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The 9th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS'15) was be held in Helsinki (Finland) on 15-17 September, 2015. The EEMODS'15 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.

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Permanent Magnet-assisted Synchronous Reluctance Motors for Electric Vehicle applications

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Abstract

Electric Vehicles represent the most viable solution to solve the pollution problems associated with the use of traditional internal combustion engine. The paper presents and compares different typologies of PM Synchronous, Synchronous Reluctance and PM-assisted Synchronous Reluctance motors suitable for Electric Vehicles applications. Some technological solutions oriented to the improvement of the motor performance are proposed.

Introduction

Electric Vehicles (EVs) represent the most viable solution to solve the pollution problems associated with the use of traditional internal combustion engine [1, 2].
The need of employ high performance and high efficiency motors has led the designers to choose Permanent Magnet (PM) motors, thanks to the advent of high-energy PMs. These motors are becoming more and more attractive and can directly compete with the induction machines. The advantages of PM motors 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 the designers to investigate other high efficiency solutions. Synchronous Reluctance and PM-assisted Synchronous Reluctance motors with low cost PM (Ferrite) are efficient alternatives and are well suited to be employed in electric vehicles.

The strong demand of high performance electric motors requires the use of innovative and efficient design procedures, by specific tools and optimization processes, and an accurate choice of the materials, in order to fully satisfy the hard specifications and constraints in terms of encumbrance, weight, reliability and cost. The improvement of power density requires a fine optimization of the active material weight and a right choice of the airgap flux density and of the stator line current density, that are limited by the temperature rise and by the available cooling.
Different typologies of PM Synchronous, Synchronous Reluctance and PM-assisted Synchronous Reluctance motors suitable for Electric Vehicles applications are presented and compared in the paper. Some technological solutions oriented to the improvement of the motor performance are proposed. The analysis of all these motors have been carried out by Finite Element models to take into account the remarkable rotor saturation phenomena. The motors have been designed by a suitable optimization procedure.

The Synchronous Reluctance Motor

The basic characteristics of an electric motor for EVs 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.

In addition, low acoustic noise and low torque ripple are important design goals. Typical torque/power-speed characteristics required for traction motors are shown in Fig.1.
Induction Motors and PM Synchronous Motors [3] fulfill these characteristics and are widely employed in EVs.

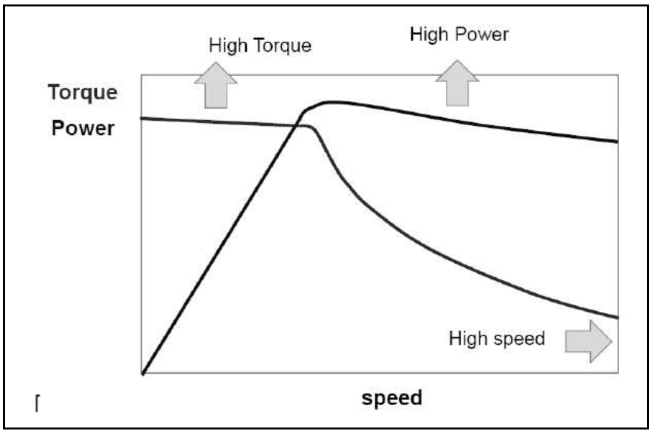


Fig.1 Torque and power requirements for a traction motor

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 [4, 5, 6] with a rugged rotor without PMs and windings and then negligible rotor losses. A typical rotor cross section is shown in Fig. 2: laminated rotors with flux barriers can be manufactured with normal punching tools at very low cost. The stator core is similar to the conventional induction motor one.
The number of barriers varies from 2 to 5 and depends on the number of pole pair and stator slots.

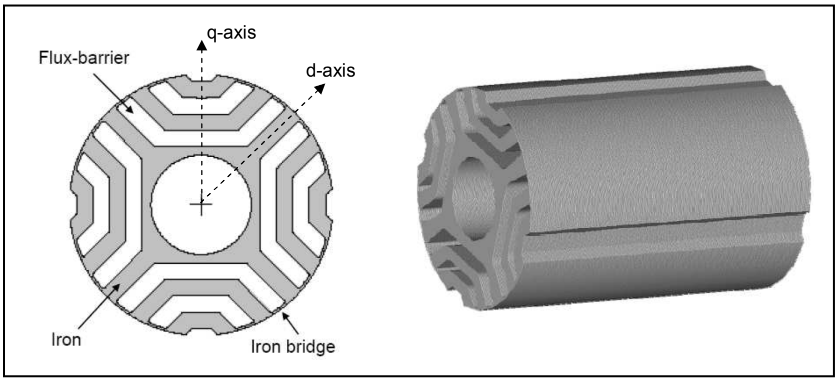


Fig.2 Rotor with flux-barriers for synchronous reluctance motor

Basics of electromagnetic torque generation in the SRM are the following.
The electromagnetic torque of a generic rotating electric machine can be written as:

$$c(t) = k\left|\underline{\lambda}_s(t)\right|\left|\underline{i}_s(t)\right|\sin\alpha(t)$$

where $\underline{\lambda}_s(t)$, $\underline{i}_s(t)$ and $\alpha(t)$ are respectively the space vector of the stator linkage flux, the space vector of the stator current and the angular displacement between them; k depends on the constant used to compute the space vectors from the phase quantities.
In the rotor reference frame, at steady state, the space vectors and their angular displacement are constant and so is the torque:

$$\underline{\lambda}_s(t) = \underline{\Lambda}_s$$
$$\underline{i}_s(t) = \underline{I}_s$$
$$\alpha(t) = \alpha$$
$$C = k\left|\underline{\Lambda}_s\right|\left|\underline{I}_s\right|\sin\alpha$$

In isotropic machines the angular displacement α is achieved by means of a rotor current space vector and/or rotor permanent magnets. Without rotor current and rotor permanent magnets the torque cannot be generate because:

$$\underline{\Lambda}_s = L_s \underline{I}_s$$

and the stator inductance is a real number.
In this case, the torque can be obtained only if the rotor machine is anisotropic so that, in the rotor *d*-*q* reference frame, the stator inductances although constants are different from each other ($L_d \neq L_q$). Then the stator linkage flux is expressed as:

$$\underline{\Lambda}_s = \Lambda_d + j\Lambda_q = L_d I_d + j \ {}_q I_q$$

with

$$I_d + j \ {}_q = \underline{I}_s \, .$$

An angular displacement α is obviously obtained between the space vectors $\underline{\Lambda}_s$ and $\underline{I}_s$ $\mathbf{I}_s$because $\Lambda_d/\Lambda_q \neq I_d/I_q$. It is also clear that the torque is generate if and only if $I_d \neq 0$ and $I_q \neq 0$ otherwise $\alpha = 0$.

Then, 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.

SRMs with multi-barriers rotor structures have been widely used in brushless AC drives and their main advantages are:

- no winding and 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.

The PM-assisted SRM for Electric Vehicles

Adding proper quantity of permanent magnets into the flux barriers of the rotor core, the operating performance of the SRM (torque density, power factor) improves. In this case cheaper PMs such as Ferrite [7] are used. The motor is similar to an Interior PM motor and it can be called PM-assisted SRM (Fig.3).

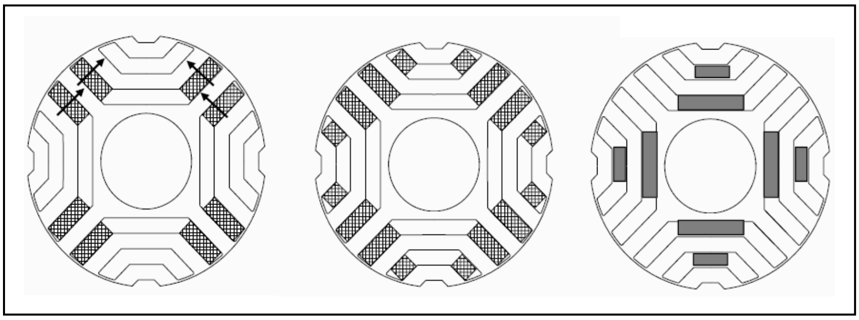


Fig.3 Rotors for PM-assisted Synchronous Reluctance Motors

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 as shown in Fig.4 (simulation results).
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).

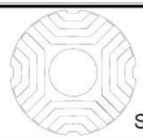
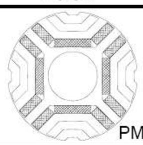
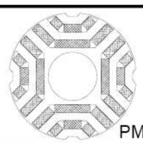
		Torque Nm	ΔTorque %	Power factor
1	 SRM	26	-	0.71
2	 PM_ass	31	+19 %	0.86
3	 PM_ass	33	+27 %	0.90

Fig.4 Effect of Ferrite PM on the SRM performance

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 for this high torque density motor is often realized with “flat wires” (hairpins) as shown in Fig.5: rectangular slots can be adopted in this case in order to increase the slot fill factor up to 0.7÷0.85 (higher respect to stranded winding and trapezoidal slot). Moreover, the fully automated manufacturing process allows the winding overhang to be reduced. High slot-fill and shorter end-turns reduce the resistance, the Joule losses, the thermal resistance and the temperature rise. In this case, the actual phase resistance should be calculated taking into account the “proximity and skin-effects” that heavily depend on the frequency and flat-wire size.

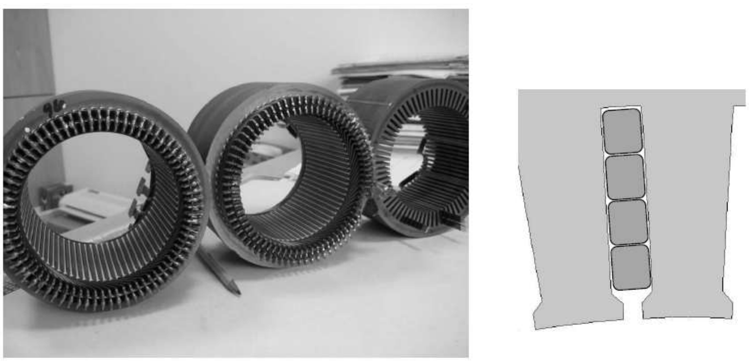


Fig.5 Bar wound stators

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 SRMs for EVs requires an accurate design in order to fully satisfy the specifications and the constraints on the encumbrance. The rotor shape and dimensions of the flux-barriers affect heavily the motor performance. For this reason it is useful to refine the design of the SRMs by suitable optimization procedures to link with the Finite Element model [8, 9].
A three-phase PM-assisted SRM is proposed for a medium size EV whose main specifications are shown in Table 1: the outer diameter and length are imposed and depend on the available space in the vehicle for the motor installation. Because of this constrain the machine is liquid cooled with a jacket around the stator core to achieve high power density.
Fig. 6 presents the cross section of the designed motor with 6 pole, 54 slots, distributed flat-wire winding, 4 conductors per slot and a filling factor of 0.8.
High performance motor requires a right choice of the electrical steel and this is an important step during the sizing procedure.
Simulations of the PM-assisted SRMs with different commercial electrical steels have been carried out with all parameters (torque, speed) and dimensions of the machines held constant, except the magnetic properties of the lamination materials and phase currents. The performance refer to the motor operation at "maximum torque-ampere ratio". Temperature of 90°C has been imposed for the stator winding and 70°C for the PMs. The simulation results are compared in Table 2.

Table 1 – Specifications of the considered electric motor

DC voltage supply	V	500
Base speed	rpm	4000
Torque @ base speed	Nm	200
Output Power	kW	83.8
Efficiency @ 90°C	%	>90
Max speed	rpm	12000
Torque @ max speed	Nm	60
Stack length	mm	100
Outer stator diameter	mm	240
Stator winding		flat-wire
PM-Ferrite		Br=0.35 T; Hc=270 kA/m @ 20°C

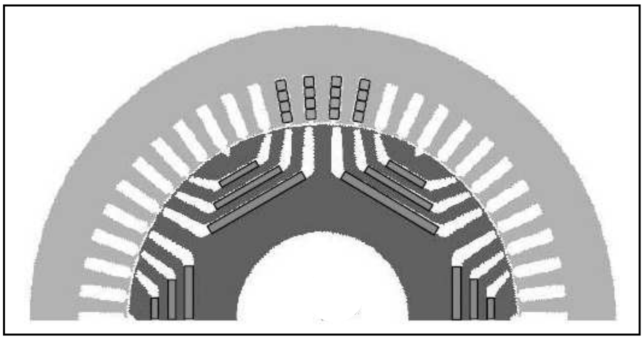


Fig.6 Cross-section of 6 pole-54 slots PM-assisted SRM

The comparison points out slight difference on the current and efficiency values, with core losses in the range between 420÷740 W notably lower respect the Joule losses. The flux densities in the narrow section of the stator teeth (Bst) are slightly higher than 1.8 T while is 1.6 T in the yoke (Bsy). The 400-50 AP electrical steel has been chosen for this specific application because combines low specific losses with high permeability and the motor shows good performance in terms of efficiency and power factor.

The performance of the PM-assisted SRM at 4000 rpm and 12000 rpm are listed in Table 3, while the continuous torque characteristic vs speed and the related power characteristic, calculated by means of the FE analyses, are shown in Fig.7.
The motor has excellent field-weakening performance with a wide “Constant-Power Speed Range” (CPSR) that represents an important requirement for the EV.
The iron bridges in the rotor core have been careful 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 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.

Table 2 – Comparison between different commercial electrical steels

		800-50	530-50 AP	400-50 AP	330-50 AP
Torque	Nm	200			
Speed	rpm	4000			
Frequency	Hz	200			
Output Power	kW	83.8			
Phase current	Arms	164	161	161	163
AC Joule losses	W	2337	2258	2258	2317
Core losses	W	735	620	553	423
Efficiency	%	95.4	95.6	95.7	95.7
Power factor		0.87	0.89	0.89	0.88
Bst ; Bsy	T	1.82; 1.60	1.82; 1.60	1.83; 1.60	1.83; 1.61

Table 3 – Performance of PM-assisted SRM – 6 pole-54 slots

		4000 rpm	12000 rpm
Phase current	Arms	161	161
Torque	Nm	200	64
Output Power	kW	83.8	80.4
AC Joule losses	W	2258	2574
Power factor		0.89	0.86
Efficiency	%	95.7	94.6

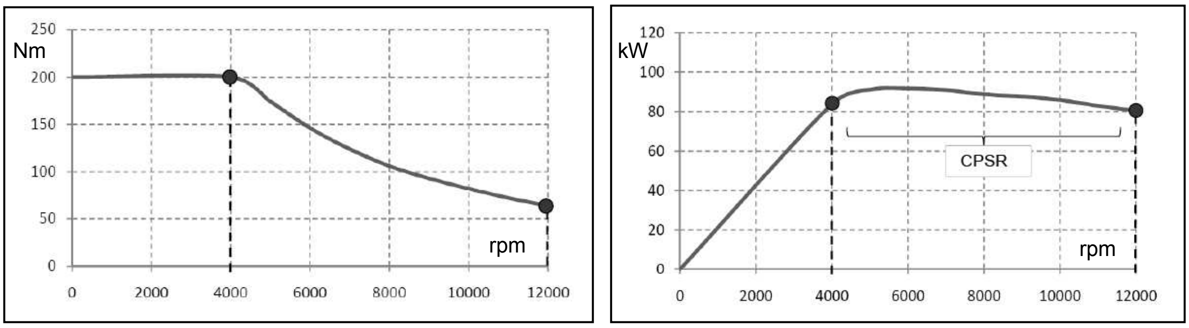


Fig.7 PM-assisted SRM: Torque and Power vs. Speed

Comparison with IPM Synchronous Motor

The proposed PM-assisted SRM has been compared with a NdFeB (B_r = 1.16 T and H_c = 900 kA/m at 20°C) Interior Permanent Magnet (IPM) Synchronous Motor having the same torque value at base speed in order to evaluate the differences in terms of performance, weight and costs. In this motor the torque generation is due to the PMs and the rotor anisotropy (different *d* and *q* inductances) and both L_d and L_q vary with saturation, but the *q*-axis inductance is more sensitive to saturation than the *d*-axis inductance due to the low reluctance path of *q*-axis flux.

The comparison has been carried out considering the same overall dimensions and winding; in particular the two motors have:

- the same stator lamination (diameters and n. of slots) and air-gap;
- the same number of turns and wire size;
- the same electrical steel (400-50 AP);
- the same temperatures of the winding and PM.

Fig. 8 shows the cross-sections of the two machines. Two different IPM motors have been proposed:

- IPM_1 with the same stack length of the PM-assisted SRM;
- IPM_2 with a reduce stack length (compact design) and the same current of PM-assisted SRM.

The results are shown in Table 4.
The comparison points out that IPM_1 motor has the lowest current, while IPM_2 has the lowest weight. Moreover, at the base speed (4000 rpm) the IPM motors have higher power factors and this allows the inverter rating to be reduced: the phase-back-emf doesn't exceed 180 Vmax.
At high speed (12000 rpm) the IPM motors exhibit good performance (see Fig.9) with a power density higher than the synchronous reluctance motor one.
However, the PM-assisted SRM has excellent efficiency, very close to that one of the IPM_2, and good constant-power operating capability (Fig.9): this motor could be a promising candidate for traction applications especially in flux-weakening operation.

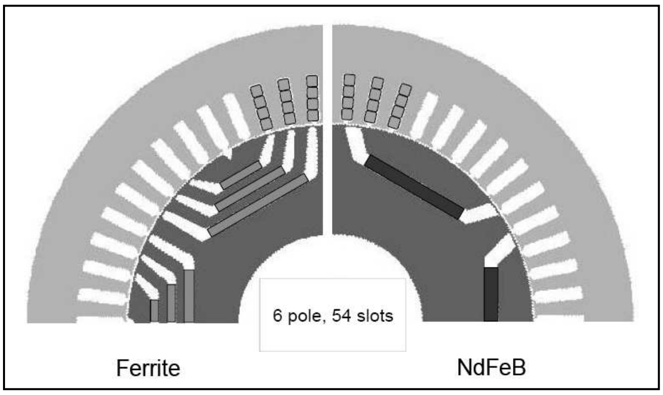


Fig.8 Cross sections of PM-assisted SRM (left) and IPM motor (right)

Table 4 – Performance of PM-assisted SRM and IPM motors

		PM-ass SRM	IPM_1	IPM_2
Electrical steel		400-50 AP		
PM		Ferrite	NdFeB	NdFeB
Stack length	mm	100	100	91
Outer stat. Diameter	mm	240	240	240
Phase current	Arms	161	150	161
Current density	A/mm^2	10.1	9.4	10.1
4000 rpm:				
Torque	Nm	200	200	200
Output Power	kW	83.8	83.8	83.8
AC Joule losses	W	2258	1945	2131
Power factor		0.89	0.94	0.90
Efficiency @ 90°C	%	95.7	96.2	95.9
12000 rpm:				
Torque	Nm	64	73	79
Output Power	kW	80.4	91.7	99.3
Power density	kW/kg	1.5	1.8	2.1

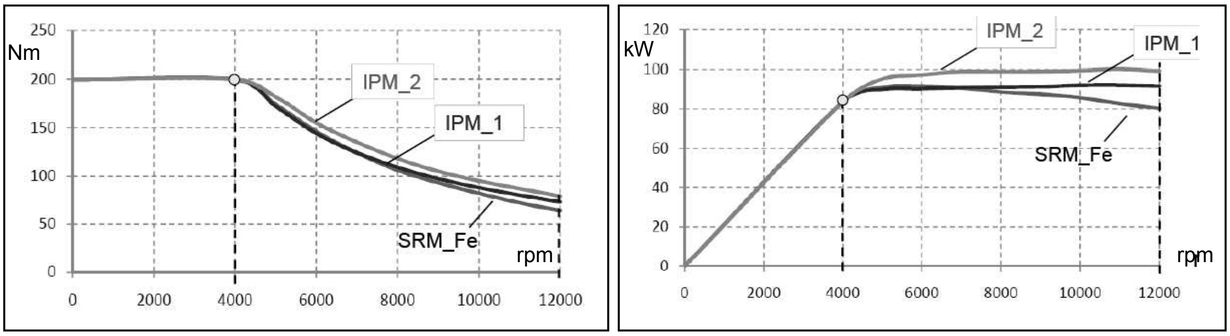


Fig.9 PM-assisted SRM and IPM motors: Torque and Power vs. Speed

The comparison has been extended to the active materials cost. Table 5 points out a significant cost reduction for the PM-assisted SRM solution of about 45%, respect to IPM_1, and 40% respect to IPM_2, mainly due to the lower cost of the PM in Ferrite. Moreover, the ferrite PM has got a positive reversible temperature coefficient of coercivity, respect to NdFeB, and this increases the demagnetization strength as the temperature increases, leading to better dynamic performance of car.

Table 5 – Weight and active material costs of the PM-assisted SRM and IPM motors

		PM-ass SRM	IPM_1	IPM_2
Stack length	mm	100	100	91
Gross iron	kg	45	45	41
Stator winding	kg	6.2	6.2	5.9
PM	kg	0.92	0.93	0.85
Cost (*):				
Gross iron	Euro	40.5	40.5	36.9
Stator winding	Euro	43.4	43.4	41.3
PM	Euro	23.0	111.6	102.0
Total	**Euro**	106.9	195.5	180.2

(*) Electrical steel = 0.90 ∈/kg; Cu = 7.0 ∈/kg; Ferrite = 25 ∈/kg; NdFeB = 120 ∈/kg

Comments and conclusions

PM Synchronous Motors fulfill most of the constraints for Electric Vehicles applications. The advantages of PM motors are their inherently high efficiency, high power density, and high reliability. The key problem is their relatively high cost due to PM materials.

Synchronous Reluctance Motor with "flux-barriers" (SRM) represents a good alternative with a rugged rotor without PMs. PM-assisted SRM improves the operating performance of the SRM (torque density, power factor) adding proper quantity of low cost permanent magnets into the flux barriers of the rotor core.

Different typologies of PM Synchronous, Synchronous Reluctance and PM-assisted Synchronous Reluctance motors have been presented and compared in the paper and some technological solutions oriented to the improvement of the motor performance have been proposed.

Combining an optimization procedure with motor Finite Element model, a three-phase PM-assisted SRM for medium size EV has been designed and compared with two NdFeB Interior Permanent Magnet Synchronous Motors with the same overall dimensions and same winding arrangement (bar wounding type). At rated operating condition, IPM motors have good efficiencies and better power factor; moreover, they exhibit a wide constant-power speed range.

However, even the PM-assisted SRM ensures good performance with high power density and reasonable cost and then it can be considered a strong potential for powertrains and an efficient alternative to IPMs and induction motors.

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Indirect efficiency determination of permanent magnet synchronous machines for sine wave and inverter operation

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Abstract

Permanent magnet machines are nowadays more and more used for traction motor applications, which have a big demand on energy efficiency. The efficiency determination by direct measurements is often too imprecise for highly utilized machines in the range above 95 % efficiency, as the required measurement accuracy cannot be reached. For this reason an indirect method for the efficiency determination is proposed by means of the summation of individual losses, which is similarly already in use for electrically excited synchronous machines. The individual loss components (current-depending and additional load losses, iron losses, and additional losses caused by inverter feeding) are determined from measurements in the no-load case and with removed rotor. By considering the equivalent circuit parameters of the machine, the losses are recalculated for the desired load case. In addition to the theoretical calculations direct efficiency measurements were done with three permanent magnet synchronous machines in sine wave and inverter operation to validate the calculation results. Two of the examined permanent magnet machines (rated power 45 kW at 1000/min) have a special stator topology with tooth coil winding and due to that an uncommon magnetic field distribution. The third machine has a rated power of 90 kW and a conventional distributed winding, which suggests a better accordance between the proposed method and the direct measurements. The efficiency of these three machines was in the range of 94 % … 95 % at rated power and speed. The experimental results showed that the indirect efficiency values followed the direct ones in dependence of speed and machine torque very well, but for Machines 1 and 2 in motor operation on a lower value with typically 0.5 % … 1 % less efficiency. In generator operation this difference is small. For Machine 3 these differences are in the range of rated speed and rated torque very small. This holds true for sine wave and inverter operation.

Background

An accurate direct determination of the efficiency of large electrical machines as the ratio of output versus input power is hardly possible for several reasons. First reason is the need of a load test with rated power. This might be technically difficult, because the full rated power must be provided for the tests. Further, big synchronous machines (several MW) are often assembled in the power plant, so that a measurement is only possible there. If the efficiency of electrical machines exceeds 95 %, a direct measurement of input and output power is too imprecise due to the tolerances of common measurement procedures, as shown in the following example (Example 1).

Example 1 (Accuracy in direct efficiency measurement):

Specifications: Motor operation, mechanical output power: $P_{\mathrm{out}} = 2\pi \cdot n \cdot M$, electrical input power $P_{\mathrm{in}} = 3 \cdot U \cdot I \cdot \cos\varphi$, real efficiency $\eta = 96$ %, measurement uncertainty $\epsilon = 0{,}2$ %

In worst-case the output power is measured too high by ϵ and the input power is measured too low by the same uncertainty.

Measured efficiency: $\eta_{\mathrm{meas}} = \frac{P_{\mathrm{out,meas}}}{P_{\mathrm{in,meas}}} = \frac{P_{\mathrm{out}} \cdot (1+\epsilon)}{P_{\mathrm{in}} \cdot (1-\epsilon)} = \eta \cdot \frac{1+\epsilon}{1-\epsilon} = 0.96 \cdot \frac{1.002}{0.998} = 0.9638$

Real total losses: $P_{\mathrm{d}} = \left(\frac{1}{\eta} - 1\right) \cdot P_{\mathrm{out}} = 0.04167 \cdot P_{\mathrm{out}}$

Measured total losses: $P_{\mathrm{d,meas}} = \left(\frac{1}{\eta_{\mathrm{meas}}} - 1\right) \cdot P_{\mathrm{out,meas}} = 0.03763 \cdot P_{\mathrm{out}}$

Measured vs. real total losses: $P_{\mathrm{d,meas}} / P_{\mathrm{d}} = 0.903$

The deviation between the measured and the real efficiency value corresponds to an error of 10 % in terms of total losses.

Example 2 (Accuracy in indirect efficiency measurement from summation of losses):

The specifications and measurement uncertainty are identical to those of Example 1. The output power is not measured directly. In worst-case the total losses are measured too low and the input power is measured too high.

$$\eta_{\mathrm{meas}} = \frac{P_{\mathrm{out,meas}}}{P_{\mathrm{in,meas}}} = \frac{P_{\mathrm{in,meas}} - P_{\mathrm{d,meas}}}{P_{\mathrm{in,meas}}} = 1 - \frac{P_{\mathrm{d,meas}}}{P_{\mathrm{in,meas}}} = 1 - \frac{P_{\mathrm{d,meas}}}{P_{\mathrm{in,meas}}} \cdot \frac{1-\epsilon}{1+\epsilon} = 1 - (1-\eta) \cdot \frac{1-\epsilon}{1+\epsilon}$$

$$\eta_{\mathrm{meas}} = 1 - (1-\eta) \cdot \frac{1-\epsilon}{1+\epsilon} = 1 - 0.04 \cdot \frac{0.998}{1.002} = 0.9602 \approx 0.96 = \eta$$

The deviation between measured and real efficiency is now smaller than 0.2 %.

For the indirect efficiency determination a well-known machine loss model and measurement methods to determine the losses are essential. For electrically excited synchronous machines an indirect method was already developed that consists of the summation of losses (IEC/EN 60034-2 [1]). In generator open-circuit operation at rated speed and thus rated frequency the no-load losses are directly determined from the input power. The load losses are measured in generator short-circuit operation at the same frequency. For these two experiments it is necessary that the excitation current is adjusted so that the rated flux occurs at no-load and the rated current flows at short-circuit operation. The friction and windage losses can be measured directly with a switched off rotor excitation in generator mode. The rated excitation current and thus the excitation losses may also be calculated from the no-load and short-circuit characteristic rather accurately. The sum of the individual losses then gives the total losses, and the efficiency is determined via the rated power. Of course, the true magnetic field state in the machine under load is slightly different. For example, a progressive load-dependent saturation of the rotor pole tips due to the armature reaction field is not detected by this method. However, due to the relatively large air gaps in electrically excited synchronous machines, this effect is small, so that calorimetric efficiency measurements of large synchronous machines at the plant show a good agreement with the calculated efficiency from individual losses.

This conventional method to determine the efficiency of synchronous machines, based on the summation of losses according to IEC/EN 60034-2 [1], is not directly applicable to permanent magnet (PM) synchronous machines (PMSM) as due to the (nearly) constant magnetic excitation from the permanent magnets no variation of excitation, as it is the case for electrically excited synchronous machines, can be done. It is not possible to separate the load-independent losses into iron losses and friction and windage losses. For smaller PM synchronous machines, like servo drives, with efficiencies below 95 % the above mentioned direct method to determine the efficiency (IEC/EN 60034-1 [2]) is possible with sufficient accuracy. For larger machines (e. g. wind generators up to 10 MW) an alternative method is required, and will be here presented, based on the summation of losses.

Alternative Concept

The proposed method is based on the electric equivalent circuit of a PM synchronous machine. There is already a comparable method used for the efficiency determination of induction machines (IEC/EN 60034-2 [1]). The following Fig. 1 shows a typical equivalent circuit of a synchronous machine with no reluctance difference between d- and q-axis for a fixed speed n [4].

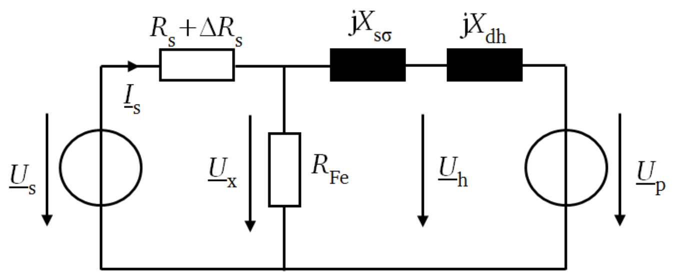

Fig. 1: Electrical equivalent circuit per phase of a synchronous machine with identical reluctance in d- and q-axis ($X_{\mathrm{d}} = X_{\mathrm{s\sigma}} + X_{\mathrm{dh}} = X_{\mathrm{q}}$)

U_s is the stator voltage, $R_\mathrm{s} + \Delta R_\mathrm{s}$ the stator resistance (as sum of DC resistance R_s and AC resistance ΔR_s), $X_{\mathrm{s}\sigma} = 2\pi f_\mathrm{s} L_{\mathrm{s}\sigma}$ the stator stray reactance (f_s: stator frequency, $L_{\mathrm{s}\sigma}$: stator leakage inductance), $X_\mathrm{h} = 2\pi f_\mathrm{s} L_\mathrm{h}$ the main reactance (L_h: main inductance), U_p the back EMF, R_Fe the iron resistance to describe the iron losses in the stator iron core $P_\mathrm{Fe,s}$ (as sum of hysteresis and eddy current losses) and U_h the main voltage of the resulting air gap field of the sum of the stator and rotor fundamental field wave. The inner electrical power as the air gap power P_δ results in the electromagnetic air gap torque M_e. The rotor losses include the friction and windage losses $P_\mathrm{fr+w}$ and the eddy current and hysteresis losses in the rotor iron due to air gap harmonic field waves and eddy current losses in the magnets $P_\mathrm{Fe,r+M}$. At the shaft the output torque for example in motor operation is

$$M = M_\mathrm{e} - \left(P_\mathrm{fr+w} + P_\mathrm{Fe,r+M}\right)/2\pi n \qquad (1)$$

Therefore the rotor losses are not present in the equivalent circuit at first. But by calculating the iron resistance R_Fe via the losses $P_\mathrm{Fe,s}$, $P_\mathrm{Fe,r}$ and P_M the rotor losses are considered approximately. The calculated shaft torque is then $M = M_\mathrm{e}$.

The AC resistance considers the eddy current losses in the stator winding due to the pulsating slot stray field. In the calculation of the iron resistance R_Fe, it is assumed that both the main flux (air gap field) and the stator stray flux close over the stator iron core and thus together cause the stator iron losses. This is not completely true, as the main flux flows through the whole stator tooth, whereas the stray flux closes more or less linearly increasing from the slot base over the tooth height. Anyway the stator stray flux takes part to the stator iron losses. If the iron resistance R_Fe was placed between $X_{\mathrm{s}\sigma}$ and X_h in Fig. 1, this would assume that there is no influence of the stator stray flux, which is not true [4].

The equivalent circuit is valid for sinusoidal voltages. In case of inverter operation, the circuit is fed by the voltage $U_{\mathrm{s},k}$, instead of U_s (harmonic order k of the inverter output voltage, frequency $f_{\mathrm{s},k} = k \cdot f_\mathrm{s}$). The back EMF U_p is zero for all harmonics except the fundamental. Then instead of the fundamental stator current I_s, the harmonic current $I_{\mathrm{s},k}$ flows, causing additional iron losses in the stator and rotor core (harmonic iron resistance $R_{\mathrm{Fe},k}$) and additional eddy current losses in the stator winding ($\Delta R_{\mathrm{s},k}$). The summation of all relevant voltage harmonics for a fixed speed and thus inverter modulation results in a nearly load independent additional loss component ΔP_inv [4].

To use the equivalent circuit for efficiency determination, all relevant loss components have to be assigned to suitable measurement methods. There are only few recent references about this topic, like [5]. Here, the proposed concept consists of two measurements:

- Open-circuit experiment (IEC/EN 60034-4 [3])
- Removed rotor test (IEC/EN 60034-4 [3])

The (average) temperature of the stator winding has to be written down for each measurement series, to recalculate the I^2R-losses to the correct temperature.

Open-circuit experiment

It is essential to carry out the open-circuit measurement at operation temperature, as with rising magnet temperature the magnetic remanence is decreasing, which leads to a lower back EMF and also lower induced voltage in the iron core. Due to the positive temperature coefficient of the iron, also the resistance of the iron sheets increases.

a) Generator open-circuit experiment

During the open-circuit experiment the machine is driven with open terminals. The tested machine is coupled via a shaft and a torque transducer (torque M_0) to a second driving machine. The speed n of the second machine is variable. The mechanical input power P_{in} of the tested machine is measured via the torque transducer as $P_{\mathrm{in}} = 2\pi \cdot n \cdot M_0 = P_{\mathrm{d0,gen}}$. For different speeds n of the machines the input power and the stator no-load voltage $U_{\mathrm{s}} = U_0 \cong U_{\mathrm{p}}$ (Fig. 2) of the tested machine are measured. The mechanical input power covers the friction and windage losses of the test machine $P_{\mathrm{fr+w}}$ (and, if present, the power of the shaft mounted fan), the iron losses in the stator due to the no-load flux $P_{\mathrm{Fe,s,0}}$ and the iron losses in the rotor (for example due to the slot harmonic field waves) $P_{\mathrm{Fe,r+M,0}}$, which are in sum the no-load iron losses $P_{\mathrm{Fe,0}} = P_{\mathrm{Fe,s,0}} + P_{\mathrm{Fe,r+M,0}}$. A separation of the mechanical input power into no-load iron losses $P_{\mathrm{Fe,0}}$ and friction and windage losses $P_{\mathrm{fr+w}}$ is only possible, if $P_{\mathrm{fr+w}}$ was determined from a generator open-circuit test with unmagnetized rotor, or from a retardation test with known rotor moment of inertia J [4].

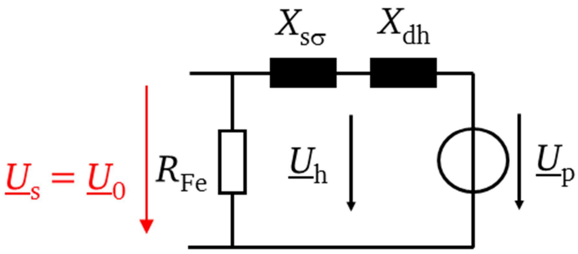

Fig. 2: Electrical equivalent circuit per phase during the open-circuit experiment

b) Motor no-load experiment (for inverter-fed machines)

In inverter operation the no-load test is carried out for different speeds n. With modern power analyzers it is possible to separate the electrical input power into the fundamental input power $P_{\mathrm{e,in,0,1}}$ and the harmonic power $P_{\mathrm{e,in,0,ad}}$. The fundamental input power $P_{\mathrm{e,in,0,1}}$ includes the losses $P_{\mathrm{Fe,0}} + P_{\mathrm{fr+w}}$ as described in part a) and additionally the stator ohmic losses due to the no-load current. If there is no possibility to measure the harmonic power directly, it can be approximated by the total electrical input power $P_{\mathrm{e,in,0}}$, the measured (fundamental) no-load current I_{s0}, and the stator resistance R_{s} with help of the measurements from the generator open-circuit experiment $P_{\mathrm{d0,gen}} = P_{\mathrm{Fe,0}} + P_{\mathrm{fr+w}}$ as

$$P_{\mathrm{e,in,0,ad}} = P_{\mathrm{e,in,0}} - \left(P_{\mathrm{Fe,0}} + P_{\mathrm{fr+w}} + 3R_{\mathrm{s}} \cdot I_{\mathrm{s0}}^2\right). \quad (2)$$

For PM synchronous machines the whole stator inductance is smoothing the stator current. As a result the current is nearly sinusoidal even at rather low switching frequencies above 1 kHz. The difference between the rms value and the fundamental is very small.

c) Calculation of the iron losses at load operation

At load operation the stator field is adding to the no-load field of the rotor magnets, so that the iron losses P_{Fe} are generally increased. These losses depend primarily on the square of total magnetic flux linkage and thus on the square of the reactance voltage $\underline{U}_{\mathrm{x}} = \underline{U}_s - R_s\underline{I}_s$ (Fig. 3). $\underline{U}_s$ and $\underline{I}_s$ are the complex phasors of the stator voltage U_s and the stator current I_s for a given operating point $P_e = 3U_s I_s \cos\varphi_s$. Therefore the iron losses are calculated via (3)

$$P_{Fe} = P_{Fe,0} \cdot \left(\frac{U_x}{U_0}\right)^2 . \quad (3)$$

For this conversion the actual value of the stator resistance R_s has to be known either from a direct measurement or from a suitable thermal sensor to determine the warm resistance value with help of the average winding temperature.

If $\underline{U}_s$ is assumed real, the current phasor can be written as

$$\underline{I}_s = I_s \cdot (\cos\varphi_s \pm j \cdot \sin\varphi_s) = I_{s,Re} \pm j \cdot I_{s,Im} , \quad (4)$$

where "+" represents a capacitive operating point and "−" an inductive operating point. The square of the reactance voltage is identical for both cases according to

$$U_x^2 = \left(U_s - R_s I_{s,Re}\right)^2 + \left(R_s I_{s,Im}\right)^2 . \quad (5)$$

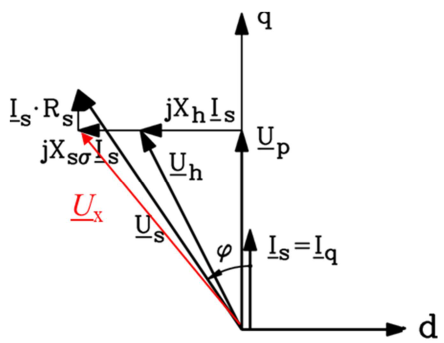

Fig. 3: Phasor diagram of a PM synchronous machine at load

In reality the calculation of the iron losses $P_{Fe} = P_{Fe,s} + P_{Fe,r+M} \cong P_{Fe,0} \cdot (U_x/U_0)^2$ is only an approximation, as the rotor iron losses $P_{Fe,r+M}$ due to harmonic field waves are generally higher than the no-load rotor iron losses $P_{Fe,r+M,0}$, however these losses are not included in $P_{Fe,0}$. Therefore the losses P_{Fe} are underestimated. On the other hand, if the friction and windage losses P_{fr+w} are not determined separately (form calculation or measurement), there will be a systematic error, as due to the assumption $P_{Fe,0} \cong P_{m,in,0}$ (for example in generator open-circuit operation) also the losses P_{fr+w} are converted quadratically. The losses P_{Fe} are overestimated.

Removed rotor experiment

During the removed rotor test, the stator ohmic losses are determined including the load-depending additional stator losses. The removed rotor test is done with variable stator voltage U_s, feeding the stator winding, and for instance rated frequency $f = f_N$, but flanged bearing shields etc. to be able to detect occurring eddy currents due to the load-depending stray flux of the winding overhangs. This concept is already used at the standardized investigation of induction machines (IEC/EN 60034-4) [3, 9]. Since the additional losses caused by inverter feeding are determined during the motor no-load test, the removed rotor experiment is carried out with sinusoidal currents and voltages, to measure the current-depending stator losses plus additional stator losses

$$P_{Cu,s} + P_{s,ad} = 3 \cdot (R_s + \Delta R_s) \cdot I_s^2 . \quad (6)$$

As mentioned before, the actual resistance value R_s and thus the winding temperature has to be known. The electrical input power $P_{e,in,B}$ contains in addition to the current-depending stator losses $P_{Cu,s} + P_{s,ad}$ also the iron losses due to the stator stray field and the bore field $P_{Fe,B}$ [9]. Fig. 5 shows a 2D-Finite-Element-Analysis (with JMAG) of an AC machine with distributed winding and removed rotor to show the meaning of the bore field and the slot stray field. To determine the stator ohmic losses, the iron losses $P_{\mathrm{Fe,B}}$ have to be subtracted from the electrical input power:

$$P_{\mathrm{Cu,s}} + P_{\mathrm{s,ad}} = P_{\mathrm{e,in,B}} - P_{\mathrm{Fe,B}} \,. \tag{7}$$

The iron losses during the removed rotor test $P_{\mathrm{Fe,B}}$ are not negligible for machines with big leakage inductance (e. g. machines with tooth wound coils). As mentioned before, these losses are calculated with help of the reactance voltage $U_{\mathrm{x,B}}$ and the measurements of the generator open-circuit experiment approximately via

$$P_{\mathrm{Fe,B}} \cong (P_{\mathrm{Fe,0}}) \cdot \left(\frac{U_{\mathrm{x,B}}}{U_0}\right)^2 . \tag{8}$$

Since the rotor iron losses $P_{\mathrm{Fe,r+M,0}}$ are included in $P_{\mathrm{Fe,0}}$, but obviously not missing during the removed rotor test, the losses $P_{\mathrm{Fe,B}}$ are overestimated. Another overestimation occurs, if the friction and windage losses are not explicitly known, and the losses are calculated via

$$P_{\mathrm{Fe,B}} \cong (P_{\mathrm{Fe,0}} + P_{\mathrm{fr+w}}) \cdot \left(\frac{U_{\mathrm{x,B}}}{U_0}\right)^2 . \tag{9}$$

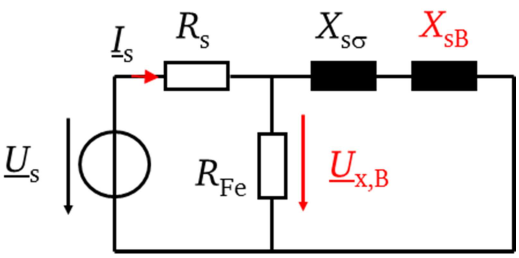

Fig. 4: Electrical equivalent circuit per phase during the removed rotor experiment (X_{B}: bore reactance)

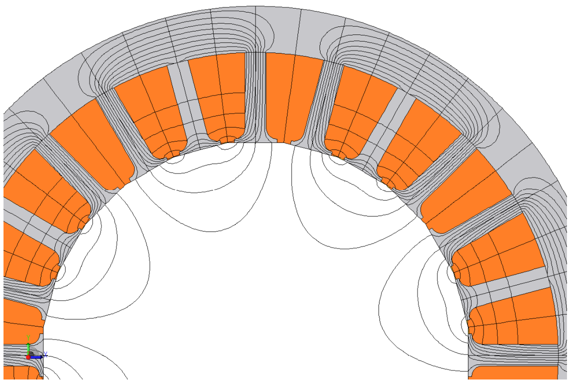

Fig. 5: 2D-FEA simulation of the stator field of a three phase single layer winding (q = 1) with removed rotor

Efficiency under load condition

Under load, the resulting fundamental air gap field represents a superposition of the rotor and stator field, depending on the relative position of the stator current phasor I_{s} and the phasor of the terminal voltage U_{s}. For this load case at rated frequency, the efficiency is determined from the measured values of the removed rotor test and open-circuit experiment, as follows.

