ \text{Pa} = \pm 65.4\ \text{Pa} \qquad (35)$$

Validation of the Model

The 1-D theoretical model was initially validated by comparison with experimental results from the standard existing fan design, as shown in Fig. 8, Fig. 9 & Fig. 10. Modifications to the impeller and inlet to the fan were informed by results from the 1-D model. The new fan, labelled version 2-5, was manufactured and tested, the experimental results being compared to those of the 1-D model, as shown in Fig. 11, Fig. 12 fig. 12 & Fig. 13 All experimental results are corrected to a density of 1.2 kg m−3.

Standard Impeller-agreement between Model Predictions and Experimental Data

Total pressures for the standard design are over-predicted by the model; typically by 3% in the operational flow range of 3-4.5 m3·s−1, but by more at low and high flows, see Fig. 8. However, the general shapes of the curves are very similar to each other. Power to the impeller is predicted more accurately, typically to within 1% in the operational region, the curves following each other very closely, see Fig. 9. The predicted maximum efficiency closely matches that measured, although it is at a slightly higher flow rate, see Fig. 10. The measured efficiency curve drops off more suddenly than the predicted either side of the maximum efficiency. At a flow 50% higher than the flow at maximum efficiency, the experimental efficiency is 10% lower than the predicted.

Analysis of Individual Losses

An analysis of the loss sources in the one-dimensional model gives clear indications of where to target efficiency improvements.

Table 5 & Table 6 overleaf show the losses in terms of pressure and as a percentage of the total losses respectively. Losses from leakage are not included, but dealt with separately. Most losses, shown in
Table 2 are proportional to the square of the flow rate. The exceptions being loss (iii), shock at blade inlet, and loss (v), the expansion at blade outlet. The shock loss (iii) is zero at the no shock flow rate and increases either side of it, whilst (v) is highest at low flow rates and decreases towards zero as the flow rate increases. These losses are due to skin friction, separation and turbulent eddies/vortices. These are a result of surface dynamics, changes in section/direction and the complex interaction of these factors in various areas of the fan.

It can be observed that losses at the inlet expansion, following improvement in the modified fan, are still around 35% of total pressure losses in the usable flow range. Outlet jet expansion losses dominate at flow rates below the usable range, and are still high (29% of total) at the maximum efficiency flow (3 $m3{\cdot}s{-}1$). At higher flow rates, they become small. Inlet shock becomes greater at high flow rates (27% maximum), as do losses in the volute (23% at maximum flow). Impeller friction is moderate and a fairly constant proportion of losses (7%) over the usable flow range. Losses in the contraction from atmosphere at inlet (4.5% maximum) and at the expansion in the outlet pipe (1.8% maximum) are small.

It is difficult, if not impossible, to measure these losses individually, so the stated values cannot be individually confirmed. However, given the complex way in which they interact, it is extremely unlikely that the analysis would produce the high levels of accuracy confirmed by measurement for the overall predictions unless individual loss predictions were accurate.

It has to be conceded that it cannot be confirmed that those losses that are small across the whole flow range, (i), (iv) and (viii), are accurately predicted. Application to smaller fans, with their higher proportion of friction losses, would enable an assessment to be made.

Development of the New Design V2-5

One of the advantages of the 1-D model is that, being a loss based approach it is quite clear where the major losses are occurring in any design. This allows changes to be focused on those areas with the biggest losses. For this fan, the aim was to produce higher efficiency in the operational range and to reduce the overall power consumption. The overall dimensions of the fan were not to be increased.

Results from the standard impeller suggested that the inlet was too small and causes significant loss. Increasing the inlet size required an increase in the blade inlet radius. To achieve this without reducing blade length detrimentally, the outlet blade angle was reduced whilst keeping the inlet blade angle constant. The inter-shroud, included for strength, was reduced in extent, thus producing a minor reduction in impeller friction losses. The resulting small increase in stress levels was handled through the use of high strength steel.

The operational flow range tends to be, for various reasons, to the right of the maximum efficiency point. It was decided that a lower pressure could be tolerated at flow rates below the usual operational range, see Fig. 14. This resulted in lower predicted impeller power across the whole flow range, see Fig. 15. As well as indicating the areas for improvement, the model showed that there was little purpose in changing some areas. For instance, changes to the volute were not made because the losses in it were small. Any reduction of the loss as the flow expands from the impeller into the volute that could be achieved was negated by increased friction within the volute. Overall, total efficiency was predicted to increase modestly across the entire flow range, see Fig. 16.

Modified V2-5 Fan-agreement between Model Predictions and Experimental Data

Guided by the model results, a new design was produced with the fundamental aim of achieving a higher efficiency and lower power consumption over the operational flow range. Model predictions are compared with experimental test results.

Total pressure is very accurately predicted over the operational flow range, but the model clearly over-predicts at lower flows, see Fig. 11. At a critical flow rate, just below the maximum efficiency point, experiments show a sudden rise in pressure not predicted by the theory. This behaviour, which many workers have found typical of centrifugal fans, would suggest it is a two-dimensional effect. Eck [33] suggests that it is caused by the flow occupying the full width of the impeller at flow rates higher than the critical, but being biased towards the back-plate at lower flows. As the 1-D model theory assumes occupation of the whole impeller width at all flows, it could not predict such an effect. This also explains why the theory over-predicts in the low flow region. As with the standard model, the power consumption is accurately predicted over the whole flow range, see Fig. 12. The efficiency is accurately predicted over the operational flow range, see Fig. 13. The over-predicted pressures at low flows result in over-predicted efficiencies at these flows, the difference becoming more pronounced as the flow gets lower.

Overall Evaluation of Model Effectiveness

An overall assessment is that the results indicate the 1-D model to be an effective predictor of fan performance, especially in the operational flow range of 3-4.5 $m^3 \cdot s^{-1}$. Such differences between theory and experiment as exist are consistent between the existing and new design, which suggests that it is a good tool for examining the effect of design changes.

Performance comparison between Standard and V2-5 Fan

The results compare the performance of the new and existing designs. Experiments show that the new design develops lower pressure below 4 $m^3 \cdot s^{-1}$, but higher above, see Fig. 17. The power consumption is significantly reduced at all flows, see Fig. 18. The efficiency has equal or very slightly increased maximum value, see Fig. 19. This occurs at a slightly higher flow rate. However, in the operational range of 3-4.5 $m^3 \cdot s^{-1}$ efficiencies are significantly increased, particularly at the higher flow rates. At 4.5 $m^3 \cdot s^{-1}$, the new fan has an efficiency of 56%, whereas the existing design is 50%. This represents an energy saving of 12%, which can recover the total capital cost of a new fan within 1 year and reduce lifetime costs many times. For a fan operating continuously at the full 50Hz speed of 2900 RPM, as opposed to laboratory speed of 2100 RPM. The original power consumption of 24kW would be reduced by 3kW, representing an approximate saving of £45,000 over a 15 year lifespan (electricity price 10p / kWhr). It should be noted that this has been achieved with no increased manufacturing cost. The total capital cost to the user is £3,000.

Table 5 V2-5 1-D Model Fan Losses in Terms of Pressure

Volume flow	Loss results by type (Pa)								
	Atmosphe (i)	Expansio (ii)	Inlet (iii)	Impelle (iv)	Volute (v)	Volute (vi)	Volute (vii)	Outlet (viii)	Total
0.9	1.8	14.5	159.2	3.0	716.8	11.6	5.6	0.0	912.5
2.1	9.4	76.4	9.8	12.8	333.3	33.6	18.5	3.8	497.5
3.0	19.7	159.7	18.0	29.3	140.3	68.1	37.4	7.8	480.2
3.5	27.4	222.3	71.7	42.2	68.4	93.0	51.0	10.9	586.9
4.1	37.1	301.6	168.7	59.0	21.3	123.7	67.9	14.8	794.1
4.6	46.4	377.0	279.1	74.9	4.5	152.1	83.6	18.5	1036.1
4.9	53.5	434.7	370.9	87.0	3.9	173.4	95.3	21.3	1240.1

Table 6 V2-5 1-D Model Fan Losses as a Percentage of Total Losses

Volume flow	Loss results by type (%)								
	Atmosphe (i)	Expansio (ii)	Inle (iii)	Impelle (iv)	Volute (v)	Volute (vi)	Volute (vii)	Outlet (viii)	Total
0.9	0.2	1.6	17.5	0.3	78.5	1.3	0.6	0.0	100.
2.1	1.9	15.4	2.0	2.6	67.0	6.8	3.7	0.8	100.
3.0	4.1	33.3	3.7	6.1	29.2	14.2	7.8	1.6	100.
3.5	4.7	37.9	12.2	7.2	11.7	15.8	8.7	1.9	100.
4.1	4.7	38.0	21.2	7.4	2.7	15.6	8.6	1.9	100.
4.6	4.5	36.4	26.9	7.2	0.4	14.7	8.1	1.8	100.
4.9	4.3	35.1	29.9	7.0	0.3	14.0	7.7	1.7	100.

Standard Impeller, One-dimensional Model and Experimental Results Comparison.

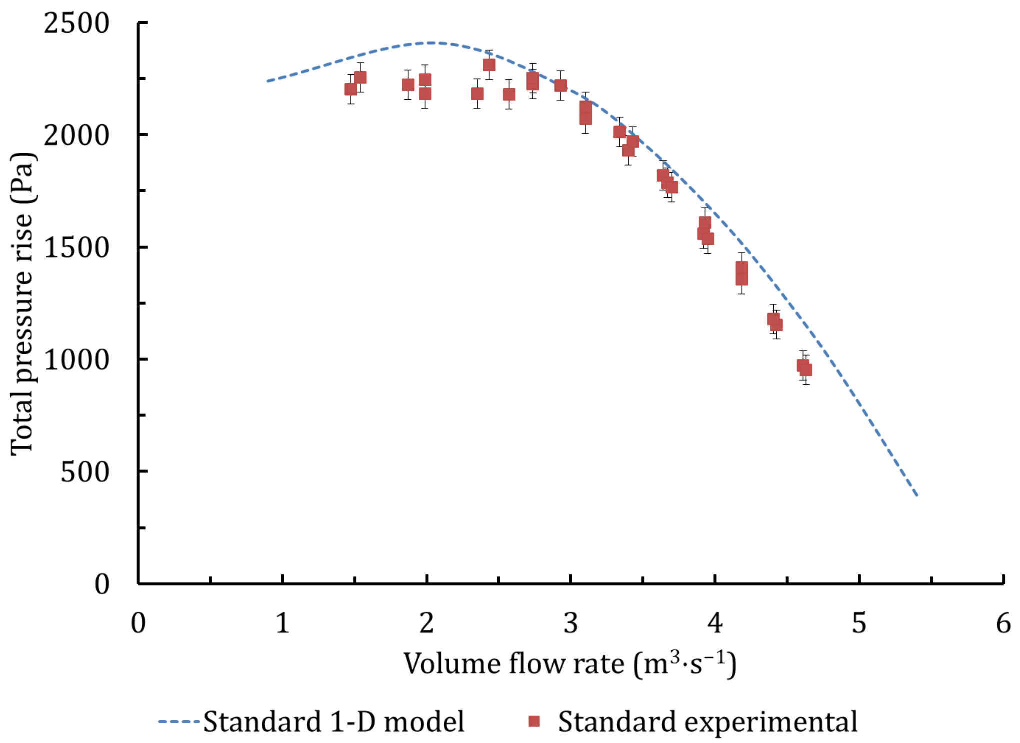


Fig. 8. Standard impeller: 1-D model and experimental total pressure rise.

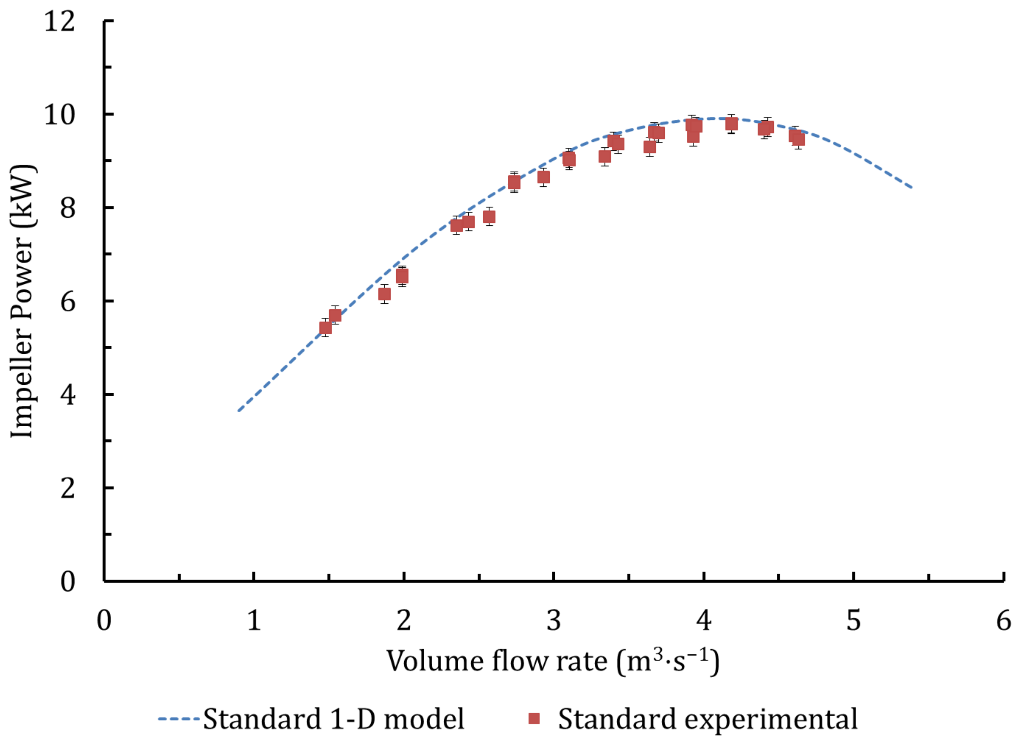


Fig. 9. Standard impeller: 1-D model and experimental impeller power.