1. From the given rms values of U_{s}, I_{s} (fundamental values $U_{\mathrm{s}} = U_{\mathrm{s}(1)}$, $I_{\mathrm{s}} = I_{\mathrm{s}(1)}$ for inverter operation) and the power factor $\cos\varphi_{\mathrm{s}}$ the positions of the stator voltage and current phasors

$\underline{U}_s$, $\underline{I}_s$ are determined and from that the square of the reactance voltage U_x is calculated with the stator resistance R_s for a specific temperature.

2. The current-depending stator losses and additional load losses $P_1 = P_\mathrm{Cu,s} + P_\mathrm{s,ad} = f(n, I_\mathrm{s})$ for a given fundamental current I_s and the fundamental frequency f_s with $= f_\mathrm{s}/p$ are known from the removed rotor experiment and converted to the given operating point by the actual stator resistance value.

3. The losses $P_\mathrm{Fe,0} + P_\mathrm{fr+w} = f(n)$ are known from the generator open-circuit experiment. With these values the iron losses P_Fe are approximated via $P_\mathrm{Fe} \cong P_\mathrm{Fe,0} \cdot (U_\mathrm{x}/U_0)^2$ or more inaccurate via $P_\mathrm{Fe} \cong P_\mathrm{m,in,0} \cdot (U_\mathrm{x}/U_0)^2$ respectively.

4. The additional losses $P_\mathrm{e,in,0,ad} = f(n)$ due to inverter feeding are known from the motor no-load test. They are for sufficient big switching frequencies nearly independent of the speed n and depend actually via $U_0(f_\mathrm{s}) = U_0(n \cdot p)$ on the voltage U_0 and thus the modulation degree of the inverter. Therefore for a given load point, the corresponding loss value $P_\mathrm{e,in,0,ad} = f(U_0)$ has to be taken into account.

The efficiency for sine wave operation is determined with (10) and (11):

- Generator operation: $$\eta_\mathrm{Gen} = \frac{3U_\mathrm{s}I_\mathrm{s}\cos\varphi_\mathrm{s}}{3U_\mathrm{s}I_\mathrm{s}\cos\varphi_\mathrm{s}+P_\mathrm{Fe}+P_1} \qquad (10)$$

- Motor operation: $$\eta_\mathrm{Mot} = \frac{3U_\mathrm{s}I_\mathrm{s}\cos\varphi_\mathrm{s}-P_\mathrm{Fe}-P_1}{3U_\mathrm{s}I_\mathrm{s}\cos\varphi_\mathrm{s}} \qquad (11)$$

Furthermore, the efficiency for inverter operation is determined with (12) and (13):

- Generator operation: $$\eta_\mathrm{Gen} = \frac{3U_\mathrm{s}I_\mathrm{s}\cos\varphi_\mathrm{s}}{3U_\mathrm{s}I_\mathrm{s}\cos\varphi_\mathrm{s}+P_\mathrm{Fe}+P_1+P_\mathrm{e,in,0,ad}} \qquad (12)$$

- Motor operation: $$\eta_\mathrm{Mot} = \frac{3U_\mathrm{s}I_\mathrm{s}\cos\varphi_\mathrm{s}-P_\mathrm{Fe}-P_1}{3U_\mathrm{s}I_\mathrm{s}\cos\varphi_\mathrm{s}+P_\mathrm{e,in,0,ad}} \qquad (13)$$

Criticism of the method:

- As the rotor iron losses $P_\mathrm{Fe,r+M}$ are neglected, the indirect efficiency values are more closely to the direct values, the smaller these losses are in reality.

- Of course, the resulting air gap field under load is different from the stator and rotor field of the open-circuit and the removed rotor experiment. Hence a different local load-dependent saturation effect occurs. This problem exists also for the conventional method for the indirect efficiency of electrically excited synchronous machines with open-circuit and short-circuit test (IEC/EN 60034-4 [3]), as already mentioned, and is not avoidable. The higher the magnetic utilization of the electrical motor, the more this load-dependent saturation effect is noticeable.

- If the friction and windage losses are not known separately, they will be converted with the square of the reactance voltage as well as the iron losses. This affects especially machines with shaft mounted fan. In case of an external cooling system, the friction and windage losses are usually small.

Measurements

Test bench

The experiments were carried out with three different PM synchronous machines. The Machines 1 and 2 are 16-pole ($2p = 16$) machines for 45 kW at 1000 min^{-1}, 430 Nm, 230 V rms phase voltage, with tooth coil stator winding (Fig. 6). Machine 1 with q = ½ (two-layer winding, semi-closed slots with parallel-sided teeth) has no sub-harmonic air gap field waves, and Machine 2 with q = ¼ (single-layer winding, parallel-sided open slots, narrow inter-teeth) shows one noticeable sub-harmonic with 8 poles. The machines also differ in the structure of the rotor. Machine 1 has surface magnets, and Machine 2 has buried magnets. Machine 3 is a 6-pole ($2p = 6$) machine with a higher nominal speed of 3000 min^{-1} and lower rated torque of 286 Nm. The stator has a distributed winding and thus a lower stator stray inductance than the machines with tooth coil winding. Also the main inductance is lower due to surface mounted magnets on the rotor. Table I summarizes the basic parameters of Machines 1, 2 and 3 [7].

Table I: Basic parameters of the three tested PMSM

	Machine 1	Machine 2	Machine 3
Rated power P_N	45 kW	45 kW	90 kW
Rated Torque M_N	430 Nm	430 Nm	286 Nm
Rated speed n	1000 min^{-1}	1000 min^{-1}	3000 min^{-1}
Rated voltage U_{sN} per phase	230 V	230 V	230 V
Rated current I_{sN}	102 A	120 A	200 A
Stator resistance $R_{s,20\,°C}$	55.5 mΩ	43.1 mΩ	13.7 mΩ
Synchronous inductance L_d	2.84 mH	2.56 mH	0.53 mH
Slots per pole and phase q	0.5	0.25	2
Air gap width δ	0.7 mm	0.7 mm	1.6 mm
Winding type	Double layer	Single layer	Single layer
Slot	Semi-closed	Open	Semi-closed
Tooth width	Constant	Not constant	Constant
Rotor magnets (NdFeB)	Surface	Buried	Surface

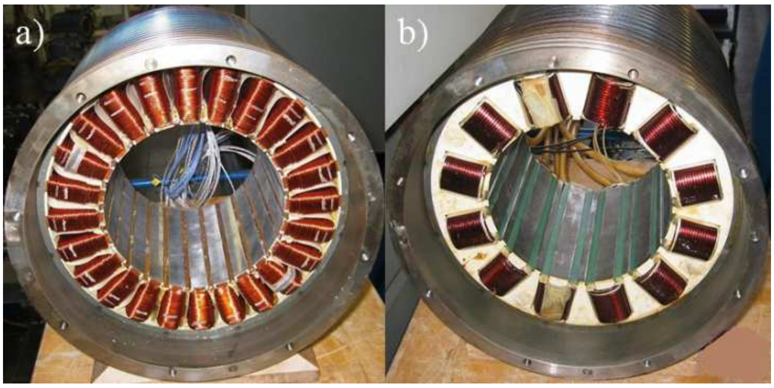

Fig. 6: Stators of the tested machines, a) Machine 1, 2/3 short-pitched winding, b) Machine 2, full-pitched winding [7]

Fig. 7 shows the test bench for the first part of the measurements with the Machines 1 and 2, fed by a voltage source inverter with a DC-link voltage of 600 V and the ability of 4-quadrant operation. The machines can be coupled via a torque transducer. Machine 3 is fed by an inverter with lower rated power. Therefore the reachable torque is limited by the current to about 75 % of rated torque. Furthermore the inverter allows no regenerative power flow, so that the generator operation is only possible with small currents via a braking resistor. Machine 2 is used as load (Fig. 8). During measurements, the RMS values and the fundamental amplitudes of the stator voltages and currents U_s and I_s as well as the corresponding power factor $\cos\varphi_\mathrm{s}$ are measured. The recording is done with the help of a power analyzer (Type Fluke Norma 5000), which was controlled by a computer system.

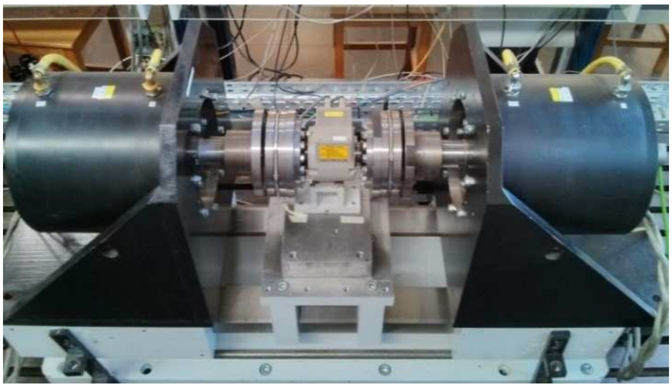

Fig. 7: Test bench with Machines 1 and 2 back-to-back to verify the proposed method for efficiency determination for PMSM

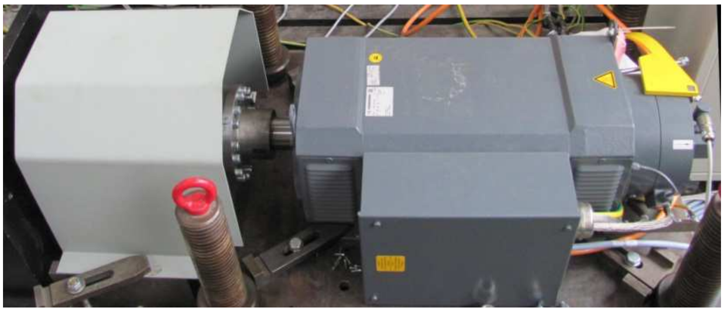

Fig. 8: Test bench with Machine 3 (on right-hand side) and Machine 2 as load

Results

Fig. 9 shows the measured losses during the open-circuit test for both Machines 1 and 2 over the speed n and thus over the stator frequency $f = n/p$. The curves have the expected shape with an exponent between 1 and 2, as the eddy current losses rise quadratically and the hysteresis losses linearly with the speed [8]. The friction and windage losses are negligible due to the smooth rotor surface and the external cooling. With the following formulas a rough estimation of the air friction losses $P_\mathrm{fr+w}$ is possible [4, 6], if no shaft mounted fan is used:

$$P_\mathrm{fr+w} = c_\mathrm{f} \cdot \pi \cdot \rho_\mathrm{air} \cdot (2\pi \cdot n)^3 \cdot r_\mathrm{ra}^4 \cdot l_\mathrm{Fe} \quad \text{with} \quad c_\mathrm{f} = 0.035 \cdot Re^{-0.15} \quad \text{and} \quad Re = 2\pi \cdot n \cdot r_\mathrm{ra} \cdot \frac{\delta}{\nu_\mathrm{air}} \tag{14}$$

(ρ_air: air mass density, r_ra: rotor outer radius, δ: air gap, ν_air: kinematic viscosity of air, l_Fe: iron length, Re: Reynolds number). The bearing friction losses are neglected. With these formulas the friction losses of the Machines 1 and 2 are determined to be only 14 W at 3000 rpm [7]. Therefore the error is small:

$$P_{\mathrm{m,in,0}} = 2\pi n \cdot M_0 = P_{\mathrm{d0,gen}} = P_{\mathrm{fr+w}} + P_{\mathrm{Fe,0}} \cong P_{\mathrm{Fe,0}} \text{ mit } P_{\mathrm{Fe,0}} = P_{\mathrm{Fe,s,0}} + P_{\mathrm{Fe,r+M,0}}$$

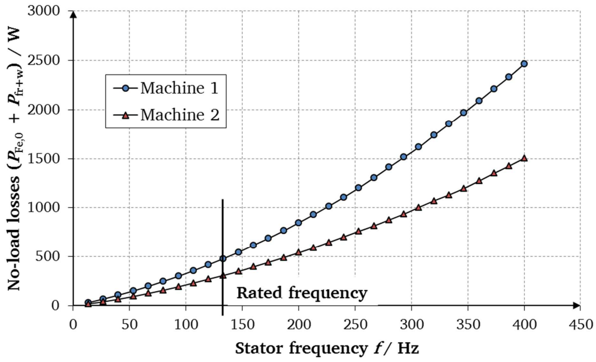

Fig. 9: Measured no-load losses $P_{\mathrm{Fe,0}} + P_{\mathrm{fr+w}}$ at the generator open-circuit experiment for Machines 1 and 2

The iron losses are smaller for Machine 2 due to the smaller magnetic flux density in the stator iron parts. A comparison of the induced voltages and a calculation of the corresponding permanent magnetic flux linkage via

$$\Psi_{\mathrm{p}} = \frac{\hat{U}_{\mathrm{p}}}{2\pi f} \tag{17}$$

shows that the flux linkage of Machine 1 is higher than the flux linkage of Machine 2 by the factor 1.46 ($\Psi_{\mathrm{p,Machine\ 1}} = 0.301$ Vs, $\Psi_{\mathrm{p,Machine\ 2}} = 0.206$ Vs). In the calculation the measured no-load voltage U_0 is equal to the back EMF U_{p}. This assumption is valid, because the equivalent iron resistance R_{Fe} (Fig. 1) is much higher than the synchronous reactance X_{d}.

The additional losses due to inverter feeding (Fig. 10) are determined during the motor no-load test as $P_{\mathrm{e,in,0,ad}} = P_{\mathrm{e,in,0}} - \left(P_{\mathrm{Fe,0}} + P_{\mathrm{fr+w}} + 3R_{\mathrm{s}} \cdot I_{\mathrm{s0}}^2\right)$. After subtraction of the very small stator current losses, the fundamental power $P_{\mathrm{e,in,0,1}}$ is nearly identical to the generator no-losses.

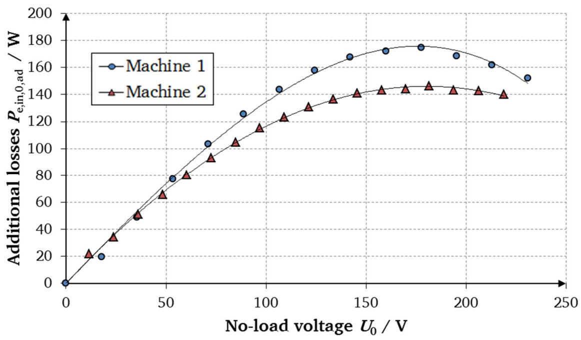

Fig. 10: Measured additional losses due to inverter feeding as difference between the motor and generator no-load losses over the fundamental no-load voltage U_0 for Machines 1 and 2

For Machine 3 the motor no-load losses are shown in Fig. 11. The difference between total and fundamental input power is higher than for the previous Machines 1 and 2, i. e. more additional losses due to inverter feeding $P_{\mathrm{e,in,0,ad}}$ occur, as shown in Fig. 12, plotted over the no-load voltage U_0.

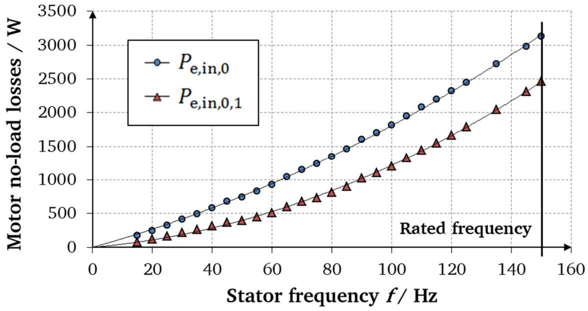

Fig. 11: Measured total losses $P_{e,in,0}$ and fundamental losses $P_{e,in,0,1}$ at the motor no-load experiment for Machine 3

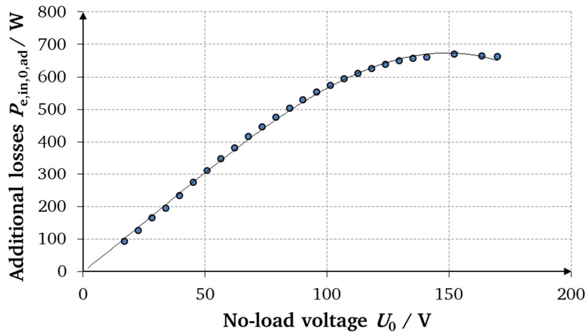

Fig. 12: Measured additional losses due to inverter feeding as difference between the total and fundamental no-load losses over the fundamental no-load voltage U_0 for Machine 3

To determine the current-depending losses $P_1 = P_{Cu,s} + P_{s,ad}$, the removed rotor test is carried out under consideration of the actual winding temperature. The iron losses due to the stray and bore field $P_{Fe,B}$ are estimated by using $P_{Fe,0}$ of the open-circuit experiment via (3) and subtracted from the electrical input power: $P_1 = P_{e,in,B} - P_{Fe,B}$. Fig. 13 shows the remaining losses plotted over the squared stator current I_s^2 for different frequencies. The curves are nearly straight lines, which is characteristic for current-depending losses. The losses rise with rising frequency due to the increased current displacement in the stator conductors.

a) b)

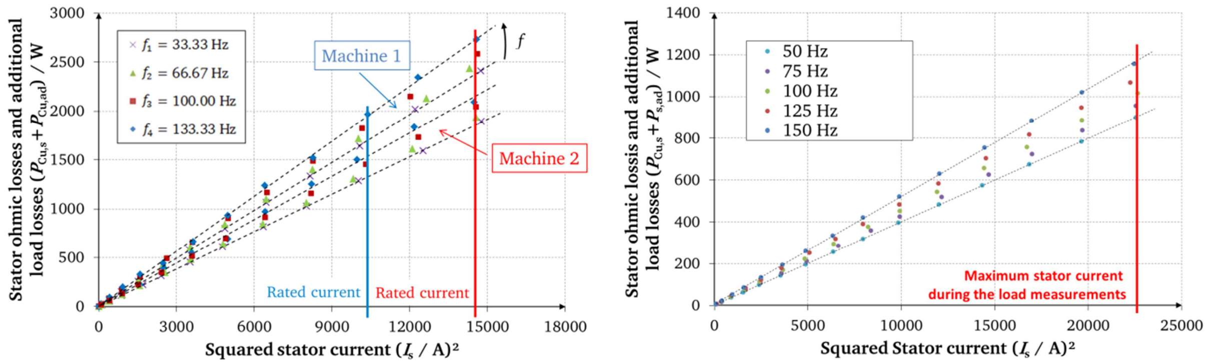

Fig. 13: Measured ohmic and additional load losses $P_{Cu,s} + P_{s,ad}$ at the removed rotor test for the stators of a) Machines 1 and 2, b) Machine 3; Converted to the temperature $\vartheta = 20$ °C

To validate the indirect efficiency method according to (10) to (13), motor and generator load test are carried out. The direct efficiency is determined with the help of the torque transducer (torque M, speed n) and the power analyzer.

$$\eta_{Mot} = \frac{P_{m,out}}{P_{e,in}}, \text{ respectively } \eta_{Gen} = \frac{P_{e,out}}{P_{m,in}} \text{ with } P_m = 2\pi \cdot n \cdot M \qquad (18)$$

If the efficiency shall be determined for “sine wave operation”, only the fundamental electrical input and output power $P_{\mathrm{e,in}}$ and $P_{\mathrm{e,out}}$ is considered. Of course, a true sine wave operation with a variable three-phase system would also be possible, but then it would be very difficult to adjust the current angle. For inverter operation $P_{\mathrm{e,in}}$ and $P_{\mathrm{e,out}}$ denote the total electrical input and output power.

At first, the efficiency is determined for the tooth coil Machines 1 and 2. In “sine wave operation” (Fig. 14 and Fig. 15) the losses are overestimated in motor operation for both machines. Therefore the indirect efficiency value is lower than the direct one. The error is bigger for lower speeds, since the relative deviation of the losses is higher for low absolute power values. In generator operation there is a good accordance, especially near the rated operating point.

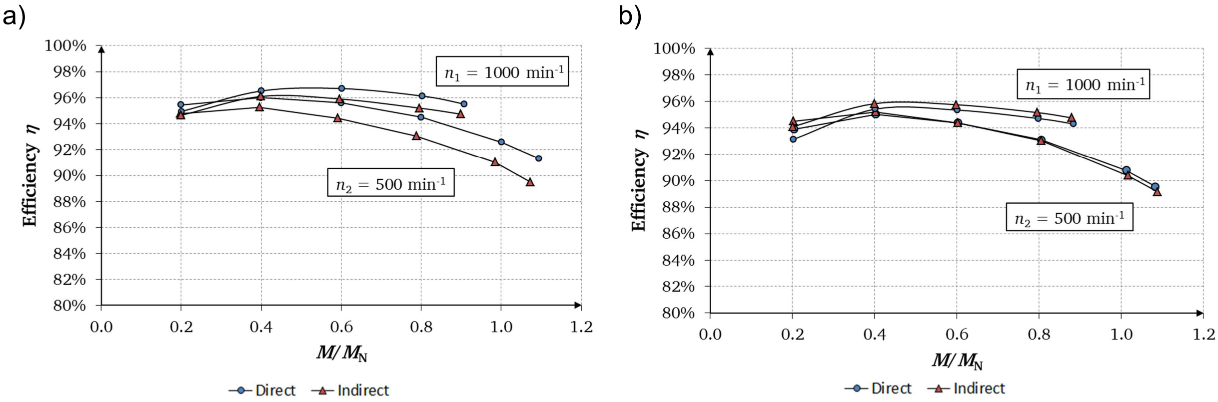

Fig. 14: Direct and indirect efficiency over the torque M for Machine 1 in “sine wave operation” (= fundamental power) at speed $n_1 = n_{\mathrm{N}} = 1000\ \mathrm{min}^{-1}$ and $n_2 = 500\ \mathrm{min}^{-1}$, a) Motor operation, b) Generator operation

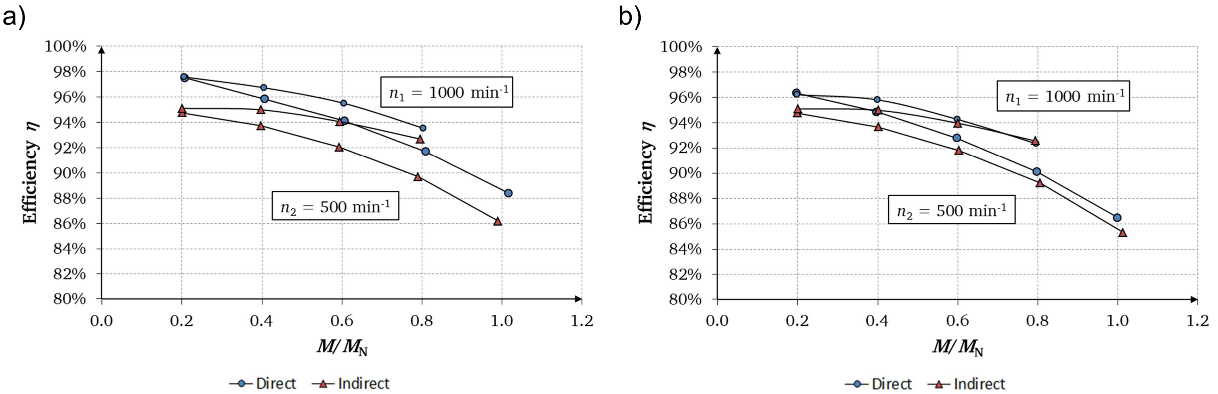

Fig. 15: Direct and indirect efficiency in “sine wave operation” as Fig. 14, but for Machine 2

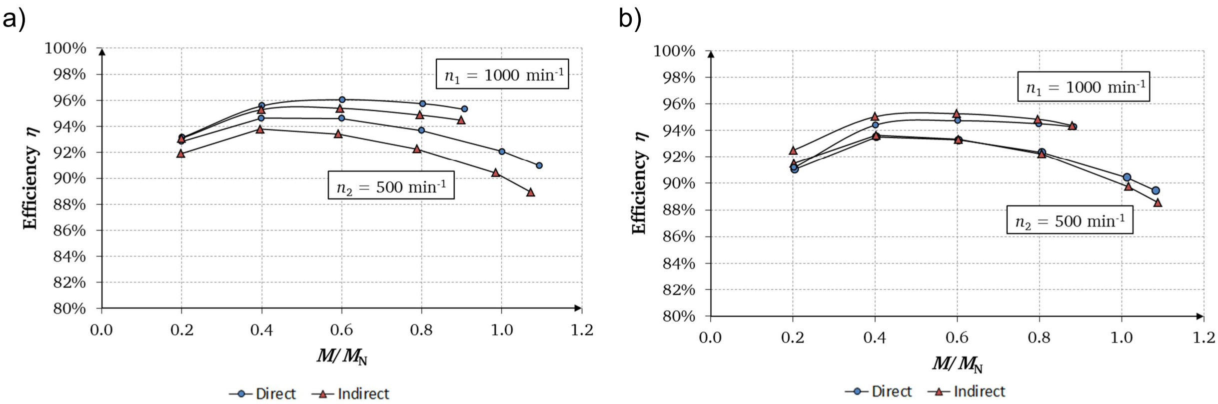

Fig. 16: Direct and indirect efficiency for Machine 1 as Fig. 14, but for inverter operation

For inverter operation, the additional losses $P_{\mathrm{e,in,0,ad}}$ have to be taken into account. As these losses are very small for both Machines 1 and 2 (< 200 W), the efficiency curves (Fig. 16 and Fig. 17) are quite similar to the curves for "sine wave operation". Again, there is a good accordance in generator operation, while the losses are overestimated for lower speeds in motor operation. The deviation does not change significantly with the consideration of the additional losses due to inverter feeding.

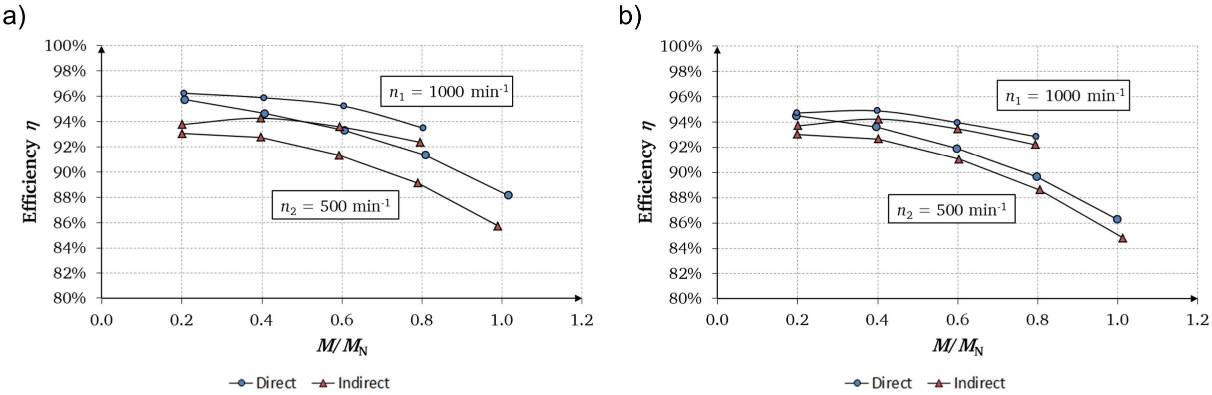

Fig. 17: Direct and indirect efficiency for inverter operation as Fig. 16, but for Machine 2

The load measurements for Machine 3 are performed in the same way as for the first two tested machines. The indirect efficiency values by means of the fundamental power ("sine wave operation") follow the direct ones quite well (Fig. 18). For low speed and low load there is a slight underestimation of the losses. A good accordance is achieved near the rated operating point. Due to the inverter restrictions, the load in generator operation was limited to approximately half of rated torque.

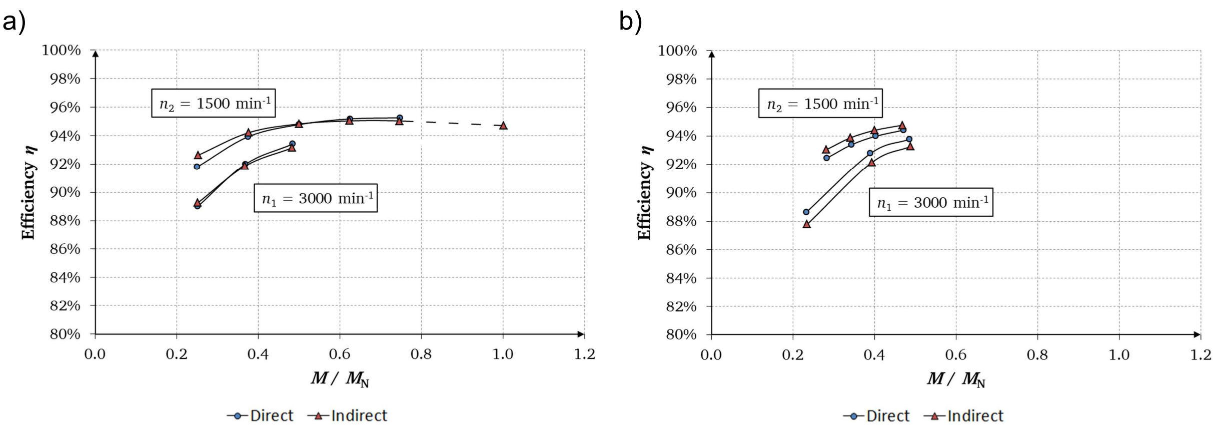

Fig. 18: Direct and indirect efficiency over the torque M for Machine 3 in "sine wave operation" (= fundamental power) at speed $n_1 = n_{\mathrm{N}} = 3000\ \mathrm{min}^{-1}$ and $n_2 = 1500\ \mathrm{min}^{-1}$, a) Motor operation, b) Generator operation

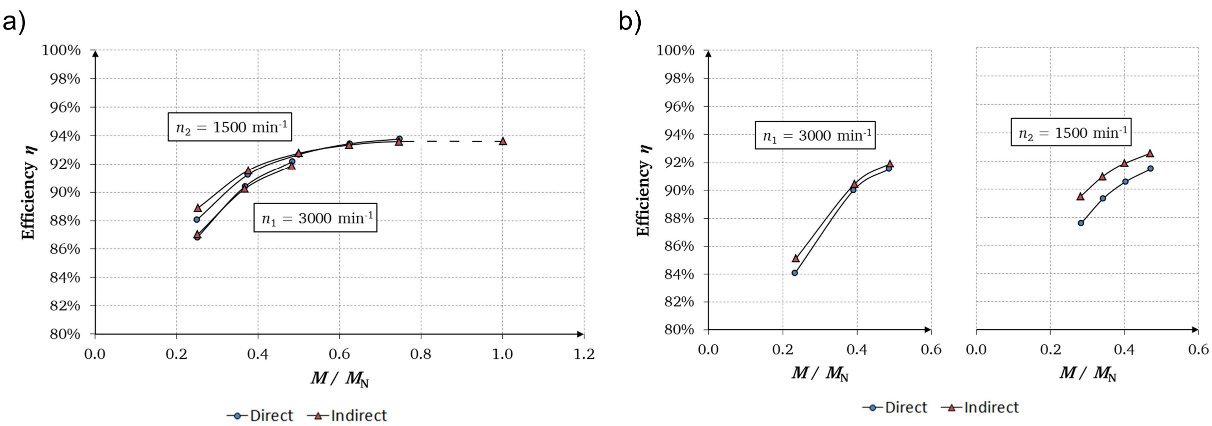

Fig. 19: Direct and indirect efficiency for Machine 3 as Fig. 18, but for inverter operation

As the additional losses $P_{\mathrm{e,in,0,ad}}$ are higher for Machine 3 than for Machines 1 and 2, the efficiency values in inverter operation (Fig. 19) are noticeable smaller than in “sine wave operation”. In motor operation, there is again a good accordance between the direct and indirect values. In generator operation, the difference is higher. This indicates, that in chopper operation with braking resistor the additional losses are higher than predicted.

Conclusion

A new method of indirect determination of the efficiency of PM synchronous machines in generator and motor operation for sine wave and inverter feeding is introduced. The method is based on the separation of the losses into voltage- and current-depending losses, respectively into no-load and load losses for a defined temperature by means of the open-circuit experiment and the removed rotor experiment. For validation, measurements were carried out on three PM machines. The first two machines have a special tooth coil winding and several different parameters (surface vs. buried magnets, stator winding with or without sub harmonic field waves, semi closed vs. open slots). The third machine has a distributed winding. At load, there is a good accordance between the direct and indirect efficiency for Machine 1 and 2 in generator operation. In motor operation, the deviation is larger and the losses are overestimated. For Machine 3, the direct and indirect values are corresponding quite well, especially near the rated speed and rated torque. The efficiency curve shapes show a good agreement for all three machines. A quantitative analysis in terms of measurement uncertainty and errors, as mentioned in the introduction, will be part of future investigations.

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Comparison of permanent magnet machine technologies based on system cost for harsh environment applications

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Nicolas Frank (Baldor Motors)

Abstract:

This paper compares three topologies of direct-drive motors considering the cost and performance for low speed applications. Induction motors with gear drives have been considered earlier as conventional drive solutions, but the increased maintenance cost, reliability and the efficiency drop due to the gear is an issue, even if the standard speed induction machine is the least expensive industrial motor solution. There are many direct drive technologies available for low speed applications, and those promising to deliver desired performance and cost saving are considered and compared in this paper. Permanent magnet (PM) technology can provide an energy efficient direct drive solution at very low speed, ranging up to 600 rpm applications. The major issue with the PM machine is the cost of rare-earth magnets. Additionally, this type of direct drive machine may be operated in harsh environments and higher ambient temperatures, which may cause demagnetization of magnets. Oversizing the magnet and adopting other magnet grade technologies like grain boundary diffusion and higher dysprosium result in higher machine cost as well as system cost. The simulation and FE analysis results are discussed in this article. This paper compares calculations of three different machine topologies: interior permanent magnet (IPM), surface type permanent magnet (SPM), and pole-modulated PM machine (vernier type machine), based on efficiency, cost and demagnetization reliability. The pole-modulated PM machine can give higher torque and power density but the magnet requirement is higher. If the magnet weight is reduced, it can still deliver good efficiency, but the power factor is poor which causes a higher drive cost. The surface type PM machines have better performance index in terms of cost saving, but suffer the penalty of increased cost due to arc shaped magnets and are more prone to demagnetization under higher ambient temperature. The IPM machine is found to be more cost competitive and least susceptible to demagnetization as compared to surface type and pole-modulated PM machine for the low speed direct drive applications under harsh environments.

INTRODUCTION

Direct drive solutions for low speed applications have great potential in the market, but a major obstacle is the initial cost to the customer. The major cost component is coming from the magnet price and the magnet price has shown instability in recent years. During the design and development of any new high-torque, low-speed motor topology, the designer has to consider many other factors. Lowering the magnet Dysprosium content can cause demagnetization of the magnet at higher temperatures and current overloading. The ambient and operating temperatures for some applications are high therefore the magnet energy product is reduced. In many applications such as cooling towers, paper mills, cranes, and hoists, the machine footprint and total weight are limited. For different magnet technology applications, close collaboration with a magnet manufacturer is required to understand the price change with grade and shape of the magnets

This paper compares calculations of three different machine topologies, internal permanent magnet (IPM), surface type permanent magnet (SPM), and pole-modulated PM machine (Vernier type machine), based on efficiency, cost and robustness. The pole-modulated PM machine can give higher torque and power density but the magnet weight is higher. If the magnet weight is reduced, it can still deliver good efficiency, but the power factor is poor which causes a higher motor current. The higher motor current sometimes leads to selection of a larger drive frame size which increases the drive system cost. The surface type PM machines have better performance index in terms of efficiency and power density, but suffer the penalty of increased cost due to arc shaped magnets and are more prone to demagnetization under higher ambient temperature. The IPM machine is found to be more cost competitive and least susceptible to demagnetization as compared to surface type and pole-modulated PM machine for low speed direct drive applications under harsh environments.

LOW SPEED APPLICATION MARKETS

The market for low speed direct drive applications is increasing due to the following benefits offered by direct drive technology:

- The overall system efficiency for direct drive is higher especially at speeds less than 100 rpm.
- The direct drive system eliminates the mechanical gear and the corresponding maintenance requirement.
- The system weight and volume for direct drive technology is lower as compared to geared drive.

There are many applications where direct drive is considered i.e., paper mills, sewage and water treatment plants, cooling towers, cranes, and mining machines. The cooling tower is an emerging market because, in the United States, 90 percent of electricity is produced by thermoelectric power plants—coal, nuclear, natural gas, and oil—that require cooling [1]. Process cooling methods include once through, wet recirculating, and dry cooling. The majority of cooling systems employ the use of a motor driven fan, typically coupled to a gear reducer via a drive shaft as shown in Fig.1. Today, many plants have lost the experienced maintenance personnel needed to properly take care of this mechanical equipment. Pressure to reduce operating costs often results in a greater focus on total cost of ownership. For these reasons, higher reliability, reduced downtime and longer maintenance intervals are required. With increasing parasitic loads such as additional cooling requirements for the cooling tower systems, plants will continue to focus not only on the process benefits that are obtained from direct drive but on the energy savings as well. The pulp and paper industry is another example of a growing market.

Fig. 1 Geared and gearless installations for cooling tower applications [1]

Fig.2 (a) Cooling tower and (b) Paper mill applications [1-2]

The motors used for the paper mill applications are typically ranging from a few kW to few hundreds of kW and with one paper mill drive, many motors are used as shown in Fig.2. There is often a cost benefit, if the life-cycle cost is considered while selecting the direct drive [2]. The payback period for utilizing direct-drive PM based technology is typically 3-4 years [2]. There are many direct drive motor technologies considered in academia and industry which are discussed in the next section.

DIFFERENT TOPOLOGY CONSIDERATIONS

Over the past 30 years direct drive technology that provides higher power density and torque density has been considered to replace geared induction motor drives. Machine performance is considered a prime objective for the replacement of a conventional drive. The replacement involves an infrastructure change and direct drive systems result in a higher cost to achieve the performance and reliability benefits. Reliability after paying a cost premium for direct drive is another key benefit of the original equipment manufacturer (OEM) market. New and interesting direct drive topologies investigated in academia, have also attracted interest from motor users and manufacturers. An investigation is necessary to compare cost and performance of these novel topologies from the system perspective to choose the best topology for direct drive applications.

This paper compares three topologies of direct-drive motors considering their cost and performance under the low speed applications. Induction motors with gear drive have been considered earlier as conventional drive solutions, but the efficiency drop due to the gear and its maintenance and reliability are issues, even if the standard speed induction machine is the least expensive industrial motor solution. Permanent magnet technology can provide an energy efficient direct drive solution at very low speeds. Different low speed topologies are considered as shown in Fig. 3 to 6 [3-8]. There are advantages and disadvantages of these topologies as described in Table – 1.

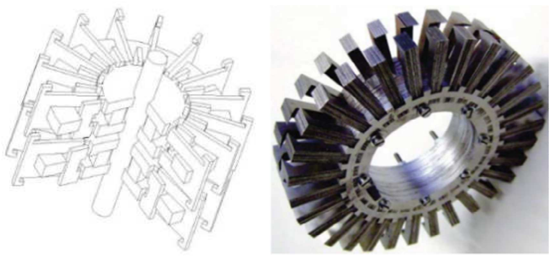

Fig.3 Transverse flux machine
University of Bremen (DE) 50 kW prototype [3-4]

Fig.4 Pole-modulated PM (PM2) Machine [5-6]

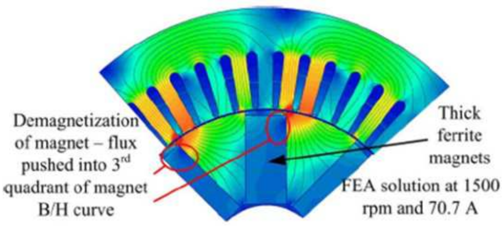

Fig.5 Radial Flux Spoke IPM machine [7]

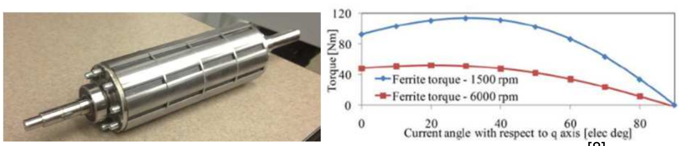

Fig.6 Pacific Scientific/Kollmorgen prototype [8]

Table-1: Qualitative Comparison of various direct drive motor topologies

Topology	*Advantages*	*Disadvantages*
Transverse flux machine	o Simple winding o High force/torque density	o Low power factor o Difficult construction o Must be at least two-phase o Force density is sensitive to air gap
Radial Flux Spoke-type machine	o Enables use ferrite magnets (low cost) o Efficient direct drive with large pole numbers	o Complicated mechanical structure o Low power factor due to lower magnetic loading in the airgap
Pole-modulated PM Machine	o Magnetic gearing effect o higher frequency drive for low-speed operation o Higher torque density	o Poor power factor o Outer-rotor configuration o More magnet weight (cost)
Surface PM Machine	o Higher Torque density	o Higher Magnet cost for arc shaped PMs o Lower pf for rectangular shape PMs
IPM Machines	o Higher torque density o Easy construction o Both PM and reluctance torque	o Higher magnet cost (but lower than arc shapes because of rectangular shapes)

Transverse flux machines have simple windings and can have higher torque and power density. However, the technology is not ready for the mass market due to its construction difficulties, low power factor and higher system cost. The radial flux spoke type machine technology is also another popular topology (also known as flux focusing topology) considered for direct drive applications due to its feasibility of using ferrite magnets and better power density. The cost of machine is lower as compared to a PM machine using Neodymium or Samarium based magnets. Disadvantages of the flux focusing technology limiting its market acceptance include its lower power factor and complicated nature of construction. Pole-modulated PM machine (PMPM) is claimed to have the highest torque density of PM Vernier family of machines.

Leakage flux

Main flux

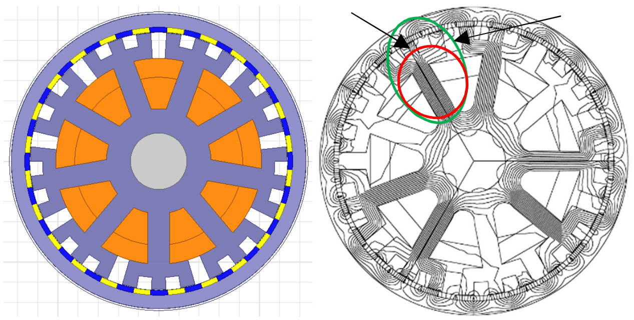

Fig. 7 PMPM machine (a) FE model and (b) Flux plot

The pole-modulated concept FE model is analyzed using a 250 hp, 125 rpm (Base IPM machine data as shown in table-2). It is found that the leakage inductance is higher due to the higher leakage permeance path for the stator phase windings as shown in Fig 7(b). The machine has the capability of delivering rated torque as well as peak torque required as shown in Fig. 8. The ripple torque is also significant but the impact on speed ripple can be mitigated by the large inertia of the total rotating system.

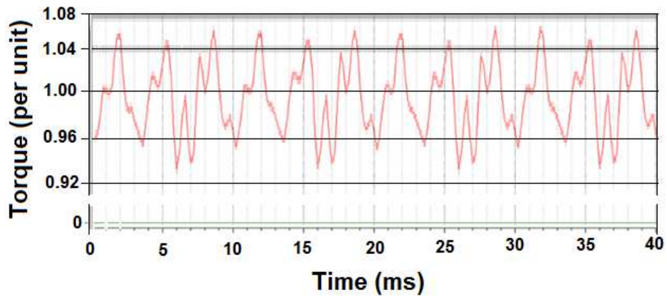

Fig. 8 Dynamic torque profile of the PMPM machine (pu change)

Table – 2 Base Machine design data

Rated Power	250 HP Base IPM	250 HP PMPM
Rated Line Voltage	460 V	460 V
Rated Current	325 A	730 A
Full load Efficiency	91.5%	94.5%
Full Load Power Factor	0.786	0.32

Applying sinusoidal terminal voltage will result in a higher current with very poor power factor compared to the base IPM machine. For pole-modulated PM machine, because of the Vernier principle [9], a gear effect is produced and the machine is operated at higher drive frequency. For a given magnet weight, the power factor is significantly affected due to the stator leakage inductance. The drive current as a consequence is very high, increasing the drive cost.

A parametric analysis is carried out to observe whether power factor could be increased by adding more magnets. The results of this parametric analysis indicates that the power factor could increase up to 0.6 with additional 50% magnet volume. The drive current requirement under that condition is still 30% more. The overall torque density is 2.5 times the IPM machine but the overall system cost, including motor and drive, is significantly higher which is not acceptable to the market. The following observations are derived from the parametric analysis.

- The airgap changes the power factor significantly. The power factor of this machine improves from 0.25 to only up to 0.6 with the airgap decreased from 2.0 mm to 0.5 mm.
- Reducing the magnet weight in pole-modulated PM machine further reduces the power factor and subsequently increases current.
- The airgap considered in the literature [5] is lower as compared to the analysis done in this paper, which can improve the power factor, but for the industry tolerance and airgap eccentricity allows to choose more than 1.5 mm for this comparison.
- Many magnets utilized for this topology cause increased in magnet cost due to the yield loss, machining cost and the assembly cost.

PM MACHINE TECHNOLOGY

The disadvantages of PM^2 machines leads one to consider PM surface and IPM topologies for direct drive applications. There are several topologies of PM surface and IPM machines considered over the last 30 years.

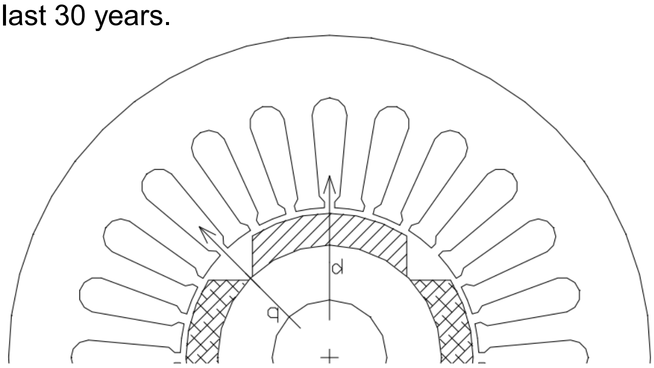

Fig. 9 Surface PM Motor with no rotor saliency [10]

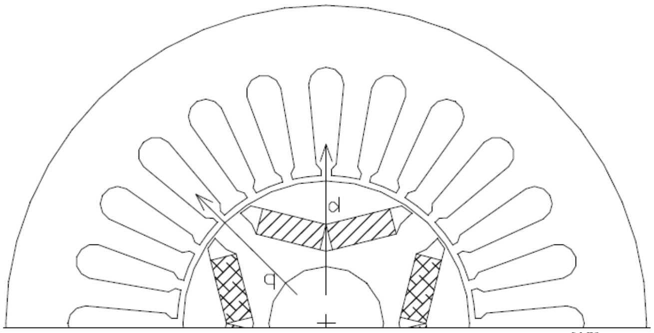

Fig.10 Interior PM Motor with rotor saliency [10]

The two common topologies of PM machine, namely surface type PM machine (SPM) [9] where the arc shape magnets are utilized as shown in fig. 9 and V-shape IPM machine where a flat rectangular shaped magnets are used as shown in Fig. 10, are considered for the comparison. These two topologies are promising to deliver desired performance at low speed and high torque.

A. Cost:

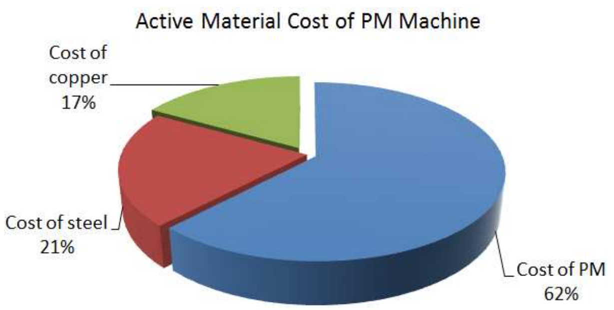

Fig. 11 Base material cost breakdown for the PM machines [11]

In the surface PM machine (SPM) shown in Fig. 9, motor torque is produced due to the interaction of stator current with magnet flux. Whereas; for the IPM machine shown in fig. 10, due to the saliency in the rotor geometry, the torque is produced by PM as well as saliency. The approximate material cost breakdown for PM motors is shown in Fig.11 which indicates that the magnet cost is a majority of the total active material cost of the machine.

The magnet cost not only depends on the weight and grade of the magnet but also the shape of the magnet. For example, the arc shape magnet is 30% more expensive than a rectangular-shaped magnet while a D-shape magnet is 15% more expensive than an arc shape magnet. The manufacturing cost of creating the arc shape magnet, including additional yield loss and machining loss, is 30% higher in terms of cost/kg as compared to rectangular blocks. Therefore even if the surface PM machine saves 15% volume and weight of the magnets, it is more expensive than the rectangular shape machine. Additionally the IPM provides reluctance torque up to 20% of the rated torque.

B. Demagnetization:

Another aspect, apart from the cost of the magnet, is the magnet performance during PM machine operation and extreme conditions. The demagnetization of the magnets can occur under terminal short circuits, starting transients and overload conditions. The temperatures under nominal operating conditions for a totally enclosed machines are higher and in some cases the magnets are operated at closed to 180°C. A demagnetization analysis is carried out under these circumstances.

Table – 3 Demagnetization analysis results
(Percentage of demagnetized volume in magnets)

Temp. (°C)	Machine	Percentage of full load stator current					
		100	125	150	200	250	300
180	IPM	0	0	0	0	0	0
	SPM	0	0	0	0	0	1.4
200	IPM	0	0	0	3.7	25.3	69.7
	SPM	0.2	1.5	7.1	39.5	54.4	96.4

Note: The color indicates the demagnetization severity (Green healthy, Yellow – caution, less than 5% magnet volume demagnetized and Red – more than 5% volume demagnetization

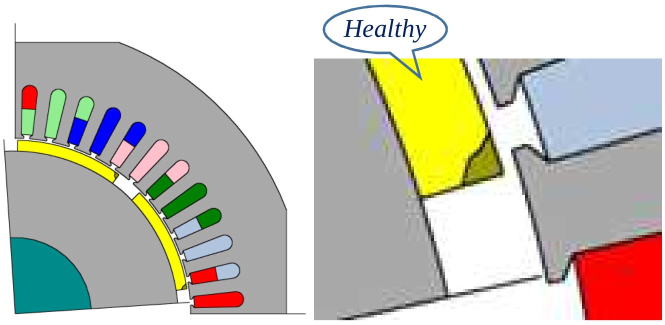

Fig.12 Demagnetization of magnets at 1.5 times rated current of the Surface PM machine at 200 °C
Healthy: Yellow and Unhealthy: Dark Yellow

As shown in Fig. 12, some portion of the magnet in the SPM machine starts demagnetizing at 180°C and 3 times load current and also 1.25 times full load current and 200°C. The results of complete demagnetization analysis are listed in Table-3. The magnets used for this analysis are rated for 180°C operations.

Grain Boundary diffusion process or equivalent technology [12] allows motor designers to employ low Dysprosium content magnets with enhanced coercivity as shown in Fig. 13. These newer low-Dysprosium NdFeB grades can match the magnet operating points and result in lower usage of the magnet while giving higher overload and over temperature capability. But the cost of this technology currently is high enough so that it would not give a cost benefit.

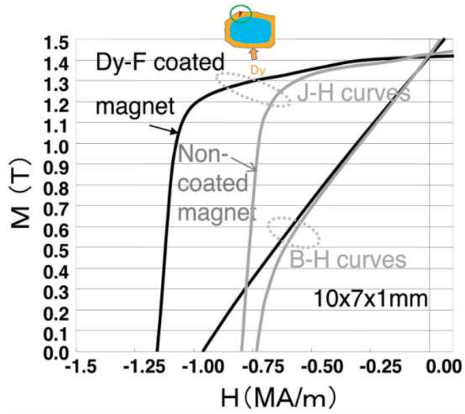

Fig. 13 Enhancement of intrinsic coercivity of the magnet using grain boundary diffusion [12]

The cost and demagnetization is the deciding factor to choose from the surface PM and IPM machine technology. The above cost and demagnetization analysis conclude that the IPM machine is more robust and cost effective for the low speed direct drive application.

CONCLUSION

Under nominal operating conditions all three machine topologies: PMPM, SPM and IPM, give high efficiency. When operated under harsh environments, the behavior of these machines are different.

Table – 4 Qualitative comparison under harsh environment

Drive System	*Machine cost*	*Drive cost*	*Performance measures*
PMPM	Very High due to more magnet weight	Higher due to poor pf and higher drive current	Poor pf and higher Drive current, No demagnetization at higher temperatures
SPM	Higher than IPM due to arc shaped magnets	Lower as compared to PMPM	Demagnetization at high temperatures
IPM	Lower due to rectangular magnets	Lower as compared PMPM	Robust under high temperatures

The pole-modulated PM machine is found to have higher power density and reliability under higher temperatures but the cost of the machine is higher due to larger magnet usage. The power factor of this machine is also at best 0.6 which causes expensive drive requirements. If the magnet weight is reduced, it can still deliver good efficiency, but the power factor is even poorer which causes an even higher drive cost.

Surface PM Machines are considered as a better choice for direct drive solutions. However, they utilize either arc shaped or rectangular magnets. The cost of arc shaped magnets are higher as compared to the rectangular magnets, and rectangular magnets reduces the power factor. Also, surface PM machines are more prone to demagnetization under higher ambient temperature.

Interior PM Machines are less susceptible to demagnetization as compared to surface type PM machines and are more reliable under higher temperatures and extreme operating conditions. The cost of IPM machines is also lower as compared to surface PM machines and PM^2 machines. Considering cost and demagnetization, IPM machines are the most competitive choice for low-speed direct-drive applications in demanding environments.

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A novel servo drive: air-cooled, multi-phase permanent-magnet synchronous machine with highly integrated power electronics

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Abstract

Multiphase[1], permanent-magnet synchronous machines without star point connection and a SST (Smart Stator Tooth)-module placed directly at each tooth coil enable novel actuator designs. With this concept it is possible to realize space and cost-saving drives for industrial use with many common parts. Due to the multi-phase structure the base field utilization can be increased. With a novel "Inlay Heat Sink" (IHS) the junction temperature of the power semiconductors can be reduced significantly. The result is a higher torque and power density and also a higher efficiency of the whole drive.

1. Introduction

State-of-the-art compact servo drives[2], in which a 3-phase inverter is enclosed in a separate housing, are only available up to 3,7 kW rated power and 16 Nm rated torque. Figure 1 shows a sample of compact servo drives with integrated power electronics available on the market and their torque and power density.

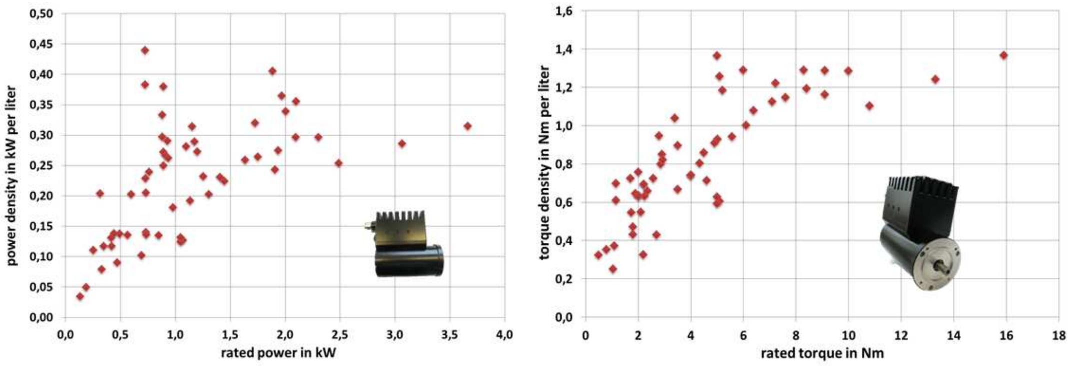

Figure 1: State-of-the-art compact servo drives, power and torque density

The integration of power electronics into a separate housing with its own heat sink creates an unfavorable form factor of the drive and needs a lot of space. For this reason, different approaches of integration of the power electronic into the machine housing have been developed [1] [2] [3] [4] [5] [11] [12], two of which are shown in Figure 2. The concepts in [1], [3] and [11] are liquid cooled, so they are inappropriate for industrial drives. The concepts shown in Figure 2 are internally ventilated, so a high protection class of IP 54 or higher, which is needed for the most industrial applications, is not possible.

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[1] More than three phases

[2] This means permanent magnet servo motors with inverter for decentralized use.

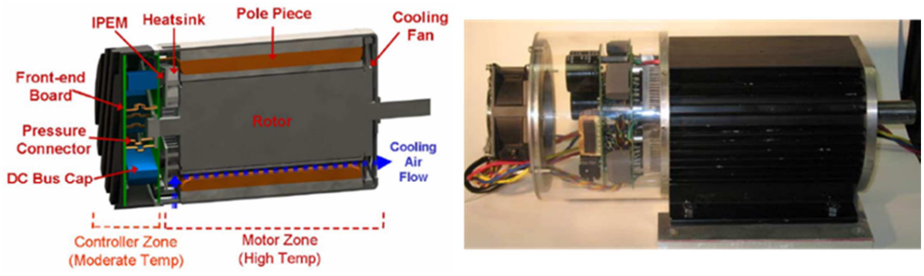

Figure 2: Integration concept of [4] on the left and [5] on the right

This was the motivation to develop a concept for a compact and highly integrated drive. In order to allow industrial use the drive should fulfill the following requirements:

1. Air cooled, but no internal ventilation
2. Protection class IP54 or higher
3. Performance similar to common servo drives
4. Energy-efficient system
5. Cost-efficient competitive for production
6. Power and torque density comparable to stand alone torque motors

So there are three main challenges:

1. Design a good concept for mounting power electronics and machine in one housing
2. Build an efficient machine with a performance like the one of a servo drive
3. Develop a control and communication concept for this drive

2. Integration of power electronics

In state-of-the-art concepts with B6-Bridge modules the losses of power semiconductors arise in a small area, as shown in Figure 3 a). So a significant increase in torque or power will cause thermal failures in the power modules after a short time, cp. [16]. If multiple power modules are used instead, the power losses can be distributed more evenly in the machine housing, and a lower peak temperature with the same power rating is possible.

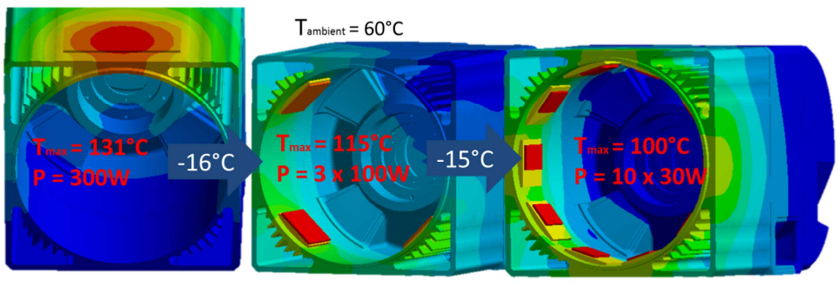

Figure 3: Integration concepts a) one B6-bridge, b) three half bridges c) ten H-bridge modules in the same machine housing.

Table 1: Simulation parameters of Figure 3

Heat contact conductance baseplate to adapter plate or housing	6000 W/m²K
Heat contact conductance adapter plate to housing	3000 W/m²K
Heat transfer coefficient on surface	2 W/m²K
Heat transfer coefficient in air channels	41 W/m²K
Material of the housing	aluminum alloy
Material of the adapter plates	copper alloy
Heat injection	whole baseplate

Mounting machine and power electronics in the same housing

To shrink the stator of an electric machine in the housing, the housing has to be cylindrical inside, but the baseplates of power semiconductors are flat. One effective way to solve the mounting problem is shown in [1] and [11]: Building up a cylindrical housing and milling a polygon at the end of the housing in which the power semiconductors can be mounted. But housings like this are difficult and expensive to produce.

A cheaper way of integration is shown in Figures 3 and 4. The power semiconductor modules are mounted on adapters which are placed in the cylindrical housing. The drawback is an additional thermal contact resistance. The reason is the gap between the adapter plate and the housing also shown in Figure 4. This gap creates an additional thermal interface between the adapter plate and the housing.

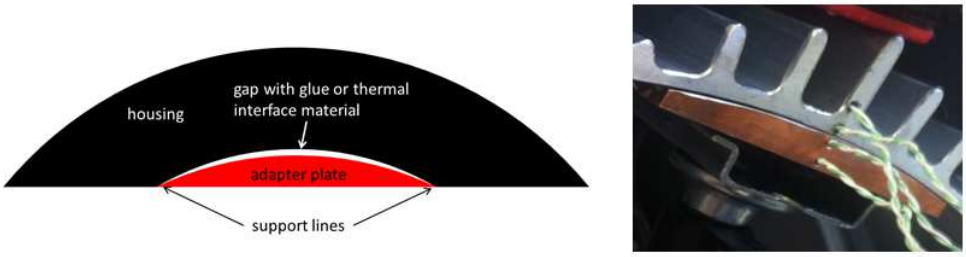

Figure 4: Sketch of the integration with adapter plates in a cylindrical housing on the left, measurement of the thermal contact conductance on the right

Because of mechanical reasons the gap is largest at the location, in which the highest heat flux density occurs. So reducing the gap is necessary but difficult, because:

1. If the adapter plate is glued in the housing, the gap is needed as adhesive gap.

2. If the adapter plate is mounted by screws or similar elements in the housing, it has to be secured, that even with manufacturing tolerances there will be two support lines, otherwise the adapter will toggle.

A second integration concept with a novel **"IHS"** was developed, the concept is shown in Figure 5, 6 and 7.

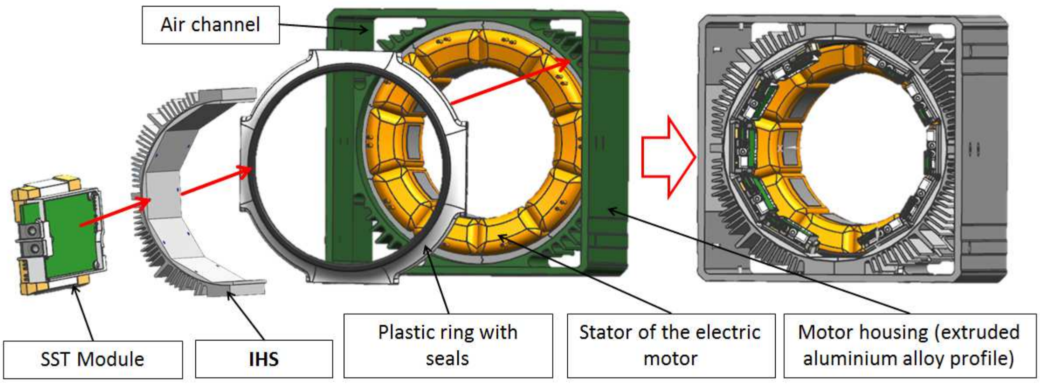

Figure 5: Integration concept of power semiconductors in a cylindrical machine housing with ten integrated power semiconductor systems and two "IHS"

The plastic ring guides the cooling air and provides a thermal insulation between the active part of the electric machine and the inlay-heat-sink. So the active part can be utilized higher without getting thermal problems of the electronics.
With air baffles shown in Figure 5 the cooling air is guided over the fins of the IHS. So there should be almost the same airspeed at all fins of the "IHS". As a result, the junction temperature of all integrated power semiconductors would be similar.

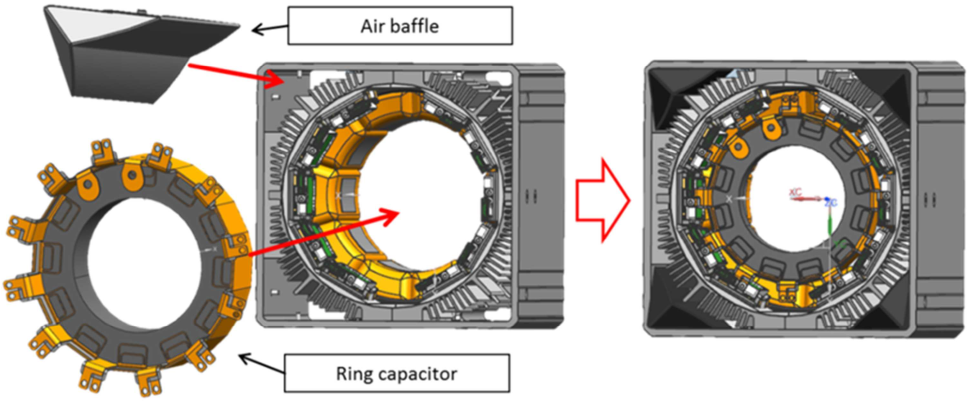

Figure 6: Housing with ring capacitor and four air baffles

The central control unit is integrated into the B-End-shield as shown in Figure 7, because this is the coolest part of the drive. The fan unit blows air into the air channels, electronic assemblies and windings are encapsulated, so IP 54 is reached.

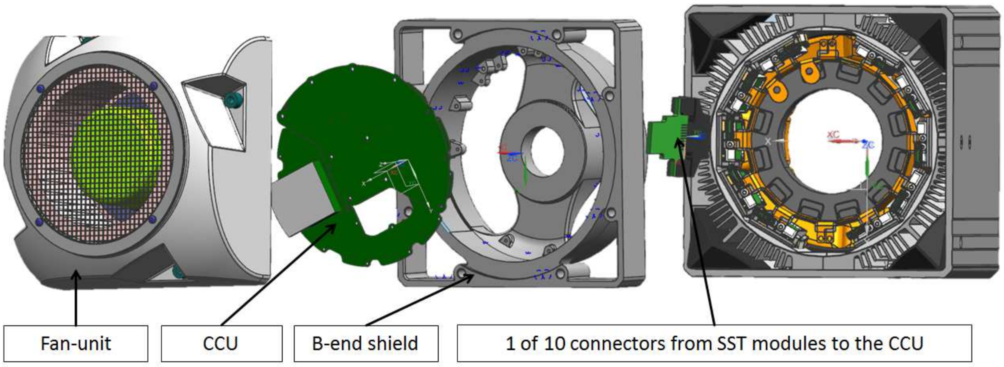

Figure 7: B-End shield with fan-unit and central control unit CCU with connections to the integrated power semiconductor systems

The fan can be adjusted by the CCU depending on the internal temperatures in order to save energy.

3. Thermal simulations

The most critical points in highly integrated drives are the power semiconductors. Due to the IHS the heat flow between the active part of the machine and the power semiconductors over the machine housing can be neglected in first approximation.

Air flow

Before the simulations can start the boundary conditions have to be determined. So the airspeed v over the IHS at different setting points of the fan was measured with a hothead probe, the measurement results can be seen in Figure 8.

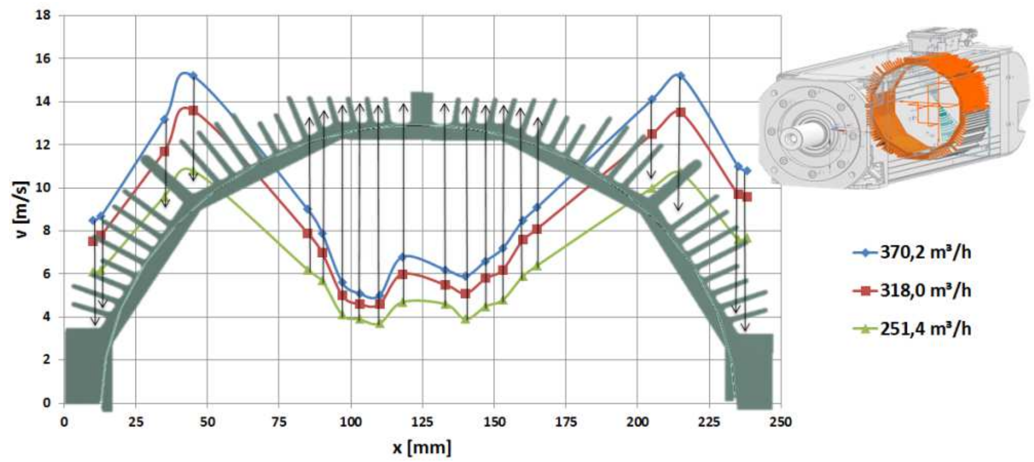

Figure 8: Measured air flow between the fins of the IHS

Heat transfer coefficient

Based on the measured air speed, the Reynolds number R_E can be calculated using the hydraulic diameter D_H and the kinematic viscosity of the air ν, cp. [10]:

$$D_H = \frac{4 * A}{U} \quad (1)$$

$$R_e = \frac{v \cdot D_H}{\nu} \quad (2)$$

In this case R_E is much higher than 10^4. So there will be a turbulent flow over the IHS and the Nusselt number N_u can be calculated using the formula of Gnielinski, cp. [6]:

$$N_u = \frac{\left(\frac{\xi}{8}\right) * R_e * P_r}{1 + 12{,}7 * \sqrt{\frac{\xi}{8}} * \left(P_r^{\frac{2}{3}} - 1\right)} * \left(1 + \frac{D_H}{L}\right)^{2/3} \quad (3)$$

$$\xi = (1{,}8 * Log(R_e) - 1{,}5)^{-2} \quad (4)$$

The temperature and pressure dependent Prandtl number P_r can be estimated 0,7 in this case. Now the thermal conductivity of the air λ the heat transfer coefficient α can be calculated:

$$\alpha = \frac{\lambda \cdot N_u}{D_H} \quad (5)$$

This had been done for every fin of the IHS, the result is shown in Figure 9:

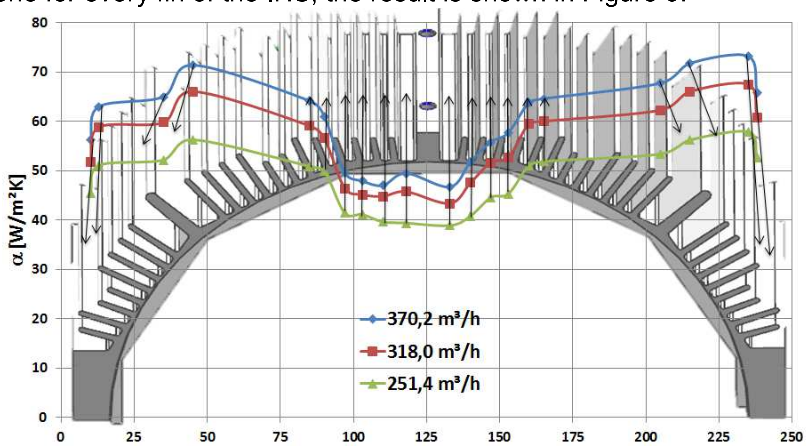

Figure 9: Calculated heat transfer coefficient at fins of the IHS

Thermal equivalent circuit diagram

With the results of Figure 9 a thermal FEM simulation had been done. Out of this a thermal equivalent circuit diagram has been extracted, which can be seen in Figure 10.

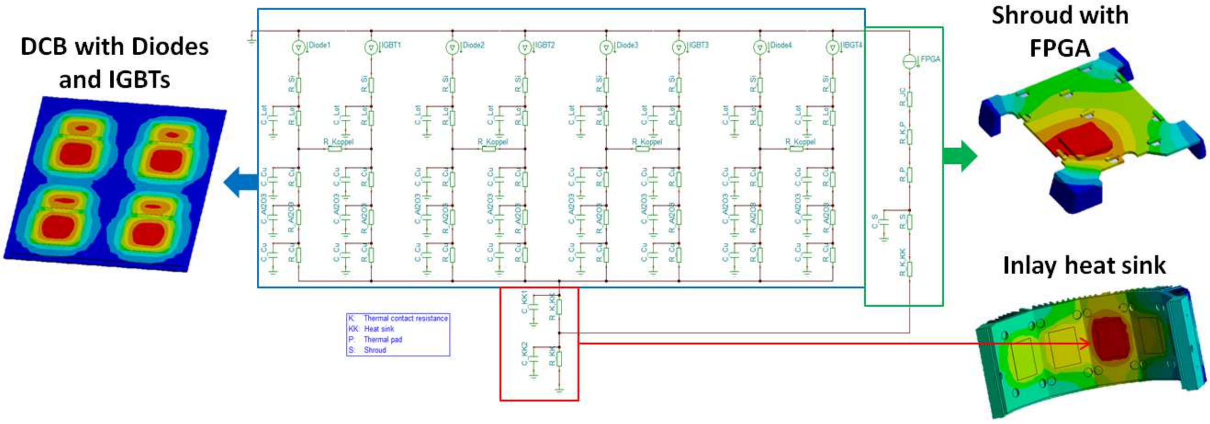

Figure 10: Thermal equivalent circuit diagram for one SST-module mounted on the IHS

As it can be seen in Figure 10, the SST-module in the middle of the IHS is critical; because of two reasons which can be seen in Figure 9:

1. In the middle the fins are shorter than in the corners.
2. The air speed is lower than in the corners and in consequence with a similar hydraulic diameter the heat transfer coefficient is also lower than in the corners.

So the nominal power of the drive is limited by the SST-Module in the middle of the IHS.

4. The multi-phase machine

To realize a lot of common parts, the drive uses the “SST concept” shown in [1] and [12]. In this concept each stator tooth has its own “SST-module”. A trade-off between higher numbers of teeth, which are better for distributing the power semiconductor losses, but increase the difficulty to manufacture, was considered. Given the design goals of the novel servo drive, the number of slots in a machine with two layer windings should not be much higher than twelve. With the formulas given in [7] it can be calculated if a permanent magnet synchronous machine with given number of phases, slots and rotor pole pairs is feasible. The feasible machines with twelve or less slots are shown in Figure 11:

Number of phases	Basic number of rotor polepairs: 1	2	3	4	5	6	7	8
3	3	6	9	3; 6; 9; 12	9; 12	9	12	12
4			8		8			
5		5	5	10		10		
6					12			
7			7	7				
8								
9				9	[illegible]			
10								
11				11	11	11	11	
12								

UMP

not feasible

feasible with given number of slots N

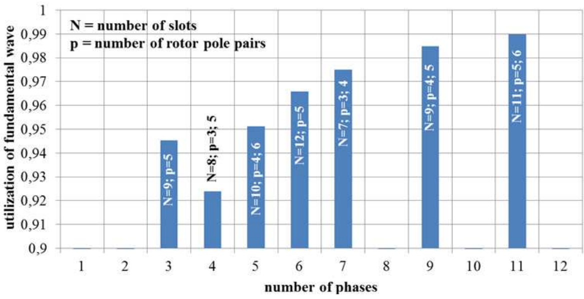

Figure 11: a) feasible multiphase machines b) corresponding maximum utilization of the fundamental wave, cp. [12]

As it can be seen in Figure 11 b) with a higher number of phases it is possible to increase the utilization of the fundamental wave air-gap flux compared to a three-phase machine. As a result, a higher efficiency of the machine can be reached. Inconveniently machines with an odd number of slots have unbalanced magnetic pull [8]. Due to this, a segmented five-phase permanent-magnet synchronous machine with six rotor pole pairs is realized, as shown in Figure 12.

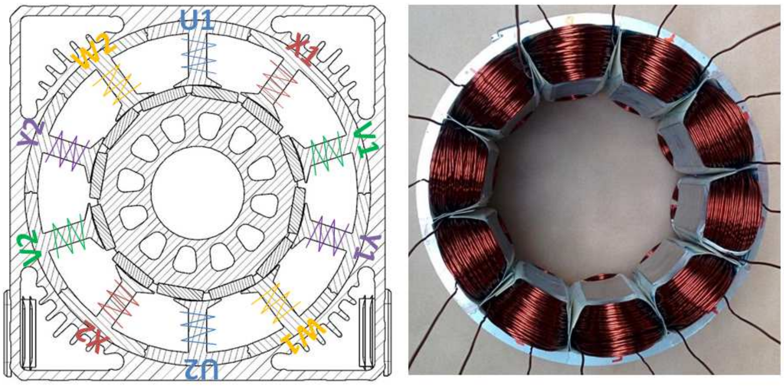

Figure 12: a) sketch of the five-phase machine b) stator of the first prototype cp. [12]

The rotor of the first prototype consists of 12 poles, which are realized as bread-loaf magnets. The design of the magnets is crucial for the overload capability of the machine, because if the stator currents are too high, the permanent magnets are irreversibly demagnetized. The aim is that at overload torque the magnetic flux in the air gap is twice as large as rated torque. So the height of the magnet must be tall enough, so that the magnet is not demagnetized at double rated torque. In a detailed analysis of the demagnetization with FEMAG DC, it can be noticed, that the highest demagnetization occurs at the upper corners of the magnet, where the magnet height is smaller. In order to reduce the maximum demagnetization, a so called shell shaped magnet, is proposed, where the magnet height is constant over the full magnet range and where the inner and outer edge is a circular arc with the same curvature radius as it can be seen in Figure 13. The difference in the shapes of the two magnets is made clear with a straight line at the bottom arc of the rotor axis.

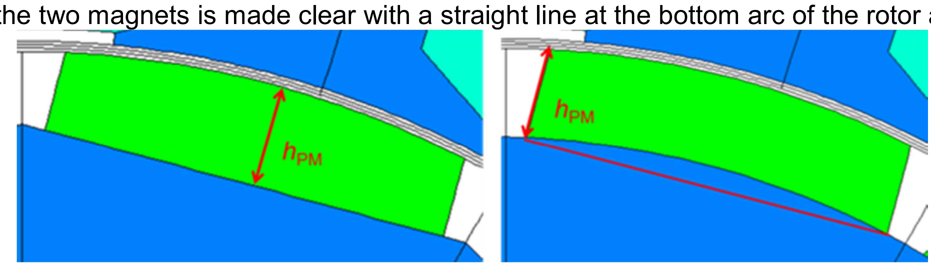

Figure 13: Cross-section of magnet shapes: bread-loaf-magnets (left) and shell-shaped magnets (right)

To compare the overload capability of the two magnet shapes the maximum demagnetization with the same magnet-volume at overload with double rated torque is calculated in FEMAG DC (Table 2). The height of the magnet is shown in Figure 13. As expected, the maximum demagnetization of the shell-shaped magnets is considerably below the demagnetization of the bread-loaf magnets. Regarding the similar power factors at overload, shell-shaped magnets are superior to bread-loaf-magnets in over-boost operation.

Table 2: Demagnetization of bread-loaf- and shell-shaped magnets at double rated torque

	Bread-loaf magnet	**Shell-shaped magnet**
Total magnet mass	2,162 kg	2,172 kg
Magnet height	8 mm	7,64 mm
Power factor	0,691	0.689
Max. demagnetization	-842,58 kA/m	-681,84 kA/m

5. Five phase vector control

The modular system, which will be described in chapter 6 with the “SST-concept”, enables the opportunity to set the current in each phase independently. A star-connection, which forces the sum of all currents and all voltages to zero, is not used in the given drive. The combination of a multiphase drive and the usage of a non-star-connected machine give additional degrees of freedom for the machine control strategy.

The goal is to extend the standard fundamental wave model to combine the controllability of a PMSM with sine-formed currents with the torque-density of a brushless DC (BLDC) machine with squared-formed currents. Furthermore the SIMULINK-models include position-dependent anisotropies as well as saturation effects.

An extended vector control for five-phase machines is developed. Therefore the well-known Clark-and-Park-Transformations are extended to a five-phase model. A transformation is used, which is a modification of the method presented in [9]. The currents are transformed into two rotation systems: one rotating with the fundamental frequency and the other one rotating with three times the fundamental frequency. To transform the five phase-currents to the rotating systems the following matrix is applied:

$$\begin{bmatrix} I_{d1} \\ I_{q1} \\ I_{d3} \\ I_{q3} \\ I_0 \end{bmatrix} = \frac{2}{5} * \begin{bmatrix} \cos(\varphi) & \cos\left(\varphi - \frac{2\pi}{5}\right) & \cos\left(\varphi - \frac{4\pi}{5}\right) & \cos\left(\varphi - \frac{6\pi}{5}\right) & \cos\left(\varphi - \frac{8\pi}{5}\right) \\ -\sin(\varphi) & -\sin\left(\varphi - \frac{2\pi}{5}\right) & -\sin\left(\varphi - \frac{4\pi}{5}\right) & -\sin\left(\varphi - \frac{6\pi}{5}\right) & -\sin\left(\varphi - \frac{2\pi}{5}\right) \\ \cos(3 * \varphi) & \cos\left(3\varphi - \frac{6\pi}{5}\right) & \cos\left(3\varphi - \frac{12\pi}{5}\right) & \cos\left(3\varphi - \frac{18\pi}{5}\right) & \cos\left(3\varphi - \frac{24\pi}{5}\right) \\ -\sin(3 * \varphi) & -\sin\left(3\varphi - \frac{6\pi}{5}\right) & -\sin\left(3\varphi - \frac{12\pi}{5}\right) & -\sin\left(3\varphi - \frac{18\pi}{5}\right) & -\sin\left(3\varphi - \frac{24\pi}{5}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} * \begin{bmatrix} I_u \\ I_v \\ I_w \\ I_x \\ I_y \end{bmatrix} \quad (6)$$

The benefit of this transformation is that constant currents I_{d1} or I_{q1} result in phase-currents oscillating with the fundamental electrical frequency and constant currents I_{d3} or I_{q3} result in phase-currents oscillating three times the electrical frequency. Therefore standard linear control algorithms can be used to inject a 3rd harmonic current in the phases. The benefit of the ability comes clear when the torque equation is regarded.