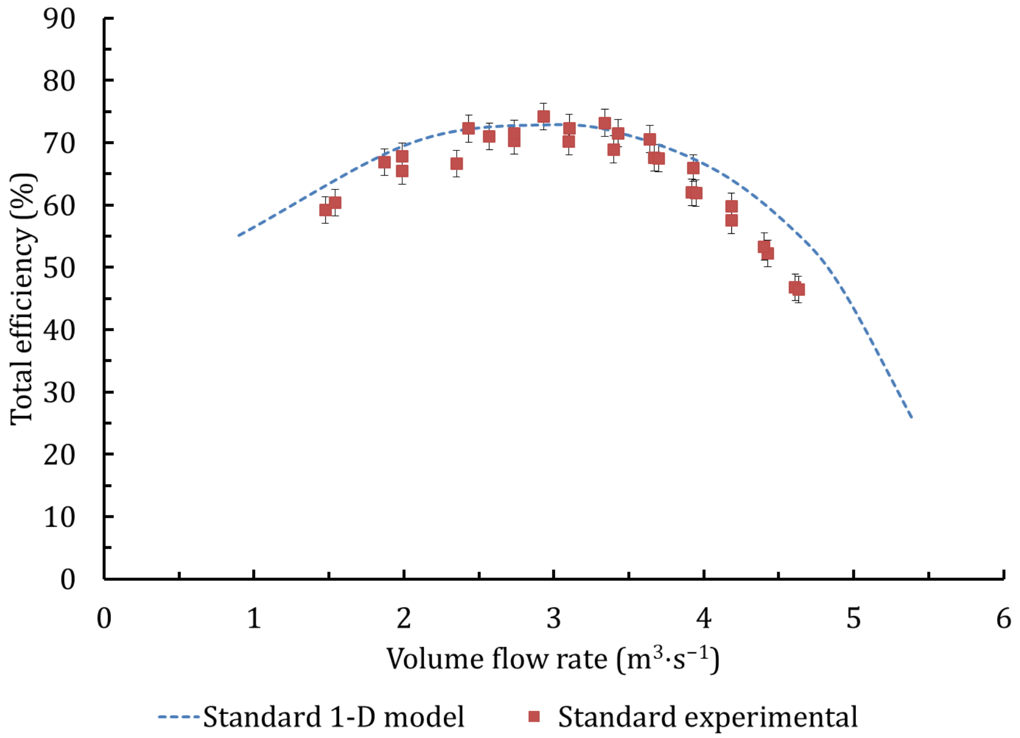


Fig. 10. Standard impeller: 1-D model and experimental total efficiency.

V2-5 impeller, One-dimensional Model and Experimental Results Comparison.

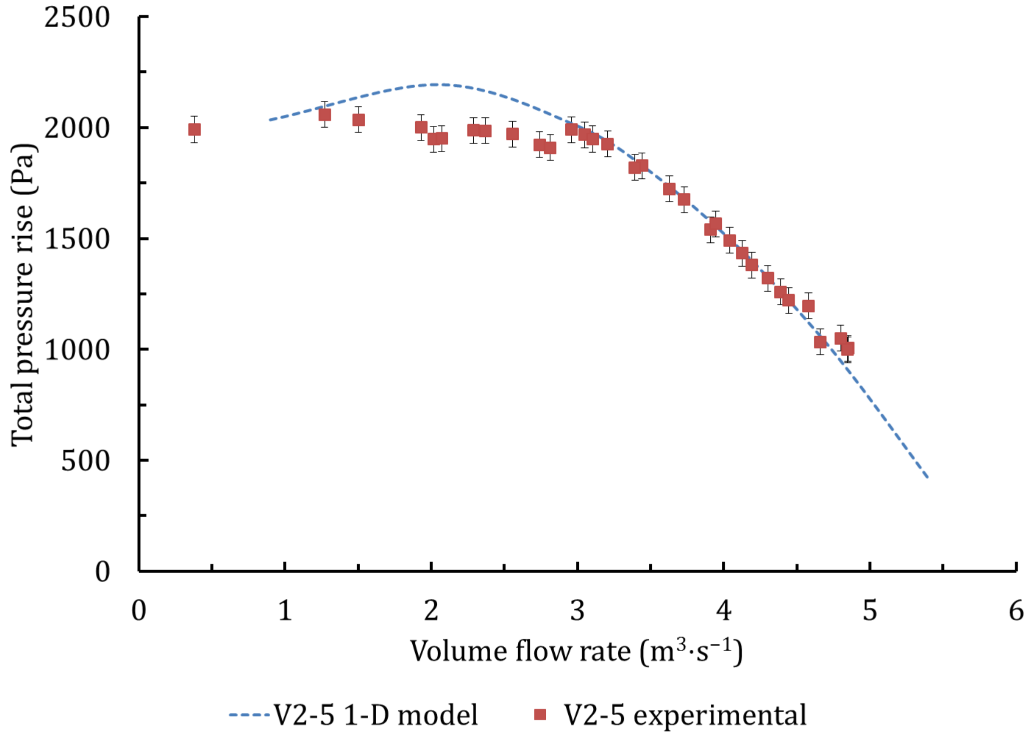


Fig. 11. V2-5 impeller: 1-D model and experimental total pressure rise.

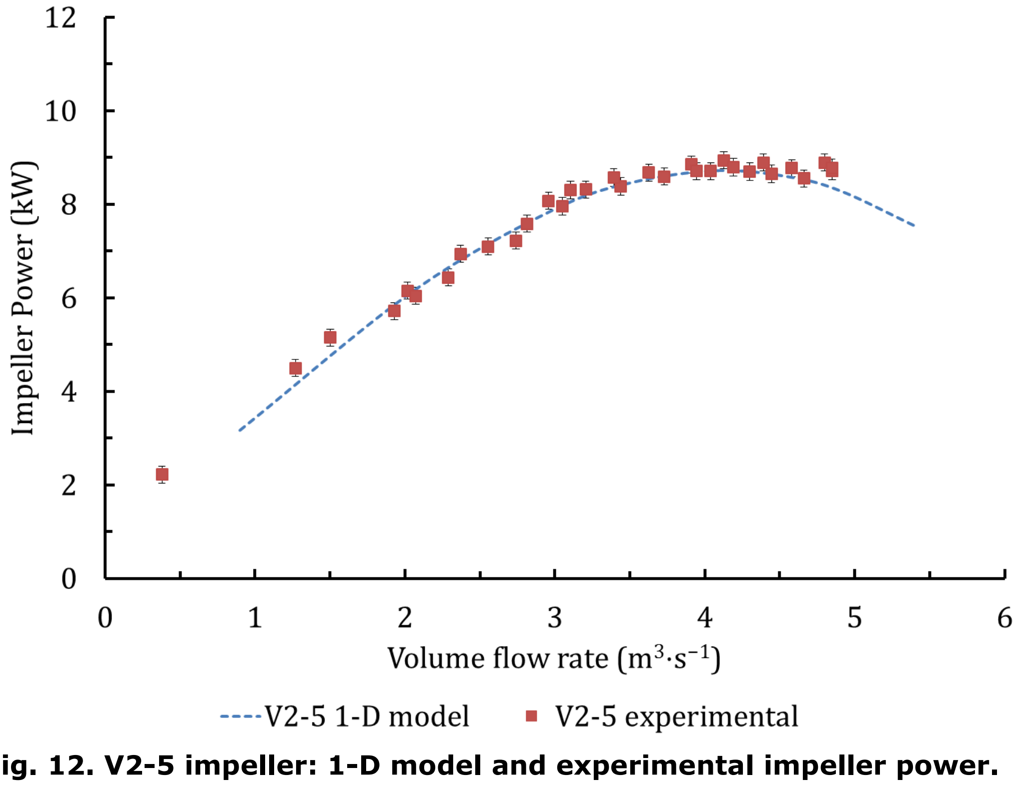


Fig. 12. V2-5 impeller: 1-D model and experimental impeller power.

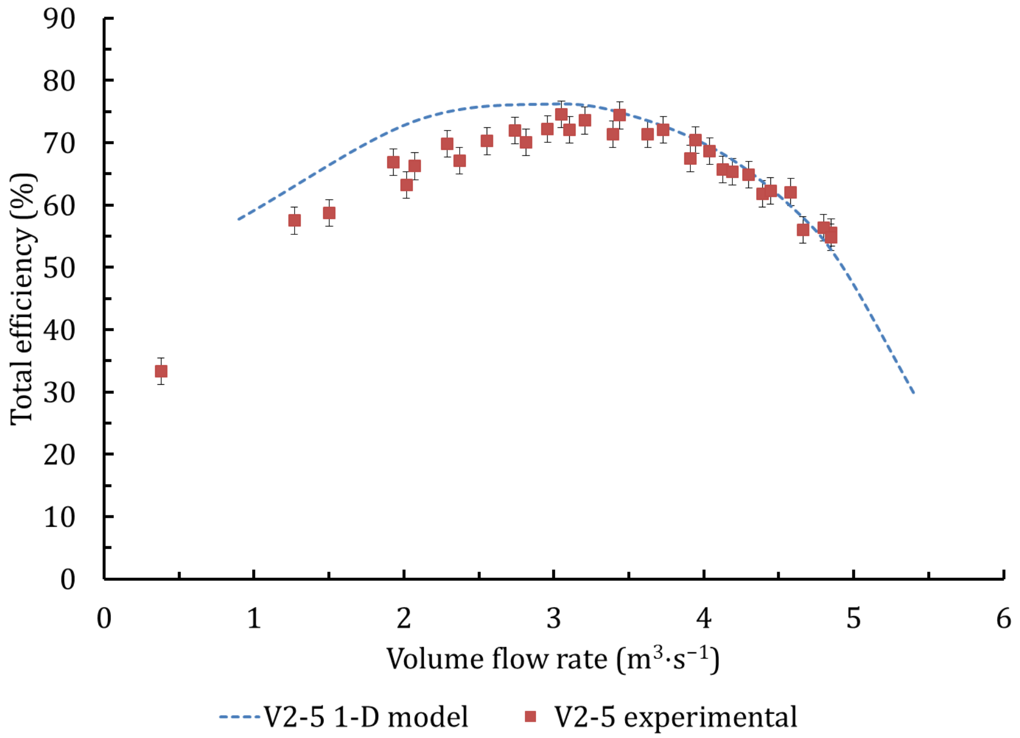


Fig. 13. V2-5 impeller: 1-D model and experimental total efficiency.

One-dimensional Model, Standard and V2-5 Impeller Results Comparison.

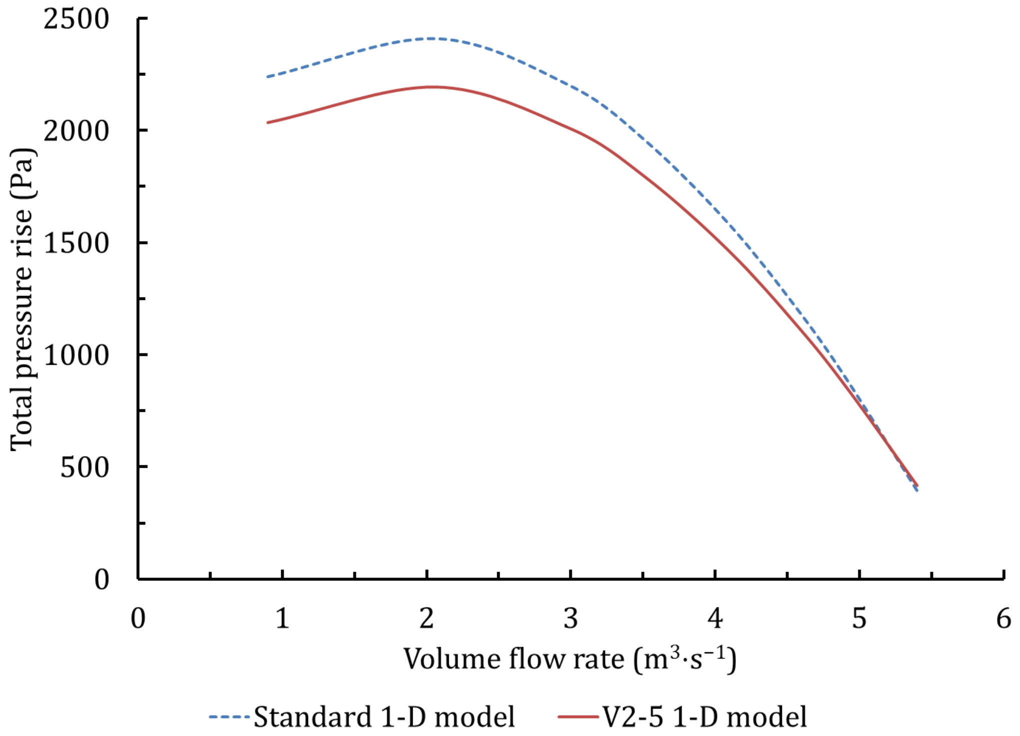


Fig. 14. 1-D model: standard and V2-5 impeller total pressure rise.

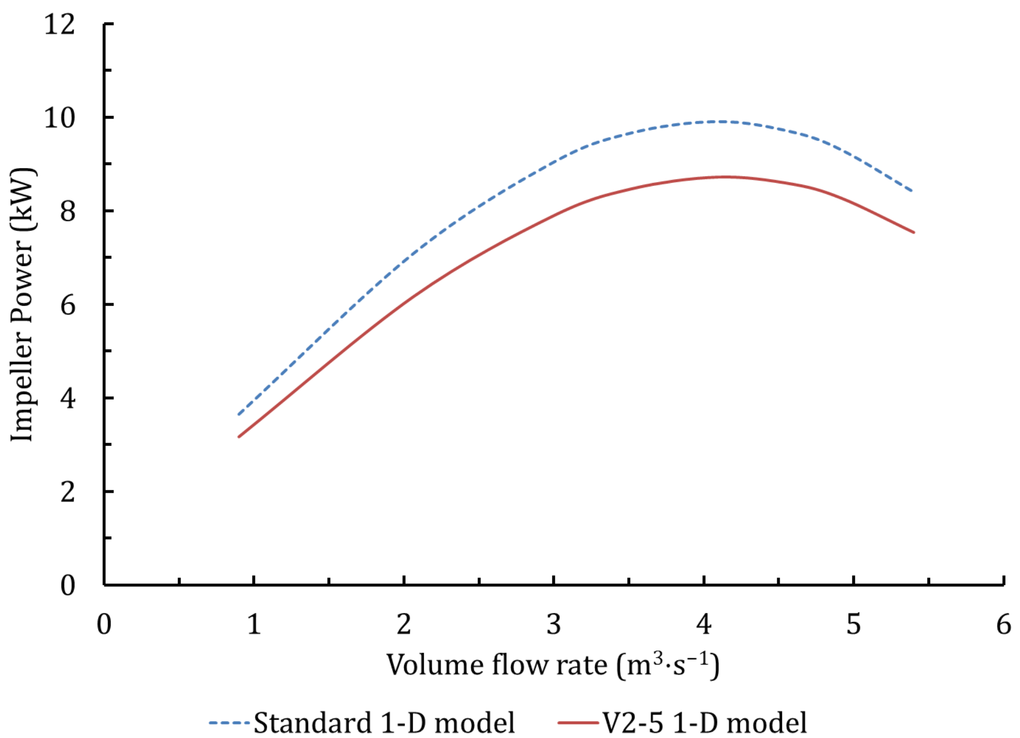


Fig. 15. 1-D model: standard and V2-5 impeller power.

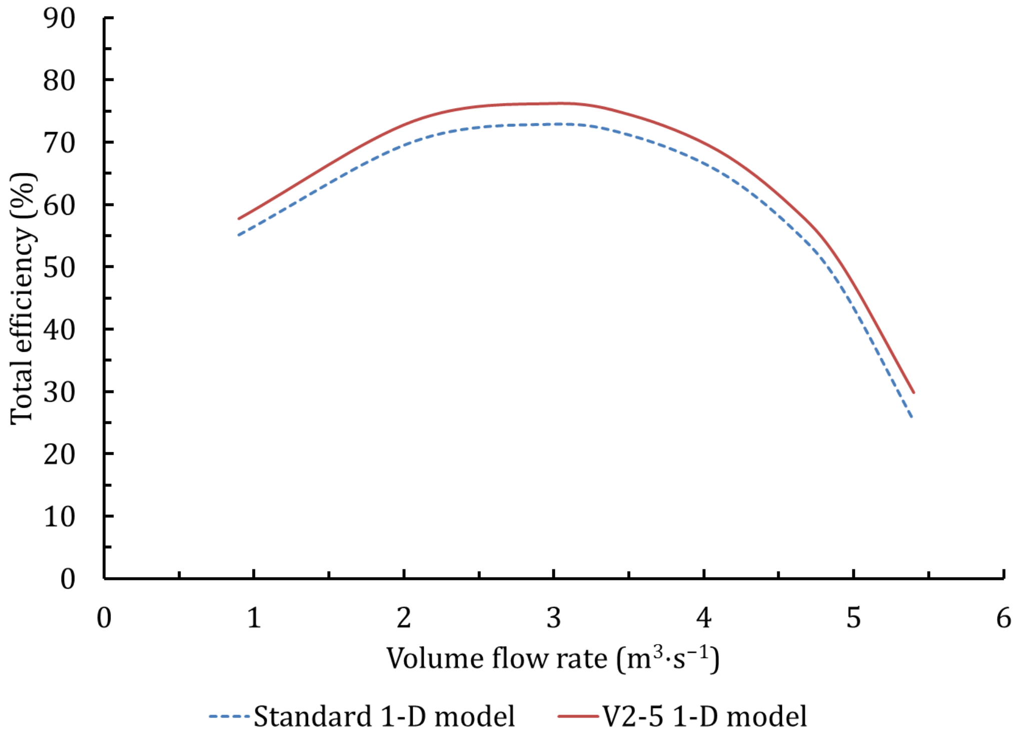


Fig. 16. 1-D model: standard and V2-5 total efficiency.

Experimental, Standard and V2-5 Impeller Results Comparison.

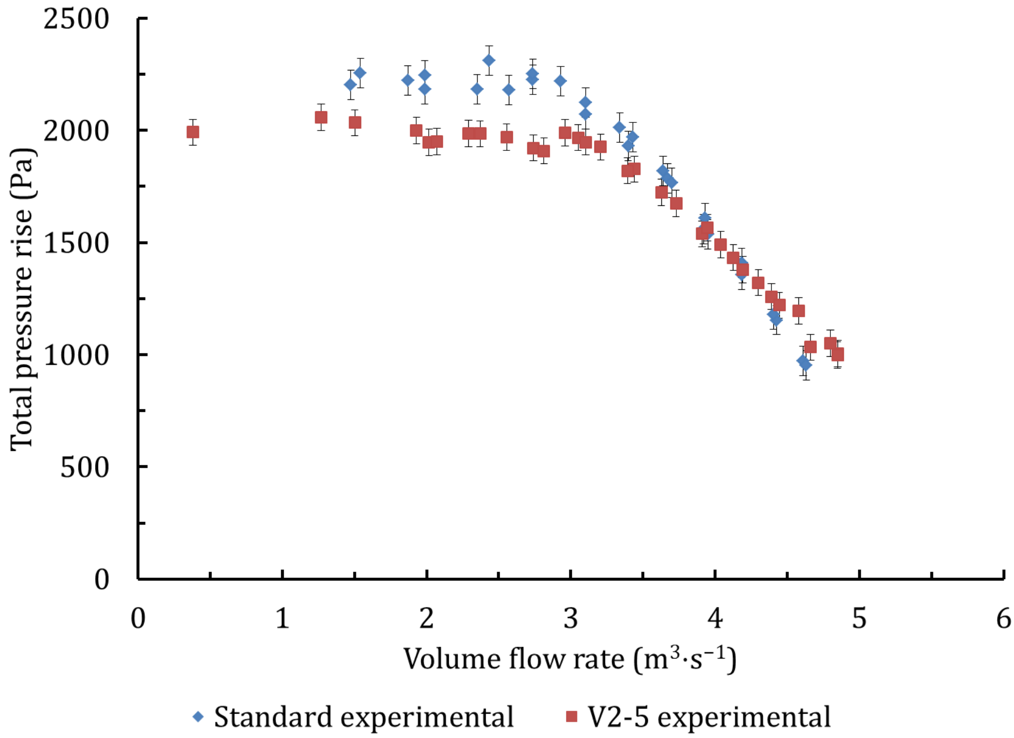


Fig. 17. Experimental: standard and V2-5 impeller total pressure rise.

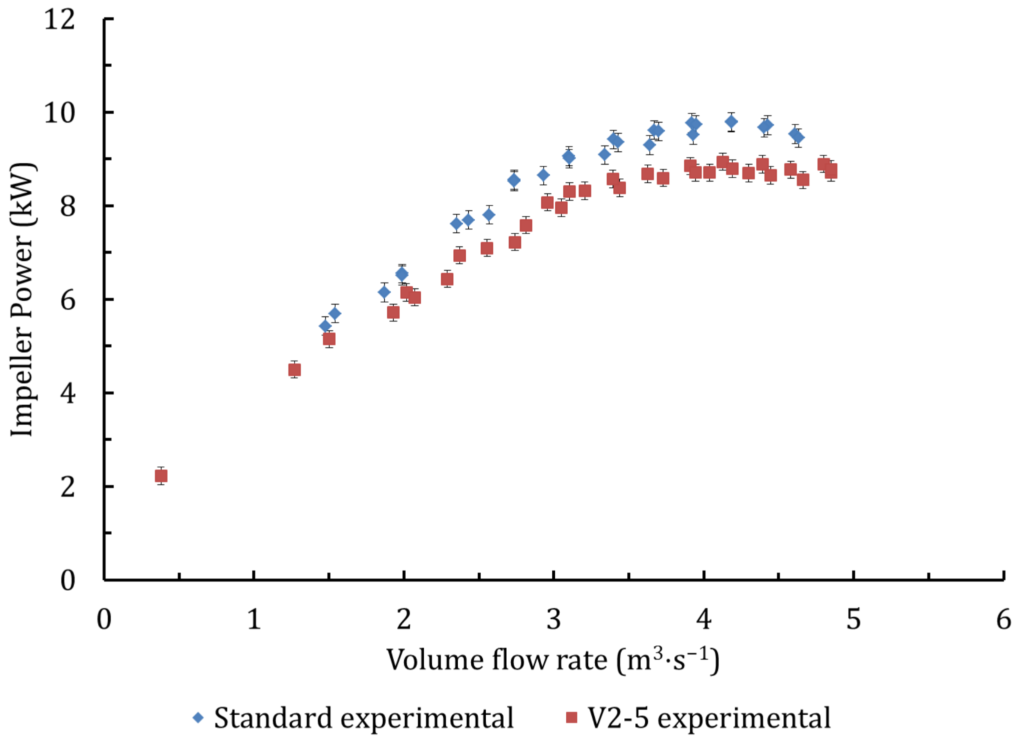


Fig. 18. Experimental: standard and V2-5 impeller power.

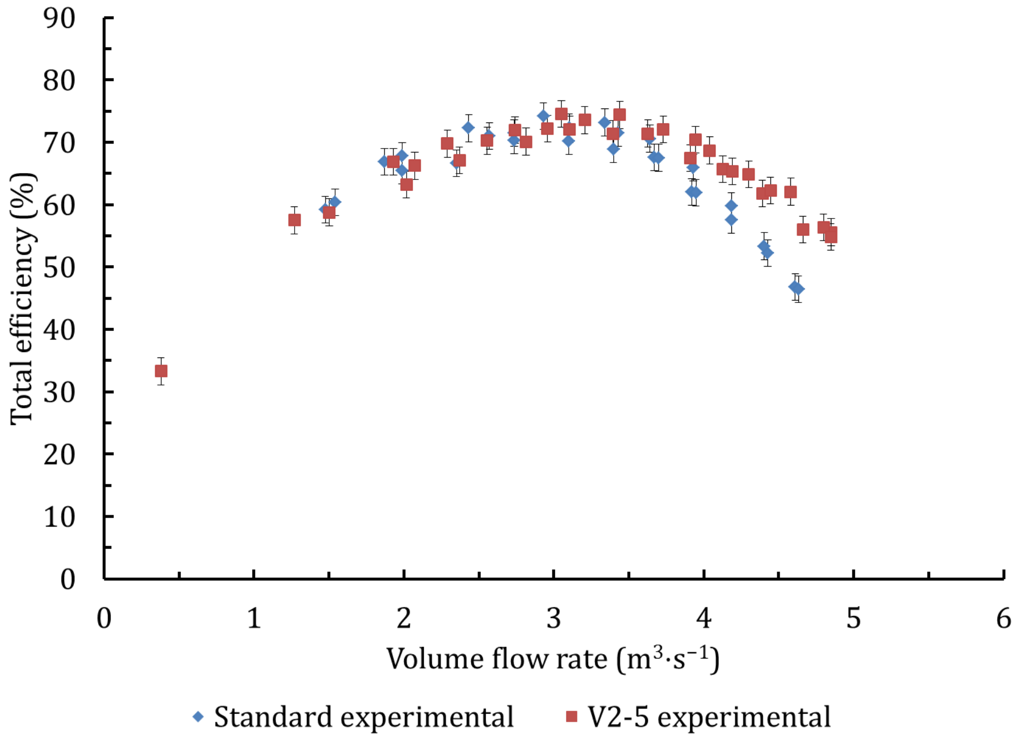


Fig. 19. Experimental: standard and V2-5 total efficiency.

Conclusions and Summary

A one-dimensional fan model has been developed using analogous pipe flow models adapted to centrifugal fans.

The model shows excellent agreement with experimental results, particularly at flows above the maximum efficiency flow and successfully predicts interactions between various fan components.

The loss predicting nature of the results identifies the areas of design that need attention and those that do not.

The model can be used to optimise the basic design parameters and is far less time consuming than more sophisticated models.

The model could easily have modules added to deal with the use of inlet or exit guide vanes.

The model cannot predict significant 2 or 3 dimensional effects, such as reversed or reduced flow through areas of the impeller, but these tend to be most important outside of the operational flow range (3-4.5 $m^3 \cdot s^{-1}$).

A new prototype impeller, V2-5 has been developed with increased efficiency, the trade-off being lower pressure but also lower power consumption.

Acknowledgments

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References

[1] C.-H. Huang and W.-C. Tseng, "An optimal volute spiral case design for centrifugal fan: theoretical and experimental studies," International Journal of Mechanics and Materials in Design, vol. 12, pp. 223-240, 2016.

[2] S.-C. Lin and M.-L. Tsai, "An integrated performance analysis for a backward-inclined centrifugal fan," Computers & Fluids, vol. 56, pp. 24-38, 2012.

[3] M. Xiao, Q. Xiao, H.-S. Dou, M. Xiaoyang, C. Yongning, H. Haijiang and Y. Xinxue, "Study of flow instability in a centrifugal fan based on energy gradient theory," Journal of Mechanical Science and Techonology, vol. 30, no. 2, pp. 507-517, 2016.

[4] J. Zhao, C. J. Wu and C. F. Xia, "Experimental on the performance of centrifugal fan with limited size by changing the openness distribution," Key Engineering Materials, vol. 693, pp. 117-125, 2016.

[5] Z. Lei, W. Rui, Y. Wei and W. Songling, "Simulation of air jets for controlling stall in a centrifugal fan," Journal of Mechanical Engineering Science, vol. 229, no. 11, pp. 2045-2055, 2015.

[6] J. Zhang, W. Chu, H. Zhang, Y. Wu and X. Dong, "Numerical and experimental investigations of the unsteady aerodynamics and aero-acoustics characteristics of a backward curved blade centrifugal fan," Applied Acoustics, vol. 110, pp. 256-267, 2016.

[7] Y.-T. Lee, V. Ahuja, A. Hosangadi, M. E. Slipper, P. L. Mulvihill, R. Birkbeck and R. M. Coleman, "Impeller design of a centrifugal fan with blade optimization," International journal of rotating machinery, p. 16, 2011.

[8] R. A. Van den Braembussche, "Optimization of radial impeller geometry," in Design and analysis of high speed pumps, Neuilly-sur-Seine, RTO, 2006, pp. 13-1 – 13-28.

[9] X.-w. Qiu, M. Anderson and D. Japikse, "An integrated design system for turbomachinery," in 9th International Conference on Hydrodynamics, Shanghai, 2010.

[10] R. Pauer and N. Muller, "Impeller design for radial and mixed flow compressors," in Proceedings of IMECE 04 2004 ASME International Mechanical Engineering, Anaheim, 2004.

[11] R. R. Singh and M. Nataraj, "Optimizing impeller geometry for performance enhancement of a centrifugal blower using the taguchi quality concept," International Journal of Engineering Science and Technology, vol. 4, no. 10, pp. 4308-4314, 2012.

[12] P. Gasparovic and M. Carnogurska, "Aerodynamic optimisation of centrifugal fan casing using CFD," Journal of Applied Science in Thermodynamics and Fluid Mechanics, vol. 2, no. 1, pp. 1-6, 2008.

[13] N. Y. Sharma and K. V. Karanth, "Numerical analysis of a centrifugal fan for improved performance using splitter vanes," World Academy of Science, Engineering and Technology, vol. 36, pp. 453-459, 2009.

[14] K. V. Karanth and N. Y. Sharma, "CFD analysis on the effect of radial gap on impeller-diffuser flow interaction as well as on the flow characteristics of a centrifugal fan," International Journal of Rotating Machinery, p. 8, 2009.

[15] O. P. Singh, R. Khilwani, T. Sreenivasulu and M. Kannan, "Parametric study of centrifugal fan performance: experiments and numerical simulation," International Journal of Advances in Engineering & Technology, vol. 1, no. 2, pp. 33-50, 2011.

[16] L. Chunxi, W. S. Ling and J. Yakui, "The performance of a centrifugal fan with enlarged impeller," Energy Conversion and Management, vol. 52, pp. 2902-2910, 2011.

[17] J. G. Purnell, "Prediction of axial and centrifugal fan characteristics for large surface effect vehicles," Naval Ship Research and Development Centre, Annapolis, 1973.

[18] D. J. Myles, "An analysis of impeller and volute losses in centrifugal fans," Proceedings of the Institution of Mechanical Engineers, vol. 184, no. 1, pp. 253-277, 1969.

[19] K. C. Thin, M. M. Khaing and K. M. Aye, "design and performance analysis of centrifugal pump," World Academy of Science, Engineering and Technology, vol. 46, pp. 422-429, 2008.

[20] J. Gonzalez, J. Fernandez, E. Blanco and C. Santolaria, "Numerical simulation of the dynamic effects due to impeller-volute interaction in a centrifugal pump," Journal of Fluids Engineering, vol. 124, pp. 344-355, 2002.