The vector of the flux-linkages for a symmetrical system is:

$$\underline{\Psi}(\varphi) = \left[\psi_c(\varphi) \quad \psi_c\left(\varphi - \frac{2\pi}{5}\right) \quad \psi_c\left(\varphi - \frac{4\pi}{5}\right) \quad \psi_c\left(\varphi - \frac{6\pi}{5}\right) \quad \psi_c\left(\varphi - \frac{8\pi}{5}\right)\right]^T \quad (7)$$

Where $\boldsymbol{\psi_c}$ is an even function periodic with $2 * \pi$ defined as follows:

$$\psi_c = \hat{\psi}_c * \overline{\psi}(\varphi) = \sum_{n=1:2}^{\infty} a_n * \cos(n * \varphi) \quad (8)$$

In equation (8) $\hat{\psi}_c$ is the maximum value of the flux-linkage and $\overline{\psi}(\varphi)$ is a normalized function. The coefficients a_n are the Fourier-values of the corresponding harmonic. The electrical torque T_{el} is the derivative of the magnetic Co-Energy with respect to the rotational angle φ_r:

$$T_{el} = \frac{\delta E_{co}}{\delta \varphi_r} = p * \frac{\delta \underline{\Psi}^T(\varphi)}{\delta \varphi} * \underline{I} \quad (9)$$

For simplification only harmonics up to the third order are evaluated. Inserting (8) in (7) and the following derivative as shown in (9) the transformed torque equation is:

$$T_{el} = \frac{5}{2} * p * \hat{\psi}_c * \begin{bmatrix} 0 \\ a_1 \\ 0 \\ 3 * a_3 \\ 0 \end{bmatrix}^T * \begin{bmatrix} I_{d1} \\ I_{q1} \\ I_{d3} \\ I_{q3} \\ I_0 \end{bmatrix} = \underline{K_{dq}^T} * \underline{I_{dq}} \quad (10)$$

In agreement with the fundamental wave model a constant current I_{q1} multiplied with the fundamental component of the flux linkage produces a constant torque. Equation XX shows the benefit of the extended transformation: a constant current I_{q3} multiplied with three times the third harmonic component of the flux linkage contributes positively to the torque as well. Depending on the ratio between the first and the third harmonic in the flux linkage a significant increase of the efficiency can be achieved. Furthermore the peak values of the voltages and currents are reduced, which enables a higher torque-density of the machine. The extended control scheme of the drive is shown in figure 14. Additional or modified parts, compared to the standard fundamental wave control, are highlighted in green.

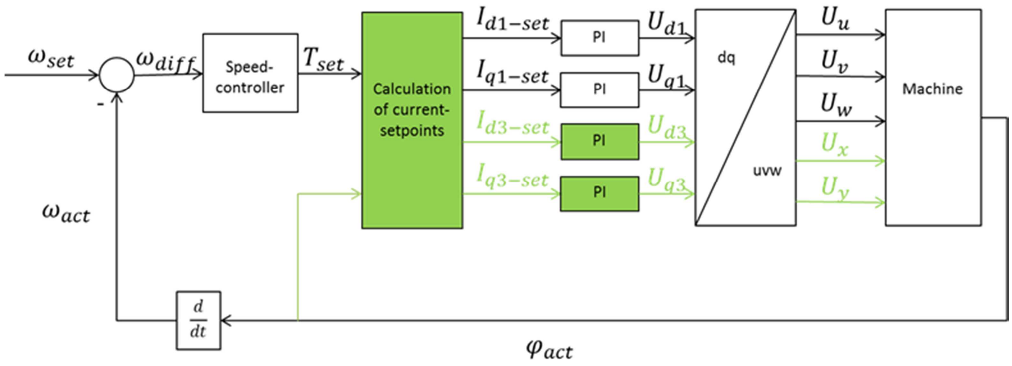

Figure 14: Block diagram of the five phase vector control

6. SST communication and power electronic concept

From an electronic systems perspective, the proposed novel servo drive consists of ten stator windings. Each ending is connected to a smart full bridge power semiconductor module (SST). On the other side, the power module is connected to the DC-link ring capacitor, as it can be seen in Figure 15.

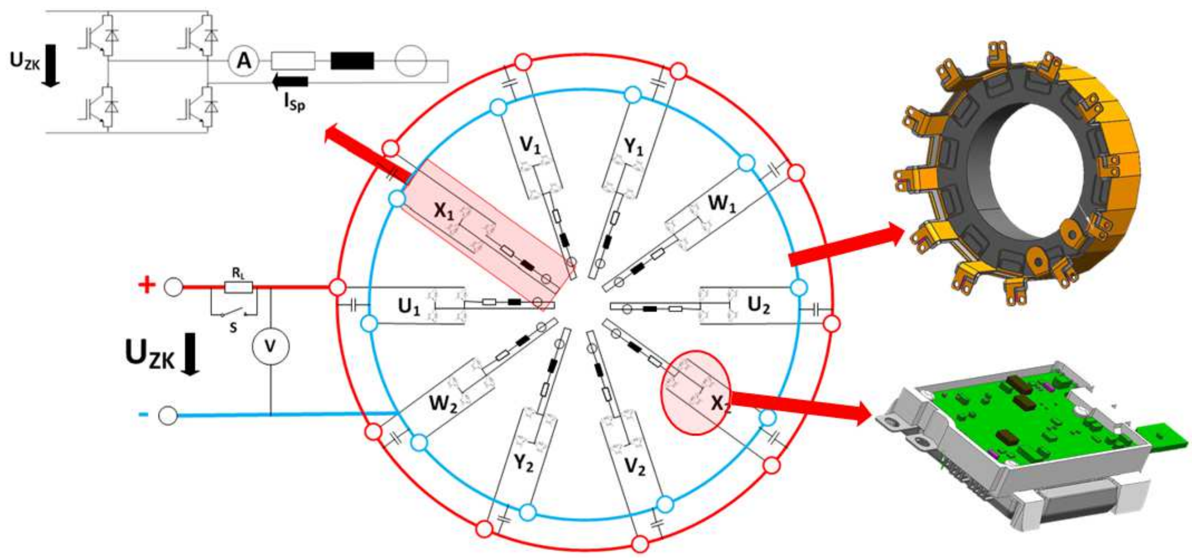

Figure 15: Power electronic topology with SST-module and ring capacitor

On top of the power module sits the SST- (smart stator tooth) board, which contains the gate drive circuitry, the current and temperature measurement ADCs, the control logic, along with the communication and auxiliaries required for the operation of a single power module. Each of these SST-boards connects through a LVDS interface to the CCU (central control unit) of the servo drive, which can be seen in Figure 15. Inside the CCU, the rotor angle is measured through the use of a low-cost, highly accurate giant magneto-resistive sensor IC, similar as it can be seen in [11], and the reference currents are computed based on the five phase vector control described in Section 4.

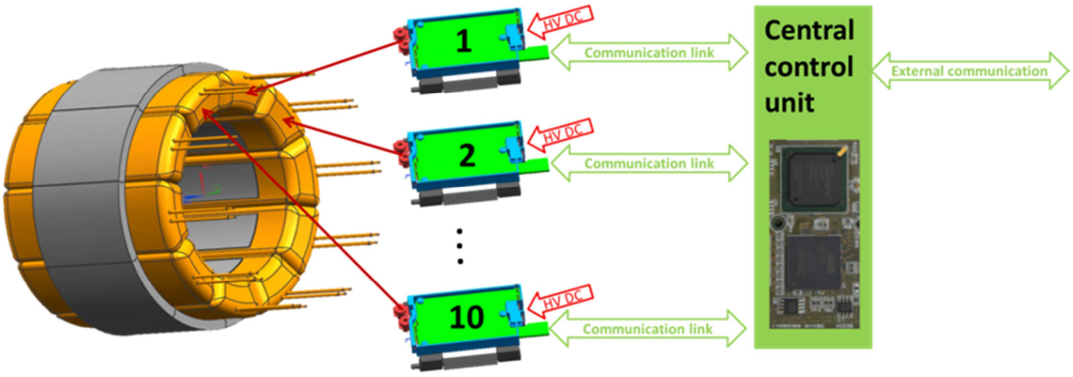

Figure 16: Power and communication concept with a SST-module for each stator coil and a CCU (central control unit)

In addition to the advantages that the SST partitioning of the motor inverter cooling concept brings, the use of a multiphase approach also reduces the required sizing of the power semiconductors. When compared to the state of the art B6 three-phase, two-level topologies, the required current per phase is reduced.

The reduced current of the smart stator tooth approach has major impacts, if the overall system is taken into account:

a) Due to the reduced phase current, a lower $\frac{di}{dt}$ is possible for a constant rise and fall time in a switching event.
b) The higher level of integration of the power semiconductors enables lower parasitic inductances L_{PARA}. In combination with a), this will reduce the transient overvoltages in the power module.
c) As the nominal threshold of 600V and 100A is not breached for the application, gate drive circuits which use Silicon-on-Insulator (SOI) technology, level-shifting and bootstrap configurations are possible. A gate drive approach like the one depicted in Figure 17 avoids additional isolated high-side gate driver supplies. As consequence, the total cost for the inverter system is reduced.

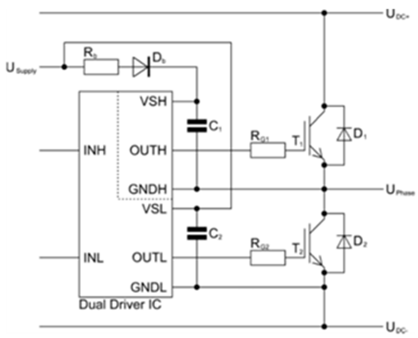

Figure 17: Non-isolated, bootstrap gate drive configuration

d) Another advantage related to point c) is the use of integrated, low-cost current sensing approaches to phase current. In the novel servo drive proposed, a power module integrated shunt resistor is used to measure the phase current for each smart stator tooth.

Due to the modular nature of the SST approach, especially the lack of a star-connected neutral point, some new control features are now possible. An important one is the fault tolerant capability of the multiphase machine. Depending on the type of failure, it is now possible to detect the fault and to continue operation in limp-mode. This is possible because of the additional sensors and the communication between the SST modules and the central control board.

7. Prototypes and benchmark

Prototypes

The first prototype was built up from November 2014 to February 2015 with the values given in Table 3. The power and control-electronic was built up on a trolley. The trolley with the motor can be seen in Figure 18.

Table 3: Values of the prototypes

Prototype	First	Second
Rated power	7,5 kW	22 kW
Rated torque	120 Nm	350 Nm
Rated speed	600 rpm	600 rpm
Overload capacity for 60s	Twice	Twice
Power electronic	On a trolley	Integrated
Cooling	Forced air by centrifugal fan	Forced air by adjustable centrifugal fan
Control	Five phase vector control	Five phase vector control
Rotor position	Incremental encoder	Infineon TLE5012 rotor position chip
Stator outer diameter	240 mm	240 mm
Rotor outer diameter	139 mm	140 mm
Length of the laminated core	100 mm	300 mm
Magnets	Loaf magnets	Shell magnets
Target application	-	Automated storage & retrieval systems, pitch control of wind turbines
Length (without shaft)	800 mm	800 mm
Width	260 mm	260 mm
Height (without terminal box)	260 mm	260 mm
Completion	February 2015	Planned for December 2015

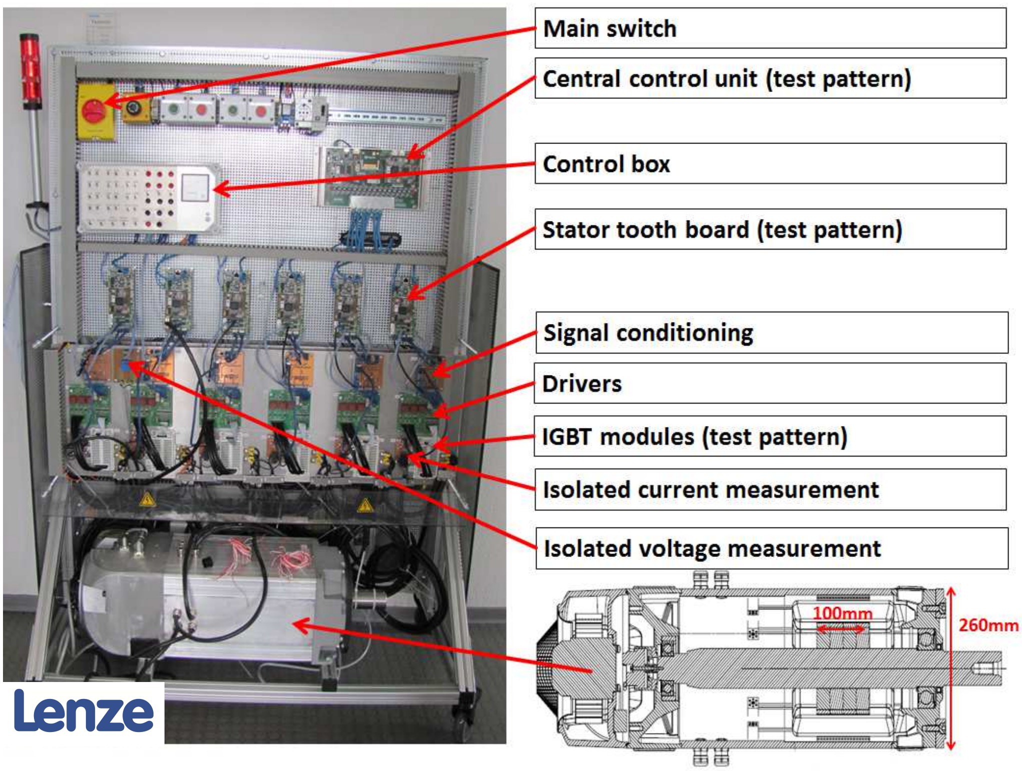

Figure 18: Trolley with multiphase Inverter and first Prototype of the electric machine

Benchmark
In Figure 16 the power density of the prototype is compared with the power density of compact servo drives [13], torque motors [14] and servo motors [15]. The compared compact servo drives, and the compared stand-alone servo motors have a rated speed that is approximately two to ten times higher than the rated speed of the second prototype. Because the volume of an electric machine is proportional to its torque, it is not surprising that the power density is not as high as by the comparable compact and stand-alone servo drives. But the power density is in the range of torque motors with no power electronic inside and a comparable[3] rated speed.

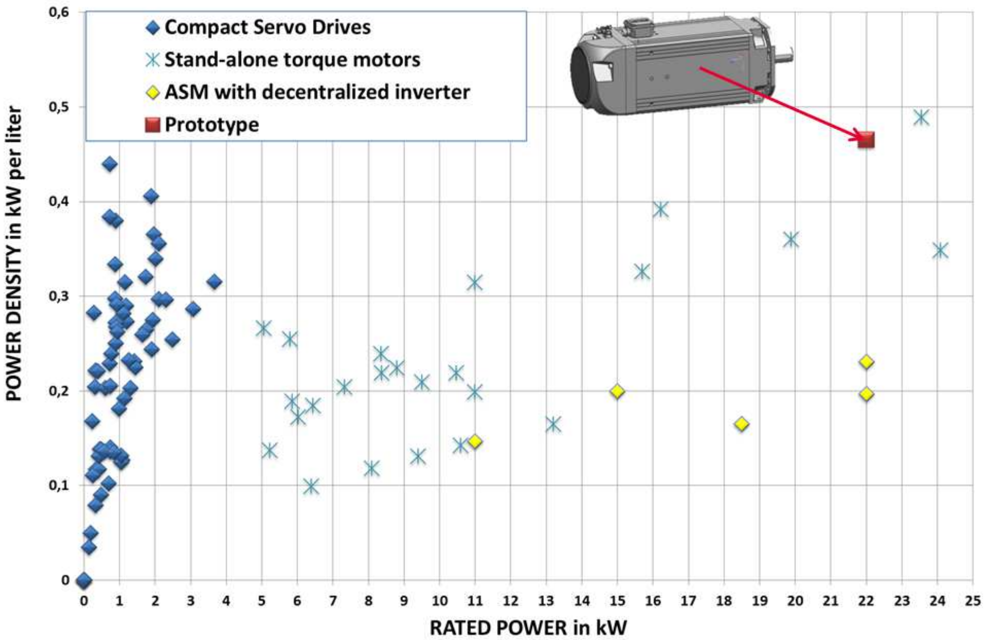

Figure 19: Power density of compact servo drives, the second prototype, torque motors and servo motors

It is useful to compare inverters by their nominal output power and servo motors by their nominal torque. So a drive with integrated inverter should also be compared by its nominal torque, this comparison is shown in Figure 17.

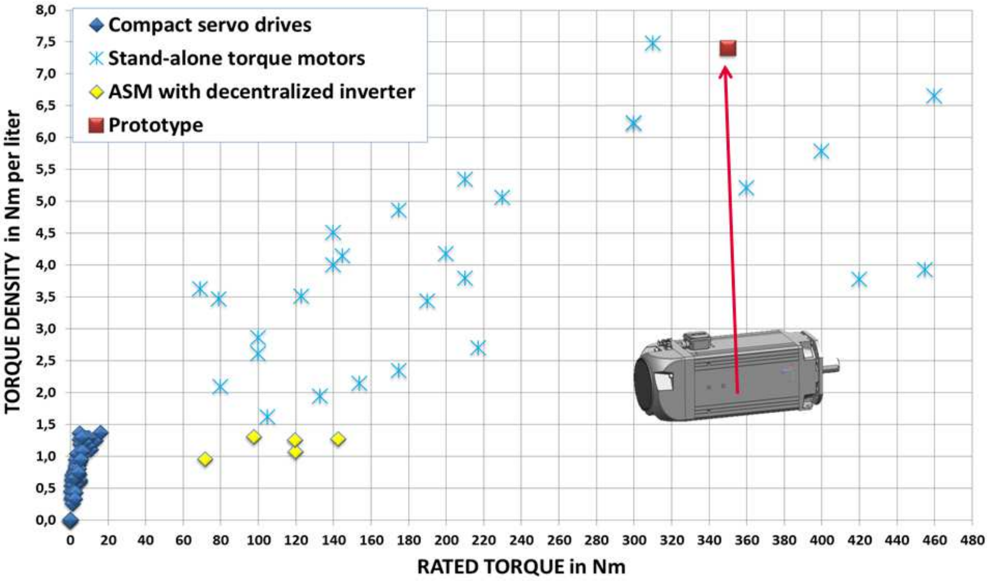

Figure 20: Torque density of compact servo drives, the second prototype, torque motors and servo motors

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[3] The listed torque motors have rated speeds between 500 and 1000 rpm

7. Conclusion

In the concept shown are four main starting points to increase energy efficiency:

1. A higher fundamental wave air-gap flux compared to a three-phase machine[4]
2. Using the third harmonics for effective torque generation
3. Energy exchange via DC-Bus
4. Setting the switching frequency depending on the rotating angel, independent for every phase.

Due to the higher rated power compared to state-of-the-art compact servo drives, the system can be used as an alternative to asynchronous machines with decentralized inverter, which have an inferior efficiency. In this context the costs for production and installation have to be considered. Therefore the shown concept has many starting points to save costs, for example:

1. Effective distributed cooling due to the novel IHS, so that smaller power semiconductors can be used
2. Rotor position detection by chip on central controlling board and magnet on the end of the shaft, so no expensive encoder or resolver and no cables are necessary
3. A lot of common parts
4. Connecting all drives in one machine via DC- and Data-bus[5]
5. Low-cost current sensing with power-module integrated shunt resistor

List of symbols and units

Symbol	Designation	Unit	Symbol	Designation	Unit
A	Flow cross-section	m²	$\boldsymbol{\alpha}$	Heat transfer coefficient	W/(m²K)
U	Wetted perimeter	m	$\boldsymbol{\lambda}$	Thermal conductivity of air	W/(m*K)
D_H	Hydraulic diameter	m	$\boldsymbol{\nu}$	Kinematic viscosity of air	kg/(m*s)
N_u	Nusselt number	-	$\boldsymbol{\varphi}$	Rotational angel	rad
R_e	Reynolds number	-	$\boldsymbol{\psi}$	Flux linkage	Vs
L	Length	m			
P_r	Prandtl number	-			
T	Torque	Nm			
$\boldsymbol{v}$	Air-speed	m/s			
$\boldsymbol{I}$	Current	A			
U_{ZK}	DC link voltage	V			

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Energy Management

Implementation of standard ISO 50001 on Eletrobras companies

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Abstract:

Eletrobras has been involved in the development of ISO 50001 since its beginning, maintaining its leading position in energy efficiency activities in Brazil. The knowledge gained in this process and the experience in conducting energy efficiency projects under the National Electrical Energy Conservation Program – Procel throughout the last 29 years, built the capacity of Eletrobras team to implement this Standard in their subsidiaries companies. At present, four companies are working on it: Eletrobras Chesf, Eletronuclear, Eletronorte and Itaipu. In the development of energy policy, a requirement of the standard, it was noted the need for adaptation of the term. As big energy company acting in generation, transmission and distribution, an energy policy covers issues that go far beyond the commitment to its management system required by the Standard. The term is then changed to energy statement, and establishes the company's commitment to adopt the requirements of the standard to achieve improved energy performance. The initial scope defined for the implementation of the Standard in the companies, was the buildings, basically air conditioning systems and lighting. The decision is based on the recommendation to start with a smaller part of the system, as a pilot phase, which allows the soft learning methodology and the creation of culture. This paper introduces the importance of ISO 50.001 by showing the state of implementation of ISO 50001 in the world and in Brazil, briefly comparing the distinct levels of implementation in different countries and presents the progress of implementation activities of the this standard in Eletrobras companies as well as its difficulties and lessons learned that will be helpful in future implementation in the productive processes.

1 – Introduction

This paper aims to show the deployment process of ISO 50001 in four companies of Eletrobras. As this implementation is recent, starting effectively in 2014, it is still not possible to be presented quantitative results in this document. However, as will be discussed by the leading role that Eletrobras has been playing since the development of the Standard, and now in its implementation in the Brazilian market, the authors of this document believe that the experience gained so far already becomes valid to be shared in the international scientific community. Within about a year, a report will be written, this time focused on presenting the achieved energy savings of ongoing implementation.

2 – Context

Before discussing the deployment process itself, it is important to contextualize the role of Eletrobras in the development process of ISO 50001.

2.1 - The Eletrobras

The Eletrobras is a publicly traded company controlled by the Brazilian government, which operates in the areas of generation, transmission and distribution of electricity. With a focus on profitability, competitiveness, integration and sustainability, the company leads a system consisting of six generation and transmission subsidiary companies, six distribution companies, the Electric Power Research Center (Eletrobras Cepel) and Eletrobas Participações S.A. (Eletrobras Eletropar) create to participate in other associated businesses and is also holder of 50% of the capital stock of Itaipu Binacional. The other half of Itaipu belongs to the government of Paraguay.

The generating capacity of Eletrobras, including half the power of Itaipu belonging to Brazil, is 42,987 MW, corresponding to 34% of the energy produced in Brazil. The company also owns 50% of Brazilian transmission lines.

Besides the above business activities, Eletrobras also supports government strategic programs, such as the program that fosters alternative electric power sources (Proinfa), the Rural Electrification Program and the National Program for Electric Power Conservation (Procel). The latter is of particular interest in this paper because contextualizes the experience of Eletrobras in the area of energy efficiency.

2.2 - Eletrobras Expertise in Energy Efficiency

Procel promotes electricity rationalization to fight waste and reduce costs and sector investments. Created by the Brazilian federal government in 1985, this project has been performed by Eletrobras, with resources of the company, Global Reversion Reserve (RGR) and international entities. Procel operates in nine sectoral programs, each focused on energy efficiency in a separate segment, such as the industrial sector, construction and home appliance equipment, among others.The National Electrical Energy Conservation Program (Procel).

Only in 2014, Eletrobras Procel contributed to a saving of 10.5 million MWh, equivalent to 2% of all electricity consumption in Brazil that year. Environmental impacts were also significant: emissions of greenhouse gases avoided by cost savings in 2014 by Eletrobras Procel reached 1.047 million tons of CO2 equivalent.

Thus, the experience accumulated by Eletrobras since 1985 in developing actions and energy efficiency projects allowed the acquisition and improvement of skills in this area, making it possible to promote energy efficiency within the Eletrobras companies, through the Integrated Committee of Energy Efficiency Eletrobras system - CIEESE, Committee promotes energy efficiency activities in all subsidiaries companies.

2.3 - Role of Eletrobras in the development of ISO 50001

In March 2007, the United Nations Industrial Development Organization started the dialogue on the development of the standard in a meeting that included the representation of developing countries, the Central Secretariat of the International Organization for Standardization (ISO), and countries that already use national standards energy management. As a result of that meeting, a request was submitted to the ISO Central Secretariat to consider the creation of an energy management standard with international operations.

The ISO 50001 standard was established with a generic framework for all kind and size of organizations, including many energy related aspects as equipment and service purchase. To provide compatibility and integration opportunities with other management systems the Standard promote the same principles of continuous improvement management system and the use of the Plan, Develop, Check and Act (PDCA) used in ISO 9001 and ISO 14001. The text of the Standard was made by a committee composed of 35 participating countries and 5 observer countries, in addition to representative organizations UNIDO and World Energy Council (WEC). After the publication of the Standard showed a clear need to develop standards and support the committee began working in the construction of five standards that today make up the ISO 50000 family.

Brazil, through Brazilian Standards Association – ABNT, shares with ANSI, American National Satandards Institute, the ISO Committee secretariat. Eletrobras is an active delegate of national committee and has been involved in the construction of the standard from the beginning, helping developing and promoting it, maintaining its leading position in energy efficiency activities in Brazil and contributing to this important event in the area, certainly being one of the largest international initiatives in this field in recent years.

3 – The Implementation Process of ISO 50001 in Eletrobras Companies

The knowledge gained in the standard construction work and experience in conducting energy efficiency projects of Procel allowed Eletrobras form a team able to lead the implementation of the standard in their companies. Currently, four companies are with the work in progress: Eletrobras Chesf, Eletrobras Eletronuclear, Eletrobras Eletronorte and Itaipu Binational. The choice of these four companies was done based on their interest, data collection and capability to maintain and improve ISO 50001 use, doing so these cases will be known as the first hydroelectric plant, thermonuclear power plant and power substation certified by this Standard in Brazil.

The methodology developed for this activity basically consists of a visit to the plant or building where the company intends to implement the Standard. On this visit the team develops, along with the team of the company itself the following activities:

- Presentation to the top management, clarifying the purpose and benefits of the Standard. It is also the opportunity to give awareness to them of the essential need of their commitment to support the implementation process;
- Explanatory course about the Standard for the team that will work directly in the implementation process;
- Technical visit to the facilities to subsidize the planning;
- Initial discussion of the definitions, planning, identification of resource requirements and schedule suggestion.

After this the companies start developing and the planning activities, making use their own skills to establish an energy management system suitable to their reality. The team Eletrobras supports throughout the all implementation phases.

In the development of energy policy, required by the Standard, it was noted the need for adaptation of the term. As big energy company acting in generation, transmission and distribution, an energy policy covers issues that go far beyond the commitment to its energy consumption management. The term is then changed to energy statement, and establishes the company's commitment to adopt the requirements of the standard to achieve improved energy performance. The initial scope defined for the implementation of the Standard in the companies, was the buildings, basically air conditioning systems and lighting. The decision is based on the recommendation to start with a smaller part of the system, as a pilot phase, which allows the soft learning methodology and the creation of culture.

Experience has shown that when the company has already implemented other management system, especially an ISO standard, ISO 50001 implementation process is significantly simplified, because besides the ease of understanding of the staff involved, the common elements of these management standards allow integrating new activities within an existing structure.

3.1 - Implementation of ISO 50001 in the Itaipu Binational

Itaipu is a binational entity and has its financial basis and provision of electricity services defined in a treaty between Brazil and Paraguay that guarantees absolute equality of rights and obligations between the two countries. The Itaipu is the world leader in the production of clean and renewable energy, producing more than 2.2 billion MWh since the beginning of its operation in 1984. With 20 generating units and 14,000 MW of installed capacity, provides about 17% of the energy consumed in Brazil and 75% in Paraguay. In 2014, Itaipu produced a total of about 87.8 million MWh. Its highest annual production was established in 2013, with approximately 98.6 million MWh.

Figure 1 - Itaipu Hydroelectric Power Plant.

The implementation of the standard was started in September 2014, when it made a presentation on the ISO 50001 for employees of Itaipu. Still in 2014 were held planning meetings, and set the scope and boundary for applying the Standard: Indoor Lighting and cooling system of two administrative buildings, part of the plant's external lighting and the treatment and distribution water system of the company. At these meetings it was decided that the energy performance indicator is the value of the annual energy consumption (kWh/year). This indicator even being simple to collect it should be carefully followed and energy baseline conditions detailed described as many variables can affect the final results .

Energy audits of company facilities in the scope and boundaries chosen are being now performed to know all the relevant variables for the implementation, that's basic condition for a consistent energy baseline. After this work in progress, it will be possible to estimate the exact amount of energy to be saved with the planned actions.

Company certification should be occurring in the second half of 2015.

3.2 - Implementation of ISO 50001 in the Eletronorte

Eletronorte, a subsidiary of Eletrobras, is a public utility company electricity. Founded in 1973 with headquarters in the capital of Brazil, generates and supplies electricity to nine states of Brazil, and sell electricity to buyers in other regions of Brazil. More than 15 million people of the approximately 25 million living in the Amazon region of Brazil benefit from the electricity produced by the Eletronorte in its four hydroelectric – Tucuruí, the largest genuinely Brazilian plant and the fourth in the world, Coaracy Nunes, Samuel and Curuá-Una - and thermoelectric parks. The total installed capacity is about 9.3 MW and transmission systems have over 9800 km of lines.

Figure 2 - Tucuruí Hydroelectric Power Plant.

The ISO 50001 implementation process was started in the first half of 2014 and the chosen location was the plant of Tucuruí. The following steps for the development of implementation of work were established:

- Energy Policy Settings, Management Representative, team energy management, scope, boundaries and schedule;
- Team Training;
- Energy Planning consisting of: Survey of energy use and consumption in the past and the present, identification of relevant variables affecting significant energy use, calculation of the energy performance, energy use and consumption analysis, identifying areas significant energy use and consumption, identification of opportunities to improve energy performance, setting goals, targets and indicators for the Energy Baseline, development and approval of action plans;
- Internal audit;
- Certification.
- Such as ISO 50,001 is being implemented, there are still no quantitative results. However, the following actions have been taken:
- Definitions of Energy Policy, Management Representative, team energy management, scope, boundaries and schedule;
- Energy demand survey of Training Centers that make up a border;
- Start the process for creation of the ISO 50001 page on the intranet;
- Start installing information boards near the main entrance of the buildings that make up the boundaries, with information on the monthly consumption of the building, the annual target and the current stage of consumption in relation to the goal;

- Preparation of Internal Communications containing procedures for use of Lighting System, Air Conditioning and Personal Computers to all employees and contractors, who will monitor compliance with the decisions.

Company certification should be occurring in the first half of 2015.

3.3 - Implementation of ISO 50001 in the Chesf

The Hydroelectric Company of San Francisco - Chesf, founded in 1945, operates in the generation and transmission of energy market. It owns currently an installed generation capacity of about 10,000 MW, as well as having a transmission network of over 19,000 km. Chesf is committed to respect nature and improve the quality of life of people and communities who are in the area of influence of its projects. In this context, Chesf is also acting within its own facilities in the area of energy efficiency, for better use of energy resources and reduce operational cost.

The starting point of implementation was the definition of boundaries in January 2014. The facilities defined as those that receive the ISO 50001 pilot project were Substation Messias and the Hydroelectric Power Plant Sobradinho. The Messias substation, located in the state of Alagoas, northeastern Brazil, is the step-down type, with voltage of 500 kV. The Sobradinho plant is located in the state of Bahia, northeastern Brazil and has six generating units with unit capacity of 175,050 kW, totaling 1,050,300 kW.

Figure 3 – Sobradinho Hydroelectric Power Plant.

The boundaries in Messias substation for implementation is substation auxiliary services and the scope are lighting and cooling systems , using the ISO 9001routines, already implemented in the CHESF, as base to be adapted to the creation of the Energy Management System to ISO 50001. At the present time, is being carried out an inventory of equipment used in refrigeration and lighting systems as well as the beginning of the action plan, the definition of strategies measurement of consumption, the energy performance indicators and baseline for the future of the energy management system to be implemented.

The Power Plant Sobradinho were visited in November 2014. On this visit were inspected the facilities of the plant and administrative buildings, focusing on the verification of the distribution of electrical circuits (to facilitate the measurement of consumption in the future), in defining indicators and Line basis. It was defined as the Project scope: Lighting, Air-conditioning, pumping system and air compressors for general use.

Company certification should be occurring in the second half of 2015.

3.4 - Implementation of ISO 50001 in the Eletronuclear

Eletronuclear was established in 1997 to operate and build nuclear power plants in Brazil. Subsidiary of Eletrobras, is responsible for the generation of approximately 3% of the electricity consumed in Brazil what means or, for example, more than 30% of the electricity consumed in the state of Rio de Janeiro. There are currently operating the Angra 1 plant, with capacity to generate 640 MW and Angra 2, 1,350 MW. Angra 3, expected to go into operation in 2018, is expected to generate 1,405 MW more.

Figure 4 - Eletronuclear Thermonuclear Power Plant.

Eletronuclear had its first activity toward ISO 50001 implemenation in 2012, when a presentation was showed to employees. After this, the possible boundaries and scope were discussed as well as the methodology to carry out planning, energy review, indicators and baseline. A big operational change stopped the activities.

The activities returned in the second half of 2014. There was a new visit to the plant when it was trained the technicians and managers who will operate the management system and drew up an action plan for the next steps. On this occasion it was also discussed matters relating to the scope, indicators, baseline and other requirements that must be followed. The chosen scope was the Electricity Consumption of Advanced Training Center with Simulator. The selected border was the building where does this training center. The next step is the appointment of top management representative who will head the energy management team, and so, to begin activities.

The implementation of the Standard requires considering the organization's operating schedule. In the case of a production process, the implementation must be adapted to the flow of production and scheduled maintenance shutdowns. In the case of a nuclear power plant, planning must be even more careful. In some cases, a simple change as an exchange lamp specification must go through a review and approval of federal agencies that legislate on nuclear safety. Thus, the process can be time consuming and require detailed documentation. For these reasons, the certification in Eletronuclear should be occurring only in 2016.

4 – Conclusion

As noted herein, the deployment process of the standard in the Eletrobras companies is in progress and the results of certified energy reduction indicators were not discussed here. In the table 1 is shown briefly the current state of implementation of ISO 50001, for each of the four companies already discussed.

Table 1 - Summary Status of Implementation of the ISO Standard for Eletrobras Companies.

Company	Current Status	Certification Intent
Itaipu Binational	Scope and boundary: chosen. Energy Review in progress.	2nd Semester 2015.
Eletronorte	Scope and boundary: chosen. Energy Review in advanced stage.	1st Semester 2015.
Chesf	Scope and boundary: chosen. Energy Review in progress.	2nd Semester 2015.
Eletronuclear	Scope and boundary: chosen. Energy review starting.	1st Semester 2016.

For a summary of understanding the current state of implementation was demonstrated only discussing the progress of work on the choice of scope, boundary and development of energy review. It is noteworthy that as discussed in this article, other documents such as energy policy, measurement plan, among others, are already in various stages of development by companies.

Although it is on the way of implementation of the standard, some points can already be highlighted:

1. The top management commitment to the implementation of the standard is crucial and really makes the difference;

2. The availability of human resources on an exclusive basis by companies at the beginning of implementation is extremely importance for full understanding of energy flow and organization's barriers;

3. Previous experience in implementation of other ISO standards facilitates the process of implementing a new standard;

4. The implementation of ISO 50001 is also facilitated when organizations already have and develop their own energy efficiency programs, even if not yet standardized. Most of the activities performed in these initiatives are common to ISO 50001 and it can be said that these organizations have the work started for the implementation of the Standard, being only necessary to structure these activities within the standard templates to request certification or make a self-declaration.

The practice of implementation of pilot projects, like this what is happening with the implementation of ISO 50001, is a common practice within the Eletrobras. At first, though the immediate effect within the total consumption is small, the trend is the company's certification as a whole, with all significant processes as a certification object.

As discussed in this article, even though it was not quantitative results, the acquired managerial experience so far is already applicable, since the implementation of ISO 50001 in Brazil is still incipient. It is noticed that the implementation of ISO 50001 has brought many indirect benefits, such as better understanding of energy flow of the companies and their current energy performance, more attention the issue of reducing operating costs and energy efficiency Since data related to energy performance being known for the implementation of ISO 50001, the largest and most effective plans can be made at the end of this process. In addition, the implementation of the standard brought up discussions on the need for natural resource management and cost reduction, as well as its relation to corporate sustainability.

The expectation is that in the short term already have the first results of the implementations that are currently under way. With this data, we intend to make a full assessment of the direct and indirect benefits of the adoption of ISO 50001 in Eletrobras companies, as well as showing all the difficulties encountered.

EASY- Lessons learned from four years of the Swiss EASY audit and incentive program

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Impact Energy Inc.

Abstract

Between 2010 and 2014 the Swiss financial incentive program EASY encouraged Swiss industrial factories to implement electric energy efficiency improvements of electric motor systems. During the EASY program period, 4142 motors have been analysed regarding their age, operating hours, size and the use of a variable frequency drive (VFD). 104 motor systems have been measured on site and analysed in detail. Based on these results, new knowledge about the current state of electric motors in Switzerland has been gained. The optimisation of all motor systems led to a total energy saving of 73.7 GWh calculated for the lifetime of the newly installed equipment (10-20 years, depending on their size, based on [1]).

Background

In 2010, the audit and financial incentive program EASY (Efficiency for motor systems, www.topmotors.ch/easy) was started, led by the Swiss Agency for Efficient Energy Use (S.A.F.E.). EASY supported companies with an annual electric energy consumption of more than 10 GWh, aiming to improve the efficiency of their electric motor systems. The program was financed with 1 million CHF for four years through public funds, from a surcharge on the electricity tariff. The target was to improve electric motor systems in industry and save a total of 69.2 GWh over the lifetime of the newly installed equipment. During the EASY program, the Motor-Systems-Check methodology, developed by Topmotors in 2010, was applied and refined. The Motor-Systems-Check [2] is a 4-step audit method for analysing and optimising motor driven processes in industry (see Figure 1). The focus of this method is always on the motor system and not only on the motor itself.

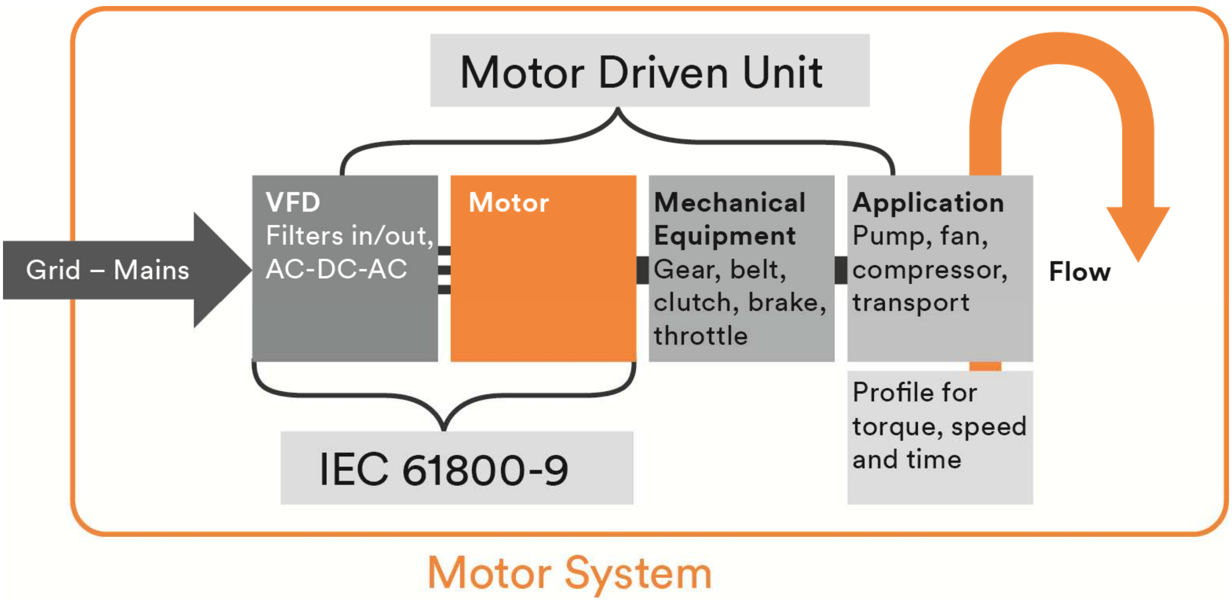

Figure 1 Definition of Motor System. Source: EMSA, 2014.

A motor system means the whole chain of components from power supply to the output of the application. The Motor-Systems-Check regards the efficiency of every single element and delivers not a single replacement with more efficient identical products; it resizes the components, application and the output flow if possible. The system integration of modern and properly-sized elements enables much higher savings compared a one-to-one replacement of components with more efficient products.

Motor-Systems-Check

The Motor-Systems-Check is composed of 4 steps to detect and harness the efficiency potential of electric motor systems:

Step 1 Determines the total efficiency potential of a company by improving all electric motors.

Step 2 Indicates the motor systems with the biggest savings potential of all motors included in the analysis, depending on their age, size, operating hours, etc.

Step 3 Creates a standard test report based on the on-site measurement with load factor, savings, costs, payback, etc.

Step 4 Implementation.

Every step is supported by software tools which help to calculate the single saving potentials on the basis of the current state or by default values based on Topmotors' estimates and experience. Every step was subsidised with an incentive between 10% and 100% (see Figure 2).

Sequence	Measures	Subsidy	**Software tool**
Step 1	Efficiency potential	100%	SOTEA
Step 2	Motor list	75%*	ILI$^+$
Step 3	On-site test	50%	Standard Test Report (STR)
Step 4	Implementation	10%	Motor Systems Tool

Figure 2 **The four steps of the Motor-Systems-Check and associated subsidies. Source: S.A.F.E., 2011.**

Results

Step 1: Efficiency potential

In the framework of Topmotors and EASY, 25 companies did the "efficiency potential" check using the software tool SOTEA[1]. The evaluation of these 25 SOTEA results was used to estimate the share of electric motors within the total electric energy consumption of these companies. The share was with 87.8% even higher than expected (see Figure 3). This is another proof of the importance of efficient electric motor systems.

Some of the companies left the program after each step either because of a small potential or because of technical, political or economic reasons.