[21] R. Ballelsteros-Tajadura, S. Velarde-Suarez, J. P. Hurtado-Cruz and C. Santolaria-Morros, "Numerical calculation of pressure fluctuations in the volute of a centrifugal fan," Journal of Fluids Engineering, vol. 128, no. 2, pp. 359-369, 2006.

[22] T. Meakhail and S. O. Park, "A study of impeller-diffuser-volute interaction in a centrifugal fan," Journal of Turbomachinery, vol. 127, no. 1, pp. 84-90, 2005.

[23] G. Pavesi, "Impeller volute and diffuser interaction," in Design and analysis of high speed pumps, Neuilly-sur Seine, RTO, 2006, pp. 6-1 – 6-28.

[24] Y. R. Pathak, B. D. Baloni and S. A. Channiwala, "Numerical simulation of centrifugal blower using CFX," in International Conference on Recent Trends in Information Technology , Chennai, 2012.

[25] A. Corsini, G. Delibra, F. Rispoli, A. G. Sheard and P. Venturini, "Aerodynamic simulation of a high-pressure centrifugal fan for process industries," in Proceeedings of ASME Turbo Expo 2013: Turbine Technical Conference and Exposition, San Antonio, 2013.

[26] O. Leonard and O. Adam, "A quasi-one-dimensional CFD model for multistage turbomachines," Journal of Thermal Science, vol. 17, no. 1, pp. 7-20, 2008.

[27] Y.-T. Lee, "Impact of fan gap flow on the centrifugal impeller aerodynamics," Journal of Fluids Engineering, vol. 132, p. 9, 2010.

[28] P. Waide and C. U. Brunner, "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems," International Energy Agency, Paris, 2011.

[29] F. J. Wiesner, "A review of slip factors for centrifugal impellers," Journal of Engineering for Power, vol. 89, no. 4, pp. 558-572, 1967.

[30] F. M. White, Fluid Mechanics, New York: McGraw Hill, 1994.

[31] "Neutrium: Fluid Flow Episode 3 - Introduction to Hydraulics," Native Dynamics, 2016. [Online]. Available: https://neutrium.net/fluid_flow/. [Accessed April 2016].

[32] E. S. Menon, Piping Calculations Manual, New York: McGraw Hill, 2005.

[33] B. Eck, Fans; design and operation of centrifugal, axial-flow, and cross-flow fans, New York: Pergamon Press, 1973.

Bearing solutions for improved centrifugal compressor efficiency and reliability in industrial HVAC applications

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Abstract

The HVAC industry develops solutions designed to improve the comfort, safety and energy efficiency of non-residential buildings and residential properties.

Air conditioning and process cooling are provided to large facilities like sky scrapes, Hospitals, airports as well as manufacturing or industrial process

The chillers use a refrigeration process to cool water that is circulated in a building or industrial process to provide cooling.

Large capacity chillers are typically equipped with centrifugal compressors.

The traditional driveline for air conditioning centrifugal compressors are of open design and gear driven. It comprises an air cooled induction motor, which is connected to the compressor low speed gear shaft through a coupling. A mechanical shaft seal separates the refrigerant and the pressure in the compressor from the outside air. The high speed impeller shaft is driven by the gear shaft through a pinion. Both the impeller and the gear shafts are supported on hydrodynamic bearings, two radial and one axial for each shaft. The motor has separate bearings. New challenges on air conditioning centrifugal compressors by demands for higher energy efficiency, sustainable operation, new refrigerants, reduced cost and improved reliability are driving improvements of the traditional driveline design. This paper discusses possible bearing types and systems that significantly improve the compressor efficiency and reliability not only by reducing the bearing friction itself but also the compressor's system efficiency and reliability for reduced total cost of ownership.

Introduction

The original driveline for air conditioning centrifugal compressors comprised of an air cooled induction motor, connected to the compressor low speed gear shaft through a coupling. A mechanical shaft seal separated the refrigerant and the pressure in the compressor from the outside. The high speed impeller shaft was driven by the gear shaft through a pinion. Both the impeller and the gear shafts were supported by hydrodynamic bearings, two radial and one axial for each shaft. The motor had separate bearings, (fig 1.)

The motor speed was fixed and defined by the number of poles of the motor and the grid frequency. The impeller shaft speed was determined by the motor speed and the gear ratio. This design is still used today on some large compressors when it is desirable to be able to repair the motor separately from the compressor.

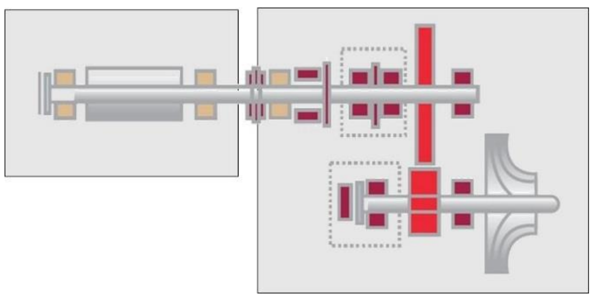

Fig.1 Open gear drive design

Semi Hermetic Design

An improvement to this design was the introduction of the semi-hermitic design, with the motor rotor mounted directly on the low speed gear shaft and contained within the pressurized shell of the compressor. (Fig 2.)

This design had several advantages:

- It eliminated the mechanical seal and the possibility of refrigerant leakage.
- It eliminated the need for maintenance of the seal.
- There was no need for separate motor bearings
- The motor was cooled by refrigerant, not air. With refrigerant cooling being much more efficient, the physical size of the motor could be reduced.
- Energy efficiency was improved
- Motor cost was reduced
- Overall motor-compressor system footprint was reduced.

The motor is delivered to the compressor OEM in components, rotor and stator, and assembled by the OEM into the compressor.

New challenges on compressors by demands for higher energy efficiency, environmentally sustainable operation, new refrigerants [1], reduced cost and improved reliability were the driving needs for further improvements.

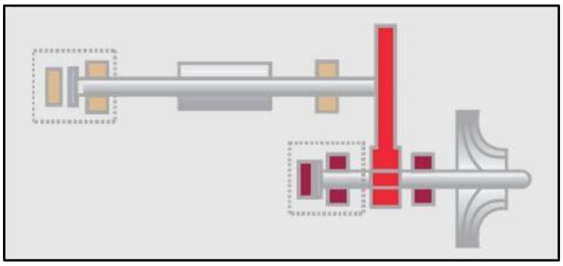

Fig.2 Semi hermetic gear drive design

Direct Drive Technology

In a fixed speed driveline with speed increasing gears, an electric motor, typically a 2 or 4 pole induction motor drives the low speed shaft at 1450 or 2950 rpm on a 50 Hz grid, or at 1750 or 3550 rpm on a 60 HZ grid. The high speed (impeller) shaft is driven by the gears and the shaft speed is determined by the motor speed and the gear ratio. Different gear sets are used for different end user applications. Fig 3.

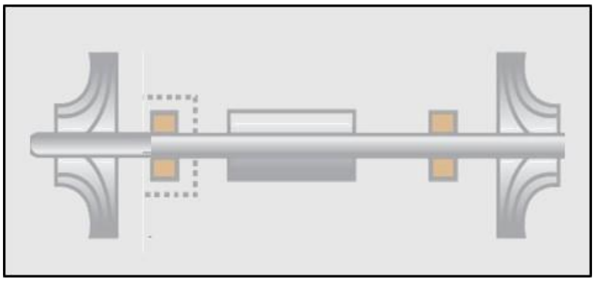

Fig. 3 Semi-hermetic direct drive with back to back impellers

Two technical and economic trends over the last 20 years have enabled the development of high speed direct drive technology. One such technology is Variable Speed Drives (VFDs), the other high speed motors. In high speed direct drives there is no low speed shaft and no gears, the impeller(s) are mounted directly on the extended motor shaft. This means simplified design, elimination of the cost and power losses in gears and simplified maintenance. It also enables oil free operation, since there are no gears that need oil and oil free bearing technologies have emerged and are available today to make oil free operation possible.

With direct drive, the absence of the gears also simplifies the mechanical design of a two stage compressor with back to back impellers positioned at opposite ends of the motor. Such a design is advantageous for high speed because of the shorter overhang of the impellers, compared to having both impellers on the same side. A drawback with this design is that it requires a crossover pipe between the two compressor stages. Two stage compression makes it possible to use two expansion valves and economizer tank between the condenser and the evaporator. This leads to an efficiency improvement of 4% to 6 %.

In a variable speed direct drive, the motor current is produced by a VFD. The impeller speed depends directly on the output frequency of the VFD, which can be either higher or lower than 50 or 60 Hz. With variable speed capability it is possible to adjust the pressure produced by the compressor to the condensing pressure for optimal performance and efficiency. Variable speed can also be used to mitigate surge.

In a VFD, AC at grid frequency is first converted to DC through a rectifier, and then converted to AC at a different and controllable frequency though an inverter. The key components in the inverter are Insulated-Gate Bipolar Transistors (IGBTs) which switch the DC to produce AC of a controllable frequency to drive the motor.

The AC produced by the inverter also contains frequencies of higher order which are not useful to drive the motor, but causes losses and heat generation. To limit the high frequencies a filter can be installed between the VFD and the motor.

The rectifier at the front end of the VFD also produces high frequency AC which goes back and contaminates the grid. Filters between the grid and the VFD can be used to limit contamination. Alternatively, an inverter can also be used at the front end (active front end). With an active front end, the contamination of the grid is reduced. With an active front end, it is also possible to use grid power of a lower voltage to produce a higher motor voltage.

The permanent magnet motor (PMM) is the most common motor type used in high speed direct drive centrifugal compressors. It has half-circle shaped permanent magnets attached to as solid steel rotor. The magnets are held in place by a metal or carbon fiber sleeve. The sleeve is needed to keep the magnets from being flung out by centrifugal force. Carbon fiber sleeves are used for the highest speeds. The magnets are made of rare earth materials and very strong. The stator is similar to that of an induction motor. A rotating electromagnetic field is produced in the stator. The rotor magnets are compelled to follow the rotating electromagnetic field, similar to a needle in a compass, producing torque on the rotor. The speed of rotation is synchronous with the output frequency of the VFD. The motor current must be exactly controlled by the VFD to produce an electromagnetic field and torque that is equal to the required torque from the compressor, (including required torque for acceleration). If the electromagnetic field is too weak, the rotor will slip, if it is too strong the motor will overheat. PMMs have high energy efficiency, up to 98%, and high power factor, close to 1.0. Motors with lower power factors use more current and need larger size VFDs.

The speed limiting factors of an electric motor are:

- Rotor stiffness. Too low stiffness means low frequency bending modes
- Bearing stiffness. Too low stiffness means low frequency rigid body modes

- Strength of the rotor to withstand centrifugal forces
- Internal motor heat generation and cooling. With high power density heat generation must be low since available cooling is limited
- Speed capability of bearings

Features that make PMMs suitable for high speed:

- Solid steel rotor supporting the magnets, meaning high rotor stiffness and high natural frequency
- High rotor strength with the high strength sleeve holding the magnets in place
- High energy efficiency and low energy losses in the motor
- Available high speed, low friction bearings

Rolling Bearings

A further improvement is possible by the use of rolling bearings instead of hydrodynamic bearings. One option is to use rolling element bearings on the high speed shaft only, since the bearing friction is higher on the high speed shaft. Other possibilities are to convert the bearings on both shafts, or on the low speed shaft only.

The advantages with rolling element bearings are:

- Reduced bearing friction. This not only directly improves energy efficiency, but also reduces the requirements for oil cooling or even eliminates the need for an oil cooler.
- Smaller bearing clearances making it possible to reduce impeller to volute clearances and thereby improve efficiency through reduced internal leakage
- Reduced oil flow requirement meaning reduced size of the oil pump and the lubrication system
- Overall, conversion to rolling bearings can lead to an energy efficiency improvement of 2% to 4%, depending on the original compressor design.

In the past there was hesitation to use rolling element bearings since they were thought of as finite life bearings as opposed to hydrodynamic bearings which were thought of as infinite life bearings. This thinking was very logic since previously it was always possible to calculate a fatigue life for rolling element bearings, even at light loads. This was different than for other machine element subjected to fatigue. For shafts for example, it is possible to avoid fatigue by making sure that the bending stresses are below the fatigue limit of the steel.

The explanation lies in the understanding of the effect of contamination and lubrication. When the theory and formula for bearing life was developed in the 1940s the effects of contamination and lubrication were not well understood. In rolling bearings operating in a dirty environment and with poor lubrication there are high local stresses in the contacts between the rolling elements and the bearing rings. Even under light external loads, the contact areas in the bearing can be highly stressed and subject to fatigue. Today, the effect of lubrication and contamination are well understood and can be predicted. Rolling bearings operation with good lubrication and controlled levels of contamination have predicted infinite life.

Rolling bearings are lubricated by means of the elasto-hydrodynamic lubrication (EHL) mechanism [2]. Since rolling bearings rely on heavily loaded contacts, the lubricant shows an increase of viscosity with rising pressure at the same time that elastic deformation of the steel bodies takes place to accommodate the lubricant. These two mechanisms are responsible of the buildup of a thin lubricating film of around one or few microns thick in EHL conditions and are able to separate the contacting bodies in normal oil-lubricated situation.

Pure refrigerant Lubrication

Researchers at the SKF Engineering and Research Centre carried out investigations in the early 1990s to test the dilution of lubricant oils with refrigerants and its consequences on bearing performance and life [3]. In refrigerant compressors, it is difficult to avoid dilution of the oil by the refrigerant, and it is important to understand how the dilution affects rolling bearings. It was found that conventional all-steel bearings started to exhibit signs of inadequate lubrication at dilution levels of 20 % to 30 %[4]. This led to the investigation of alternative bearing designs and materials to improve bearing operation and life under these poor-lubricant conditions. The studies showed that it was difficult to find a limiting dilution ratio for hybrid bearings, with steel rings and ceramic balls made of silicon nitride (Si_3N_4) [5]. Finally, in 1996, hybrid bearings were run in pure refrigerant with no traces of oil, and the bearings after the feasibility test were in as-new condition. This was a critical test result, which opened up the possibility to use refrigerant as a lubricant for rolling bearings. Since then, research and application development has continued and lead to several additional product features enabling long term reliable operation [5-8].

In analytical studies that followed, it was found that refrigerants can actually form an elasto-hydrodynamic lubricant film. This is possible because refrigerants, similar as oils, increase their viscosity under the very high pressure developed in the contact areas between rolling elements and bearing raceways. The increase is not as significant as with lubricating oils, but is sufficient to produce a very thin lubricant film [8]. In conventional all-steel bearings, this thin film would be inadequate for lubrication, but the ceramic/special steel material combination and other features allows for reliable operation with a very thin film of refrigerant. Previously it was not thought possible to use refrigerants as lubricants because of very low viscosity of refrigerants.

The ceramic – high nitrogen steel material combination not only makes refrigerant lubrication possible, other advantages are:

- Lower density (60%)of silicon nitride than steel, means lower effect of gyroscopic moments and centrifugal forces on the balls. This means higher speed capability compared to bearings with steel balls.
- Insulating properties. As a non-conductive material, silicon nitride protects the bearing rings from passing of electric current, which causes damage to the races.
- Silicon nitride has lower coefficient of thermal expansion than steel. This means less sensitivity to temperature gradients within the bearing and more precise control of preload/clearance
- Silicone nitride has higher modulus of elasticity than steel, ensuring less bearing deflection under load

PRL Bearings in Centrifugal Compressors

One application for refrigerant-lubricated ball bearings is centrifugal compressors for chillers in large air conditioning systems and industrial processes. Chillers use refrigerant in a vapor-compression cycle to cool water, which is then used as a cooling medium in an industrial process or to provide air conditioning in a building. Large capacity chillers, above 300 tons of refrigeration, are typically equipped with centrifugal compressors. (Fig 4)

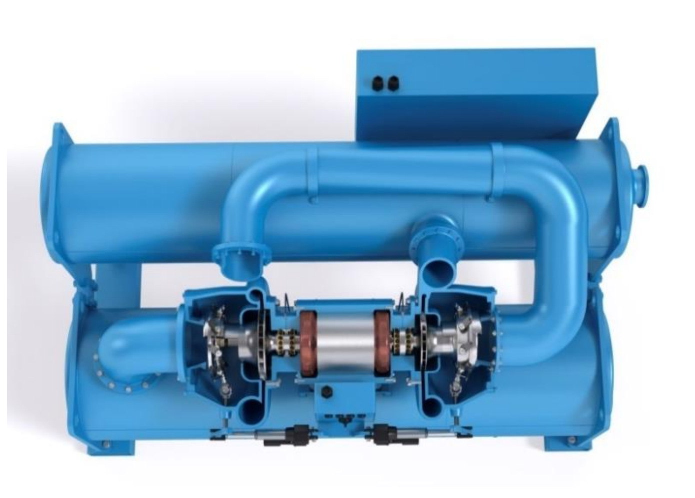

Fig. 4: Centrifugal compressor chiller

Normally there is a single compressor for each chiller. Centrifugal compressors have one or more rotating impellers. The speed of rotation of the impeller is determined by the required impeller peripheral speed, and depends on compressor size, capacity and type of refrigerant used. Compressors using low pressure refrigerants rotate at lower speeds than compressors using medium or high pressure refrigerants. Even with oil lubrication, the operating conditions of the bearings in compressors present difficult lubrication problems due to the presence of refrigerants.

Traditional compressor designs with hydrodynamic bearings use large amounts of circulating oil for lubrication and have separation systems to separate out the oil mixed with the refrigerant so that the oil can be used as a bearing lubricant. Since refrigerants are typically very good solvents, it is difficult to avoid dilution of the oil by the refrigerant. Oil lubricated rolling bearings require less flow of oil and have less friction, but also need separation systems to reduce the dilution of refrigerant in the oil. Therefore, the use of oil free PRL technology is very attractive. Another advantage of the lower viscosity of refrigerants compared to oil, is that the viscous friction of PRL bearings is lower than that of oil lubricated ball bearings. The difference in compressor efficiency is approximately 0.5%.

Advantages of oil free operation

Oil-free operation has several advantages; there is no need for oil maintenance, no need to dispense of used oil, no need of an oil heater, and for air cooled chillers, no risk of contamination of soil in case of pipe breakage. There is also better heat transfer in the condenser and evaporator and no problem with separation of oil and refrigerant in the system.

The Industrial PRL Bearing Solution

An industrial bearing solution that is reliable in PRL conditions has resulted from the various SKF in-house tests, laboratory experiments and simulations [3,4,9,10]. PRL bearing s are made of the highest quality bearing grade silicon nitride (Si_3N_4) rolling elements and the most stringent SKF defect inspection procedure, cage with a strong design shape and fiber reinforced PEEK material, rings made of through-hardened, high nitrogen stainless steel, according to SKF specification VC444, heat treated and ground to super finished raceways in special processes developed by SKF. The steel has a super fine microstructure, making it superior material for rolling bearings, - compared to bearing grade AISI 52100 bearing steel. It also has very good corrosion preventing properties, this proved to be important since the absence of oil makes the bearing surfaces extremely clean in operation. If the compressor is opened up for inspection or repair, conventional steel bearing would corrode in the presence of humid air, but the high nitrogen stainless steel does not corrode. All this assisted by expert application engineering to define bearing arrangements, lubrication methods, filtration degree, pre-load and tolerances.

Fig 5 and 6

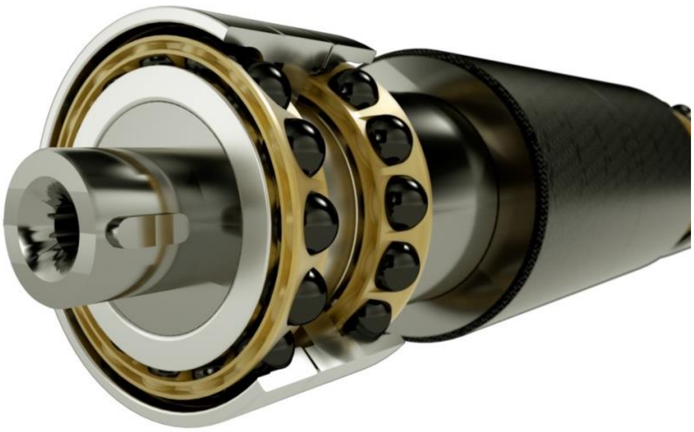

Fig. 5: SKF PRL bearing (inner and outer rings to SKF specification VC444, ceramic balls, fibre fibre-reinforced PEEK cage).	**Fig. 6: 3D view of PRL bearing arrangement.**

The refrigerant used for lubrication is supplied to the bearings by means of jet flow. It is important to keep a sufficient amount of the refrigerant in liquid state as it enters the bearings, since refrigerant in vapor state cannot be used for lubrication.

Conclusion

Different compressor designs and bearing arrangements were briefly discussed. Two direct drive technologies to improve the energy efficiency were briefly discussed. Bearing and pure refrigerant lubricated rolling bearing technology were described in details. PRL technology is summarized and different technological solutions to mitigate the old and new challenges to rolling bearings lubricated with oil–refrigerant mixtures are discussed.

The following conclusions can be drawn from this study:

Rolling bearings

- Reduced bearing friction compared to hydrodynamic bearings
- Smaller bearing clearances, reduced volute clearances, improved volumetric efficiency
- Reduced oil flow compared to hydrodynamic bearings

- Improved compressor energy efficiency

PRL bearings

- Reduced bearing friction compared to oil lubricated rolling bearings
- Elimination of lubrication system
- Improve heat transfer in condenser and evaporator
- Elimination of oil heater
- Elimination of risk of passing of electric current through the bearings

Advantages of oil free operation

- No need for oil maintenance
- No need to dispense of used oil
- No need of an oil heater
- In air cooled chillers, no risk of contamination of soil in case of pipe breakage
- Improved heat transfer in the condenser and evaporator
- No problem with separation of oil and refrigerant in the system.

References

[1] United Nations, Kigali Amendment to the Montreal, Cindy Newberg, Chief Alternatives and Emissions Reduction Branch Office of Atmospheric Programs U.S. Environmental Protection Agency, 2016.

[2] Gabelli, A., Morales-Espejel, G.E., Ioannides, E., Particle Damage in Hertzian Contacts and Life Ratings of Rolling Bearings, Tribol. Trans., vol. 51, pp. 428–445, 2008

[3] Wardle, F.P., Jacobson, B., Dolfsma, H., Hoglund, E. Jonsson, U., "The Effect of Refrigerants on the Lubrication of Rolling Element Bearings used in Screw Compressors", Proc. Int. Comp. Conf. Purdue, pp. 523-534, 1992.

[4] Meyers, K., "Creating the Right Environment for Compressors Bearings", SKF Evolution Magazine, No. 4,November, 1997.

http://evolution.skf.com/creating-the-right-environment-for-compressor-bearings/

[5] Morales-Espejel, G.E., Gabelli, A., Vieillard, C. "Hybrid Bearings Lubricated with Pure Refrigerants". In:SRM, Technical Screw Compressor Conference, Stockholm, 4–7 September, 2001.

[6] Wallin HH and Morales-Espejel GE. Hybrid bearings in oil-free air conditioning and refrigeration compressors, SKF Evolution Magazine, 2002, No. 2.

[7] Morales-Espejel GE, Meeuwenoord R, Fe´ lix Quin˜ onezA, et al. Film thickness and traction measurements of refrigerant R1233zd used as lubricant in elastohydrodynamic

conditions. Proc IMechE, Part C: J Mechanical Engineering Science 2014; 229: 244–253.

[8] Morales-Espejel GE, Hauleitner R and Wallin H. Pure refrigerant lubrication technology in oil-free centrifugal compressors. SKF Evolution Magazine, 2017, No. 1.

[9] Jonsson UJ and Hansson N. Lubrication limits of rolling element bearings in refrigeration compressors. In: Proceedings of international compressor engineering conference at Purdue, West Lafayette, IN, USA, 1998, pp.129–134.

[10] Gabelli A, Kerrigan A and De Blic E. HN rolling bearings for extended service life. In: Proceedings of the fifth ASM heat treatment conference on progress in heat treatment and surface engineering, Gothenburg, Sweden, June 2000.

Air Compressor Total Energy Consumption

Carl Wouters, Atlas Copco

Abstract

This paper presents conclusions of an ongoing data collection effort of more than thirty thousand fixed speed oil injected screw compressors in operation logged in the period 2014 till 2016. An easy to use calculation method is defined to calculate the total annual energy consumption of these air compressors. This method is explained by an example of a fixed speed and variable speed screw compressor.

Introduction

The compressor industry is continuously investigating new technologies and upgrades of current technology to improve the efficiency of their products. For a long time the focus was on improving the individual product and its steady state behaviour and efficiency on one specific condition, the design point. The current trend in the industry is to focus more and more on the overall compressed air system in comparison at only looking at a specific products design point. There is a general consensus that there still is a lot of efficiency gain possible when taking the complete system behaviour in account.

The evaluation of the overall efficiency of a complete compressed air installation is much more complicated and difficult to generalize due to the high variability and complexity of all the possible configurations and applications. Much more information is required of each and every component to take all aspects in account. The first step to evaluate the overall efficiency is to analyze how the different products are actually being used in the field and how the different running states are affecting their performance. Only looking at the steady state behaviour of an air compressor is far from sufficient to define the efficiency of a compressor during actual operation. For example a fixed speed compressor package often performs cyclic operations from Load to Idle and vice versa due to the erratic air consumption profiles that occur in the air application range. Where the measurement of Load and Idle performance have been clearly defined (e.g. ISO1217:2009 [1] for displacement compressors), the transients are not yet specified. The paper "Measurement Principle to define Cycle Energy Requirement" [2] details a measurement methodology to accurately define the additional energy consumption caused by these cyclic operations by the different compressor technologies on the market, e.g. Oil-injected Screw, Oil-free Screw, Centrifugal and others. Figure 1 shows this additional energy use during cyclic operations for load-unload controlled compressors.

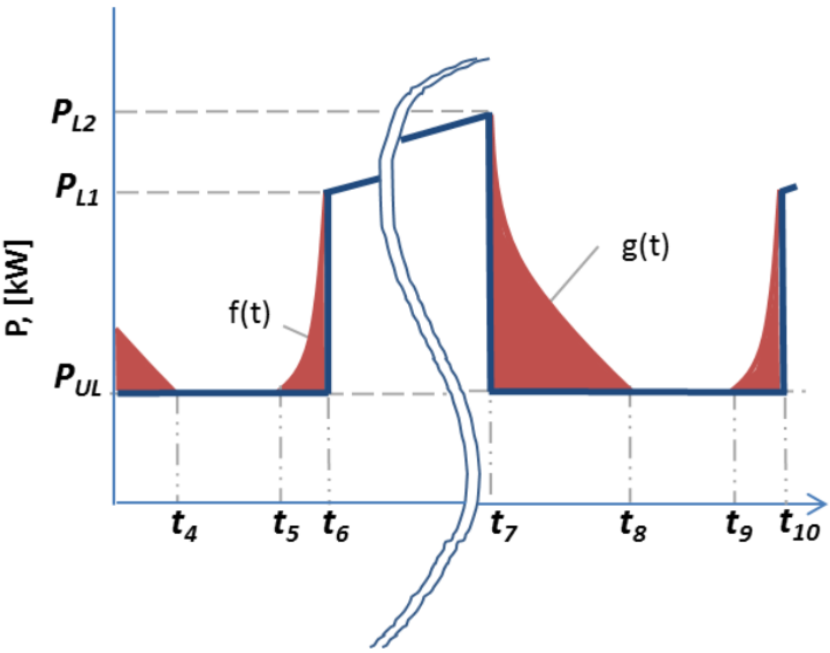

Figure 1: Energy consumption during cyclic operations

The question "What is a representative air consumption profile?" is a difficult one and should be handled with care. Luckily with modern data-mining techniques a lot of data becomes available to analyze the overall behaviour of a specific product and its actual field usage. This paper presents the data analysis of over 30.000 fixed speed oil injected screw compressors. Based on this analysis, an algorithm is shown which can be used to easily calculate the overall efficiency of a specific product taking in account the possible cyclic operations of these products. It is explained by a case study.

Data analysis

To analyze the real performance of air compressors, it is important to understand how these machines are actually running in the field. Due to this a big data mining effort has been setup on more than thirty thousand oil injected screw compressors within all kinds of different customer applications. of these the total running hours, the running hours in load and the total amount of cyclic operations are logged during a period of two years.

Following definitions are used.

- **Running Hours per year**
  The total time the machine is running during a full year. It doesn't include the time when the machine is stopped such as for waiting in standby.
- **Load Ratio**
  The Load Ratio is the ratio defined by the time the machine is running in Load divided by the total time the machine is running. Remark: The time the compressor is running Load is the time the compressor is delivering air to the customer.
- **Cycles per hour**
  The average amount of cyclic operations the machine undergoes during an hour running. It is the total amount of cycles during a year divided by the Running Hours per year.

Although compressors are used in a lot of different applications, it should be possible to allocate typical running profiles and trends based on actual data collection. For each and every entry of the more than 30.000 compressors, the three key values are defined, the running hours per year, the load ratio and the cycles per hour. All of these entries are grouped in sections based on their nominal power. For each section, the averages are calculated together with the first and seventh octile which correspond respectively to 12.5% and 87.5% of the population.

Figure 2 shows the Running Hours per year in function of the nominal power for the different sections. It is clear that the averages of the running hours represented by the blue circles are relatively small. Across all sections, defined by the green vertical lines, the average of the running hours per year are between 2804 and 4703 hours (Table 1). There is a very clear trend upwards for higher nominal powers of the machines, but stabilizes above 100kW. It should also be noted that the spread defined by the first and seventh octile represented by the blue bar graph is significant. This is expected due to the high variability of customer applications.