[1] Available for download at www.topmotors.ch/Download/

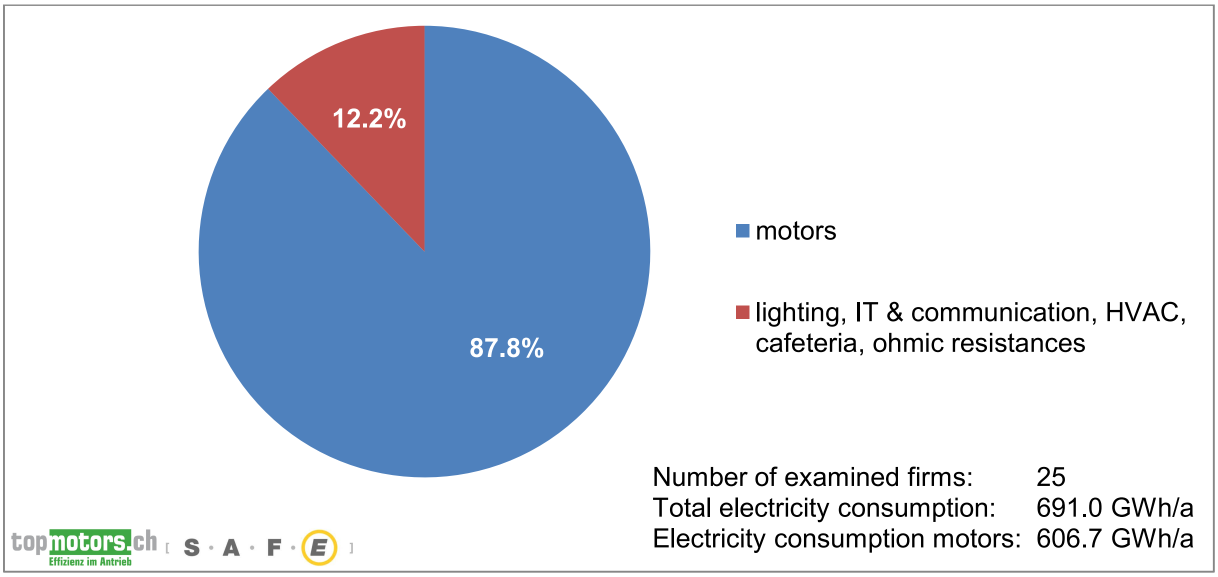

Figure 3: **Share of motors' electricity consumption in industry. Source: S.A.F.E., 2013.**

Step 2: Motor list

The next step was to create a database of all relevant motors of a company with the tool "Intelligent Motor List" (ILI^+). Ten companies used the tool to list between 40 and 650 motors each and to identify the motor systems with the biggest efficiency potential. The "Decision Maker" of ILI^+ helps to select these motors and gives an indication where to start. The criteria for the selection of motors can be set manually for several input values like age, operating hours, size or VFD existing (yes/no). It also allows the use of the “20-80-rule”, which means that by optimizing only 20% of all installed motors 80% of the total potential savings can be realized.

Age

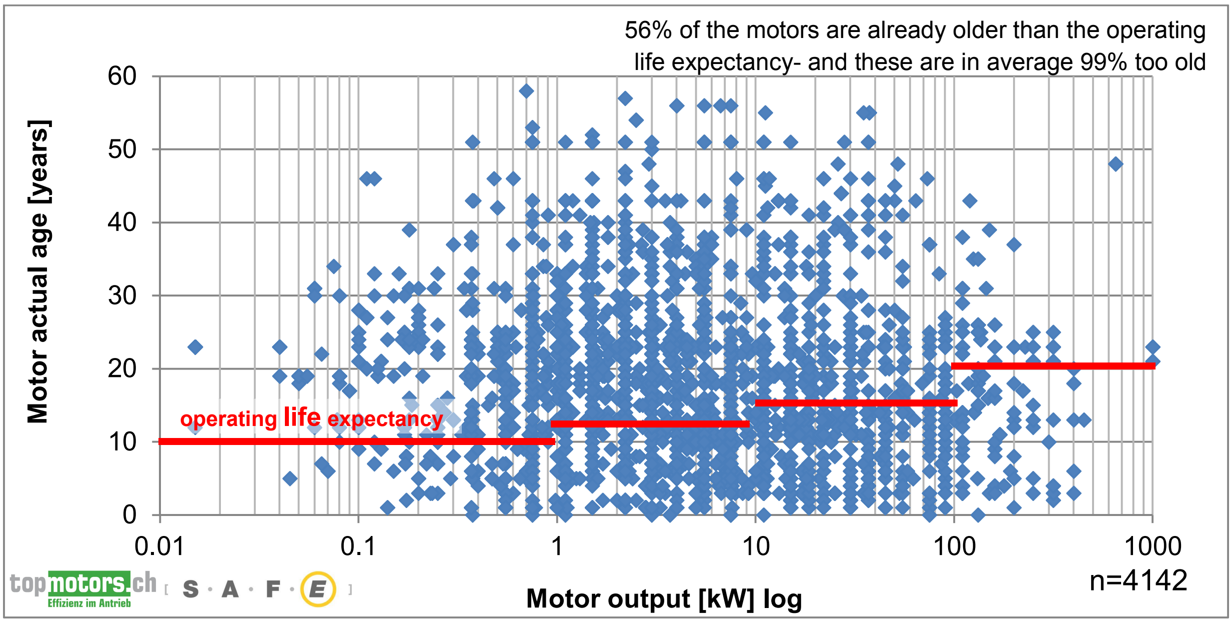

Figure 4 **Motors are too old (and still running). Source: S.A.F.E., 2013.**

The analysis of 4142 motors revealed that 56% of these are already running almost twice as long as their operating life expectancy. This suggests there is barely any continuous improvement process for replacing old, mostly oversized and inefficient motor systems. In many cases, the needs of the process have changed over the years but the single applications like fans and pumps have not been adapted accordingly. That is why the motor and operating point of the driven application has often shifted to an inferior point with lower efficiency. Forty year old motors have missed a large technological evolution and may have also lost some efficiency by rewinding and wear. This is why the age is one important selection criterion in the "Decision Maker".

Operating hours

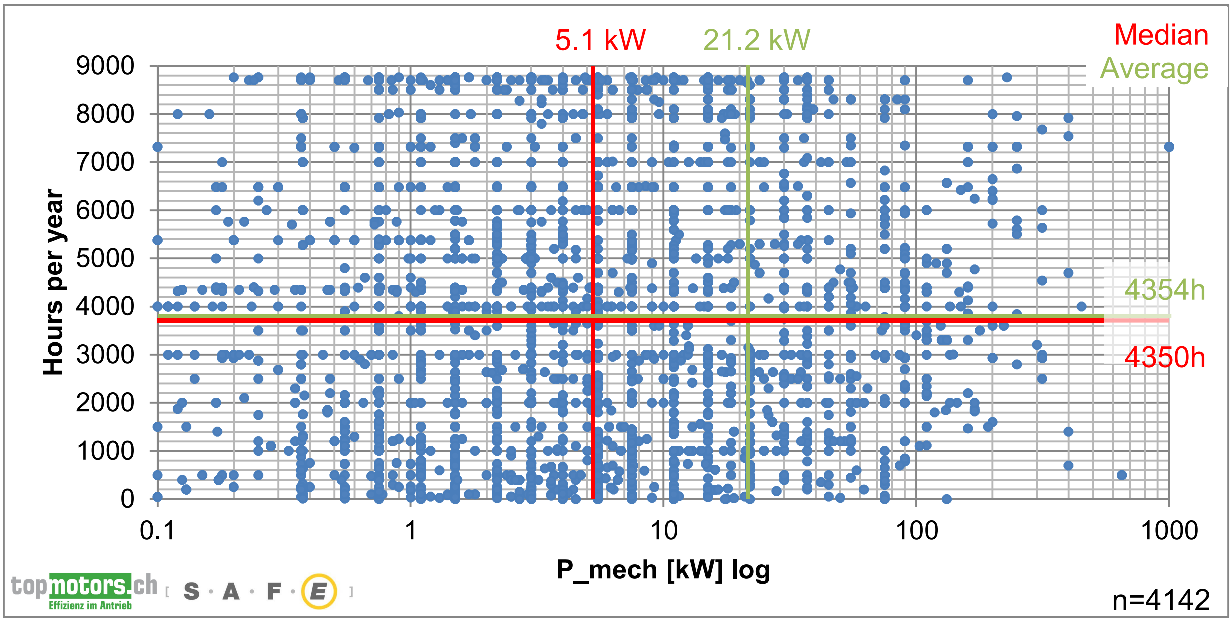

Figure 5 **Operating Hours. Source: S.A.F.E., 2015.**

The operating hours also have been analyzed (see Figure 5). No relationship between output power and operating hours per year has been found. The average output power of all motors is 21.2 kW. The median size of all motors 5.1 kW. This means 50% of all motors listed are smaller and 50% bigger than 5.1 kW output power.

Variable Frequency Drives

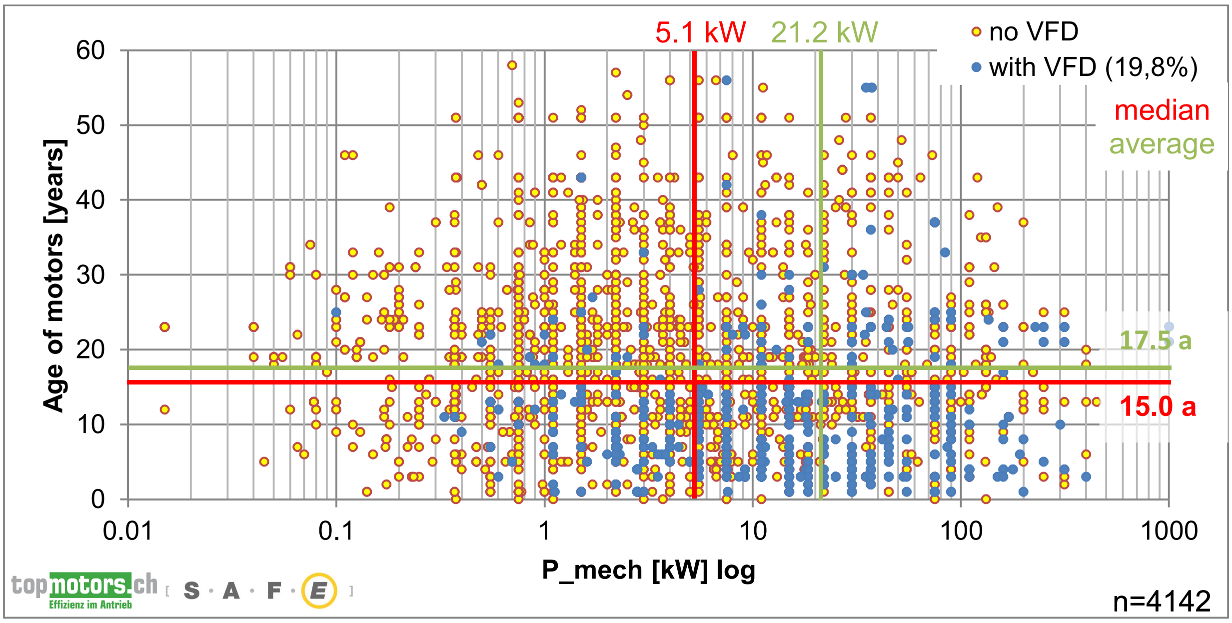

Figure 6 Use of variable frequency drives. Source: S.A.F.E., 2015.

The analysis of the VFD revealed the share of motor systems already powered by a variable frequency drive. In total, 19.8% of all motors already have a VFD. The majority of the motors that are equipped with a VFD is younger than 15 years with an output power between 1 and 100 kW. The authors believe a VFD would be useful for up to 50% of all drives. Smart controls of motor systems by reducing the speed enables huge efficiency potentials.

Step 3: On-site test and Standard Test Report (STR)

After the on-site measurement, a Standard Test Report (STR) is created for every single motor system. All improvement proposals were aimed at optimizing the whole motor system and not exchanging individual components.

Typical improvements include:

- Resizing motors and applications, adjust to the real needs of the process, based on on-site measurements and observations.
- Optimized flow rate, pressure, temperature and time of operation according to the real process requirements.
- Upgrading the motor system with VFD, especially pumps (closed loops) or fan systems with square torque.
- Installing and optimizing higher level controls for complex motor systems (factory automation systems) to coordinate and optimize the operation time and load to the real needs.
- Replacing old components by highly efficient equipment, avoid transmission belts and gears (if possible), choose flat- or synchronous instead of V- belts.
- Installing electric motors of higher efficiency levels (IE3 or IE4).

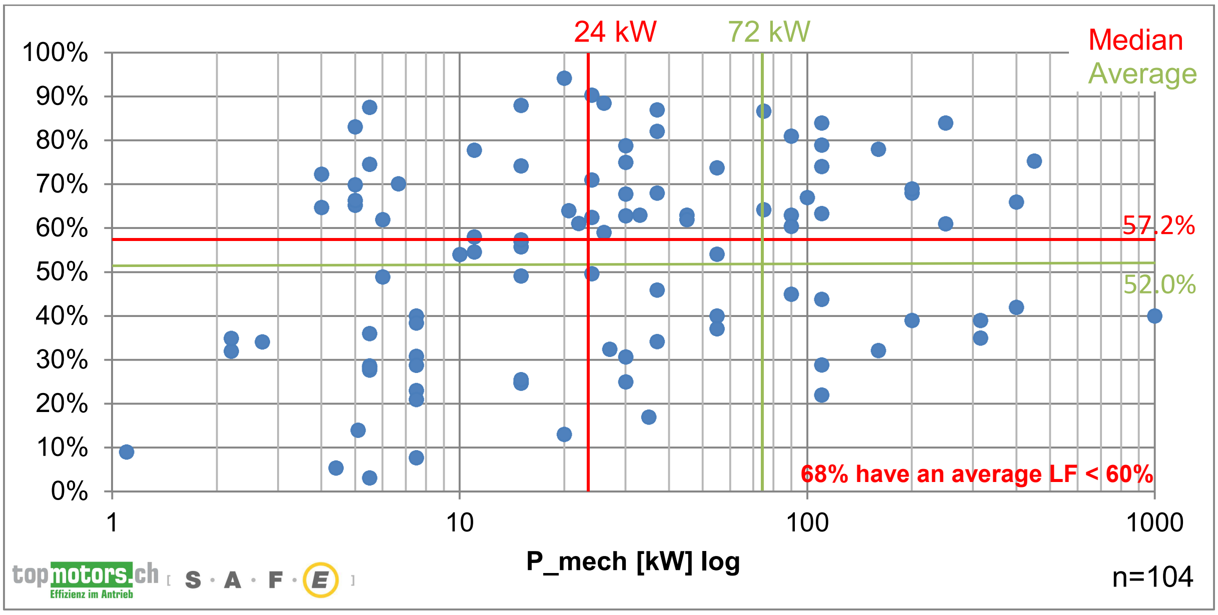

Figure 7: **Average load factor. Source: S.A.F.E., 2013.**

Based on the results of the on-site measurement, the STR has been structured and filled with data. The STR contains the best recommendation for an energetic improvement with all proposed measures and associated costs, life-cycle savings and payback. Figure 7 shows the average load factor of all measured motors. The average load factor is only 52% of the output power. A motor with an average load factor of less than 60% is oversized. So this means, 68% of all tested motors are oversized.

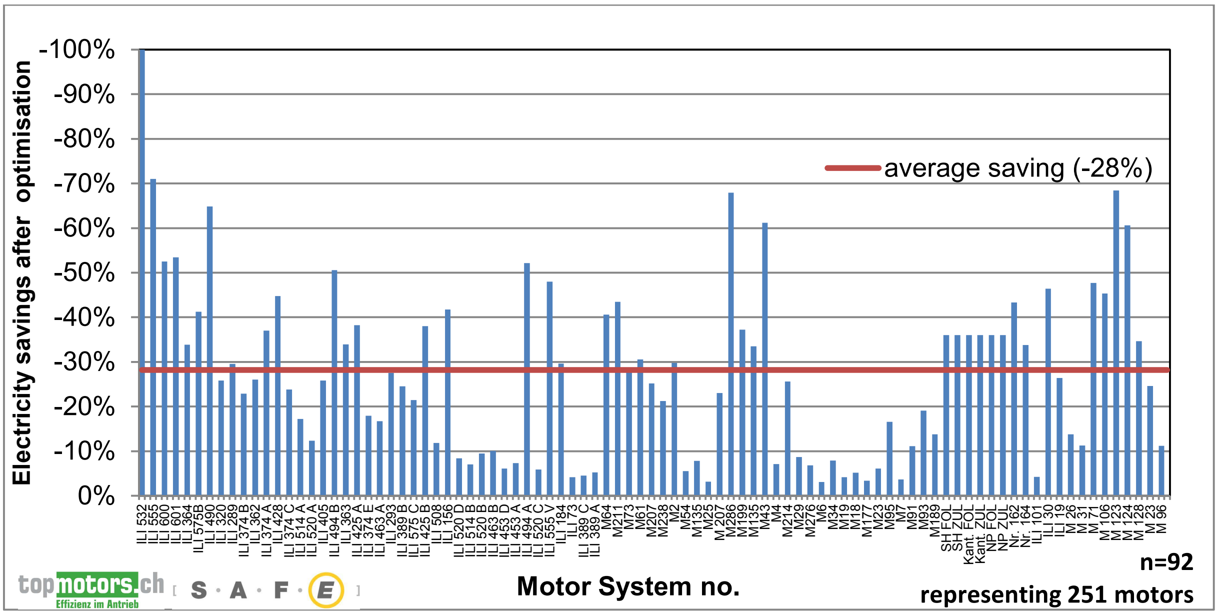

Figure 8: **Relative electricity savings after optimisation. Source: S.A.F.E., 2014.**

For 92 of 104 tested motor systems, it was useful to use the structured analysis of the STR (see Figure 8). Some of these 92 STR represent several similar motor systems. All STR are representing 251 motor systems in total with a saving potential between 3% and 71% respectively. One motor even had a savings potential of 100% because it was running in the basement without any use, the machine it drove was already retired. The efficiency potential of all motor systems show on average 28% lower electric energy input after the implementation.

Step 4: Implementation

After the implementation of the recommendations from the STR, there have been random tests to verify the expected savings. Many of the measurements have shown better results than expected. In some cases there have been fewer savings than what the STR predicted. In all cases the difference can be explained by deviations between the implementation and the STR or by differences of the process parameters (e.g. more output).

Lessons learnt

To implement energy efficiency improvements in industry takes significantly more time than assumed. A lack of responsibility, internal decision standards and budgeting cycles are causing many delays.

Companies are concerned about external engineers in their factories. It takes time to build up trust (even if confidentiality is warranted).

The main focus of the companies is always on their core business: the production of high-quality goods and minimizing the risks of interruptions. Saving energy has a much lower priority in their daily business- if at all.

The main criterion for investment decisions is still the payback time. In most cases, companies are ignoring the life cycle costs and base purchase decisions on first cost. The technical staff is often not trained or not motivated to convince the decision maker of a more efficient solution.

As shown in Figure 4, motor systems are in operation since 20, 30 or even more than 40 years. Compared to their expected life time between 10 and 20 years, this is way too long and shows a lack of continuous improvement based on a structured and systematic replacement process. The entire technical evolution during the lifetime of the machines has been missed. The needs of the process have changed and thus most of the equipment today is oversized.

Companies depend strongly on their regular suppliers of components and systems who also provide maintenance of machines. Competitive offers were required only in rare cases. The delivery of more efficient components was delayed in many cases as it would have required a change in the business model (regular products on stock) of the supplier.

The effort for the EASY program management has been substantially higher than expected. Companies need continuous support during the whole 4-step audit program. The lack of knowledge generates a need for extensive "guidance support" through all steps.

Conclusions

The main goal of the pilot program EASY was to save energy by improving motor systems in industry and overcome barriers which are preventing the autonomous implementation of efficiency measures in companies. A main goal was also training of staff, reducing the lack of knowledge and encouraging companies to do systematic analyses without external support.

The measurable goal of saving 69.2 GWh over the lifetime of the newly installed equipment was overachieved with 7%, gaining total savings of 73.7 GWh.

The analyses of the database with 4142 motors confirmed several assumptions about the use of VFDs, oversizing, age of the motor stock, etc.

The main goal for a company is to make sure that it produces the planned amount and quality of their products. Factory staff is trained to ensure the undisturbed daily business. Energy saving has a very low priority. There is no, or only a very limited incentive to save energy or to resize an old motor system. Nobody wants to take the risks (e.g. equipment failure, higher costs than anticipated, lower savings than anticipated, etc.) without any personal advantage or reward.

The electricity costs of the factories that participated in Easy were between 1% and 3% in relation to their total turnover. Therefore, the net financial gain through the savings is small.

The software tools help to identify the motors with the biggest potential and an economically attractive payback. The effectiveness of the implementations with short paybacks is proven by random checks.

EASY has also shown that a financial incentive helps to get into the factories and it stimulates activities in industry that were hindered or neglected before.

EASY also caused additional administration work which in some cases led to irritations.

Way forward

Based on the lessons of the EASY program, a training program for factory technical personnel is being built up in Switzerland: energy technology and management in industry, incorporating the Motor-Systems-Check methodology with its software tools.

Based on the research of Cooremans [3] and the lessons learnt from EASY, the Swiss cooperative project "Management as a Key Driver of Energy Performance"[2] is researching between 2015 and 2017 if companies with an energy management system tend to invest more into energy efficiency.

A direct follow-up of the EASY program is the SPEED program (www.speed-program.ch) operated by Planair (www.planair.ch/en), an EASY program partner.

Acknowledgements

The authors would like to thank the Swiss Federal Office of Energy, the EASY project partners, especially Planair SA and the participating companies for their engagement in the program.

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Training for Energy Management and Technology in Industry: ET&M

Rita Werle, Conrad U. Brunner, Rolf Tieben

Impact Energy Inc.

Abstract

Training programs for energy efficiency in Switzerland have focused in the last decades on buildings and renewable energy. Recently also industrial thermal processes have been addressed with associated tools for analysis (e.g. PinCH analysis[1]). Efficient electrical energy use in industry has been a neglected topic so far. In addition, experience throughout the implementation of the Swiss motor systems audit and financial incentive program EASY (www.topmotors.ch/easy), managed by the Swiss Agency for Efficient Energy Use (S.A.F.E.) has shown that there is a lack of know-how concerning the retrofit of old and the design of new energy efficient motor systems in industry. This is often coupled with a lack of resources (time, financing) and clear responsibilities within industrial plants.

Impact Energy, a member of S.A.F.E., has designed a training program for energy technology and management in industry (ET&M), to close the identified knowledge gap in industry. The goal of ET&M is to empower in-house company staff to systematically analyze their rolling stock of electric motor systems, identify and propose energy efficiency projects, design and secure a multi-annual investment plan with the management and have the improvements implemented in a multi-year campaign.

The first key element in the design of the program was the clear identification of the target group: technical staff working in middle and large-sized industrial plants. Subsequently, program length and minimum criteria for enrolment, taking into account the potential participants' prior educational background, had to be defined.

The program is unique in the sense that it combines technical, management and organizational topics, recognizing that successful project proposals do not only need to be technically solid but also need to gain (management) support within the organization. Consequently, ET&M consists of the following three modules: introduction, management and technology.

The module introduction will provide a general overview about the global, European and Swiss national energy and electricity consumption and market, as well as the fundaments of project management and economic assessment.

The module management will include topics on general energy management (method, tools, implementation), elements of change management, company decisions (including strategic and financial aspects) and convincing management, including presentation and negotiation techniques.

The module technology will specifically focus on electric motor systems. In particular: best available technology, applications (fans, pumps, compressors, other), controls (variable frequency drives), transmission, demand (flow, pressure, speed, time, etc.). The Swiss Motor-Systems-Check method, a four-step audit method for identifying motor systems with the highest efficiency potential within an industrial plant is also part of the program. Practical knowledge transfer is enabled through lab tests, site visits and concrete optimization assignments.

The program is unique, because it combines technical, organizational and human aspects. It is in the build-up phase, the first preliminary edition is planned to be executed in 2016 in Switzerland.

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[1] http://pinch-analyse.ch/index.php/en/

Background

Focus so far on thermal energy

Thanks to the Swiss CO_2 law and the subsequent activities of market players, thermal energy efficiency has experienced much attention and a positive development in the last decade. Electric energy efficiency has been less in focus, however, it is now gaining ground, backed up also through the energy strategy 2050 of the Swiss government.

Training programs for energy efficiency in Switzerland have focused in the last decades on buildings and renewable energy. Recently also industrial thermal processes have been addressed with associated tools for analysis (e.g. PinCH analysis: http://pinch-analyse.ch/index.php/en/). Efficient electrical energy use in industry has been a neglected topic so far as well as the role of the energy manager in industry. This is the main reason for introducing a new training program in this field, the need for which has been proved through real-life experience with energy efficiency projects in Swiss industry.

Also, many technical universities offer bachelor and master programs on electro-mechanical engineering. They generally provide the fundamentals of electrotechnics, mechanics and thermodynamics but do not touch specific applications like motor systems, pumps, fans, compressors, transport and process machines. In addition, they do not provide training on how to deal with existing machines, their analysis and improvement.

Practical experience

The Swiss Agency for Efficient Energy Use (S.A.F.E.) had run Easy (Efficiency for motor systems www.topmotors.ch/easy), an audit program for retrofitting motor systems in Swiss industry from 2010 until 2014. [1] The program followed the four-step audit methodology Motor-Systems-Check, developed by S.A.F.E. in the framework of the Topmotors program (www.topmotors.ch) in 2010. For every step, financial incentives were paid to participating firms.

During the course of the program, 4 142 motor systems in 18 factories were listed and assessed in detail. A major finding is that 56% of motors are older than their expected lifetime (see Figure 1). These are on average twice as old as their expected life time. This shows that there are no processes in place for the continuous improvement of the running stock of motors.

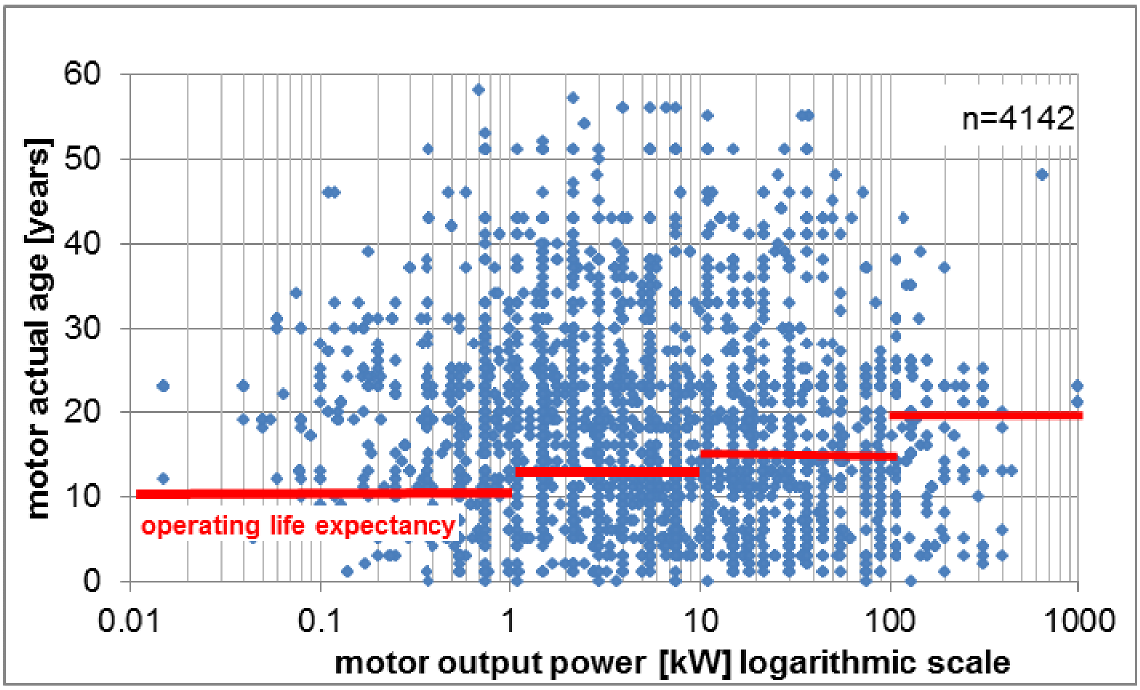

Figure 1 56% of motors are older than their expected life time. Source: S.A.F.E., 2013

In addition, one of the main lessons learned throughout the Easy program is that technical personnel in Swiss industry lacks:

- an orientation towards efficiency in electric energy,
- technical know-how for making electric motor systems more efficient,
- the necessary internal resources in terms of time, financial funds and responsibilities to manage and implement efficiency projects.

Based on these observations, the training program "Energy technology and management in industry" (ET&M) has been designed.

Goal of ET&M

The goal of the training program ET&M is to empower in-house company staff to systematically analyze their rolling stock of electric motor systems, identify and propose energy efficiency projects, design and secure a multi-annual investment plan with the management and have the improvements implemented in a multi-year campaign. This requires a sufficient number of skilled, motivated and trained staff in management and technical positions that is able to launch an in-house energy efficiency improvement program. The goal is therefore, to qualify companies to deal with their energy issues and plan improvements in a dialogue with manufacturers, external engineers and service companies. This means also, to wean the companies from their current dependency on external knowledge and manufacturers delivering service routines and designing improvement without up-to-date technological knowledge and without using competitive tenders.

Also, the combination of skills and the interaction between technical ("boiler room") and management ("board room") areas is crucial for a successful implementation of energy efficiency projects in industry and needs to be trained (see Figure 2).

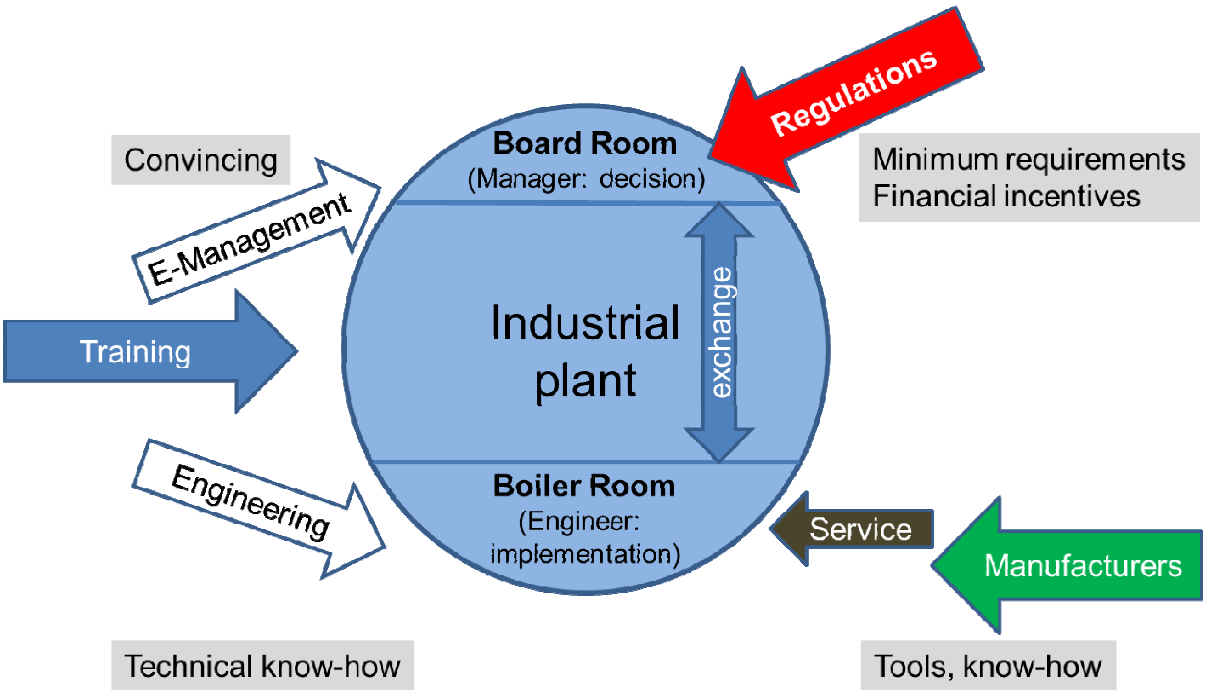

Figure 2 **Necessary interaction between "boiler room and board room"**

Approach

In order to clarify the training concept and to engage technical universities in the development, a feasibility study was made between July 2013 and November 2014 by S.A.F.E. for the Swiss Federal Office of Energy [2]. A survey to explore the interest of schools to participate in ET&M and to learn about experiences in organizing training courses for professionals was made. Sixteen educational institutes, the majority universities of applied sciences, were interviewed. Most of them showed great interest in the program. They had experience only in their segment of training for basic engineering (bachelor) and not in the continued education of engineers already working as technical managers in factories. They had no practical experience in factory audits, building up energy management systems, performing on-site measurements, making life cycle cost analysis and the like.

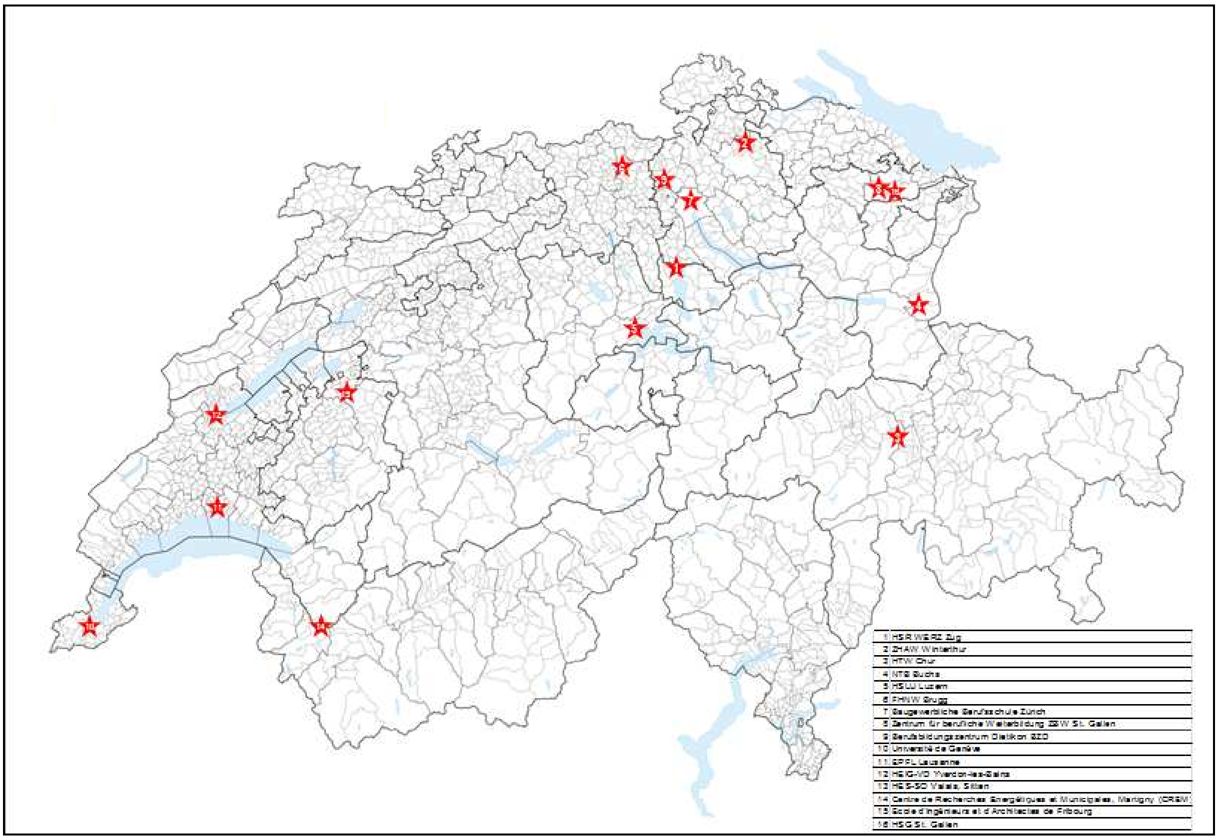

Figure 3 Map of Switzerland with the interviewed educational institutes

The survey also targeted consulting engineers, manufacturers, industry associations, power utilities, cantons and industrial end-users (see Figure 4).

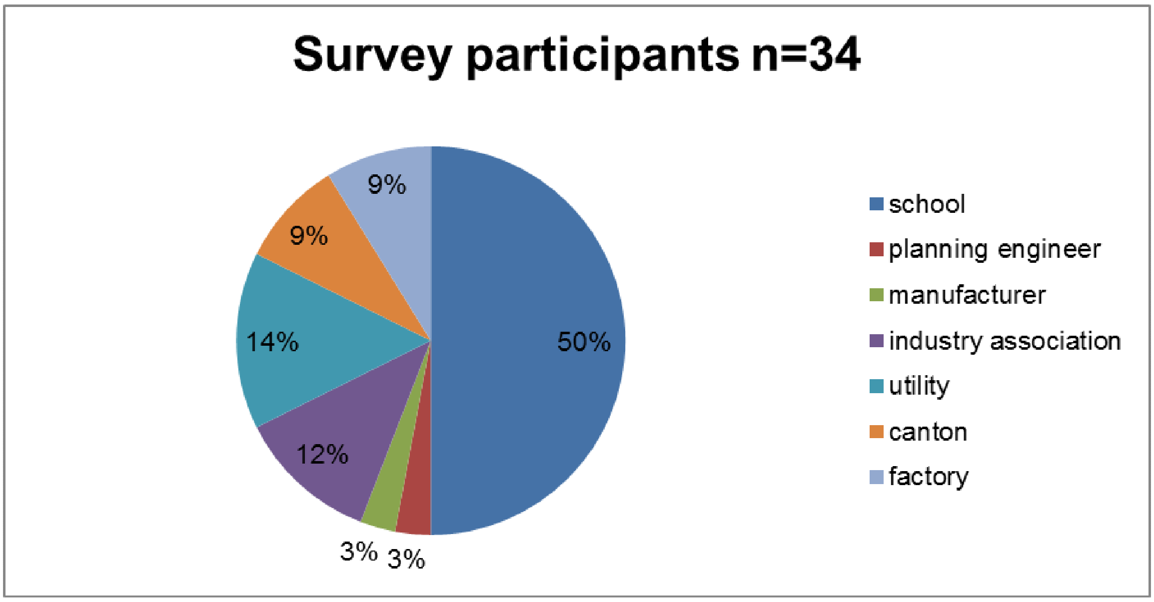

Figure 4 Survey participants during the feasibility study

Concept of the training program

During the feasibility study and the program conception, it became clear that some specific issues need to be considered when introducing a new training program for industry.

First, just like for any other training program, the target group needs to be clearly defined.

The respondents of the survey during the feasibility study have indicated factory staff as the primary target audience of the program, while also seeing an opportunity for other groups to participate in the program (see Figure 5).

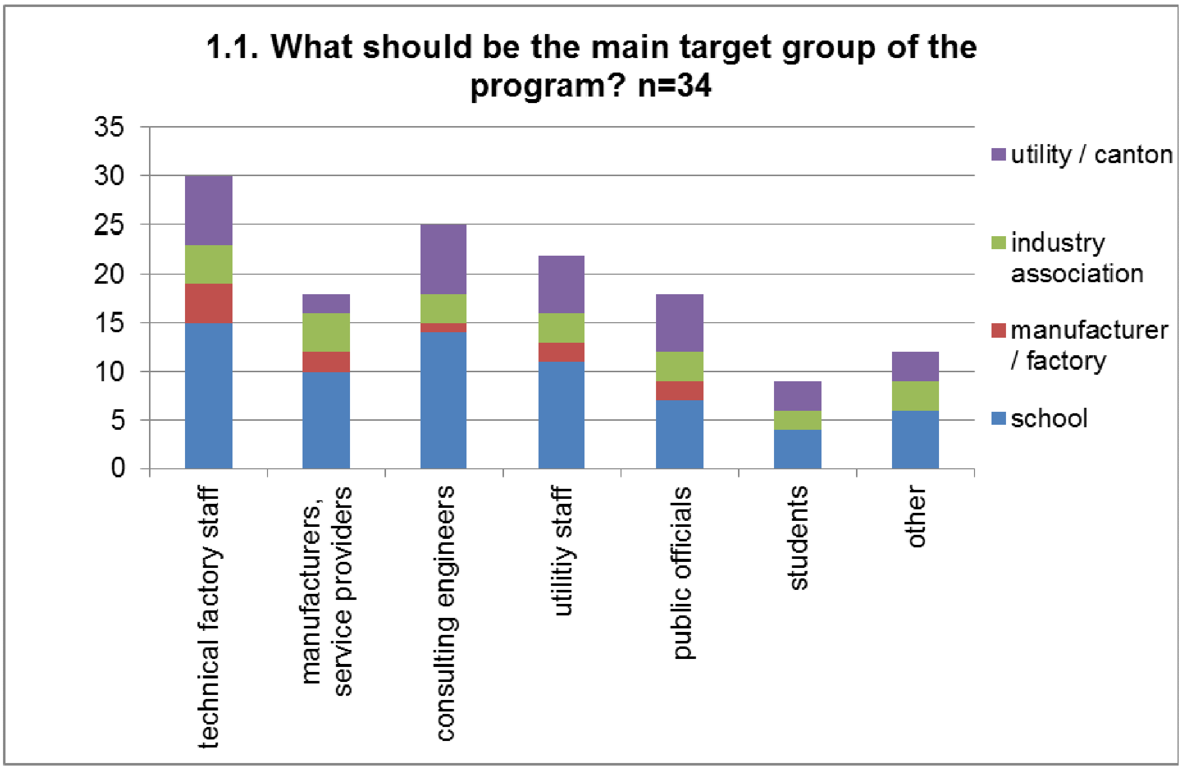

Figure 5 Indication of potential target groups of ET&M by survey respondents

After evaluating the responses received during the feasibility study and resonating those with the advisory group, the target group of the program ET&M was defined to be oriented towards technical staff working in mid-size or large industrial factories (end users), with some years of work experience.

The recommended factory size can be clearly identified (see numbers of factories with electricity consumptions by size, Figure 6):

- Small factories (below 0.5 GWh/a electrical energy consumption) usually have no qualified in house staff for energy efficiency projects (this group represents 96.1% of the factories, using 38% of the electricity use of the Swiss industrial and service sectors).
- Mid-size factories (between 0.5 and 10 GWh/a electrical energy consumption) often have some technical in-house staff that lacks energy efficiency competence and capacity (this group represents 3.7% of the factories using 34.5% of the electricity).
- Larger size factories between 10 and 100 GWh/a electrical energy consumption usually already have their own internal management and technical staff (or at the headquarters) that run energy management programs and efficiency improvement plans but lack specific knowledge and experience in improving electric machines (this group represents 0.2% of the factories using 27.5% of the electricity)

The mid-size and larger companies together represent 3.9% of the total number of factories but use 62% of the electric energy. It makes sense to focus on training staff that will eventually be working in the mid- and larger size type of factories.