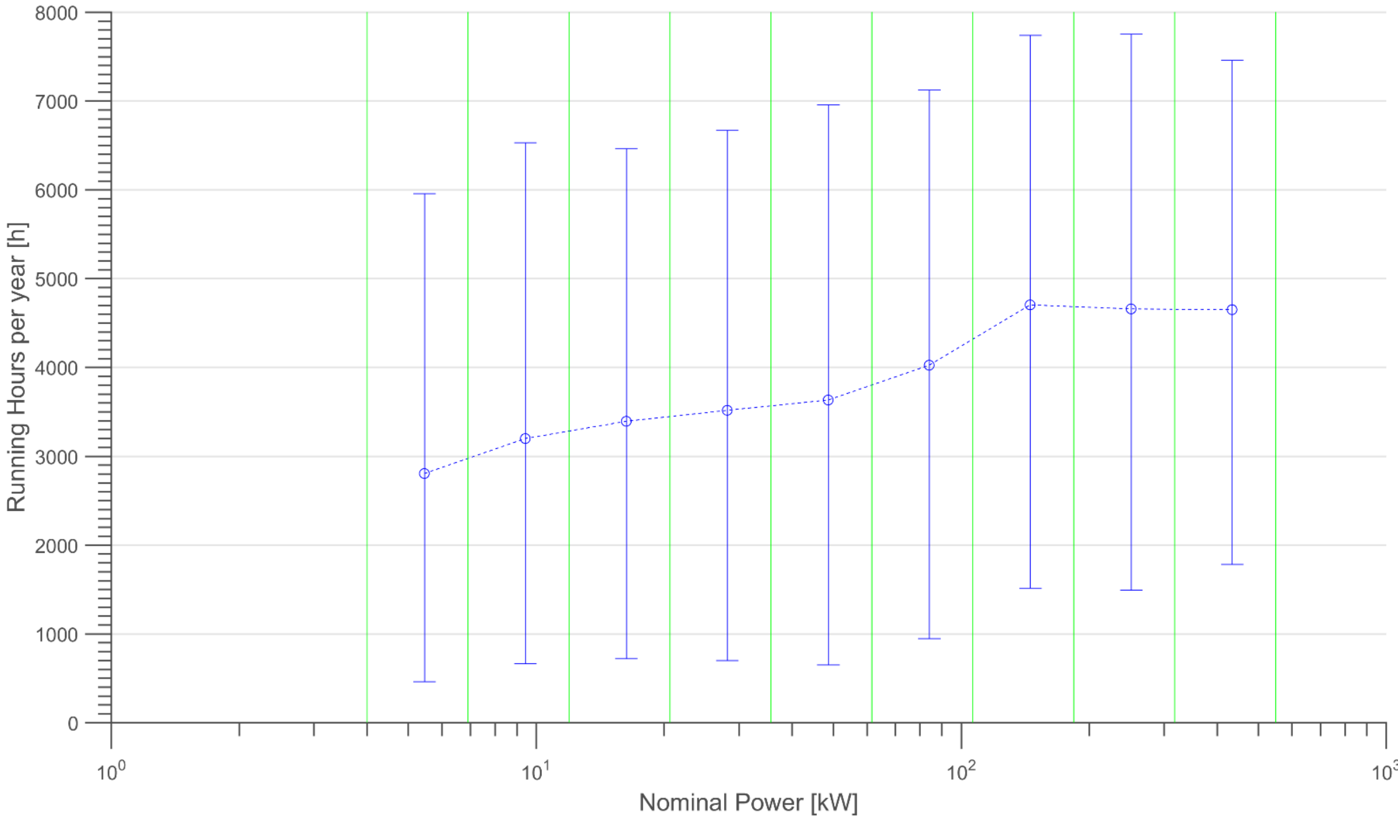

Figure 2: Running Hours per year

Nominal Power (kW)		4 - 6.9	6.9 - 11.9	11.9 - 20.6	20.6 - 35.7	35.7 - 61.7	61.7 - 106.6	106.6 - 184.2	184.2 - 318.3	318.3 - 550
Running Hours per year (h)	First Octile	463	664	723	698	653	946	1513	1492	1784
	Average	2804	3198	3392	3516	3632	4023	4703	4658	4649
	Seventh Octile	5958	6532	6461	6669	6956	7125	7742	7753	7457
Load Ratio (%)	First Octile	18.5	16.2	17	21.4	24.5	33.6	40.7	46.3	41
	Average	43.4	43.3	47.8	54.5	59.6	70	74.1	77.3	76.7
	Seventh Octile	73.5	76.5	84	90.7	94.8	98.6	98.8	99.4	99.6
Cycles per Running Hour (1/h)	First Octile	9.1	9.9	9.7	7	3.6	1	0.5	0.2	0.1
	Average	21.6	29.9	36.2	37.1	35	28.2	17.8	13.9	9.8
	Seventh Octile	33.7	53.9	66.2	71.5	69.4	63.2	41.3	32.6	18.9

Table 1: Overview of Data

When looking at the amount of hours the compressors are delivering air to the customer, the data analysis shows that most machines are running a big part of their time in an

Idle state or transitioning from Idle/Stop to Load and vice versa. The load ratio of the thirty thousand logged machines, shown in figure 3, have average values across the sections of 43.3% for the lower nominal powers up to 77.3% for the higher ones. Similar as the running hours per year, the ratios stabilize above 100kW. As can be seen in the spread of the data (table 1), there are a lot of machines running at very low load ratio's below 40% and high ratio's above 80%. Compressors with low load ratios are running a big part of their time without delivering air to the customer whilst consuming valuable energy.

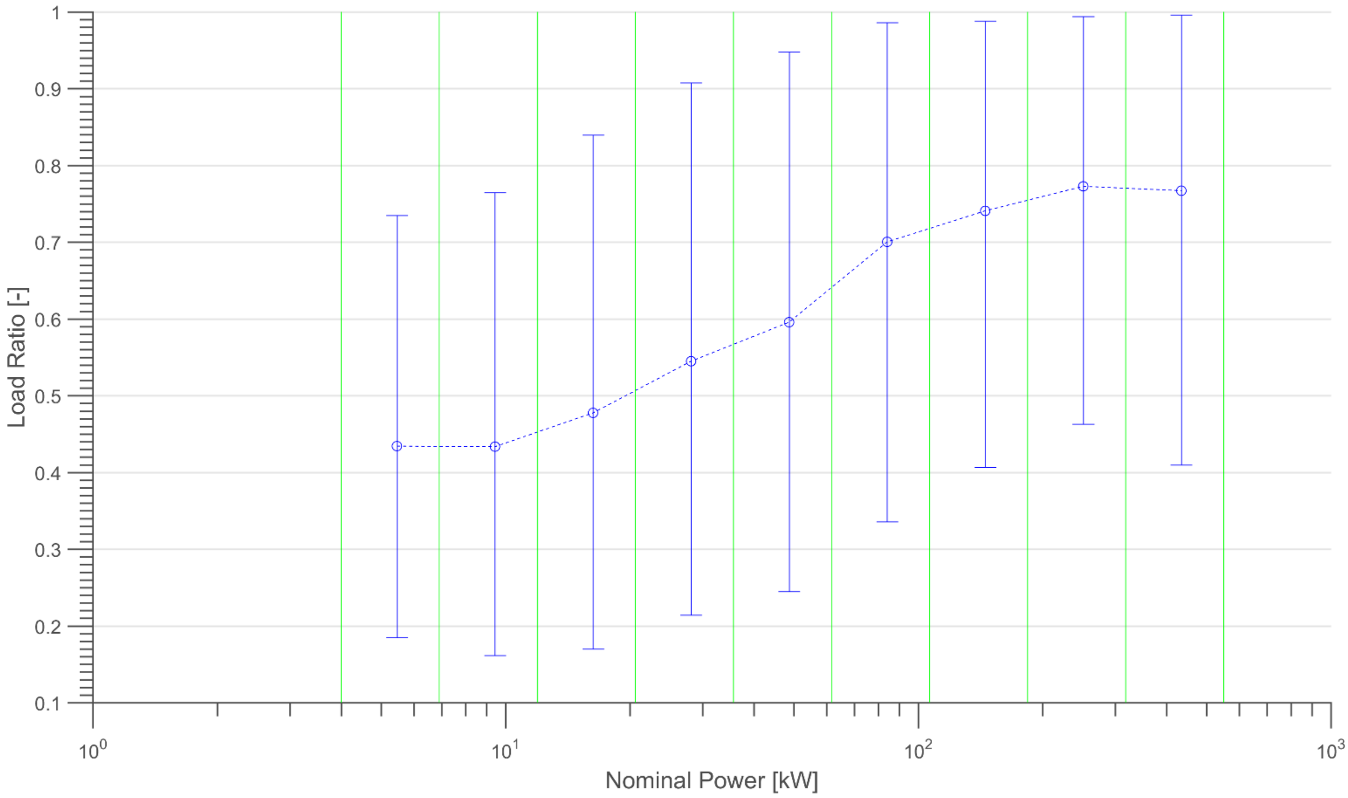

Figure 3 Load Ratio

The third key parameter is the amount of cyclic operations these machines are doing per running hour. This defines how often the compressors are transitioning between different states. Figure 4 shows the amount of cycles per running hour for each section. The averages have values between 9.8 to 37.1 cycles per hour which corresponds to a cyclic operation up to each 90 seconds. Depending on the energy consumption during these transitions, the effect on the overall efficiency can be significant and should be taken in account.

In general the data collection shows that due to the data mining effort, there is a clear view on how these air compressors are running in real customer applications. The data also shows that when looking at the overall performance of a specific product all parameters should be taken in account i.e. load ratios, cycle energy losses and others. This analysis also gives a good starting point to define methodologies to calculate the overall efficiency of a product.

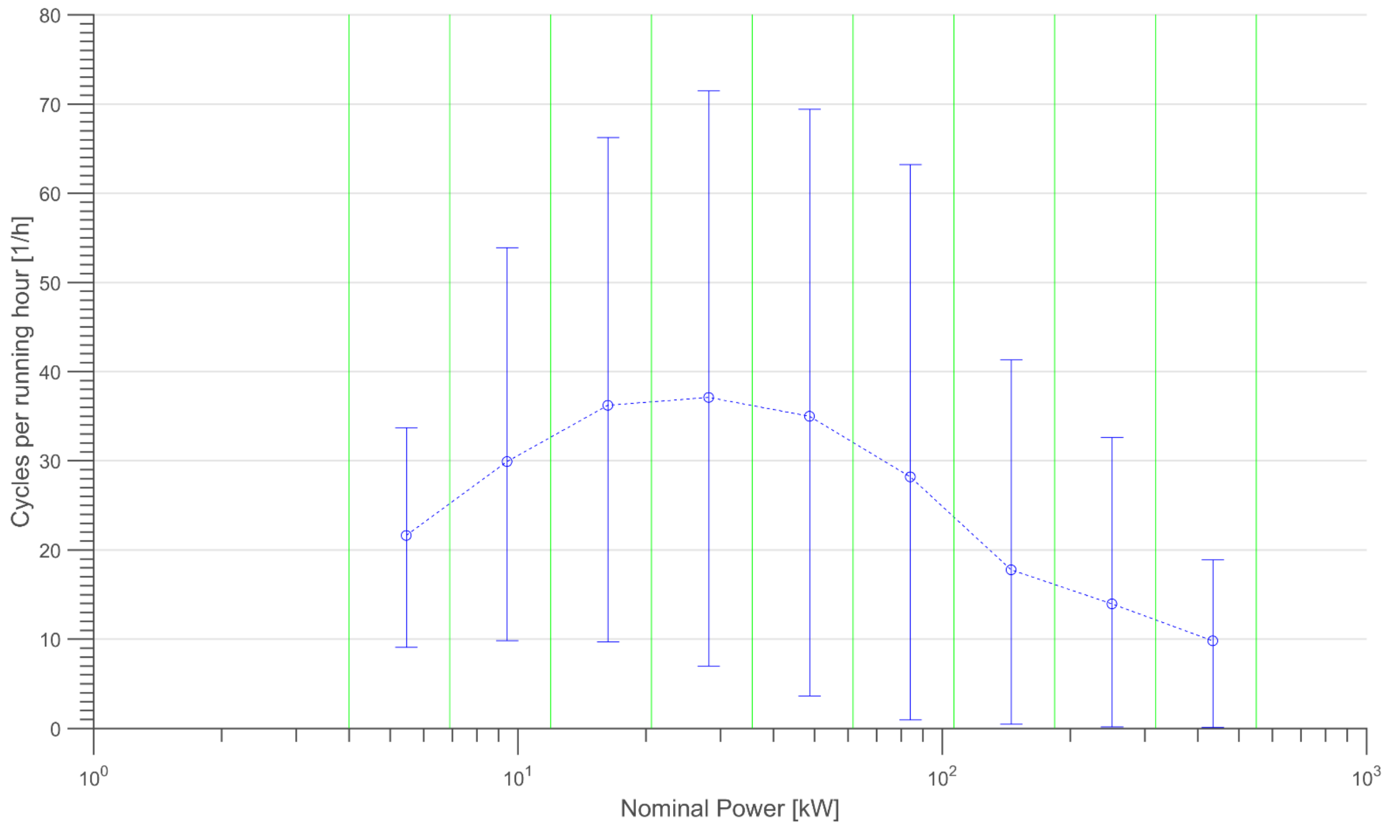

Figure 4: Cycles per running hour

Overall efficiency calculation method

The data analysis shows that when the overall efficiency of a specific product needs to be evaluated, the steady state efficiencies aren't sufficient. This section describes a methodology to easily calculate the performance of air compressors at part load and to take the energy losses due to the cyclic operations in account. This methodology can be used for all kinds of compressor technology and can form the basis to evaluate their overall performance to each other.

The main concept of the method is to calculate the energy consumption for one running hour and the accumulated useful volume of air which is delivered to the customer. Based on these values, the corresponding overall Specific Energy Requirement (SER) can be calculated. From SER it is an easy step to isentropic efficiency.

Figure 5 shows a typical cyclic operation where three key parts can be defined, Loaded energy (blue), Idle energy (yellow) and Cycle energy (red). The Loaded energy corresponds to:

$$E_{load} = P_L * R_L * H$$

where P_L is the average power level during Load typically defined as the nominal power, R_L is the Load Ratio and H corresponds with the amount of running hours. The Idle energy consumption can be expressed as,

$$E_{idle} = P_{UL} * (1 - R_L) * H$$

where P_{UL} is the Idle or Unload power level. The additional energy consumed by the transients due to the cyclic operation of the compressor as shown can be expressed as,

$$CER = \int_{t5}^{t6} f(t)dt + \int_{t7}^{t8} g(t)dt$$

with CER defined as the Cycle Energy Requirement, which can be measured in a robust and reliable way [2].