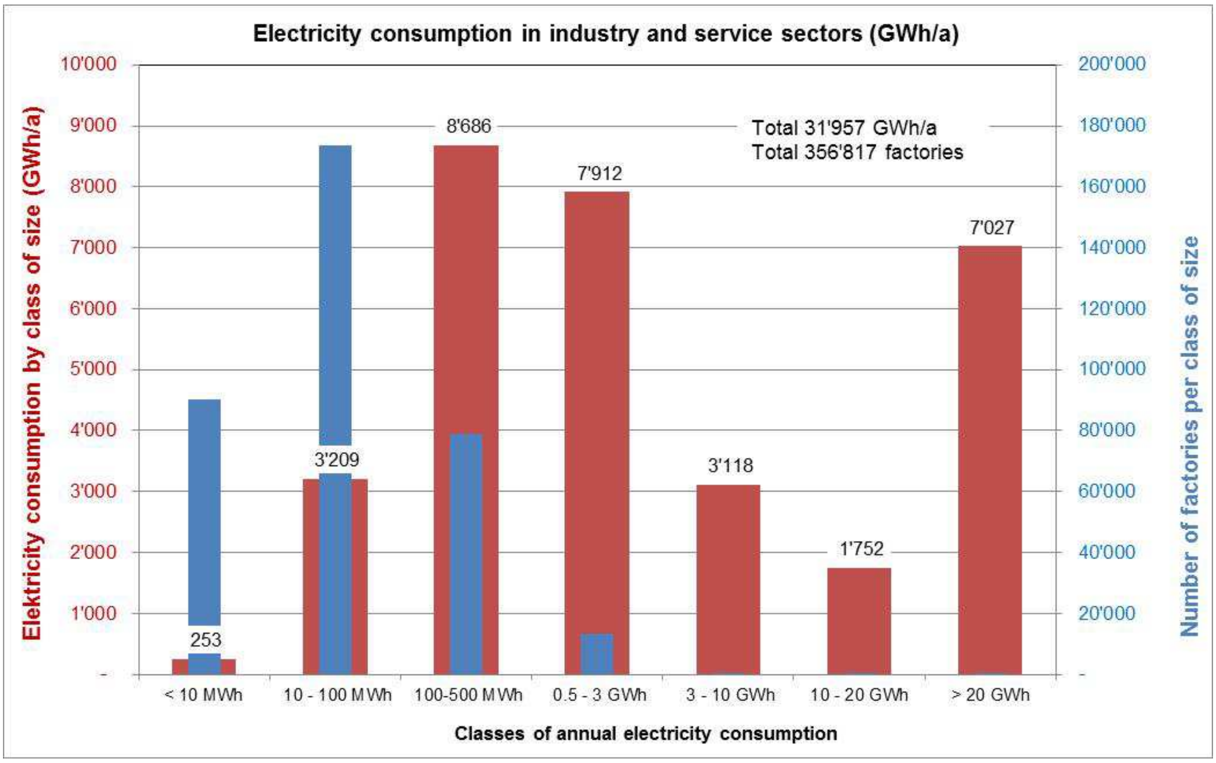

Figure 6 **Small and large factories in Switzerland (Source: SFOE 2011)**

Training format

The training program was conceived for technical staff already working in factories. Hence, it was clear that the training had to be construed in a way that allows extra-occupational attendance.

There were two main challenges identified with regard to the target group:

- the level of prior training of the students is very diverse,
- the number of days they can abstain from their main duty in the respective factory, hence their available time for the training is limited.

During the feasibility study, the schools were surveyed concerning the training format, in particular the level and length. The largest group with 40% of the answers (see Figure 7) recommended a Certificate of Advanced Studies (CAS). Still a fairly large group of 27% recommended a Diploma of Advanced Studies (DAS).

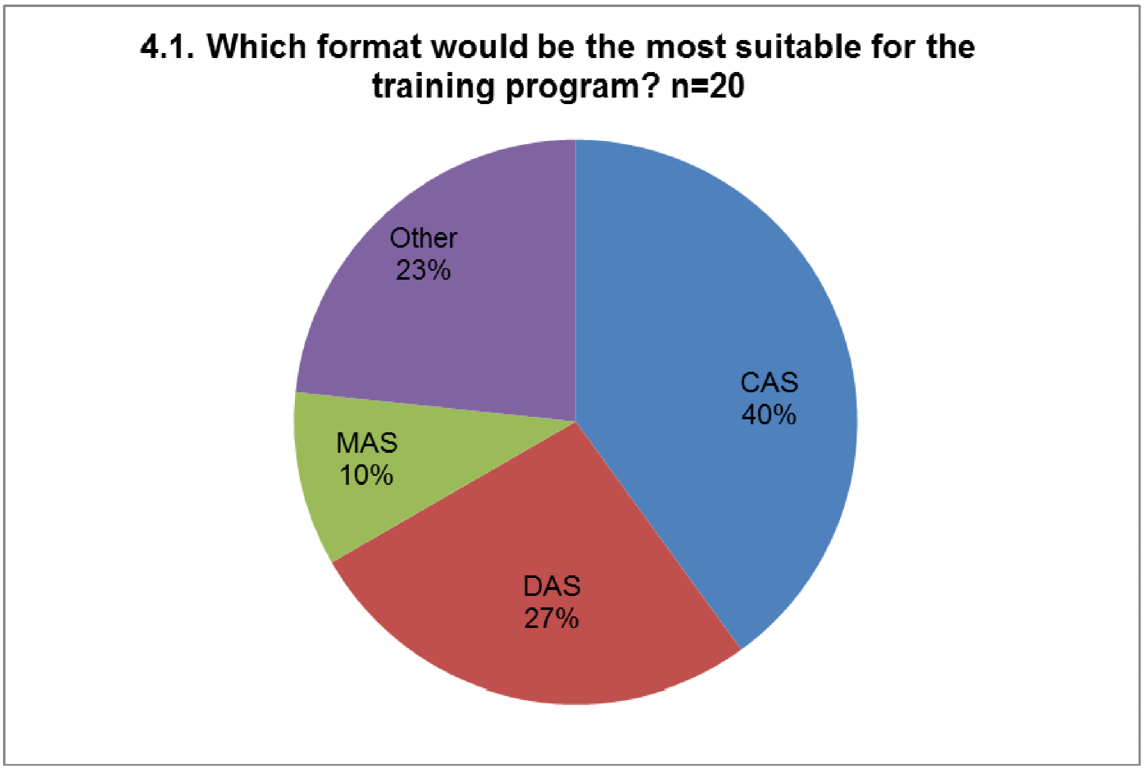

Figure 7 Results of survey: on what level should the training be held
CAS = Certificate of Advanced Studies, DAS = Diploma of Advanced Studies, MAS = Master of Advanced Studies

Although the majority of the interviewed institutions choose a CAS or MAS (Master of Advanced Studies) level program with a 12 to 20 days training format, it was decided to start with a 5 to 6 days course. The key argument for a shorter version - at least in a pilot phase - was that a prolonged absence from work would be difficult for factory personnel, limiting the number of participants to a level below the required minimum attendance that is necessary to cover the operating costs of the ET&M program.

It is envisaged that in the shorter program (5 to 6 days) the employers will be more willing to grant the employees the time to enroll in the program and follow the training.

The other critical question was to define the minimum criteria for program participants. An important part of the training involves a factory level audit (Motor-Systems-Check) that also includes the use of several software tools and the analysis and measurement of electric motors systems in order to be able to design improved systems.

During the feasibility study it was found that most of the technical factory operators in Switzerland have an electrical or mechanical background but no bachelor degree. It seemed necessary to also allow electrical and mechanical factory workers with 4 year training in an apprenticeship and a subsequent period of practical work experience of 5 years into the program. Training these technicians with little theoretical engineering background on life cycle cost methods and cost/benefit analysis of complex motor systems may prove to be challenging.

Most of the 16 survey respondents indicated that they would support training participants from their organization by work time and/or training fee compensation.

Several respondents stressed that the course fee is the smaller barrier compared to the necessary time away from the factory during the training.

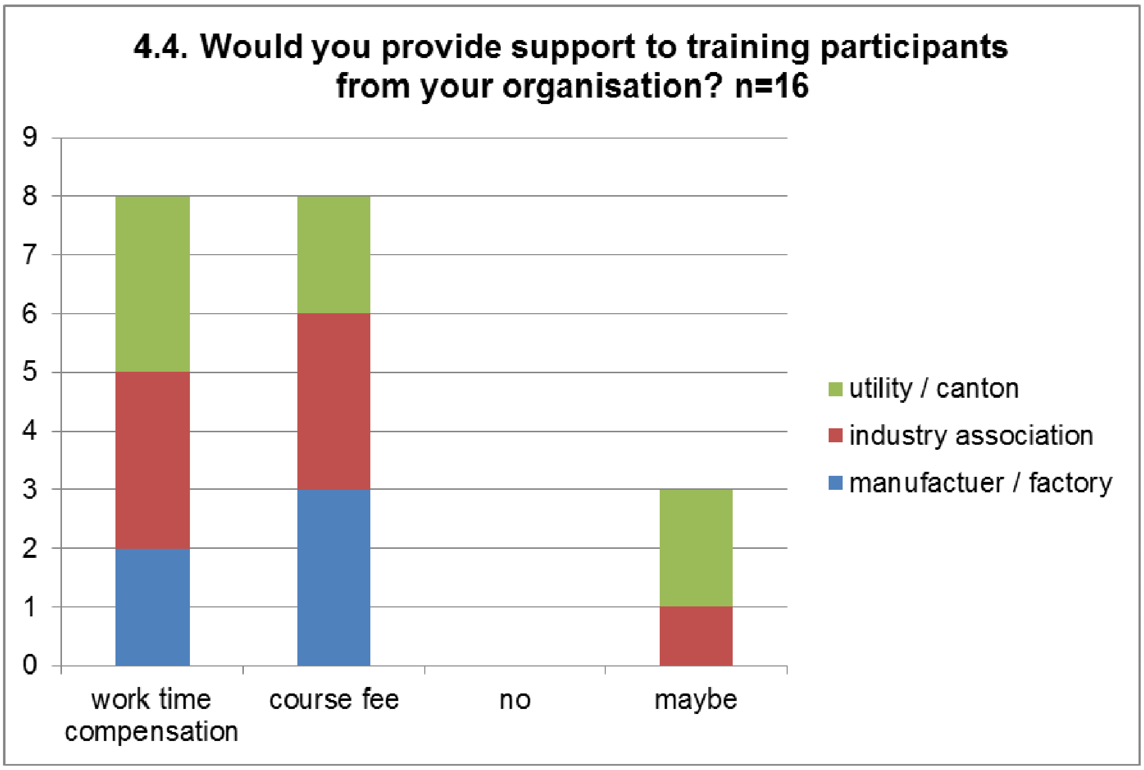

Figure 8 **Survey respondents' indications on potential support to training participants**

Mix of technical and management skills

The concept of ET&M is unique in the sense that it combines the technical, management and organizational domains. The goal is to develop and train technical and managerial skills of technical personnel for a successful implementation of efficiency improvement projects. Hence, the program is recognizing that successful project proposals do not only need to be technically solid but also need to gain support within the organization across different departments with diverging interests (e.g. maintenance, purchasing, etc.) and several hierarchical levels (e.g. upper management, technical manager, administrator, etc.).

The feasibility study reinforced the program concept (see Figure 9), consisting of the following three main modules:

1. Introduction
2. Energy management
3. Energy technology.

Module 1 Introduction will give a general introduction to the Swiss energy policy background, minimum energy performance requirements (MEPS), standards, electricity markets and electricity price. It will also include topics of general project management and profitability.

In module 2 Energy management the concept of a continuous improvement process within industry will be conveyed, including an introduction to ISO 50001 and the importance of monitoring and verification. According to Cooremans [3], investments into energy efficiency are often not implemented even if they are profitable, because they are not perceived as strategic. The training will need to explain the complex interaction of industrial energy efficiency investment decisions where risks, value and costs have to be balanced. An important element of this module is the part on communication, change management, developing skills for successful negotiations and presentation. Technical managers should be able to convince other departments or the upper management to invest into energy efficiency. This is only possible if they can formulate and "sell" a project proposal.

While module 2 Energy management will be covering both electric and thermal energy, module 3 Energy technology will focus on electric energy use. The reason for this is twofold. On the one hand, while there have been good mechanisms in place in Switzerland to reduce thermal energy consumption during the course of the past decades, the subject of electric energy use in industry has been so far neglected. On the other hand, motor systems are responsible for more than 70% of electricity consumption in industry. [4] According to the analysis of S.A.F.E. in 25 industrial and infrastructure plants in Switzerland, the share of the electricity consumption which can be attributed to motor systems is 87.8%. This new training program will be the first of its kind in Switzerland with a clear focus on motor systems.

		Day 1	Day 2	Day 3	Day 4	Day 5
		INTRODUCTION	ENERGY MANAGEMENT	TECHNOLOGY 1	TECHNOLOGY 2	TECHNOLOGY 3
Session		Registration				
1	09 - 10	Course introduction	Energy management, ISO 50001	Motor systems	VFDs	Excursion: Lab, manufacturer, end-user
2	10 - 11	Swiss energy policy	Monitoring & verification	Efficiency	Pumps	
3	11 - 12	MEPS for motors, pumps, fans	Decision factors	Other electric consumers	Fans	
Lunch						
4	13 - 14	Standards, regulations	Communication	Motor-Systems-Check	Hydraulic systems	Presentation of assignments
5	14 - 15	Electricity market & price	Change Management	Software tools SOTEA, ILI, STR	Air compressors	
6	15 - 16	Project management	Negotiating	Measuring on site	Cold compressors	
7	16 - 17	Profitability	Presenting project proposals	life cycle cost, bundling measures	Transmission, gear	Evaluation, Feedback, Questions

Figure 9 Program concept of ET&M. Source: S.A.F.E., 2015.

Module 3 Energy technology will cover all relevant topics concerning efficient motor systems, including the Motor-Systems-Check audit methodology and its software tools, efficient motors and applications (pumps, fans, compressors, transport and process machines), the use of variable frequency drives, etc. A part of the training will be held in a pilot factory where practical observations of systems in operation can be made, performance measurements can be taken, and subsequent evaluations can be trained.

Participants will have to complete an assignment to receive the course certificate. The purpose of the assignment is that participants carry out a system optimization preferably within their production facility, enabling them to gain practical experience, facing the usual obstacles and finding solutions.

A visit to a testing laboratory or a manufacturer is also planned to strengthen the practical part of the program.

Program costs

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, locations, etc.

2. The 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 editions, etc.), selection of training locations, cooperation with local universities,

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.

The financing of the program needs national and local government support, an association of interested industry and utilities plus students' fees. The basic research of the program was supported by the federal government. The preparation of training courses needs a combined sponsorship of the national and local government together with the association. The implementation of the training needs to be fully paid by the students' fees.

Program build-up

The program is now in the build-up phase. The next step is to evaluate the educational institutes and determine which are the ones best qualified for hosting the program. The criteria for this evaluation will include: qualified university staff in this domain, existing laboratory and measurement instruments, links to industry, good reputation and experience with continued education programs, geographical location and accessibility, etc.

This will be followed by setting up an organizational scheme where the various stakeholders (associations, universities, energy efficiency agencies and government institutions) form an institutional set-up to run a national program.

Then, in collaboration with a number of experts and trainers, directly involving the tutors, the program layout will be defined. It may prove to be a challenge to bring together a qualified group of experienced experts and/or university staff willing to cooperate within the framework of the program and using the same terminology and methodology, especially in terms of the audit method. Many university teachers lack practical experience and need to be trained first.

The financial concept is based on government subsidies for the build up of the program and participants' fee to cover the operating costs. Also power utilities and universities along with professional associations and local governments will be invited to contribute to the costs and make the fees palatable. A business plan for multiple years is under development to estimate the necessary financial support to the build-up and continued execution of the program.

The first ET&M training is planned to be a 5 or 6 days long. While there is a clear intention of offering the course for a longer duration (10 - 12 days) at a much higher level of intensity, covering its topics more in-depth, it is understood that even a shorter edition could constitute a challenge for the targeted audience in terms of being absent from the production facility for a number of days.

The first trainings are planned to be held in 2016 in the German and French part of Switzerland, with course offerings both in German and French.

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Energy Audits and Energy Management Systems under the Energy Efficiency Directive: what is the current situation?

Paolo Bertoldi and Tiago Serrenho

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Abstract

In order to meet the energy saving target for 2020 the European Union (EU) has adopted the Energy Efficiency Directive (EED), which request EU Member States (MSs) to adopt energy saving targets and a number of specific policies in order to reduce barriers to energy efficiency investments in all the sectors.
For the industrial sector one of the most relevant article of the EED is article 8 on "Energy Audits and Energy management Schemes". Energy audits are an essential step in order to identify energy efficiency opportunities in industry and give to the end-user clear information on which type of actions and/or investments should be carried out. Energy Audits in the industrial sector are an important tool for promoting energy efficiency projects in motor systems in existing plants. Article 8 requests MSs to make available high quality audits for Small and Medium Enterprises (SMEs) and encourage SMEs to undergo audits and then implement the recommendations from the audits. In addition, Article 8 requests MSs to ensure that large company carried out an independent audit every 4 years. The Article also allows audits carried out in the frame of voluntary programmes and energy and environmental management systems to fulfil the obligation for large companies.

The paper presents how the MSs have implemented Article 8 in the frame of existing voluntary programmes, including information on the quality of audits and the auditor qualification, or as a new legislative obligation. The, information has been collected through a survey sent in spring 2014 to national experts and national contact points in the MSs and through the analysis of the 2014 National Energy Efficiency Action Plans prepared by MSs. The paper identifies best practices in place in the implementation of article 8. Reference to existing European and international standards is also presented.

Introduction

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% by fixing a maximum level of primary and final 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 meet the target by 2020, and paves the way for greater energy efficiency beyond that date. The EED measures include a requirement to establish energy efficiency obligations schemes or equivalent policy measures in all MSs (art.7), a requirement to draw up a roadmap for the renovation of all buildings up to 2050 (art. 4), an obligation to renovate annually 3% of buildings owned and occupied by central government (art. 5), and an undertaking to conduct cost-benefit analyses for the deployment of combined heat and power (CHP) installations (art. 14).

Article 8 of the EED addresses energy audits and places the following obligations on MSs with respect to the promotion of energy audits. 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

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[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.

enterprises[2] that must be carried at regular intervals and MSs must ensure 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 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) to undergo energy audits and implement the recommendations from these audits. The EU industry sector consumed 283 Mtoe in 2012 or 25.6% of total EU final energy consumption and still offers a large saving potential of 9% by 2020 compared to the business as usual scenario. However several barriers still prevent the full uptake of all the cost-effective energy efficiency solutions [2] [5] [6]. For these reasons polices need to be introduce to remove these barriers and enlarge the number of energy efficiency projects in the industrial sector.

Energy Audits under the EED

An energy audit is defined as a systematic inspection of energy use and energy consumption of a site, building, system or organisation with the objectives of establishing energy flows, identifying the potential for energy efficiency improvements and reporting them to the energy user.

Energy audits offer many benefits to both small and large energy consumers [1] [2][10].

- Energy audits should identify the greatest opportunities for energy savings. Therefore they offer the opportunity to reduce the energy costs of an organisation. This improves profitability and enhances competitiveness;
- Energy audits can identify potential for improvement in business and production processes and thereby contribute to improved productivity;
- Energy audits can help organisations reduce the environmental impact of their activities;
- Energy audits can help some organisations to fulfil obligations under their national with respect to emissions to air and pollution control;
- Energy audits can also help improve employee satisfaction and project a positive image to customers and the wider community.

The EED Annex VI contains the minimum criteria that must be fulfilled by obligatory audits in order to comply with requirements:

- They must be based on measured up-to-date energy consumption data;
- They must contain a detailed review of the energy consumption profile of relevant buildings, operations or installations;
- They should, where possible address life-cycle costs (or returns on investment) rather than simple payback periods;
- Audits should be proportionate, and sufficiently representative to form a clear picture of energy performance and to enable identification of the most significant opportunities for improvement.

[2] 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*".

The Annex states that detailed and validated calculations should be presented for the measures proposed in energy audits so that the potential savings are clear. It further stipulates that it should be possible to store the data used in energy audits for historical analysis and for tracking performance.

While Annex VI provides minimum criteria for energy audits, the EED does not contain much information about required or recommended audit processes, types of data needed or levels of detail in audit reports. The EED does not refer to any specific standard with respect to implementation of the Article 8, however adherence to international standards for energy audits can provide a consistent approach and ensure that audits undertaken are of a high quality.

The European standard EN 16247-1:2012 Energy Audits General Requirements defines the properties of a good quality energy audit. It specifies the audit requirements, a common methodology and defines the deliverables. It applies to all forms of organisations and all types of energy consumption, excluding energy consumption in private dwellings. The standard attempts to harmonise common aspects of energy auditing to bring more clarity and transparency to the market for energy auditing services. The audit process is presented as a series of steps: contract, start-up meeting, data collection, fieldwork, analysis, report and hand-over of results. It does not address properties of an energy audit programme such as administration, auditing tools, training of auditors or quality control. In the preamble of the EED it is stated that energy audits in the MSs should take relevant European and international standards such as EN 16247-1.

A number of further related European energy auditing standards are in development and are currently in draft form. This draft European standard prEN16247-2 addresses the specific requirements for energy audits for buildings or groups of buildings excluding private dwellings. Draft standard prEN16247-3 provides guidance for energy audits of industrial process. According to the proposed standard, an industrial site can incorporate one or more sections of activity, each with its own specific operating conditions, including production lines, offices, laboratories, research centres, packaging, warehouses and onsite transportation facilities. The standard can be applied to an energy audit addressing a complete industrial site or part of a site. Energy auditing of transportation systems is addressed by the draft standard prEN16247-4. A standard dealing with the qualification of auditors, prEN16247-5, is also planned and a first draft is currently in preparation.

Following the publication, in 2011, of ISO 50001 for the implementation of Energy Management Systems, it is now under preparation the standard ISO 50002 which gives guidance for the execution of energy audits comprising a detailed analysis of the energy performance of organizations, equipment, systems or processes. It is based on appropriate measurement and observation of energy use, energy efficiency and consumption. Energy audits are planned and conducted as part of the identification and prioritization of opportunities to improve energy performance, reduce energy waste and obtain related environmental benefits. An energy audit can support an energy review and can facilitate monitoring, measurement and analysis as described in ISO 50001, or it can be used independently. The energy audit process is presented as a simple chronological sequence, but this does not preclude repeated iterations of certain steps.

Energy Management Systems

In the survey on the implementation of Art.14 sent in 2014 to EU national experts, the authors also aimed at assessing the role and implementation of Energy Management Systems (EnMS) in MSs and the national efforts to promote energy management. An EnMS is a systematic process for continually improving energy performance. The EED defines an EnMS as a *"set of interrelated or interacting elements of a plan which sets an energy efficiency objective and a strategy to achieve that objective"*. Unlike a one-off energy audit an EnMS is a process of continuous improvement which requires that organisations continue to seek out new opportunities for energy savings in all areas of activity.

Establishing an EnMS requires an organisation to follow a series of defined steps. They typically include developing an energy policy and assigning responsibilities, identifying main energy users, setting goals and targets that are measureable, implementing actions that meet the goals, checking for success of actions, and continuous review of the system. Similarly to other management systems like the ISO 9001, the principle of Plan, Do, Check, Act also applies with the continuous improvement as a main driver for the evolution of such system.

Implementing an EnMS may address an organisation's obligations with respect to obligatory energy audits. The EED states that organisations that are implementing an energy or environmental management system that incorporates suitable energy audits will be exempt from the audit obligation in Article 8. Article 5 of the EED also calls on MSs to encourage public bodies to incorporate energy management into their energy efficiency plans.

After the publication in 2009 the European standard for energy management EN 16001[3], ISO 50001 was adopted in 2011. It outlines a cyclical continuous improvement process as the standards that preceded it, respectively the ISO 9001 on Quality Management Systems and the ISO 14001 on Environmental Management Systems. ISO 50001 applies to organisations at any size, and gives guidelines for establishing, managing and improving their energy consumption and efficiency.

With an energy management system an organisation can enjoy all of the benefits of energy audits outlined in the previous section. In addition to these an EnMS can offer the following benefits:

- As a continuous process, it can bring about on-going improvement in performance and productivity and can continue to reduce energy costs over a longer period;
- A successfully EnMS will ensure commitment from senior management to energy efficiency;
- An EnMS can involve all staff in an organisation in the improvement process;
- It may fulfil an organisation's obligations with respect to Article 8 of the EED.
- A successfully EnMS contributes to improving companies competitiveness due to lower energy costs.

Energy Audits in the Member States: Current Status and Best Practice

The following sections contain the results of the survey on the Article 8 status of implementation, carried out in spring 2014 before to the entering in force of the EED (June 2014), during the preparation of the transposition of the EED into national legislation by the MSs. We collected inputs from 25 contact points from the 28 MSs and this section reflects the main findings collected from the received answers. This was complemented by the evaluation of the respective section in the first National Energy Efficiency Action Plans (NEEAP) as submitted by MSs under the EED in June 2014. Overall there were 31 replies. No information from national contacts was received from Belgium, Ireland and Luxembourg. In the cases of Belgium and Ireland, due to the fact that these countries have in place consolidated policies regarding Energy Audits, it was still possible to gather general information from their programmes. One of the main objectives of the survey was to assess if MSs had already in place programmes with the objective of promoting energy audits and what were their main drives or in the case of inexistent programmes in place if there were policies already aligned for the near future in order to comply with the Article 8 requirements.

From the responses obtained it was possible to realize that the majority of MSs have programmes already in place or planned. Among the MSs with consolidated programmes ongoing, the majority has in place voluntary agreements [12] that promote energy audits, even if indirectly, leading to a compliance with the EED.

Overview of existing programmes to promote energy audits in the Member States

From the responses received the following existing programmes exist either on a voluntary or mandatory basis. In figure 1 it is possible to get an overview perspective of the status of the type of programmes in place at the time of the survey.

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[3] This was the first international energy management standard which was built on national standards that were already in existence in a number of MSs: DK, IE, NL, SE

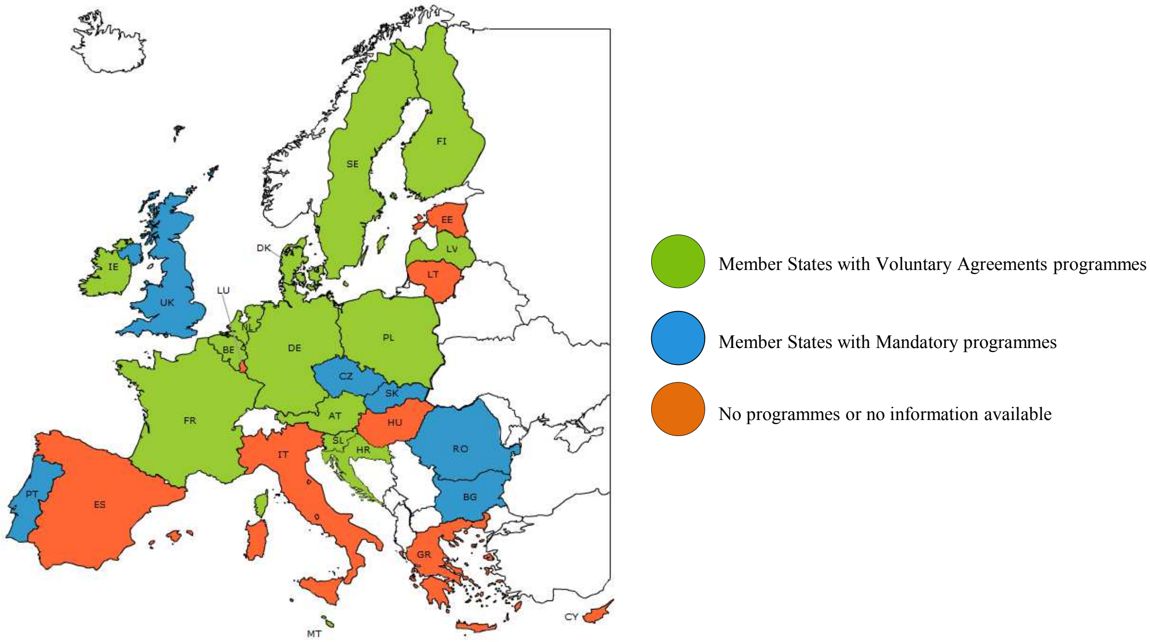

Figure 1 – Types of programmes in place in the EU 28

MSs with voluntary programmes for audits

Austria

The klima:aktiv, the climate protection initiative promoted by the Austrian Energy Agency, acts as the umbrella for the soft measures on energy efficiency. The Energy Saving programme and more specifically the Efficient Companies Programme has the objective to raise awareness for energy efficiency in industry by organizing information events in cooperation with sector associations, promoting the implementation of Energy Management Systems according to ISO 50001, implement energy efficiency measures in industrial enterprises in co-operation with private partners and implement standardized energy audits by organizing trainings for energy auditors. Klima:aktiv promotes, on a yearly basis, training courses for energy auditors which are financed by the Ministry of Environment. For auditors of large industrial companies the Austrian Energy Agency developed a series of specific advanced training courses on motor driven system, steam, cooling, ventilation and AC systems and/or lighting systems. These trainings are advanced training courses aimed at experienced energy auditors who can also get training on guidelines to conduct special audits, auditing according the EN 16247 and get familiarized with the templates for audit reports. A basic training programme for auditors in industrial companies is planned to be in place as soon as the unique requirements for qualification of auditors are published.

There are available subsidies for investment in projects promoted by the Klima Energie Fonds, the Climate and Energy Fund. This fund subsidizes energy efficiency measures which can be associated to the audit programmes allowing the access to lines of funding for the implementation of measures related to areas such as heat pumps and heat recovery installation, air conditioning and cooling, LED lamps installation, upgrading to IE3 motors and thermal building refurbishments.

In the Austrian NEEAP, it indicated that it is expected an overall cumulative energy savings value of 25000 TJ in the 2014-2020 period from measures implemented following an energy audit.

Belgium

In Belgium each region develops its own set of incentives and regulations regarding energy efficiency. For industry, the energy efficiency policy has been focussed on voluntary agreements between industry and the regional governments of Flanders and Wallonia. In Flanders, these agreements are "benchmark" agreements that are signed by individual companies with energy consumptions larger than 0.5 PJ per year. In the Wallonia region, voluntary agreements, named Branch Agreements, have been signed by 13 sector associations which commit themselves to a quantified energy efficiency improvement over the years.

The Benchmarking Covenant was drawn up for the participation of large energy intensive industries, from all industrial sectors. By the participation in the covenant, industries commit themselves to bring or keep energy efficiency of their process installations on the level of the 'best international standard'. As compensation for the efforts of the industries, the Flemish Government guarantees that it does not impose additional measures concerning energy efficiency or CO_2 reductions. No later than 18 months after entering the covenant, the participants draw an Energy Plan which contains all measures necessary to realize and maintain the best international efficiency levels. From that moment on, the industry will annually draw up a monitoring and progress report.

The Auditing Covenant is also a voluntary agreement promoted by the Flemish government that focuses on medium-sized energy-intensive industrial companies with consumptions between 0.1 and 0.5 PJ per year and that do not fall inside the scope of the benchmarking covenant. The companies commit themselves to perform an energy efficiency audit and to implement cost-effective measures.

Companies that sign the Auditing covenant have an energy audit conducted in their facilities and are obliged to implement the energy-saving measures proposed from the audit. The measures offered by the Flemish Government are the same as in the benchmarking covenant.

In the Belgium Flanders Region NEEAP it is referred that besides the voluntary agreements, energy studies submitted for new licences must demonstrate installations energy efficiency and are evaluated by the Flemish Energy Agency (VEA). The VEA assesses also energy plans submitted for licences renewal and obliges enterprises to implement the energy efficiency measures included in their plans within three years in case these measures have an internal rate of return (IRR) above 15%. The energy audits to be carried out every four years under the above mentioned energy policy agreements with companies operating under or outside the ETS are also indicated among the measures in place to comply with Art. 8 requirements.

The Walloon region government has established the Branch Agreements. These are made on a voluntary basis between the government and the different industrial sectors, represented by their federations. Energy Audits financed by the public authorities are carried out on every industrial site by independent auditors formally recognized by the same public authorities. Based on improvement measures identified by the audits, each of the companies defines an objective for improving their energy efficiency and reducing greenhouse gas emissions. The sector association consolidates the individual company objectives and determines the sectorial objectives followed by the actual signing of the sectorial agreement by the companies, the professional federation and the regional government. The energy audits provide an analysis of energy flows of the activities of each site and identify a range of actions to be implemented, which are feasible and cost effective based on the calculation of a payback period. All audit results are sent to the regional government for validation and progress of the implementation of measures is evaluated by the annual calculation of an energy efficiency indicator.

In what concerns the financing of energy audits the Walloon Region Energy has developed the AMURE programme that gives companies a subsidy to carry out an energy audit in their facilities. This audit is conducted according to a set of specifications defined by law and performed by an approved expert by the Walloon Region. The Energy Audits from the AMURE programme must meet the specifications described by the agreement and be carried out by independent auditors approved by the Walloon Region.

Denmark

Denmark has a voluntary agreement scheme since 1996. This voluntary programme requires that a signatory company implements an Energy Management System according to ISO 50001 (which was partly based on the existing Danish standard denominated DS2403, created in the absence of an international standard). Companies have to make a comprehensive evaluation of their energy consumption patterns and implement measures identified with a payback horizon of less than four years. Companies joining the voluntary agreement get a rebate on the CO_2 tax applicable to all fossil energy sources.

If the company does not comply with the prerequisite of the certification of the Energy Management System, the evaluation of energy consumption and the implementation of the measures identified, then the agreement is made void, and the company has to pay back the tax rebate. The evaluation of the energy consumptions or special investigations allow for a comprehensive analysis of energy consumption of a process, plant, or overall production and energy system and include an evaluation of the profitability of energy efficiency projects.

The Danish Energy Agency has developed collective agreements with industrial sector associations that can negotiate with the Energy Agency on behalf of groups of enterprises in their sector, like paper, glass or cement industries, gathering information from companies with similar processes, while signing the agreements.

Energy audits are performed by registered energy consultants that have to pass certain criteria to be registered and the information gathered in the audits is collected centrally by the Energy Agency while the quality of such audits is assumed to be assured by the professionals performing audits, that must keep a high level of professional proficiency in order to maintain their status in the official registry.

With the transposition of the EED into national legislation, the Danish NEEAP mentions that in April 2014, the Danish Parliament has adopted an Act which requires Danish enterprises to carry out mandatory energy audits every 4 years and it is estimated that around 5000 enterprises will be audited under the new framework.

Finland

Finland has had an Energy Audit Programme operational since 1994 managed by Motiva, the Finnish energy agency, which is responsible for the development of the energy audit models, training and certification of auditors. In this programme energy audits are made according to specific models for different customer groups (industry including both SME's and energy intensive industry, public and private services sector and energy industry) and have been subsidised since then. The subsidies attributed to the participants in the voluntary Energy Audits Programme go up to 40 to 50 % of the audit costs and are provided by the Ministry of Employment and Economy. The condition for granting subsidies is that the implementation and reporting guidelines are actually followed through. Participants can then be eligible to other energy efficiency subsidies to implement the results of the audits.

The Finnish Energy Efficiency Agreement Scheme has in place Action Plans for 5 specific industrial sectors and 3 private service sectors and also general action plans for industry, the public sector, and service SME's which are not falling under specific sectors. In all action plans there is an obligation to identify the different energy uses and possible energy efficiency improvement measures. The majority of energy audits in most sectors are conducted under this umbrella.

The main objective of the subsidized audits is to get a comprehensive picture of energy consumption and how it is split to different consumption areas as well as to find out possible energy efficiency measures including calculations on energy saving potential and investments costs. Calculations made by auditors are based on the data (observations, questionnaires, measurements) gathered during the field work as well as information gathered from other sources. The savings are calculated by engineering estimates for the proposed measures based on the data collected.

The Energy Audit Programme manages a database organized by Motiva that gathers the information of all subsidized audits. Energy audits carried under the Energy Audit Programme are carried out by authorised energy auditors trained by Motiva that promotes this training programme for subsidised energy audits auditors. All auditors need to have a sufficient energy technical back ground education to be allowed to participate the auditors' trainings.

Germany

Germany has had in place two types of programmes promoting energy audits at a federal level. Starting in 2008, the KfW, the German Development Bank has been promoting a voluntary energy audit programme aimed to SMEs. This programme consists in the attribution of grants for onsite energy audits for companies with less than 250 employees and consists of an initial audit of two days that has its costs covered up to 80% and a detailed audit of up to ten days and has its costs covered up to 60%. This programme has been successfully working since the beginning with about 5000 audits per year, with roughly two to three energy efficiency measures being adopted per audit [10]. In most cases these are building related measures. This audit programme benefits from a close relationship with regional partners like local industry chambers or local energy agencies that make the bridge between companies and the promoting partner. The companies that are object of energy audits can also benefit from the KfW soft loan programme for financing energy efficiency investments, even if it is recognized that despite the existence of this soft loan programme, financing is still a barrier for many companies.

The requirements on the qualification of auditors are: auditors must have proven qualifications such as a degree in engineering or be authorized to issue energy performance certificates plus further professional training and years of experience in the energy field. Independence is also a major issue on the concerning the qualifications of auditors who may not be hired or take provisions from, or have a share in an energy utility, or a producer of products used when implementing energy efficiency measures and also be neutral respecting to the producer, provider and distributor of energy.

Ireland

The Large Industry Energy Network (LIEN) is a voluntary grouping of companies, organized by the Sustainable Energy Agency of Ireland (SEAI), that work together to develop and maintain robust energy management. LIEN organizes regular workshops, seminars and site visits in which members keep up to date on best practices and new technologies. By learning from experts and sharing knowledge and experiences, members save valuable research time, invest wisely and maximise returns. By participating in LIEN, members commit to develop an energy management programme, to set energy targets, undertake an annual energy audit and produce an annual statement on energy. Companies can be members if they spend more than €1m on energy yearly or are part of the Energy Agreements Programme.

The Energy Agreements Programme (EAP), which is a subset of LIEN was launched in May 2006 and is a voluntary programme suited for large energy consumers. The companies commit to implement an Energy Management System according to the ISO 50001 within 12 months after the signing of the agreement with SEAI as a path to maximise energy saving in their activities. In return, SEAI provides advice, networking assistance and financial support. In this process SEAI performs an agreement gap analysis that is carried out to determine the gap between where the companies are and what they need to do to achieve certification. This allows for the companies to know what actions they have to take and what kind of resources the companies will need to allocate to achieve such certification. The gap analysis is performed by third party experts contracted and trained by SEAI and takes up to two days, while the Irish National Accreditation Body supervises the quality of the assessment.

For each EAP member, SEAI allocates an Agreement Support Manager (ASM) that helps members with advice and visits onsite, while helping the members meet their EAP commitments. Depending on the sector, ASM can provide technical support in areas they are most familiarized since ASM possess a mix of technical/business/relationship management skills and experience of energy management in industry.

In what concerns the support for SMEs, SEAI has developed an SME Support Centre with services of advice, mentoring and also training in energy management tailored for this type of companies. There is a set of tools suited for SMEs with material easy to use in order to make a successful energy saving campaign. These sets of tools are provided in the form of templates for calculating energy usage and cost savings. Another of the tools developed by SEAI is the Energy Map that is an online application that provides a step by step guide to creating a best practice action plan for SMEs. This Energy Management Action Plan is divided into 20 steps that companies can follow themselves in order to implement their energy management system without having the costs of a certification. By registering online, companies can easily track their progress through the whole process.

The Netherlands

In the Netherlands, voluntary agreements are the policy instruments that stand out as a success towards the promotion of energy audits and energy efficiency savings. The Long Term Agreements (LTA) are voluntary agreements signed between sector organizations, ministries, and competent authorities. The first generation of LTA (LTA1) started in 1992 with a focus in onsite process efficiency. The second generation of the LTA (LTA2) that started in 2001 had a change of focus with more attention being given to life cycle efficiency, where the companies are obliged to implement energy management systems and also be more concerned about the sustainability of energy by generation onsite and in the procurement of different energy sources and goods. The third generation of the LTA (LTA3) that started in 2009 has the focus on the long term on energy consumption. This is made by the elaboration of Road Maps to remain competitive and energy efficient in the coming years. The great majority of industry is covered by the LTA with more than 70% coverage with an overall involvement of 1100 companies from 17 industry sectors.

Enterprises have to implement an energy management system according to Dutch Specifications that is similar to EN16001 or ISO 50001, formulate an energy efficiency plan and implement opportunities identified in such plan and report annually their progress on energy performance. Companies inside the LTA are obliged to draw the energy efficiency plan every four years from the outcomes of the audits by establishing energy efficiency goals, define energy efficiency measures concerning processes, supply and product chain and sustainable energy and must define a time plan for the implementation of the measures. During this period companies are accompanied by external expert support that backs the companies to implement such plan. The energy audits within the voluntary agreements must comply with minimum criteria, even if carried out as a part of an energy management system. Energy audits are based on real and updated data and energy consumption is divided between buildings facilities, industrial operations and transportation. As support schemes, the LTA mechanism covers the costs of the audits experts and the costs of the feasibility studies, provides financial incentives through the Energy Investment Deduction and gives access to credit lines.

Sweden

In Sweden there has been in place, since 2005, a voluntary agreement between industry and the government named “Programme for Improving Energy Efficiency in Energy Intensive Industries” (PFE). Companies that are willing to participate get a tax reduction on electricity. Even if it is a voluntary programme, once signed, the requirements are legally binding.

Energy intensive enterprises that participate in the PFE have the requirement to perform an Energy Review and implement a certified energy management system according ISO 50001. The achievements of the requirements are checked by the Energy Agency. The duration of the participation in the PFE is of five years. In the first two years the company has to achieve certification for a standardized energy management system. It must also carry out an energy review, which leads to the identification of energy efficiency opportunities. In the remaining three years the participant company has to implement the measures identified and to submit a report to the Swedish Energy Agency on the energy management system implemented, the energy review and the list of measures identified. At the end of the five year period a final report has to be submitted in order to summarize the actual savings resulting by the implemented measures.

The involvement in the PFE gives participating companies access to tools for the successful implementation of the programme such as manuals on Energy Management Systems, energy audits, analysis and mapping and also provides templates for life cycle costing and guides to procedures on purchasing energy-intensive equipment and project planning. Seminars for programme participants and best practice dissemination are held on a regular basis.

In Sweden, energy audits are carried out by energy consultants and in the case of the PFE are often made in cooperation with the companies’ own staff. Energy Audits within the PFE must be carried out both with a long term and short term vision, which means that companies must consider changes that can influence their energy use over a ten year period. Since certification is obliged for the participant companies in PFE, the quality control is assured by the Energy Management Systems certification bodies. Although spot-checks are made by the Swedish Energy Agency.

Another programme in place, since 2010, is the Energy Audit support programme that is suited mainly for SMEs. It gives a grant of maximum € 3500 up to a maximum of 50% of the audit cost. The overall use of energy is considered including processes, buildings and other usages and a report on how the energy is used in the different parts of the site is produced. The outcome of these audits is a set of recommendations measures to improve the energy efficiency, resulting in an energy plan.

United Kingdom

The United Kingdom has had in place since 2001 the Climate Change Agreements (CCAs) that aim to achieve energy savings and energy efficiency improvements in energy-intensive industries. These voluntary agreements contain targets for eligible industry sectors to increase energy efficiency or reduce carbon dioxide (CO2) emissions. An operator holding a CCA can claim a discount on their climate change levy up to a 65% provided that they met specific targets. The new stage of the CCA that will run up to 2023 allows participants to claim a discount at the revised rate of 90% of the climate change levy for electricity and 65% for other fuels.

There are two types of CCA agreements. The Umbrella agreements that set commitments for eligible industry sectors, and are negotiated between the sector associations and the Department for Energy and Climate Change and the Underlying agreements that contain targets allocated by the sectors to the operators in each sector.

The new phase of the CCA scheme applies to 51 sectors with umbrella agreements, The CCAs cover a wide range of industry sectors, from major energy-intensive processes, such as steel, chemicals and cement, and agricultural businesses. The CCAs targets are set for two-yearly intervals covering a ten year period and the individual operators targets combine to give the sector target overall.

If an operator is under performing considering the initial target, must ‘buy-out’ by paying a penalty for equivalent figure in tonnes of CO2. In the case of over-performance this may be banked for own future use.

The Energy Savings Opportunity Scheme is the primary instrument in order for the UK to implement Article 8 requirements by obliging to carry out of a mandatory energy assessment and energy saving indentification scheme for large undertakings, every four years, with the alternative to implement an Energy Management System in order to comply with the ESOS.

MSs with a Mandatory legal framework for audits in force

Bulgaria

According to the Energy Efficiency Act energy audits are obligatory for every industrial enterprise having annual energy consumption over 3000 MWh and for public buildings with a total floor area over 500 m^2. The term of validity of one energy audit of an industrial enterprise is of 5 years. Summaries of all audits are collected centrally by the Sustainable Energy Development Agency (SEDA).

As part of the obligation of performing energy audits, industrial enterprises above the energy consumption threshold of 3000 MWh have then to implement certain mandatory individual savings targets. Measures recommended by energy audits must be implemented to such a degree as to ensure the achievement of individual targets of each enterprise. Companies are also required to have specialized staff in charge of energy efficiency, to draw up plans and programs and to submit an annual report to SEDA about the implemented energy efficiency activities and achieved energy savings. Exceptions to these obligations are large industrial installations that are included in the EU Emission Trading System (ETS).

According to the Bulgarian NEEAP, in the period from 2011 to 2013, under the above mention Energy Efficiency Act 1286 energy audits in public buildings have been carried out, 183 of which are state owned. In the Bulgarian NEEAP, the measure concerning energy audits of industrial systems consuming more than 3 000 MWh energy per year, estimates a 151ktoe/year savings up to 2020.

Energy audits within the mandatory framework are controlled by SEDA. In the case that audits are prepared in the framework of any specific energy efficiency program usually it is decided that control is not necessary because a chosen project assistant by SEDA, which is the only one who executes the audits or if the audits are executed by many licensed energy auditors the Project Assistant is those who take care about the quality control.

In what concerns funding the Energy Efficiency and Renewable Sources Fund (EERSF) that was established through the Energy Efficiency Act adopted by the Bulgarian Parliament in February 2004 has the combined capacity of a lending institution, a credit guarantee facility and a consulting company. It provides technical assistance to Bulgarian enterprises, municipalities and private individuals in developing energy efficiency investment projects and then assists their financing, co-financing or plays the role of guarantor in front of other financing institutions.

During 2011 in Bulgaria launched programme "Bulgarian Energy for Competitive Industry Financing Facility (BEECIFF)" which is funded by the EU/EBRD Energy Efficiency Finance Facility Fund. The program is fully geared to support SMEs in the preparation of projects for increasing energy efficiency. Under this programme licensed energy auditors across the country are trained to perform simple energy audits in SMEs and present examples of good practices. The purpose of the programme is to assist SMEs in auditing to obtain grant funding up to 50% of the investment needed to improve energy efficiency.

Czech Republic

Energy audits are one of the key instruments for energy efficiency improvements in both the public and private sector and have been introduced in the Czech Republic at the beginning of 2001. Energy Audits were made compulsory for any entity which submitted request for financial support for energy efficiency-related measures to the national programme for promotion of Renewable Energy Systems and the Rational Use of Energy. Audits are also compulsory for energy consumers with total annual energy consumption exceeded a the threshold as specified in the law (35 thousand GJ per year for private companies and 1,5 thousand GJ per years for any public institution), with the exception that the energy audit does not have to address individual buildings with annual consumption lower than 700 GJ per year.

The obligation for Energy Audits development by end-users consuming more energy than the stipulated by the legislation had to be fulfilled within 3 years since the entry of the law in force (i.e. by the end of 2004). For public sector institutions, there were provided grants for energy auditing under condition that recommended measures would be implemented.

Quality control of Energy Audits is limited to a common format prescribed by the legislation and energy auditors are required to obey its stipulations and take responsibility for its correctness. Furthermore, audits geared to the purpose of submitting an application for financial support from any support programme are subject to a control by the programme administrators. That also contributes to better quality of Energy Audits. Since 2013 each auditor must upload basic information on any energy audit completed into a national register kept by the Ministry.

Portugal

Portugal has mandatory regulations concerning energy audits since the 1980's. Following the previous experience, in 2008 the Portuguese government put in place the SGCIE – Management System of Intensive Energy Consumptions - that aims to promote energy efficiency and to monitor consumption of energy intensive installations. It applies mainly to the industry sector, namely individual plants or installations with energy consumption greater than or equal to 500 toe per year. The operators (owners or companies exploiting installations covered by SGCIE) are obliged to register the plant or installation and to undertake a comprehensive energy audit, that has to be carried out by individual auditors or audit companies recognized by the Portuguese Directorate General for Energy and Geology (DGEG). Companies have also to submit an Energy Consumption Rationalization Plan (PREn), together with the Energy Audit Report, for DGEG's approval, with the period of implementation of the PREn depending on the energy consumption level of the plant: 6 years, if ≥ 1000 toe per year or 8 years above 500 toe per year and below 1000 toe per year. After approval by DGEG, the PREn is converted into an Energy Consumption Rationalization Agreement and penalties are foreseen for operators that, after implementing the energy saving measures contained in the PREn, do not reach the targets set. Operators are also obliged to submit a Progress Report on PREn's implementation to ADENE (the Portuguese national energy agency), every 2 years.

Operators of plants with total energy consumption lower than 500 toe per year may also adhere to SGCIE on a voluntary basis. These will have the same obligations and incentives as those obliged to follow the regulation.

DGEG has the role of supervision and inspection and is the governmental organization that gives final approval to the Rationalization Plans submitted by the Operators, and analyses and decides on the requests presented by individuals and companies for qualification as energy auditors. ADENE, being responsible by the operational management of SGCIE, checks the energy audit reports and PREn's uploaded in SGCIE website, before sending them for DGEG's approval. In the extreme cases that the submitted PREns are not satisfactory, ADENE also performs energy audits after a meeting and a visit to the plant in order to evaluate the quality and accuracy of the audit and identify possible additional energy saving measures not included in the original PREn.

Through the National Energy Efficiency Fund, financial incentives for energy efficiency improvements are provided to operators for the realization of energy audits and/or energy monitoring and management systems. Grants cover part of the costs in the case of energy audits (only valid for plants with a total consumption between 500 and 1,000 toe/year) and 25% of eligible costs for the purchase and installation of energy consumption monitoring equipment and Energy Management Systems . Since 2013 operators who comply with SGCIE regulation can benefit from tax incentives, namely a tax exemption for certain fuels (coal, fuel oil, oil coke, LPG, and natural gas) and for electricity.

Romania

In Romania, there is a legal framework that obliges companies with energy consumption larger than 1000 toe per year to annually make an energy audit elaborated by an energy auditor empowered by the Romanian Agency for Power Conservation, according to legal regulations. This audit is then at the basis of the establishment and implementation of energetic efficient improvement measures. The companies have also to prepare an energy efficiency master plan based on three payback periods of the implemented energy efficiency measures: short term measures (no cost or low cost measures), medium term (payback period for energy efficiency investments less than 3-5 years) and long term measures (mainly big investments related to change of technology). Finally, companies consuming more than 1000 toe per year need also to have a certified energy manager. This energy manager is the responsible to send an annual a report to ANRE, the National Regulatory Authority for Energy, regarding the main indicators of energy consumption and have to renew their certification every three years. Companies have the alternative to outsource the energy management activities by hiring an energy service company that, like the energy managers, have to be accredited by ANRE. In order to assure the quality of energy audits, minimum quality criteria have been defined in the legislation together with a code of conduct for the realization of audits.

Economic operators annually consuming an energy between 200 and 1000 toe, must perform an energy audit every 2 years made by a legal entity or person authorized by the ANRE under the conditions of the law.

Slovakia

Slovakia has in its legislation the obligation to conduct energy audits for individual enterprises and agricultural holdings, based on their total annual energy consumption since 2008. In the 2011–2013 reporting period have been conducted 210 energy audits. With the entering into force of the EED and its national transposition into the Energy Efficiency Act, energy audits will become mandatory for the 614 identified large companies. For the period of 2014-2020 the new Operational Programme Environmental Quality projects in industry encompasses measures focusing on support for energy auditing at industrial enterprises (SMEs only) and on the implementation of measures derived from energy audits (all industries), including the introduction of measurement and management systems. It is also foreseen, within the scope of the Operational Programme Environmental Quality, that the Slovak Innovation and Energy Agency will support municipalities and higher territorial units in the preparation and implementation of plans on sustainable energy and in the introduction of systems of energy management (including energy audits). In order to be approved as an energy auditor the professionals must pass an examination of professional competence organised by the Slovak Innovation and Energy Agency and already registered energy auditors are required to attend periodic training every three years. This training is attended by an average of 60 energy auditors every year.

Other MSs without specific legislation and/or voluntary programmes

Regarding other MSs that did not reply to our questionnaire or did not have any programmes promoting energy audits, prior to the publication of the EED, the NEEAPs analysis give some information on the transposition of Article 8 into national legislation.

In *Italy* the Italian energy agency, ENEA, is working on a database that will include information on all enterprises to be obliged to undertake energy audits. A certification scheme and specific standards have been also put in place for companies that will supply energy audits. According to the NEEAP, the decree transposing the EED establishes that a specific public tender procedure will have to be published by 2014 for specific programmes implemented by Italian Regions to financially support SMEs in the implementation of energy audits with 15 million Euros to be annually allocated between 2014 and 2020 to provide this financial support.

Cyprus is complying with certain provisions of Art.8 (e.g. Art.8(2) on programmes for SMEs and Art.8(4) on mandatory audits in large enterprises) which included in the new 2014 Law on Energy Efficiency in End Use and Energy Services. The remaining Art.8 provisions such as auditors registry, registration/training procedure, technical guidelines to be followed etc. are already covered by existing legislative measures. Despite the above, the Cyprus NEEAP stated that no energy audits have been carried out thus far and the training and licensing of energy auditors only began in the second half of 2013.

In *Estonia*, a grant scheme for financing energy audits in apartment buildings is already existing with 1156 energy audits having been supported by this scheme between 2011 and 2013. The full transposition of Art. 8 (i.e. including the legislation for mandatory audit in large enterprises) is expected to enter into force by 2015.

Greece has had a legal framework for conducting energy audits published in 2010 that has set the institutional framework for conducting energy audits (Art.8). However, certain Art.8 requirements have not been met. These include mandatory audits by large enterprises (Art. 8(4)) and minimum criteria which energy audits need to meet according to the EED Annex VI together how compliance with these minimum criteria is to be enforced. In the Greek NEEAP it is stated that the Centre for Renewable Energy Sources (CRES) will develop an information system presenting the total number of energy audits, energy audits in large enterprises, and large enterprises which are obliged to carry out energy audits. The system will be ready in September 2015 and a call for energy auditors is also expected in 2015.

According with the *Latvian* NNEAP, for the promotion of energy audit and energy management system, two specific regulations have been already implemented in Latvia: Regulation on Industrial energy Audits and on Independent Experts in the energy Performance of Buildings. A plan to finance up to 60% of the cost of industrial energy audits is under discussion, together with the introduction of mandatory audits for large industries.

Measures on the introduction of mandatory energy audits for SME are not yet in force, as *Lithuania* is planning to introduce changes in the national legislation to address requirements of Art. 8. No further information is provided and there is no clear indication of the starting year of its operation. Other measures on energy audits include ongoing adaptation of methodologies and appraisal procedure to requirements of Art.8. In addition, energy audits are required for receiving financial support from energy efficiency improvement programmes.

The *Luxembourg* NEEAP mentioned that the introduction of legislation for mandatory audits in large enterprises has been planned, but the timeline was not mentioned. The mandatory energy audits should be carried out in 100 to 150 large enterprises. According to the NEEAP, there is a voluntary agreement in place that obliges companies to carry out energy audits while introducing energy management systems. About 60 larger Industrial enterprises participate in the voluntary agreements with the industrial sector.

Activities to encourage SMEs to undergo energy audits

Point 2 of Article 8 of the EED asks MSs to develop programmes to encourage SMEs to undergo energy audits and to implementation the recommendations from the audits. A significant number of MSs have programmes in place to encourage SMEs to undergo energy audits. However there are still MSs that do not have such programmes in force or not even planned. The following good examples of programmes suited for SMEs, already in place before the transposition of the EED, have been identified.

In Bulgaria the Energy Efficiency and Green Economy Programme foresees a higher percentage of grant intensity (% of total eligible costs) in case of energy audit driven projects, as well as a bonus grant for technology-driven projects based on an optional energy audit if the beneficiaries are the SMEs. The Energy Efficiency and Renewable Sources Fund provides low-interest loans covering up to 75% of the resources required for implementation of energy audits and of projects for improving energy efficiency in SMEs and others. There is also the BREECL which is a program that provides grants to SMEs up to 15% of the project. Energy audits are an obligatory document, are executed by a Project Assistant and the cost is covered by the programme. The programmes present in MS such as Austria, Germany, Finland or Sweden presented in the previous chapters are tailored for SMEs and promote energy audits specifically for these type of companies.

There are examples of MSs that even if the programmes are not designed for SMEs only, these companies can still participate, like the cases of Cyprus or even Denmark where the voluntary scheme obliges for participating companies to implement an energy management system according to the ISO 50001, or in the Netherlands or Ireland where SMEs can participate in the voluntary agreements and implement an Energy Management System with the support of the governmental bodies.

Energy Management Systems in the Member States

In the evaluation of the survey responses on Energy Management Systems (EMS) implementation in the MSs it can be observed that even if in some cases, these EMSs are active due to private initiative of individual enterprises to improve their energy performance, there are some MSs pro-actively promote EMSs to enterprises. Programmes in Denmark, Germany, the Netherlands, Sweden, Finland or Ireland have allowed these MSs to gain a high level of expertise in relation to ISO 50001, which is the standard most generally implemented. [4] [9]

Another finding from the survey is that in MSs with programmes promoting EMSs, these programme were essential to stimulate the uptake by companies of EMSs. It remains to be seen whether the transposition of Article 8 will change this or whether companies will demand only audits rather than implement Energy Management Systems.

In the Netherlands even if there is a significant number of companies (around 20 in November 2013) with a certified ISO 50001 system, a bigger part of the enterprises have a certified ISO 14001 management system in place were energy is included as significant environmental aspect. Within the third stage of the LTA covenants enterprises have the obligation to implement an energy management system and within the paper sector implementation of ISO 50001 is being promoted and support is being offered to the respective enterprises.

In Sweden there is an estimation of more than 100 enterprises certified, mainly energy intensive industrial companies and the activities to develop EnMS are made in networks of energy intensive SMEs in order to introduce simplified versions of the systems.

Germany is the country in the world with more enterprises ISO 50001 certified with more than 3000 certifications. The major reason to this kind of figures relates to the fact that enterprises that implement an Energy Management System can obtain exemptions from electricity tax. In order to get access to this benefits, companies must prove that they have an energy management system (certified by DIN EN 16001 or DIN EN ISO 50001) implemented or alternative systems for SMEs including audits at the latest by 2015. Companies may benefit from reductions on electricity or energy taxes of up to 90%. EN ISO 50001 certification or EMAS registration is a prerequisite for granting of these tax reductions and SMEs may choose to adopt alternative systems for energy efficiency improvement, satisfying the requirements of EN 16247-1in order to get the tax reductions.

Another mechanism in Germany is the Exemption from EEG-levy. Since 2000 Germany uses the Feed in tariff system “Erneuerbare Energien Gesetz” (EEG) to support electricity generation from renewable sources and the subsidies are passed on to electricity consumers who pay the so called EEG-levy. In order to sustain international competitiveness, exemptions of payment are possible, when companies have a certified Energy Management System.

It is evident that energy efficiency by itself is not yet the driving force for the implementation of an EMS and that incentives are the main drivers for companies to get ISO 50001 certified

Implementing Article 8 in the Member States: An Analysis

From the survey analysis it is possible to identify three types of compliance towards the transposition of the Article 8 of the Energy Efficiency Directive. First are the MSs with mandatory programmes in place that oblige "large" energy consumers to perform energy audits on a regular basis and this comes nearest to the requirements of the article 8 of the EED. Secondly, the MSs with voluntary programmes in place that can also meet the requirements of the Directive by the promotion of energy audits in agreements signed normally between sectorial associations and the governmental bodies, and lastly the MSs that still have a great amount of work in order to meet the deadlines established for the transposition of the Directive into national law.

While countries with programmes in force, mandatory or voluntary, have already in place mechanisms to comply with the article's requirements, needing less effort to adjust their national structures to fully meet the terms of the requirements, there is still a large number Member States that are still in the planning phase or not even, which will lead to a great effort from all parties, government and enterprises, to adjust in order to comply with all the requirements.

Even if it is possible to conclude that some MSs are adapting national situations to the requirements of the EED, there is still a great work to be done in order to assure that large enterprises undertake energy audits every four years with a high level of quality, meeting the requirements of Annex VI and are performed in an independent way by qualified auditors. The existing types of programmes that encourage energy audits are mainly voluntary agreements, especially from sectorial agreements with governmental promotion and mostly tailored for large companies, leaving SMEs still in the need to be addressed, since there is still a lack of attention toward the promotion of energy audits in this type of companies. The periodicity of energy audits in voluntary agreements is another subject that still needs to be addressed since basically only the programmes that promote the certification of Energy Management Systems, due to the requirements for the maintenance of such systems, oblige the execution of periodic audits.

Even if in the Member States with criteria already in place regarding the quality of audits, the level of quality is not similar in all Member States, which may lead to a great effort to ensure that audits are realized on a common ground throughout the European Union. This is especially important in the case of multinational companies with facilities in different locations.

The same may occur with the criteria on the qualification of auditors. The Directive leaves to MSs to establish the minimum criteria for qualifications of energy auditors and in a great part of the Member States this is passed on to the programme administrators or to the certification bodies that have to guarantee that auditors have the qualifications to perform such technically demanding work, instead of being clearly stated in the national legislation. A common framework establishing criteria for training programmes could be a way to overcome this potential disparity.

EMSs are no new to large energy consumers. Communication and incentives related to the implementation of such management tools are means to be taken into consideration when promoting EMSs, following the cases of success previously mentioned.

One of the most significant barriers to the implementation of Article 8 of the EED is the difficulties found by MSs to identify the companies that are obliged to perform energy audits according to its size instead of defining them by an energy consumption threshold. The delay of the transposition of the EED requirements into national legislation and the lack of financial resources in companies to comply with the EED requirements were also points raised by the survey participants.

Conclusions

Energy Audits are an important instrument to improve energy efficiency in organisations. Energy audits may be stand-alone initiatives or part of an EMS. Audits may also be promoted as part of national policies, e.g. as part of a voluntary agreement. Art 8 of the EED imposes to MSss to introduce mandatory audit for large companies. There is still a large amount of work to be made by the MSs in order to implement Art 8 in the different national legislations since at the present time there are still MS without any policies to perform mandatory energy audits in large companies every four years. Nevertheless it was possible to identify MSs already complying with these requirements, mainly by the implementation of mandatory or voluntary programmes.

From the barriers identified by Member States, the clarification on the qualification of auditors and the quality of energy audits criteria and the ability to identify every non-SMEs were pointed as main obstacles for the correct implementation of the requirements of the EED.

Large companies (including often the large energy consumers) represent the companies that somehow are already more aware of the benefits of energy efficiency due to the energy costs. Many of these companies have executed energy audits and have implemented the measures identified or have implemented an EMS. However, SMEs should be considered by MSs, when designing their energy policies and in the transposition of the EED into national legislation. The same applies to the promotion of Energy Management Systems which until now have been mainly promoted by market forces, and had so far a limited success or within voluntary agreements requisites. EMSs are key instruments to contribute mininise energy consumption in the various industrial sectors.

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Drives 1

Loss Measurement System for Variable Speed Drives

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Abstract

The paper presents a loss measurement system for variable speed drives systems. Experiments and notes from two alternative measurement systems is presented, discussed and analyzed. The first method is the direct input-output method and the second one is the calorimetric method. The pros and cons of the both methods are highlighted. The calorimetric systems suitable for motor and converter loss measurements up to 30 kW of loss powers are presented. True loss measurement result from example case are used to demonstrate the challenges in the variable speed drive measurement.

Introduction

The electric motors are the most important type of load in the industry, consuming about 65–70% of the electric energy [1]. Hence, thermal and efficiency issues are among the hot topics in the electrical machines and drives community [2]. The motor and drive efficiencies are linked to the thermal behavior of the devices. In the battery power systems such as vehicle traction applications, the efficiency is even more important than in the typical grid-connected use [3], [4]. In general, the electric motor efficiency is continuing to improve and this poses new challenges to the motor loss determination. New and more efficient constructions have to be verified by the measurements. The accurate measurement of losses of high-efficiency devices such as converters and motors are challenging. In the frequency converter measurements, the challenges are mainly due to extreme high efficiency, distorted input current due to the rectifier bridge and PWM-voltage in the output. In the motor measurements extra problems arises from the temperature dependency of losses and from the low power factor with partial loads. The frequency converter and motor are used together, but only rarely the loss measurement results for both devices can be obtained simultaneously. The desired operating points differs from each other and the voltage sensing points have to be chosen differently – motor terminals are used in the motor measurements and converter terminals in the converter measurements. The cable between the devices creates unwanted losses and uncertainty component that should be excluded from the results. The behavior of maximum power loss error with different measurement methods as a function of the overall efficiency is illustrated in Fig. 1.

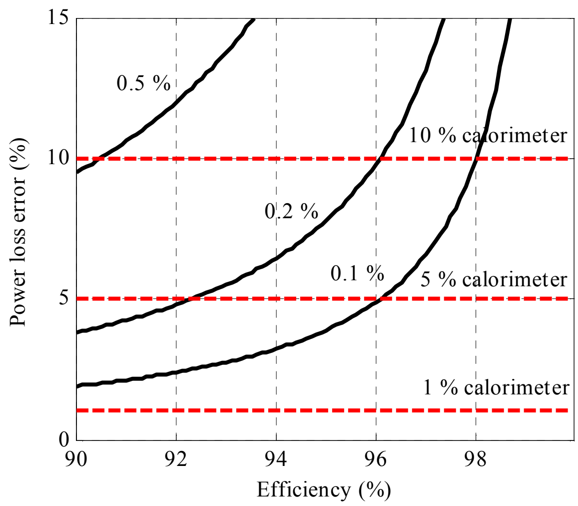


Fig. 1. The worst case uncertainty of power loss with the input-output method as a function of overall efficiency with different power measurement uncertainties as a parameter (0.1%, 0.2%, and 0.5%). The same uncertainty is both in the input and output powers. A calorimeter with an uncertainty of 1%, 5% and 10% is given as a reference (dashed line).

Fig. 1 is giving the worst case uncertainty of the input-output method. To get the power loss uncertainty below 5 % when measuring the losses of the device with 96 % efficiency you will need the power measurement uncertainty to be less than 0.1 % in the input and output powers. If the input power is assumed to 1000 units then the output power is 960 units and losses are 40 units. With the 0.1 % measurement uncertainty, the input power uncertainty will be 1 unit and the output power uncertainty the same 1 unit. This leads to loss uncertainty of 2 units that is 5 % from the 40 unit losses.

Calorimetric measurement system

The calorimetric measurement method has not been widely used to determine the losses of electric drive system since the method has been considered too difficult and troublesome to arrange. The method has its advantages over the input-output method and old misbeliefs should be forgotten and the method should become more common method in determining the electric drives efficiency and the method should be also included in the corresponding international standards.

When considering the disadvantages of the calorimetric measurement method, the most commonly used arguments are 1: the slow measurement rate, 2: the heat leakages through the walls and 3: the air properties variation during the tests and naturally the complexity of system. The measurement rate of single operation point can be easily maintained when using standard balance type calorimeter where the main and balance tests are carried out sequentially and the balance test is carried out automatically during nighttime. Traditionally the motor losses are obtained using the heat run test in the thermal equilibrium so using the calorimetric method, it will not extend the measurement time at all, since the thermal time constant of the calorimetric chamber is shorter than of the motor. The measurement rate can be increased by using pre-determinated loss curve that is created using the heater resistor, using series or parallel chamber structure [1] and the loss can be viewed online. When the air is used as a coolant fluid there is no need for heat exchanger and the extra time delay from heat exchanger does not exist.

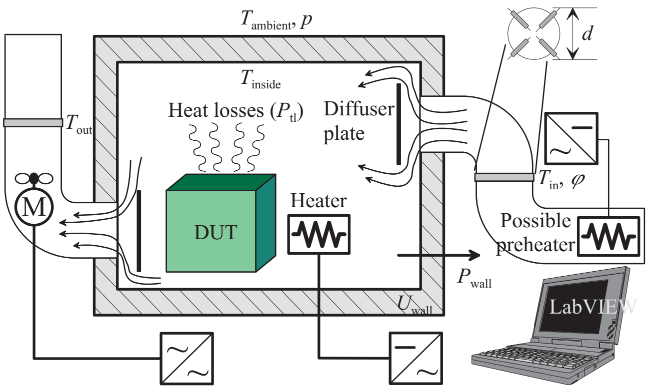
The heat leakage problems are from the time that polystyrene was used as insulation in the calorimetric system and the usage of polyurethane decrease the problem to the level that can be neglected in most cases since the polyurethane is twice as good insulation as the polystyrene and the insulation is airtight. Air tightness of the chamber is essential, because with this it can be guaranteed that the air is circulated through the known route where it can be measured and the possible changes detected. The polyurethane insulation boards are available with various thicknesses and can be easily clued together with polyurethane foam to guarantee air tight chamber structure with low heat leakage. The effect of the air properties variation during the measurements is not significant that is often denoted. The effect of the humidity, barometric pressure and temperature variation is given in [6] and how to perform the mass flow correction in [7].

The complexity of the system is reduced when there is no need for active loss control over the walls and only the volume or mass flow rate of the coolant must be controlled and the temperature of the inlet and outlet have to be measured. Nowadays, many manufacturers are selling frequency converter driven blower as a package and they can be easily used to controlled volume flow purposes in most of the cases and still gain high accuracy. The frequency converter driven blower speed can be used to control the chamber or chamber outlet temperature with closed-loop control.

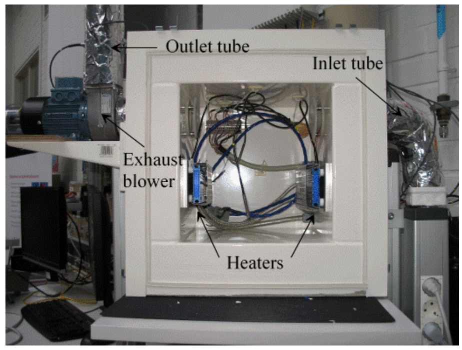
Two main benefits of the calorimetric system are that the accuracy is not a function of the efficiency and the measurement method is totally independent of the input and output voltage of current waveforms. Naturally, the efficiency cannot be determined using only the calorimetric system and there is still need to measure the input and or output power of the device. But it should be noticed that then the power measurement has not that big role for the uncertainty of the efficiency as without the calorimeter. Therefore, to use of the both methods simultaneously makes really sense.

Calorimetric measurement systems in Lappeenranta University of Technology

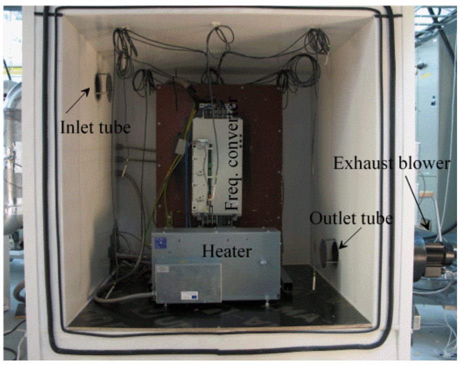
The open and balance type calorimetric system is easily scalable to different sizes [8] and can be used to determine the losses of converters, motors or other electric devices [9]–[12]. To use appropriate size of the calorimeter chamber for different devices it enable higher accuracy control over volume (mass) flow and less uncertainty that is related to the losses through walls. Three different size of chambers are used to obtain the power losses of power electronics and electric motors up to 30 kW within uncertainties of 0.3%...0.7%. The basic construction is a single box with insulation material of polyurethane to minimize uncontrolled heat fluxes. The chamber is designed according to the size of devices to be measured. Overview of the calorimetric measurement systems in Lappeenranta University of Technology is illustrated in Fig. 2.



Basic concept of heat loss measurements. The heater is applied to the balance test and to warm the chamber before the start. The temperature sensors at the inlet and outlet tubes are at a 90° angle to each other, and the distance from another sensor is $\boldsymbol{d/3}$.



Small size. The chamber of the small size calorimeter is designed to measure power losses up to 300 W. The chamber has internal dimensions of 0.3 m × 0.3 m × 0.3 m ($\boldsymbol{l} \times \boldsymbol{w} \times \boldsymbol{h}$).



The chamber of the middle size calorimeter is designed to measure power losses up to 2 kW. The chamber has internal dimensions of 1 m × 1 m × 1 m ($\boldsymbol{l} \times \boldsymbol{w} \times \boldsymbol{h}$). A sandwich form of 120 mm polyurethane plane between two layers of fiberglass laminates is employed in the structure.

The chamber of the big size calorimeter is designed to measure power losses up to 30 kW. The chamber has internal dimensions of 2 m × 2 m × 2.5 m ($\boldsymbol{l} \times \boldsymbol{w} \times \boldsymbol{h}$). A sandwich form of 100 mm polyurethane plane between two layers of metal plates is employed in the structure.

Fig. 2. The overview of the calorimetric measurement system in Lappeenranta University of Technology.

Example measurement case

In this example measurement case the data from 160 kW voltage source converter is used. The calorimetric measurement results have been obtained with the big size system. The converter structure is very basic, the diode bridge is used as a rectifier and three arm IGBT-module is used to generate the PWM- voltage output with carrier based modulation. The measurement procedure of the calorimetric measurement system with example data from high power converter measurements is illustrated in Fig. 3 and the example data set is tabulated in Table 1. The numerical data in Table 1 is gathered at the end of the main and balance tests. The data set length is 2000 seconds, 100 samples with 20 s interval. The curves in Fig. 3 and the numerical data in the Table 1 show that thermal equilibrium has been reached and very small variation in the quantities that are used for determining the calorimetric loss result can be seen.

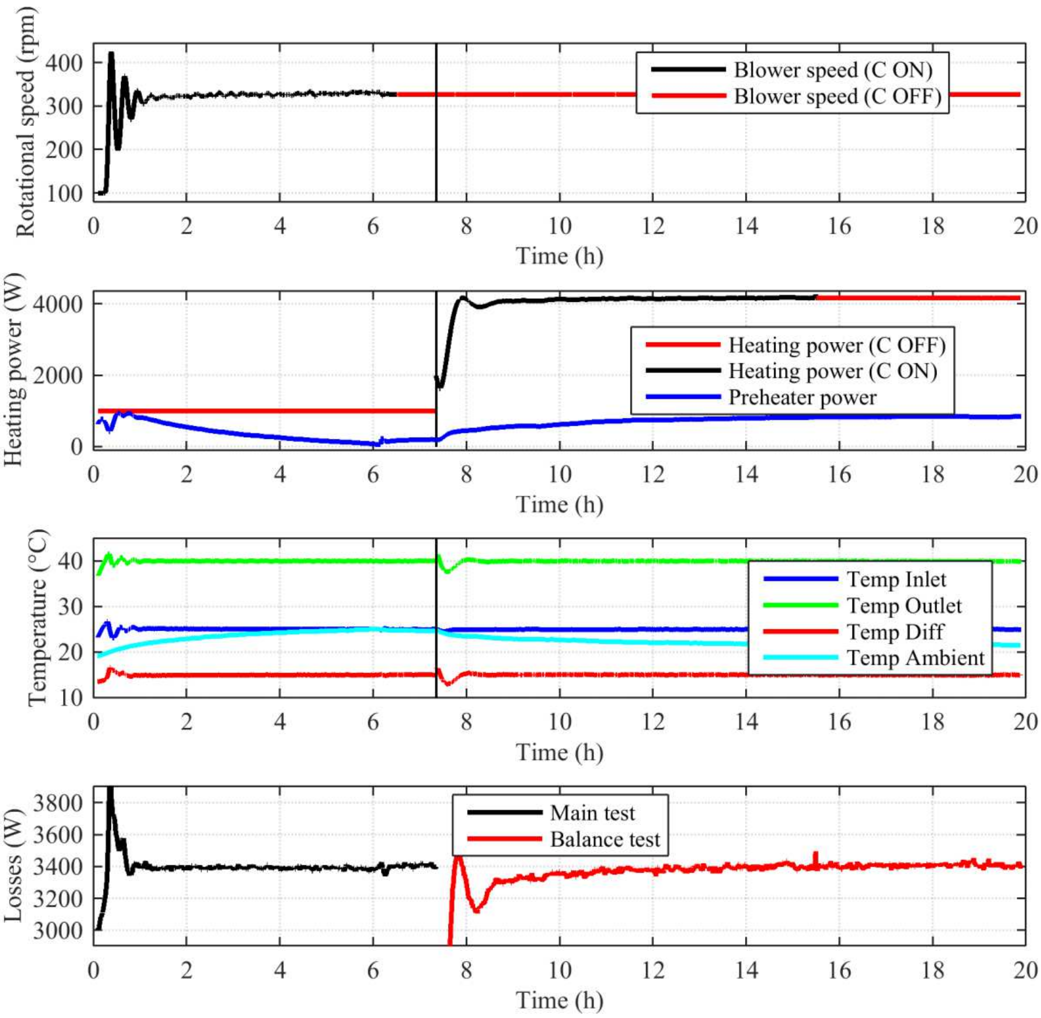


Fig. 3. Calorimetric measurement procedure. Example data from high power converter measurements.

Measurement procedure

1. The inlet air temperature is kept at fixed – predetermined level with a preheater (25 °C).
2. DUT is driven with a constant load. The exhaust blower speed is controlled with respect of outlet air temperature (40 °C). The calorimetric chamber inside temperature is close to outlet air temperature.
3. The exhaust blower speed control is turned off, when the system is close to thermal equilibrium (no remarkable changes in temperatures). The blower speed reference is fixed.
4. The system settles down to thermal equilibrium that is equivalent to DUT losses. The losses transferred by the air flow and the conducted losses through the walls are constant.
5. The measurement results in the main test are written down, when there exists no changes in the temperatures. See Table 1 – Main test column.
6. The balance heater power control is turned on. The DUT is powered down.
7. The exhaust blower is still kept running with fixed speed (part 3). The balance heater power control finds the correct power that produces exactly the same outlet temperature than in part 5.
8. The heater power control is turned off (no remarkable changes in temperatures anymore). The heater is driven with fixed power reference so long that there exists no visible changes in the air temperatures.

9. The balance tests results are written down. If the air humidity and barometric pressure are the same at the end of the balance test measurement and at the end of the main test, the resistor power shows exactly the DUT losses. See Table 1 – Balance test column.

Table 1. Example of calorimetric data gathered from high power converter measurements.

	Main test			**Balance test**		
	Min	Average	Max	Min	Average	Max
Ambient temperature (°C)	24.68	24.70	24.71	21.45	21.49	21.53
Chamber temperature (°C)	-	37.08	-		37.32	
Pressure (Pa)	102017	102020	102023	101731	101738	101748
Humidity (RH)	17.72	17.81	17.88	17.49	17.58	17.65
Input temperature (°C)	24.97	24.99	25.01	24.96	24.98	24.99
Output temperature (°C)	40.00	40.02	40.03	39.94	39.97	39.99
Temperature difference (°C)		15.03			14.99	
Heater power (W)	1000.00	1000.00	1000.00	4155.00	4155.00	4155.00
Ventilation blower power (W)	270.0	270.0	270.0	270.0	270.0	270.0
Blower motor speed (rpm)	326.20	326.20	326.20	326.20	326.20	326.20
Calorimetric losses (W), 2000 s	-	-	-	3393.7	**3401.9**	3411.6

In the calorimetric method, the losses are determined using the air flow and heat losses through the chamber walls

$$P_{\mathrm{loss,cal}} = q_{\mathrm{m}} c_{\mathrm{p}} \Delta T_{\mathrm{air}} + U_{\mathrm{wall}} S_{\mathrm{wall}} \Delta T_{\mathrm{wall}}, \tag{1}$$

where q_{m} is the mass flow rate, c_{p} the specific heat capacity of moist air, ΔT_{air} the temperature difference of moist air between the inlet and outlet tubes, U_{wall} the overall heat transfer coefficient of the chamber, S_{wall} the area of the chamber walls, and ΔT_{wall} the temperature difference across the chamber walls. When examining the resolution and accuracy of the calorimetric measurement system we can neglect the loss difference through the wall in the main and balance tests, so we can neglect the latter part in (1) and the air humidity, temperature and barometric pressure (if examining strictly, the barometric pressure change in the example data set has the 12.5 W effect on the result) are almost the same in both tests and the ventilation blower is rotating all the time with the constant speed, the losses are directly related to the temperature difference between the incoming and outgoing air. Thus, the temperature difference of 15 °C is directly related to the 4155 W of total power losses generated inside the chamber, this means that every 0.15 degrees is equivalent to 42 W of losses, which is in the range of resolution that even the low cost temperature measurement devices can achieve.

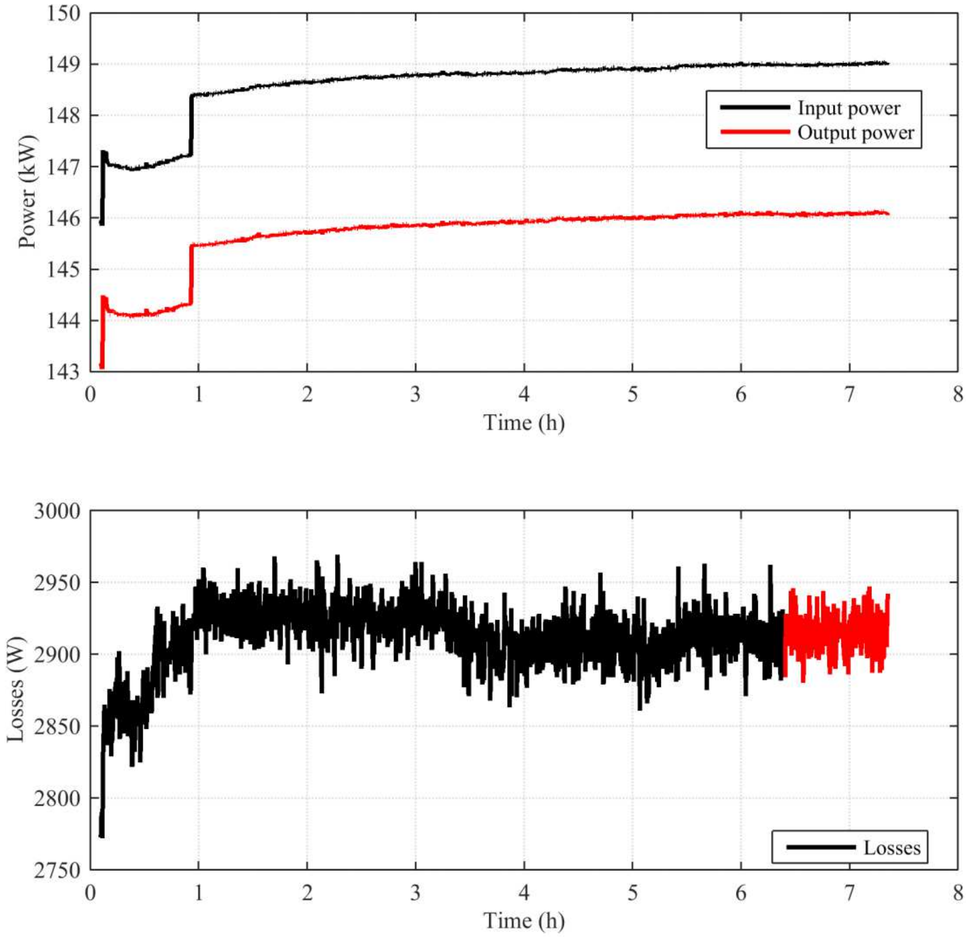


Fig. 4. The measured input and output power variation and the loss variation as a function of time in high power converter measurements. The last 2000 samples marked with red in the loss curve are used as a result for measurements and given in Table 2.