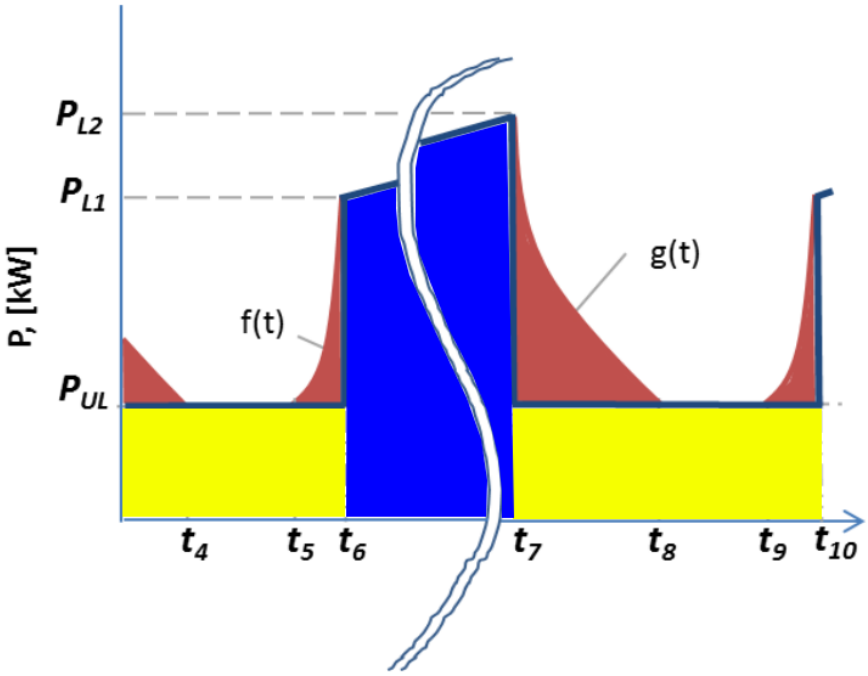

Figure 5: Energy consumption during cyclic operations

These three key values can be summarized in below equation to get the overall energy consumption of one individual running hour of a specific machine.

$$E_{total} = E_{load} + E_{idle} + CER * n_c * H$$

where n_c is the number of cycles per running hour. The corresponding useful volume of air during this time period can be defined as

$$V_{load} = V_L * R_L * H$$

where V_L is the average free air delivery (FAD) level during Load typically defined as the nominal flow. The overall Specific Energy Requirement is calculated as

$$SER_{total} = \frac{E_{total}}{V_{load}}$$

This value is easily understood by everyone in the industry as it already corresponds with known definitions. Annex H of the ISO1217:2009 can be used to move from SER to an isentropic efficiency by the formula:

$$\eta_{isen} = \frac{1}{SER} * p_1 \frac{\kappa}{\kappa - 1} * \left(\left(\frac{p_2}{p_1} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right)$$

An additional definition for flow ratio should be introduced when comparing fixed flow machines with variable flow machines (i.e. variable speed air compressors or centrifugals). The Flow Ratio is then defined as,

$$R_F = \frac{V_L * R_L}{V_{max}}$$

where V_{max} is the maximum flow of the air compressor at the specified running conditions. The Flow Rate of fixed speed machines as analyzed in the data mining effort can be presented as $R_F \cong R_L$.

To summarize, only below values need to be known to analyze the part load behaviour of an air compressor:

- Load Power
- Flow Rate during Load
- Idle Power
- Cycle Energy Requirement

Most of these values can be measured according agreed upon standards (i.e. ISO1217).

It should be clear that this method allows an easy calculation to compare different technologies with each other at actual running conditions. It allows the comparison of fixed speed machines to variable speed or centrifugals at part load. The above calculations can also be applied to centrifugal or variable speed compressors which can't reach the requested customer flows and will go into cycling operations due to this. Next to this, the methodology and data analysis would be a good starting point for standardization around efficiencies of real running conditions versus the current nominal efficiencies.

Case Study

As a case study, the calculation methodology defined in previous sections will be used to calculate part load efficiencies of a 160kW fixed speed oil injected screw compressor. Next to this, the same method will be applied on a 160kW variable speed oil injected screw compressor.

The fixed speed compressor has a measured average package power at load of 180.6kW, an average volume flow rate of 507.6l/s, an idle power of 50.6kW and a Cycle Energy Requirement of 2167kJ. The flow rate's and powers have been measured according ISO1217:2009[1], the CER is defined by the previously described paper[2]. Table 2 shows the results of the calculation method applied on this use case. At nominal running conditions, this machine reaches an SER of 355.8J/l. If a comparison is made with the data analysis, where these machines run on average around 70% in Part Load and 15 cycles an hour, this would correspond with an actual SER of 423.9J/l.

Overall SER (J/l)		Cycles per running hour (1/hr)				
		0	15	30	45	60
Flow Ratio (%)	100	355.8	-	-	-	-
	85	373.4	394.3	415.2	436.2	457.1
	70	398.5	423.9	449.3	474.7	500.2
	55	437.4	469.7	502.0	534.4	566.7
	40	505.3	549.8	594.3	638.7	683.2
	25	654.8	726.0	797.1	868.3	939.5
	10	1253.0	1430.8	1608.7	1786.6	1964.5

Table 2: Fixed speed Overall SER

The same methodology is applied on a variable speed compressor with a turndown ratio of 60% which means it can reach a Flow Ratio of 40% without doing any cycles. When lower flow ratio's are requested, this variable speed compressor will also go in cycling mode similar as the fixed speed machine. The results can be seen in table 3. In comparison with the fixed speed compressor at nominal working condition (100% Flow Rate), it has a 3% higher SER, while at 70% Flow Rate which on average these machines are running, the variable speed has 19% better SER which correlates with an energy saving of 66.7J for each liter the customer requires. In a total year this would mean a saving of 111.5MWh/year or approximately 11150 euro/year depending on the country.

Clearly moving in flow rates where the variable speed compressor is running part load and cycles, will have a significant effect on the efficiency. Similar effects can be seen with centrifugal compressors with typically lower turndown rates.

Overall SER (J/l)		Cycles per running hour (1/hr)				
		0	15	30	45	60
Flow Ratio (%)	100	367.3	-	-	-	-
	85	359.5	-	-	-	-
	70	357.2	-	-	-	-
	55	361.8	-	-	-	-
	40	377.9	-	-	-	-
	25	534.0	605.2	676.3	747.5	818.6
	10	1132.1	1310.0	1487.9	1665.8	1843.7

Table 3 Variable speed Overall SER

Conclusion

This paper started with the conclusions of an in depth analysis based on a substantial data collection effort of oil injected screw compressors. It showed that only looking at nominal running conditions to define the efficiency is far from sufficient due to the fact that most air compressors are running a significant part of their time in part load coupled with high cycle frequencies.

A calculation methodology has been developed to have an accurate and measurable way to define the total efficiency and energy consumption of air compressors in part load.

In contrast to the advances in the motor and pump industry with the development of the extended product approach [3], it should be clear that the efficiency of a compressor can't be easily defined as a chain of individual components and their efficiencies. The complete compressed air system needs to be taken in account.

References

[1] Displacement compressors - Acceptance tests, ISO1217:2009

[2] Measurement Principle to define Cycle Energy Requirement, Carl Wouters, Erik Moens, Jan Van Gilsen, Jan Stoffijn (2016)

[3] prEN 50589-1 Procedure for determining the energy efficiency or motor driven applications by using the extended product approach and semi analytical model, CENELEC, 20xx

The Extended Product Approach in EN 50598 and IEC 61800-9: principles, comparison and perspectives

Benoit LEPRETTRE & Andreas KRAETZSCHMAR

CAPIEL

Abstract

Significant energy savings for motor-driven applications are only obtained when considering the requirements of the application and properly matching the electrical and mechanical equipment to said requirements. This application-level approach is the subject of the Extended Product Approach specified first in the EN 50598 series of standards, then in the IEC 61800-9 series.

In this paper we remind the principles and interests of the Extended Product Approach as well as the main stakeholders and expectations. We then compare the EN 50598 series and the IEC 61800-9 series in terms of structure and technical requirements, pointing out the main similarities and differences. Finally, we propose investigation topics for the next editions.

1 Principles of the Extended Product Approach

1.1. Motor-driven applications offer huge potential savings

Applications driven by electric motors account for nearly 70% of the electrical energy consumed in the industrial sector, and for a significant fraction (22% to 39%) in other sectors [1]. Historically though, little attention has been paid to the efficiency of these applications. The installed base includes a lot of motor systems that are poorly sized and/or fitted to the application. Therefore, motor-driven applications represent a huge potential of energy savings.

1.2. Significant savings require an application-level approach

It is now well understood [2, 3] that for motor-driven applications, buying more efficient motors is not sufficient. Significant energy savings can only be obtained by implementing an application-level approach to make sure that the motor chosen for a given application meets the following requirements:

- The motor and all the components of the application should not be oversized.
- The control system (motor starter or variable speed drive) should be well matched to the requirements of the application. As a guideline:
    - If the application really requires varying the speed of the motor, variable speed drives are often the most appropriate solution since they allow to control speed and torque independently.
    - Otherwise, motor starters (contactors, star-delta starters, soft starters) are often a more efficient solution because they consume less power. The necessary variations of the load will be taken into account by the motor by varying its torque, as required by the application.
    - If it is necessary to manage the starting phase carefully (e.g. in case of high inertia mechanical load), star-delta starters or soft starters are highly efficient solutions.

In practice however, it can prove difficult to select the most appropriate set of components for a given application, or to compare different motor control solutions, or to assess the efficiency of a solution already in place. This difficulty has two main sources:

1) The necessary data (e.g. power losses of components) are not readily available, or are not yet available in a standard form.

2) There is no standard procedure for assessing the efficiency of a given motor-driven application.

The EN 50598 and IEC 61800-9 series of standards aim at solving these difficulties. Each series provides requirements regarding the data to be provided by component manufacturers, as well as standardized assessment procedures. This is done in the context of an application-level approach referred to as the Extended Product Approach (EPA).

1.3. Purpose and principles of the Extended Product Approach

At a high-level view, the Extended Product Approach takes power loss data provided by manufacturers (of motors, speed drives, load machine…) and the characteristics of the application (e.g. load-time profile). It uses specified procedures for determining the power losses of the whole application. Finally, it produces an Energy Efficiency Index (EEI), as illustrated in **Figure 1**.

Figure 1 – General principle of the Extended Product Approach

The EEI resulting from the Extended Product Approach is any indicator quantifying the energy efficiency of the Extended Product for this application. The EEI considered in the IEC 61800-9 or EN50598 series are the weighted average electrical power consumption (or losses) and the ratio of the latter to a reference power. Other relevant EEIs can be considered.

It is important to note that the EN 50598 series and the IEC 61800-9 series allow, for a given application load-time profile, to determine the power losses of the motor system only. The losses for the mechanical part of the Extended Product, that is, the transmission and the load machine, need to be obtained from other sources (e.g. extended product standard, component manufacturer). But the general method of the EPA can also be used for the mechanical part.

More specifically, the EN 50598 series and the IEC 61800-9 series introduce the notion of Semi-Analytical Model (SAM). A SAM is a model for determining the losses of a motor system, driven equipment, or Extended Product. It may include measurements at select operating points, description models, and calculation algorithms.

The Extended Product Approach mentions the necessity of including the SAM of the driven equipment in the EEI determination process, because it is as important as the motor system in terms of efficiency. More specifically:

- Part 1 specifies a very generic methodology that covers the whole equipment used for the application. It calls for other bodies to define the SAM of the Driven equipment.
- Part 2 is about the SAM of the Motor system, used to compute its power losses.

In order to conduct the Extended Product Approach, several SAMs need to be considered:

- The SAM of the motor system is specified in EN 50598-2 and IEC 61800-9-2 based on relative power losses at several standardized operating points.

- If the motor system is a Power Drive Systems (i.e. if it contains a variable speed drive), the SAM of the motor system is based on the definition of a Reference PDS, to which any physical PDS is compared.

The power losses determination procedure is somehow complex, because the association of a variable speed drive and a motor potentially has a great impact on the overall efficiency. One needs to make sure that the impact is actually positive in terms of energy efficiency, and this depends on several factors.

- If the motor system is based on a motor starter like a contactor, a star-delta starter or a soft starter, the power losses determination is simpler. The power losses of the motor starter are evaluated as 0.1% of the motor rated power, and it is considered that the efficiency of the motor is not changed by the addition of the motor starter.

- The SAM of the driven equipment (including transmission and e.g. pump, fan or compressor) yields the power losses of the load machine at typical operating points. It is not specified in the EN 50598 or IEC 61800-9 series, because load machines are not in the scope of Technical Committees dealing with motor systems and each type of mechanical load is very specific.

It is expected that bodies and product committees responsible for transmission and load machines will provide SAMs for the product under their responsibility.

The Extended Product Approach combines both SAMs with application-specific characteristics (e.g. load-time profile) and determines the Energy Efficiency Index (EEI) of the Extended Product for the application considered, as illustrated in **Figure 2**.

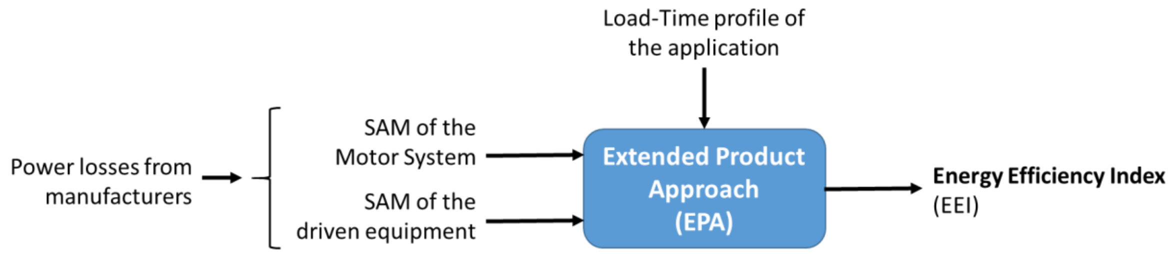

Figure 2– Notion of Semi-Analytical Model in the EPA

Annex D of EN 50598-2 and Annex C of IEC 61800-9-1 provide an example of how the weighted average power losses can be used as an EEI to compare several motor control solutions for two different pumping applications characterized by two different load-time profiles.

These examples clearly show that the motor control system shall not be selected based on habits or beliefs. If we aim for significant savings, the motor control system shall be selected as the result of an application-level analysis. The Extended Product Approach allows conducting this analysis in a standardized, fair and comparable manner.

1.4. Who are the customers of the EN 50598 and IEC 61800-9 series?

The EN 50598 and IEC 61800-9 series are essentially intended to be used by technical committees and other professional bodies. However, they may also be used with profit by OEM and other individuals to help designing efficient motor-driven applications.

Standardization committees and professional associations dealing with applications (pumping, conveying, lifting…) are expected to use the general guidelines in the IEC

61800-9 or EN 50598 series, in order to derive their own relevant Extended Product Approach for determining the energy efficiency of the Extended Products under their responsibility. This may include:

- Adapting the terminology (e.g. using flow/pressure instead of speed/torque for pumping applications),
- Providing reference load-time profiles for typical service conditions,
- Specifying the Semi-Analytical Model (SAM) of the driven equipment, based on e.g. reference operating points, reference torque versus speed profiles, etc.
- Requesting to provide the EEI in a standardized form.

Clause 4 of IEC 61800-9-1 illustrates more details about the Extended Product Approach and [8] for an example of adaptation of the EPA to pumping applications.

Original Equipment Manufacturers and application designers can also use the Extended Product Approach to assess the energy efficiency of future installations, compare several possible options regarding the application profile and the equipment, and eventually choose the most appropriate components for a given application.

2. Comparison between EN 50598 series and IEC 61800-9 series

2.1. Introducing a standardized terminology around the Extended Product concept

The different documents and bodies dealing with the energy efficiency of motor-driven applications do not use the same terminology. For example, a term such as "motor system" can refer sometimes to the motor and its control system, sometimes to the whole application. This is confusing for the readers when they try to gather information from several sources.

A great merit of the Extended Product Approach in EN 50598 and IEC 61800-9 is to specify a common terminology to be used to refer to the different components used in a motor-driven application. The Extended Product (EP) is defined as the set of components necessary to perform a motor-driven application, from the mains supply to the mechanical load machine (e.g. a pump) coupled to the motor via a transmission. It is illustrated in **Figure 3**, taken from IEC 61800-9-1 definition 3.1.3.

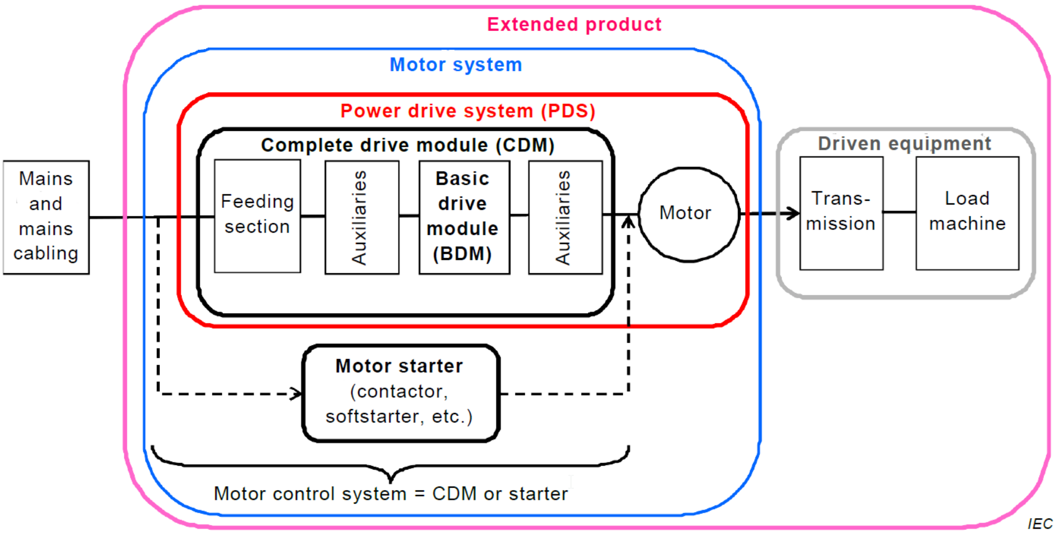

Figure 3 – Standardized terminology for the components of an Extended Product

Since the most efficient motor control strategy depends on the application, the generic concept of Motor control system has been introduced. It may be a motor starter (contactor, star-delta starter, soft starter), or a complete drive module featuring a variable speed drive, depending on the application.

The Motor system is defined generically as the combination of the motor and its control system, regardless of whether the latter is a motor starter or a complete drive module (in which case the motor system can also be referred to as a Power Drive System or PDS, figure 3). The Driven equipment is defined as the combination of a transmission (direct shaft coupling, belt, gearbox…) and a load machine (e.g. a pump or conveyor).

This standardized terminology allows to conduct the Extended Product Approach in all practical cases with limited risk of confusion and misunderstanding between all the different stakeholders. It is the result of discussions between the different stakeholders (component manufacturers, OEMs, Academics) within the Working Group. We believe that this standard terminology represents a good consensus and should be propagated.

2.2. A common structure and philosophy

Both the EN 50598 series and the IEC 61800-9 series have the same structure in two main parts with identical names, as detailed in **Table 1**. The EN series also features a third part on environmental impacts which is not yet featured at IEC level.

Table 1 – Structure of the EN 50598 and IEC 61800-9 series

	EN 50598 series	**EC 61800-9 series**
Series name	Ecodesign for power drive systems, motor starters, power electronics & their driven applications	Adjustable speed electrical power drive systems – Ecodesign for power drive systems, motor starters, power electronics and their driven applications
Part 1 **General description and requirements regarding the Extended Product Approach (EPA) & Semi-Analytic Model (SAM)**	Part 1: General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA), and semi analytic model (SAM). Published in 2014	Part 9-1: General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi analytic model (SAM). Published in 2017
Part 2 **Determination of the losses of a motor system considering the operating points induced by the application characteristics.** **Definition of IE classes for motors and CDMs, definition of IES classes for PDSs.**	Part 2 – Ecodesign for power drive systems, motor starters, power electronics & their driven applications – Part 2: Energy efficiency indicators for power drive systems and motor Starters. Published in 2014	Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications – Energy efficiency indicators for power drive systems and motor starters. Published in 2017
Part 3 **Environmental aspects, life cycle assessment, environmental declaration**	Part 3 – Quantitative ecodesign approach through life cycle assessment including product category rules and the content of environmental declarations. Published in 2015.	Considered but not scheduled for the moment.

The vast majority of the content of the IEC 61800-9 series is basically identical to the EN 50598 series that inspired it, except minor editorial corrections.

The Extended Product Approach is identical and is based on the principle of judging the energy efficiency of a motor system by assessing how well it matches the requirements of the application. Therefore, the terminology, purpose, stakeholders and key concepts are identical in both series of standards.

2.3. Some technical differences

There are a few technical and structural differences between the EN 50598 series and the posterior IEC 61800-9 series, essentially for the purpose of writing a clearer standard and remove some ambiguities found in the EN series.

Compared to EN 50598-1, IEC 61800-9-1 essentially contains more definitions and clarifications. The responsibility of the information on the driven equipment is clarified because the notion of Extended Product technical committee used in EN 50598 was imprecise. The process for interpolating PDS power losses between tabulated values for speeds lower than 25% is also clarified. Some structural changes have also been made. The differences between EN 50598-1 and IEC 61800-9-1 are shown in **Table 2**.

Table 2– Main differences between EN 50598-1 and IEC 61800-9-1

Topic	EN 50598-1	IEC 61800-9-1
Publication year	2014	2017
Definitions		Clarified definitions for: duty profile (load-time profile), motor control equipment, motor system, transmission
Load-time profile terminology	Duty profile	Load-time profile, also called duty profile
SAM wording	Semi-Analytical Model	Semi-Analytic Model
Responsibility regarding the information about the driven equipment and Extended Product Approach	Load manufacturer or extended product technical committee	Clarified to: Load manufacturer or other pertinent entity (e.g. regulatory authority, other specified organization)
Detailed consideration about the load-time profile and the torque versus speed profile	Clause 5.2 and 5.3	Moved to new informative Annex C
PDS losses determination by two-dimensional interpolation of losses of adjacent loss points		Clarification of the interpolation process for speeds lower than 25% in clause 7.3.3

IEC 61800-9-2 contains a couple of minor technical changes that have been implemented to remove ambiguities and inconsistencies found in the EN version.

For example, the permissible deviation from reference operating points for the reference devices at 0Hz has been changed from 5% of rated frequency, to 12Hz regardless of rated frequency.

Regarding Complete Drive Modules, the CDM output current is given at several voltages from 200V to 690V in the IEC version. A factor of 1.35 has been specified to be used for assessing the IE class of a CDM with input voltage less than 200V.

Concerning Power Drive Systems, the tolerance on the lower test frequency for PDS loss determination has been increased from 5Hz to 12Hz. The application of a temperature correction coefficient is not required if the test conditions are between 15°C and 30°C. The order of the tests to be performed when using the input-output loss determination method has been relaxed a bit.

The clause on IE class for motors operated by a CDM refers explicitly to IEC 60034-30 (all parts) in the IEC version.

The information to be provided in the documentation regarding the boundary conditions for assessing the IE or IES class of a device contain the maximum CDM output voltage in addition to the supply voltage amplitude and frequency, rated test load stator frequency or rated motor speed.

Also note that some significant structural changes have been made for clarity, and that the application example from EN 50598-2 Annex D has been moved to part 1 (IEC 61800-9-1 Annex C).

The main differences between EN 50598-2 and IEC 61800-9-2 are highlighted in **Table 3**.

Table 3 – Main differences between EN 50598-2 and IEC 61800-9-2

Topic	EN 50598-1	IEC 61800-9-1
Publication year	2014	2017
Definitions		Clarified definitions for: duty profile (load-time profile), motor control equipment, motor system, transmission
Load-time profile terminology	Duty profile	Load-time profile, also called duty profile
SAM wording	Semi-Analytical Model	Semi-Analytic Model
Responsibility regarding the information about the driven equipment and Extended Product Approach	Load manufacturer or extended product technical committee	Clarified to: Load manufacturer or other pertinent entity (e.g. regulatory authority, other specified organization)
Detailed consideration about the load-time profile and the torque versus speed profile	Clause 5.2 and 5.3	Moved to new informative Annex C
PDS losses determination by two-dimensional interpolation of losses of adjacent loss points		Clarification of the interpolation process for speeds lower than 25% in clause 7.3.3

3. Status & evolution of the EPA standards

The problem of assessing the overall power losses (or efficiency) of a motor-driven application is very complex. For example, if the motor system is a Power Drive System (i.e. it contains a variable speed drive), the motor, transmission and mechanical load can operate at virtually any possible operating points.

Also, the components for performing an application are not always properly sized to the requirements of the application, and this can cause the motor, transmission and load machine to operate at non-optimal operating points. The determination of power losses at any operating point is a complex topic because the different components of the Extended Product are complex, non-linear machines.

Therefore, the determination of the overall power losses must be the subject of an application-level approach, considering the application requirements and modes of operation on the one side, and all the pieces of equipment used or considered on the other side. Only a proper match between one and the other enables significant savings.

The Extended Product Approach described in the EN 50598 series is a first serious and credible attempt at addressing the complex problem of determining the power losses of a motor-driven application in a standardized way. It has been discussed several years and is the result of good consensus between the different stakeholders: component manufacturers, extended product manufacturers, academics, regulation authorities.

The IEC 61800-9 series can be seen as a minor upgrade from the EN 50598 series, with clarifications and structural changes implemented for clarity. It is expected that the IEC 61800-9 series will eventually supersede the EN 50598 series through parallel voting.

The Extended Product Approach as it is today in EN 50598 and in IEC 61800-9 is not perfect, but it is usable to e.g. compare several design solutions for a given application. Load manufacturers or professional organizations can use these guidelines in part 1 to derive the Semi-Analytic Model of the products under their responsibility, in order to "connect" their mechanical power loss model to the electrical power loss model specified in part 2, see [8] as an example.

In order to make the series of standard even clearer and more easily usable by all the stakeholders, we can think of possible evolutions for future editions. There is room for improvement on several aspects, e.g.:

- Some losses are required to be determined at zero speed, which can be inconvenient for some equipment and testing methods. Although tolerances are associated to this requirement, it could be considered specifying more practical test points at a standardized speed greater than zero.
- When using the input-output measurement method to assess the power losses of a CDM or a PDS, the question of measuring mechanical and electrical power in an accurate and reproducible manner arises. Converters typically produce high-frequency electrical signals that are certainly not easy to measure.

This calls for precise specification of the measurement system (e.g. sensors, cabling, shielding, meters) and process (e.g. duration of test, power measurement method, averaging, sampling frequency). While guidelines are given in the present editions based on the work done when writing the EN version, we believe that the measurement of power losses of CDMs and PDSs could deserve further investigation.

- The present series of standards focus on induction motors because this is the most widely used type of motor in the Industry today and they represent a great fraction of the electrical consumption in this sector. Nevertheless, since the scope also includes other types of motors, providing data and guidelines related to other types of motors (synchronous motors, etc.) could also be a task.

Other related initiatives are emerging to better address the energy efficiency of motor systems, from the point of view of customers and regulators. For example, the *Extended Motor Project Label Initiative* (EMPLI), currently under development, aims at developing relevant metrics and energy efficiency labels for extended products.

Conclusion

In this paper we have recalled the principles of the Extended Product Approach (the EPA) specified in the EN 50598 series and in the IEC 61800-9 series. The EPA is an application-level general methodology to assess the energy efficiency of motor-driven applications. It is somehow complex because the problem is complex! While certainly not perfect as it is today, it represents a first usable solution for tackling this complex problem and focusing on obtaining real savings.

We have compared the EPA approach in the EN 50598 series with that of the subsequent EPA approach in the IEC 61880-9. The latter can be considered as a minor upgrade from the former. We have analyzed the main differences in structure and technical content, and shown the differences are minor.

Several investigation topics for the next editions have been suggested, based on the most obvious concerns regarding the present series of standards. We are confident that the working group in charge of the maintenance of these series will further improve them in a spirit of pragmatism and consensus. We are also confident that manufacturers and other stakeholders will progressively propose relevant data and tools to facilitate the application of the Extended Product Approach to motor-driven applications.

References

[1] International Energy Agency, Waide P. & Brunner C. *Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems*, 2011

[2] Kraetzschmar A. & Leprettre B. *Impact of IE3/IE4 Motors on Switchgear Standards, Manufacturers and Customers*. EEMODS 2015 conference, Helsinki, 2015.

[3] Leprettre B. & Kraetzschmar A. *Selecting the most efficient motor control system for a given application: the Extended Product Approach in prEN 50598 series of standards*. EEMODS 2013 conference, Rio de Janeiro, 2013.

[4] IEC 61800-9-1 – Adjustable speed electrical power drive systems - *Part 9-1: Ecodesign for power drive systems, motor starters, power electronics and their driven applications – General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi analytic model (SAM)*, 2017

[5] IEC 61800-9-2 – Adjustable speed electrical power drive systems – *Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications –Energy efficiency indicators for power drive systems and motor starters, 2017*

[6] EN 50598-1 – Ecodesign for power drive systems, motor starters, power electronics & their driven applications – *Part 1: General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA), and semi analytic model (SAM)*, 2013

[7] EN 50598-2 – Ecodesign for power drive systems, motor starters, power electronics & their driven applications – *Part 2: Energy efficiency indicators for power drive systems and motor Starters, 2013*

[8] EUROPUMP. *Extended Product Approach for Pumps*, 2013. Can be downloaded at: http://europump.net/publications/guides-and-guidelines

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