Table 2. Example input-output measurement data gathered from high power converter measurements.

	Min	Average	Max
Input Power(W)	148962	149005.7	149049
Input Current(A)	233.6	233.7	233.8
Input Voltage(V)	237.2	237.8	238.7
Output Current (A)	285.5	285.6	285.7
Output Power(W)	146034	146090.4	146148
Converter Losses (W)	2903	**2914.4**	2927

The electric quantities are gathered in Table 2 from the same high power measurement than in the calorimetric method quantities in Table 1. The values are very stable because the total system is in the thermal equilibrium and the power analyzer is set to take 5 second samples with 20 second intervals. So for example the single current is the average value during 5 second sample calculated using 1 million data points and active power is the mean of the current times voltage multiplication using 3 times million individual voltage and million current samples. If shorter sample times are used, more variation in the quantities can be seen.

The input-output losses after removing the minimum and maximum values and adding the ventilation losses and averaging are 3184.4 W. The losses minimum and maximum values are as a calculated difference with the same time step samples not from input and output power extreme values. The 2000 samples show that the converter losses during this time vary from 3173 to 3197 W (value includes 270 W ventilation blower power). The calorimetric measurement result was 3401.9 W. The results seem to be far away from each other, the difference is 217 W, around 6 % of the total losses or 0.75 degrees in temperature difference. If the difference is compared to the input power, that is 0.14 % from the total electric power at the converter terminals. Now we can say that the loss results are very close to each other when we keep in mind that the basic 1 year accuracy of the used power analyzer is 0.15% from power reading plus 0.075 % from power range with sinusoidal quantities and unity power factor and in the case of converter, these conditions does not apply.

Electric drive measurements

Despite the calorimetric method has advantages over the input-output method, it can only give the total losses of the device and no indication why the losses are what they are. The electric drives laboratory of the Lappeenranta University of Technology has highly educated staff with three decades of experience in loss measurements and equipped with recently updated high accuracy measurement systems. The key rules for new measurement equipment acquired in the laboratory are the Ethernet connection and LabVIEW compatibility. The Ethernet connection is easily controllable, fast, reliable and easily extensible using hubs or router and accessible with any laptops or desktops inside the university network. In addition to data collection, the Ethernet connection can be used to reset, set and save the settings in the most devices. This guarantees the correct settings of the measurement instrument in all measurements and also adds traceability of the results. LabVIEW software guarantees that the measurements are carried out in the same way every time and the setups of the measurements are documented at the same time when the software is developed.

In an electric drives measurement, you can rarely use the direct inputs of the power analyzers and therefore the external current sensors are needed. The lab is equipped with Zero-Flux sensors from HITEC that can be used to measure DC or AC current with high accuracy and bandwidth. Since, the uncertainty of the current measurement is related to the rated value of the sensors, the lab has 6 piece sets with different rated current values of 100 A, 300 A, 600 A and 3000 A.

The basic uncertainty of the power measurement of the power analyzers are related to the voltage, current and power factor. More specifically, the uncertainties or accuracies are given as reading plus a range error where the reading error uncertainty is directly related to the reading and the range error for the selected current or voltage range. Normally you have to choose the minimum voltage and current ranges (peak or RMS) to achieve the most accurate results even though the quantity to be measured is power, often denoted as active power. The power measurement uncertainty is related to

$$\boldsymbol{U}_{\mathrm{c,\,Power\,Range}} = 3\boldsymbol{U}_{\mathbf{range}}\boldsymbol{I}_{\mathbf{range}}\boldsymbol{N}_{\mathbf{sensor}}, \tag{2}$$

where $\boldsymbol{N}_{\mathbf{sensor}}$ is the current transformation ratio. Normally, you cannot play with the voltage range, but the power uncertainty can be minimized when selecting the current range times the sensor ratio. This should be considered when choosing the current sensors for a certain power analyzer. The power analyzers can be equipped with different power modules with different maximum current ratings (e.g. 2, 5, 30 or 50 A). If the target of the measurement system is the devices below 30 A current, the current can be fed directly to the power analyzer to get the most accurate results with high rated power modules, but if the same power analyzer is used to measure higher power DUT where current measurement device is needed the accuracy can be very low.

As in the case of the current measurement devices, the uncertainty of the motor measurements are related to the nominal value of the torque transducer and therefore the measurement instruments should be chosen according the DUT. The LUT electric drives lab is equipped with different size of the torque transducers from HBM with the rated torques of 100 Nm, 200 Nm, 500 Nm, 1 kNm and 2 kNm. There are also torque sensors for lower and higher torques from Magtrol. One of the benefits of the HMB T12 is the true digital data acquisition directly to the computer without any additional A/D conversion that creates additional uncertainty to the measurement results. One crucial thing in the motor loss measurement is the lineup of the system. The parasitic loads such as bending moment will influence in the torque measurement results and good laser alignment system used by trained staff should be used to line up the system.

Data analysis

The international measurement standards do not give exact rules how the measurement data should be processed or filtered to obtain the final result. How many samples should be used and what is the correct sampling time? Is the single 50 ms or 500 ms value enough? The post processing of the data is much easier to perform than to do it in real time. The filtering is the most used data processing method, but the problem in low-pass or moving average filtering is that single totally erroneous value can shift the average value considerable amount. Therefore, more reliable results can be obtained with removing the extreme values and then averaging the rest. The amount of the samples needed really depends on the nature, size and thermal time constant of the device and what is the purpose of the measurements.

Preferable method

The both method input-output and calorimetric method have their own benefits. The calorimetric measurement system comments are related to the open balance type calorimeter presented in this paper. The open air cooled system is an easy choice because the majority of the installed electric motors are air cooled. The calorimetric measurement system advantages and disadvantages over input-output measurement are highlighted here.

The independency of the loss measurement accuracy from current and voltage waveforms

In the calorimetric method we do not have to measure the electrical signal and therefore the all results gathered with the calorimetric method are equally accurate even the current and the voltage signals are heavily distorted. In addition, the independency of the electric waveforms means that the power factor or frequency of the waveforms is not reducing the measurement accuracy and therefore calorimetric loss measurement method is preferable when accurate measurement with low power factor or high frequency are needed. One of the problems in input-output measurement is to measure the power spectrum accurately where both the voltage and current results are needed simultaneously over wide frequency band without additional delay between the signals, in this kind applications the calorimetric measurement methods should be considered.

DUT efficiency has no effect on loss measurement uncertainty

As explained in the introduction of this paper and presented in Fig. 1. The input-output loss measurement uncertainty is approaching infinity when the efficiency is approaching unity. More generally, the same measurement instruments are less accurate if they are used when determining the losses of high efficiency device than low efficiency device. Or with other words, to get the same loss measurement uncertainty in the input-output loss measurement with high efficiency device than with the low efficiency device, the accuracy of the measurement instruments must be raised to higher level.

No torque or speed limit

Similarly, as in the case of electric power measurement, the mechanical power measurement instruments have they own limitations. Very small or very high torques or speeds are difficult to be measured accurately, thus the mechanical power measurement accuracy is limited by these facts, but the calorimetric method does not share the limitations, but equally accurate loss results can be obtained from the motors with 100 rpm, 1500 rpm or 100 000 rpm.

More complex system

The most of the calorimetric systems are typically specially tailored system that are more complex than the input-output system. It is mainly because they are used in the research institutes where an alternative method for input-output measurement is sought, when the capabilities of the input-output system are not enough. The less complex calorimetric system could also be used in more general used. Very simple open balanced type calorimeter can be used to obtain the DUT losses with 5 % accuracy and basically all what is needed is insulated box, blower with speed control, two temperature sensors and resistor with power control.

Long measurement time

The long measurement time is due to thermal equilibrium that is needed to obtain the accurate calorimetric loss result. Typically, in the motor efficiency testing the heat run test is performed, thus the motor is driven to near to thermal equilibrium and the calorimetric test run would be equal in length. The calorimetric measurement rate can be increased with two chamber design, using the chambers in series of in parallel to obtain the loss result on-line. Naturally, the calorimetric measurement system cannot be used to obtain the losses in transients and the input-output measurement method is the only choice.

The both methods can be used simultaneously and thus we can get two totally independent loss results at the same time. The usage of the methods simultaneously can be used to lower the measurement uncertainty and to validate the results without further calibration when extreme accuracy and reliability is needed.

Conclusions

The paper presents experiments and notes from the loss measurements of two different methods that the authors have used and developed during the last years. Both methods have their strengths and weaknesses but together they are more reliable and have smaller uncertainty than alone, when using two parallel measurement methods, the human mistakes have smaller effects on the results or the mistakes can be detected because two measurement results are received. There are always differences in the measurement results between different measurement instruments, different measurement series and different laboratories. The measurement results can be considered correct even they do not hold exactly the same value. There is always variation in the measurement quantities and the reasons behind it beyond the scope of this paper. The single numeric value of the losses or efficiency is always an average value in certain conditions and cannot be treated as an absolute truth. If comparable measurement methods are desired, the computer aided data acquisition systems with commonly agreed data processing methods should be used.

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Accurate Calorimetric Measurement of Efficiency of a Frequency Converter

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Abstract

Quantitative knowledge of electrical device's power loss aids in understanding the device's operation, and in identifying the major causes of losses. They also serve as relevant markers for future design processes for device optimization. Calorimetry is gaining ground as a viable means for power-loss measurement of electrical machinery and other electrical devices. In this paper, we present a closed-cycle, water-cooled calorimeter to measure losses of highly efficient power converters (power class <1 kW). A 0.75 kW frequency converter was tested calorimetrically and its efficiency was confirmed to total to 97 %, with measurement accuracy of 1.1 %.

Introduction

As devices of higher power density and accuracy are desired by the industry, the need to accurately measure these parameters becomes increasingly important. In electric machinery, the dominant methods of loss analysis and quantification are: Input-Output Method, Segregated Loss Method, and Calorimetric Method. While the first relies heavily on the measurement system accuracy, the segregated losses procedure involves measuring loss components separately. However, calorimeters enable precise measurement of the Device Under Test's (DUT) net heat-dissipation and thus allow accurate determination of the total power loss, as illustrated by existing systems in [1]-[3]. It has also been adapted for segregated loss measurement of machine stator losses and stray losses as reported in [4] and [5] respectively.

Overview

Calorimeters employed in electrical engineering can be classified broadly into two, firstly based on their heat-exchange mechanism and secondly on their design. The mechanism of heat-exchange from the DUT to coolant can be direct or indirect. In an ideal calorimeter, the heat absorbed by the coolant will equal the power lost by the machine. An air-cooled calorimeter is a directly cooled, open system, which is simple enough but inaccurate due to the tendency of air's thermal properties to fluctuate over a period of time. Alternatively, an indirectly-cooled, water-cooled calorimeter is considered more reliable, owing to the predictable and controllable nature of the thermal and physical properties of water. Water circulates through a radiator to absorb heat from air, which is heated directly due to the operation of the DUT.

On the basis of design, calorimeter's architecture maybe described as one of the following four kinds: balanced, series, parallel and double-jacketed. The balanced air-cooled calorimeter in [6] was first tested with a known power source, thus calibrating the calorimeter and solving the open-type calorimeter's biggest drawback. Nevertheless, the issue remained that the conditions during the calibration test and actual test of the machine differ. The series or double-chamber calorimeter (DCC) [7] addressed this effectively, but was riddled with higher heat leakages in the second chamber with the DUT, and was expensive to build too, due to the larger volume. A new concept of parallel calorimeter was introduced in [8]. It performs the actual calorimetric test with DUT and balance test with reference heater parallelly in separate chambers, while maintaining a constant coolant temperature gradient and duplicating the coolant flow conditions in the balance chamber.

The Double Jacketed Calorimeter (DJC) [2], [3] is a water-cooled, closed calorimeter which employs a novel concentric, double chambered construction and intervening air-gap's temperature control to prevent heat leakage through the calorimeter walls. The recorded measurement times for the DJC are lesser than DCC's, but may require more elaborate systems of control, depending on the level of automation. Electronic ballasts of compact fluorescent lamps and phone chargers were also tested for their efficiency with the DJC in [9] to successfully do so with an accuracy of ± 0.1 W for 25 W of power loss.

The best accuracy of closed calorimetric systems was 0.2% for 50 W measured, as reported in [3]. Accuracy of 1% was achieved in measuring losses of 10-100 W for power electronic systems with full range power between 1-10 kW, also with a Closed DJC in [1]. In most such systems, the coolant flow rate has been controlled with a flow sensor and a pump. A commonly observed disadvantage of this is the inlet water temperature fluctuations, resulting in reduced measurement accuracy at lower power levels. Additionally, the specialized calorimeters such as in [9] are highly individualistic with a narrow measurement range where they are able to perform with respectable accuracy. A wide-range calorimeter which can measure power losses ranging from tens to few hundreds of watts with an accuracy of at least 1% has not been fully realized yet.

Objectives

The aim of this work is to address these lacunae by constructing a highly efficient calorimeter to test high-efficiency power converter devices of up to 1 kW rated power, with measurement accuracy of 0.5 %. The wider measurement range and simpler construction is meant to make it an acceptable alternative to the automated Double Jacketed Calorimeter (DJC) [2] with wall temperature-control. The design objective is simplicity and versatility. To fulfill these requirements, a water-cooled, single-chambered, single-jacketed calorimeter, dimensioned suitably to make measurements of different small-sized power converters and other electrical devices of rated power of 0.5-1 kW was built. The following sections describe the calorimeter's design procedure and the measurement results. A key feature of this calorimeter is input water temperature control.

Methodology

Operating Principle

In an ideal system, the power lost by the device P_{loss}, is absorbed completely by the water coolant P_{water}. Thus,

$$P_{\text{loss}} = P_{\text{water}} = \dot{V}\rho c_p \Delta T. \qquad (1)$$

Here $\dot{V}$, ρ, c_p are the volume flow-rate, density and specific heat capacity of water. A 0.75 kW frequency converter is chosen to serve as a median for the calorimeter's measurement range, with reported efficiency of 95-98 % at nominal power. If its power loss is around 75 W it will result in water temperature rise of about 5 ℃, assuming inlet water temperature is 15 ℃. The water flow rate would be around 220 ml/min.

Design Considerations

A calorimeter should be built to the specifications of the device(s) that is to be tested. Therefore, the target test devices and their dimensions, efficiency, cooling requirements etc. have to be known before a suitable calorimeter design can be decided upon. Certain factors of importance in the calorimeter design are:

- Calorimeter's inner heat transfer volume.
- Insulation thickness.
- Coolant temperature limits.
- Heat-exchanger capacity.
- Choice of instruments which sense, control and record the process parameters.

The inner calorimetric chamber should be spacious enough to accommodate DUT's of varying sizes and also to allow proper mixing of air. Nevertheless, being too expansive can increase the system's response time. Hence, an optimum dimensioning suitable to the experimental study should be decided. This can be accomplished through a thorough analysis of the previous works and a process of trial and error. Also metal parts inside the test chamber should be avoided to prevent additional eddy-current losses.

Physical Design

A single chambered, water-cooled design for the calorimeter was chosen. An optimal wall-thickness provides sufficient insulation, while at the same time minimizes the time-constant of the measurement system. The DUT here is a high-efficiency device, and since the overriding objective of this work is to attain the maximum possible calorimetric accuracy, the insulation along the four walls was doubled to prevent heat leakages, at the risk of higher settling times. The calorimeter design which resulted opened like a box from the top. This is an additional means to trap the heat which might otherwise escape through the wall joints.

This calorimeter has two shells:

1. The inner calorimetric shell (100 cm x 80 cm x 60 cm) with top open.

2. The outer calorimetric shell (120 cm x 100 cm x 60 cm) acting as the lid.

Both shells are made of extrusion-compressed polystyrene sheets of 10 cm thickness each. The outer box is constructed to just fit over the inner shell, leaving the least gap between the walls. This structure offers better accessibility to the calorimeter's interior, thus allowing easy alterations and maintenance. All electrical, coolant and sensor circuitry are channeled to the outside through two insulated tunnels on lower bottom of calorimeter walls. Figure 1 shows the inside layout of the calorimeter.

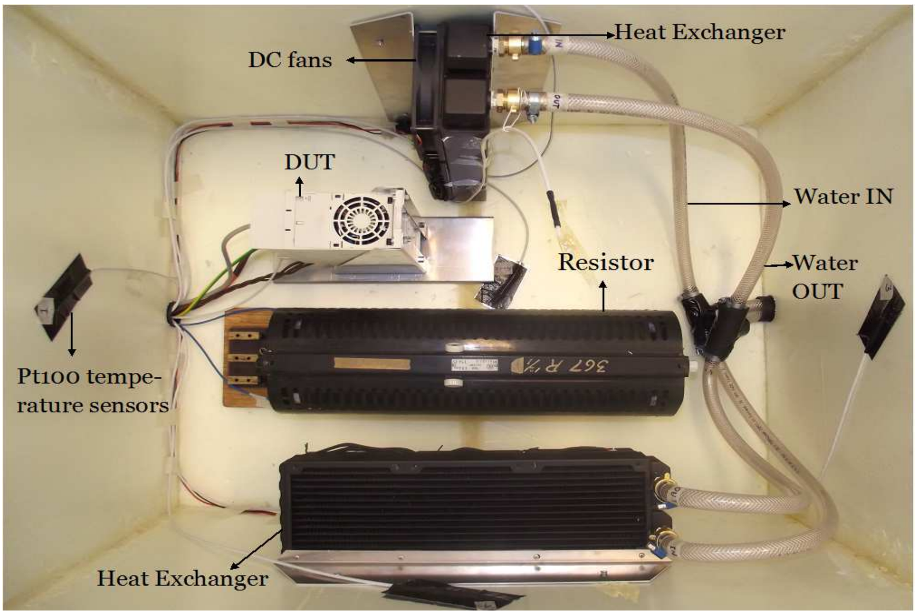

Figure 1: The calorimeter interior, top-view.

Thermal Resistance and Time Constant

Even though the material properties of an insulation sheet may be uniform throughout, the effective thermal resistance offered by the calorimeter is anisotropic due to the varying insulation thickness. It is important to observe how this can affect the heat flow patterns in the calorimeter. Based on the manufacturer's data on the insulation's thermal conductivity, the equivalent thermal resistance of the calorimeter is 1.11 K/W. Thermal resistance of insulation is,

$$R_{\mathrm{th}} = \frac{d_{\mathrm{wall}}}{\lambda A_{\mathrm{wall}}}, \tag{2}$$

where d_{wall} is its thickness, λ is the thermal conductivity and A_{wall} is the insulation slab surface area. The time constant of the calorimeter was determined to be around 3 hours, which indicates the delay at which changes in system parameters are reflected in the system performance. It is given by

$$\tau = \frac{C_{\text{th}}}{R_{\text{th}}} \; . \tag{3}$$

C_{th} is the calorimeter's heat capacity.

Heat-Exchanger and Coolant temperatures

Choosing a radiator is an important design decision, which has to be carefully made after considering factors like the maximum required water and air flow-rates, the maximum possible coolant temperature rise, calorimeter's measurement capacity, and the heat-exchanger's thermal resistance. Such an analysis will ensure good system performance, limit vital parameters and allow them to stabilize.

Fixing the upper-limit of coolant temperature rise based on the flow controller range can be a starting point. If the coolant flow-rate is too low, the heat will not be effectively transferred from the primary coolant (air) to the secondary (water) which can lead to overheating. Moreover, hotter the air within, greater is the incentive for heat to leak to the ambience. The maximum air temperature is limited by the insulation's temperature limit. Additionally, the inlet water has to be cooler than the air to immediately facilitate the heat transfer. The temperatures of the primary coolant is of importance in the heat exchanger performance (or 'effectiveness'), as seen from the expression;

$$E = \frac{P_{\text{actual}}}{P_{\text{max}}} = \frac{P_{\text{air}} \text{ or } P_{\text{water}}}{\min(\dot{C}_{\text{air}}, \dot{C}_{\text{water}}) \cdot (T_{\text{air,hot}} - T_{\text{air,cold}})} \tag{4}$$

Effectiveness E is the ratio of the actual heat transferred P_{actual} and the maximum heat transfer P_{max}. $\dot{C} = \dot{V}\rho c_p$ denotes the heat capacity rate of the respective coolant and $T_{\text{air,hot}}$, $T_{\text{air,cold}}$ represent the temperatures of hot air and cold air entering and leaving the heat exchanger respectively. The radiator should maintain a reasonably good effectiveness for different powers measured. After such an iterative design process, the maximum power measurable by the calorimeter was determined as 520 W, at a maximum water flow rate of 300 ml/min.

Measurement Uncertainty

The meters and sensors chosen for the calorimeter should have the best possible accuracy and repeatability. The final accuracy of the calorimeter is directly dependent on those of the constituent meters and sensors. The choice of instrumentation for a task has to be made after considering the weight or impact of the variable being measured on the final measurand, which in this case is the power-loss of the DUT.

Realistic Perturbation-Based Estimation (RPBE) which operates in the root sum squared sense, is best suited to estimate the uncertainty in measurement compared to the Worst Case Estimation method which overestimates the overall measurement inaccuracy. As per RPBE, the uncertainty in the measurement of the coolant power is expressed as,

$$u(P_{\text{water}}) = P_{\text{water}} \sqrt{\left(\frac{u(\Delta T)}{\Delta T}\right)^2 + \left(\frac{u(\dot{V})}{\dot{V}}\right)^2} \\ \text{where } u(\Delta T) = \sqrt{u(T_{\text{out}})^2 + u(T_{\text{in}})^2} \tag{5}$$

$u(Y)$ refers to the uncertainty in the measurement of Y. The actual measurements are assumed to be distributed uniformly. The best possible sensors and instrumentation was chosen for the experiment, and the absolute combined measurement uncertainty was found to be ±0.8 W (or 1.05 %) when measuring coolant power of 75 W. Expressing this at 95 % confidence level, the '*expanded uncertainty*' is 2.12 % at 75 W.

Measurement System

Since the power losses to be measured are low, instrument inaccuracy can fatally alter the results. The most important measurements in the system are those of water and wall temperatures, and the water volume flow-rate. The sensor data from the various Pt-100 temperature sensors deployed in the calorimeter was acquired with a HP DAQ 349970A Data Acquisition/Switch Unit and read on the PC with the Agilent VEE Pro graphical programming software. The electrical power supplied to the calorimeter was read at the connection terminals by Fluke Norma 4000 and read with the Agilent VEE Pro software as well. The table below lists all the measurement devices used in the calorimetric system.

Table 1: Measurement devices and controllers used.

Parameter	Device Type	Meter/Sensor	Manufacturer	Properties
Water flow-rate	Volume flow-controller	LFC 8718	Bürkert	Accuracy: 0.5% F.S., Repeatability: 0.5% F.S.
Water Temperature	Ceramic wire-wound RTD	Pt-100 1/10 Class B	SKS Group	4 wired. Accuracy: ±0.03 ℃
Air/Wall temperature	Ceramic wire-wound RTD	Pt-100 1/3 Class B	SKS Group	4 wired. Accuracy: ± 0.10 ℃
Air-water heat exchanger	Radiator	Airplex XT 360	Aqua Computer Gmbh	Brass casing, copper lamellae
Air-flow	DC Fans	-	Aqua Computer Gmbh	12 V, 5 fins
Water pressure	Pressure regulator	-	Gerhard Gotze & Co.	Max. inlet pressure 25 bar
Water preheater	Heating cables	Deviflex™	Devi	2 m long, 40 W heating capacity
Temperature control	Temperature controller	Model T16	Redlion	PID control
Power regulation	TRIAC	FC11AL/2	United Automation	Integral 26 A TRIAC

Control Scheme

To avoid measurement discrepancies, the temperature of the inlet water was controlled to remain fixed, at a constant flow-rate. Thus, the water temperature rise recorded will correspond exactly to the heat it absorbs in the calorimeter chamber. Although we can consider the temperature of the water in the calorimeter cooling channels to be more or less uniform, the same cannot be said about the public water supply, whose supply temperature is prone to fluctuations. This can affect the measurement accuracy and stability of the calorimeter and can adversely influence its settling time. Hence the solution would be to heat the water from the supply to a fixed level before supplying it to the measurement system. This control loop consists of a PID controller and TRIAC, along with a water heater and heater cables. This system performs well, but lower flow rates can be challenging.

Alternatively, another control scheme for maintaining a constant water temperature for different power-levels can be implemented. This can be done by varying the water flow-rate according to the water temperature feedback. Both these schemes can be coupled as well.

Water Temperature Measurement

The temperatures of water are measured at its points of entry and exit to the calorimeter. The water flows through small sections of insulated copper piping, whose copper surface temperature is measured by Pt-100 RTD’s to yield the water temperature. The measurement data from four different locations on the pipe surface is averaged to obtain the water temperature. The control schematic of the calorimeter is presented in Figure 2.

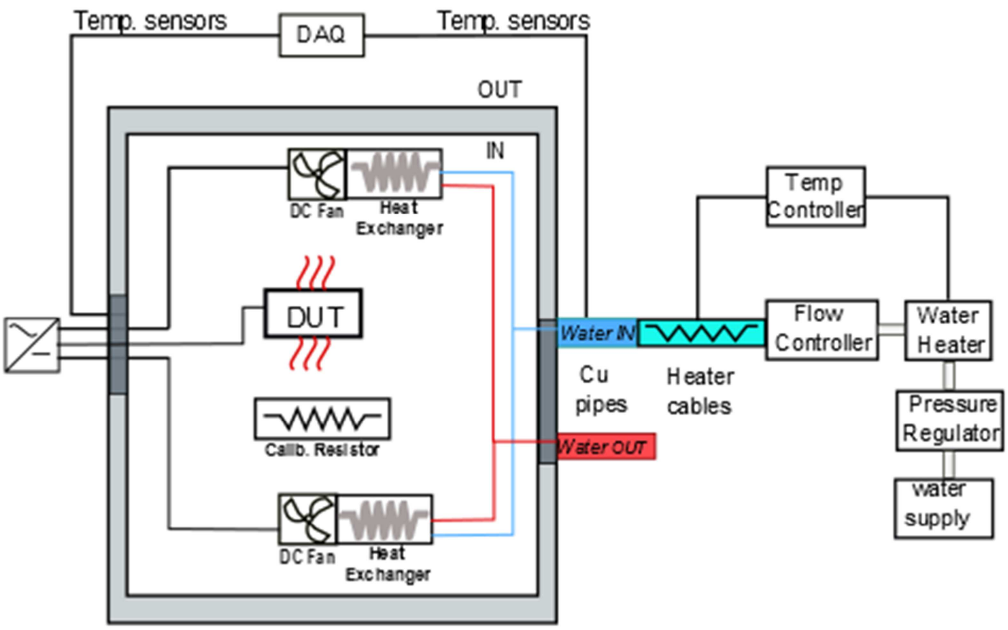

Figure 2: The calorimeter and control schematic.

Experimental Results

Balance Test

The balance test was carried out at a fixed flow-rate of 200 ml/min, with a 15.6 Ω resistor supplied by a regulated DC power supply to dissipate powers from 25-125 W. The steady-state analysis of the measurement system was done in accordance with the standard IEC 34-2A 1972 (the tests presented in this paper were carried out in late 2012 [11], before IEC 60034-2-3 and EN 50598-2 standards were published). It states that stable conditions are achieved when “measurements of rise in temperature and volume flow rate of cooling medium indicate that losses are constant to within ±1 % over a period of two hours or when the temperature rise of the cooling medium does not vary by more than ±1 % in one hour, the volume rate of flow being constant.”

Both these steady-state requirements were considered simultaneously to check the stability of the measurements. The setting times varied from 4-12 hours, in inverse proportion to the power measured. Once the steady-state was reached, the thermal power and wall-leakage calculations were carried out from the recorded sensor measurement data.

As per the least-squares method, a curve was fitted to the measurement points to obtain the calibration curve. The wall leakages were calculated and compensated to obtain the calibration curve shown in Figure 3. The linear relationship between electrical and coolant thermal power is,

$$P_{water} = 0.924 P_{loss} + 0.216 \quad \text{W} \tag{6}$$

It represents the relationship between the total electrical power dissipated inside the calorimeter and the coolant thermal power, and will be the reference for actual test with the DUT. The electrical power lost by the DUT (P_{loss}) and the coolant power are related as:

$$P_{loss} = P_{water} + P_{wall} \pm P_{Cu} - P_{fan} + P_{stray}, \tag{7}$$

where P_{wall} is the heat-leakage through insulation, P_{Cu} is the heat leakage through the copper conductors in the electrical connections in the test chamber, P_{fan} is the heat generated by the fans and P_{stray} refers to the other non-quantifiable loss. The electrical power dissipated as heat in the calorimeter is the sum of the DUT losses, copper wiring's possible heat contribution and the fan power.

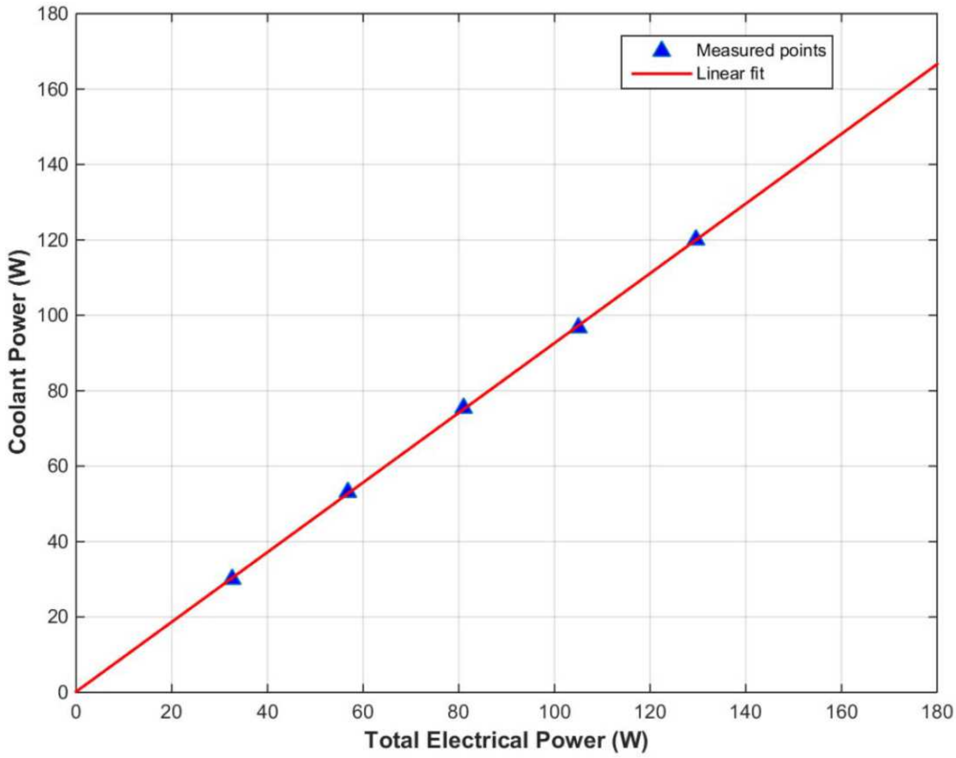

Figure 3: The calibration curve at 200ml/min.

Actual Test

Following the calibration of the calorimeter, an ABB frequency converter ACS 350-01E-04A7-2 was tested in the calorimeter. The converter was supplied 230 V at 50 Hz and loaded with a 3-phase resistor. Only the DUT is enclosed within the calorimeter. The thermal power was calculated as per equation (1). The wall leakages were determined from the inner and outer wall temperature measurements. The measurement results are shown in Figure 4.

With wall-leakages compensation, the average power lost by the frequency converter was around 21.35 W. Separate electrical measurements indicated that the power input to the DUT was 0.75 kW, and the output was 0.727 kW, indicating the power loss to total 23 W. The heat conducted from test chamber to ambient by current carrying copper conductors was measured to be negligible. Thus, the electrically measured power loss fits closely with the coolant power measured by the calorimeter. The calorimetric experiment was thus able to successfully verify that converter's efficiency to be 97 %.

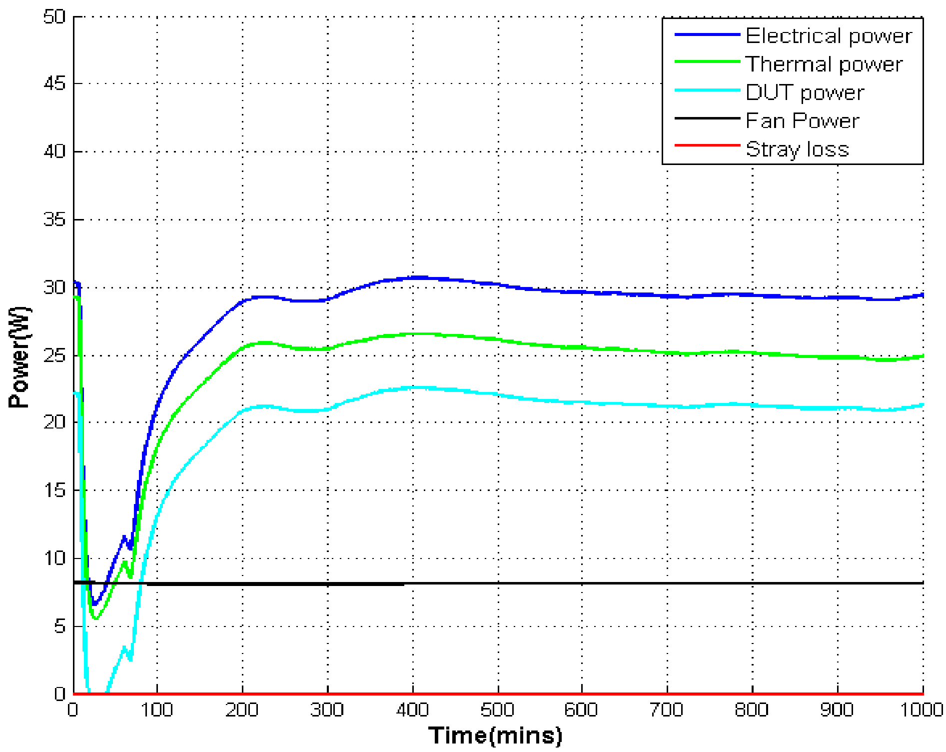

Figure 4: Measured powers from the DUT's calorimetric test at 200 ml/min.

Discussion

The attempt at building a wide range, simple, water cooled calorimeter was fairly successful. While the inlet water temperature control scheme efficiently prevented oscillations in the coolant circuit, wall leakage prevention by double insulation was inefficient. The novel construction may have resulted in the stray losses without which the calorimeter calibration would be much better. These unaccountable losses may be the result of possible leakages through the contact gaps in the inner and outer insulation boxes and also through the wiring channels.

Also, although the thermal resistance offered to various heat paths was high, the overall thermal resistance of the calorimeter remained low. Apparently, the heat conductivity of the insulation slabs was higher than expected. Higher the power measured, higher was the leakage. However, it was possible to determine these leakages quite well through wall temperature measurements. Copper conductors were not found to leak any heat to outside, at least at the power levels measured. At higher powers though, this may be a problem, which can be mitigated by using suitably dimensioned conductors. The higher settling times observed in the experiment may be due to fluctuating ambient temperature, which also influences the wall heat leakages.

Conclusion

As targeted, a water-cooled calorimeter, with larger measurement range and versatility was implemented. The highly accurate temperature sensors and flow controller enable it to measure 25-520 W of power with fairly good accuracy. For 25 W of power measured, the extended uncertainty in measurement is approximately 0.5 % at 200 ml/min flow rate. Above 75 W of losses measured, the extended uncertainty is at least 2 %. The max range of the flow-controller is 300 ml/min.

As far as calorimetric measurement of low (<10 or 20 W) or fractional powers are concerned, the parameter of vital importance is the calorimeter heat exchange volume. If the calorimeter is too large and the coolant temperature rise is low, then the system will take much longer to stabilize. Lowering the flow rate correspondingly is not an option though, as it engenders another issue of uneven fluid mixing. Even the choice of calorimetric method might need to be reassessed, and specialized calorimeters like the one reported in [12] might be required. The considerations of test duration and coolant temperature rise are valid even for higher power measurements (>100 W). But of higher importance here are the heat leakages, which can considerably compromise the calorimetric measurement's efficiency.

Although this double walled calorimeter is less effective than the DJC in countering the wall leakages, an extensive design optimization (with respect to dimensioning, insulation) and professional construction can improve its accuracy. The design process should only proceed once the dimensions of the heat exchanger, balance resistor and DUT are known in advance. Also, the water temperature rise control schema can be implemented and compared with the inlet-water temperature control scheme for its effectiveness. Conducting the test in a closed space can ensure a near-constant ambient temperature, which shall prevent rogue measurement errors. A good addition to the calorimetric system would be a cooling system which recirculates water and thus avoid unnecessary wastage.

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Loss measurements analysis of VSD motors using both direct input-output and calorimetric methods

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Abstract

Continuous demand for energy saving products and solutions has led to more advanced research in motor and motor drive systems. The standardization committees are proposing next level of efficiency classes for motors, with much smaller gaps efficiencies at higher levels. On the other hand, it is becoming equally challenging to address measurement systems uncertainties and spread of measured efficiency for motors in higher efficiency levels. Measuring smaller quantities of losses i.e., high efficiencies is getting more challenging for the measuring instrumentation used in different test methods. Thus having reliable and accurate test equipment together with equally reliable uncertainty calculations has become extremely important when measuring high efficiency motors and drive systems.

Apart from the reliable measuring instrumentation, the test procedures employed for measuring high efficiencies fall into discussion due to various uncertainties associated with each component of instrumentation system involved. An alternative to the electrical loss measurement other than direct method is provided by the calorimetric method, where the power losses are measured directly from the generated heat. The calorimetric test procedures are complicated and time consuming in nature, making their adaptation difficult in associated standards as “preferred” test methods for testing high efficiency motors and motor system.

This paper presents the efficiency measurement results and comparisons of a frequency converter driven synchronous reluctance machine measured using direct input-output and calorimetric test methods. A series of efficiency measurement tests have been performed in three different laboratories and the motor losses are obtained with two alternative measurement methods – with the direct input-output technique and with the calorimetric method based on open and balance type calorimeter. The direct (input-output) method is performed in three laboratories, combined with the calorimetric method in two of these laboratories. The paper also includes the analysis of measurement uncertainty estimation for direct input-output and calorimetric measurements and the factors affecting the measurement uncertainty are highlighted. Based on this, the basic guidelines to reduce the measurement uncertainty are described for both direct and calorimetric measurements.

Special emphasis is made on loss measurements in partial load conditions where electrical measurements have a higher level of measurement uncertainty mainly due to the instrumentation, whereas the calorimetric loss measurements have relatively lower measurement uncertainty. The calorimetric tests performed serve the important purpose for benchmarking and validation of input-output method in this work. The paper also gives suggestions on guidelines to be employed in order to improve the measurement uncertainty within allowable tolerance limits at partial load conditions

Keywords: - IEC60034-30-1, IEC60034-30-2, IEC60034-2-1, IEC 60034-2-3, Direct input-output efficiency measurement, Calorimetric loss measurement, uncertainty of efficiency measurement methods

Introduction

Electric motors are the most important type of load in many industrial applications, consuming about 65–70% of the electric energy [1]. This demand has eventually triggered the push to increase overall motor-drive system efficiency even greater; also due to the increasing costs of the energy and the substantial concerns about global CO_2 emissions. There is a constant push towards higher and higher efficiency motor designs in order to meet the compliance requirements for existing eco-design requirements as well as the new eco-design directives which are currently under investigation. The current research is focused mainly on efficiency enhancements of motor-drive systems through design improvements, usage of better materials and more efficient alternative motor technologies, like permanent magnet (PM) motors and synchronous reluctance motors (SynRM). In addition to it, the wide availability of variable speed drives (VSD) and research in robust control solutions for newer machine types has given a totally different dimension to the energy saving potential in many industrial applications. The saving potential especially in applications like pumps and fan drives is enormous. The higher efficiency drive systems are increasingly replacing conventional motors, thanks to the energy awareness created by many energy efficiency improvement measures and new regulations which have made it mandatory to use higher efficiency motor systems.

Above mentioned constant push for eco design requirements as well as incentives for using high efficiency motor-drive systems, has led to major development initiatives by many manufacturers of motor drive systems to introduce novel products in the market which meet the higher efficiency requirements. Due to the strict implementation of requirements by eco-design directives which came into force from 2015, the motor manufacturers have updated their common product portfolios from IE2 level to IE3 level, especially in Europe. The Permanent Magnet (PM) and Synchronous Reluctance Machine (SynRM) technology based products with IE4 and unofficial IE5 efficiency classes are already available in the market [24], [25]. Moreover, there are already efforts to show demonstrators which can meet the IE6 efficiency class and there are newer concepts under study which can possibly take newer motors designs to IE5 level or beyond; indeed these technologies will take some time to mature before products can be available in the market [26],[25]. Basically, the research efforts in motor design are towards increasing the power or torque densities in industrial motors, mainly focusing on active materials with lower losses and improved design. The permanent magnet versions are looking for different type of rare earth, non-rare earth based magnet materials. Apart from material research, the manufacturing processes are also looked upon for simpler, cost effective manufacturing techniques, for newer motor types.

Today's trend in the motor design technologies to reach higher efficiency levels also puts enormous attention on methods to accurately measure the losses and determine the efficiency class of motors as well as drive systems. The accuracy of measurements is dependent on various factors like ambient conditions, measuring instruments characteristics and personnel factors in the case of non-automated testing. Thus, even with the use of a consistent and accurate efficiency test methods, variations in results for the same motor do occur. It's worthwhile to note that the measurement standards also specify the accuracy requirements for instrumentation used in the electrical loss measurements. By far, even with use of the instrumentation which fulfil the above accuracy specifications, it has been reported that it was not possible to reproduce the same efficiency values [20].

Regarding measurement of efficiency of high efficiency motors and drives, it is even more demanding in terms of accuracy requirements. This is primarily due to the big uncertainty involved in measured torque for input-output test method. With high efficiency motors, a slight error in input or output powers may lead to a large variation in losses, and may in turn lead to a large variation in the efficiency value. A slight inaccuracy in any measurement can lead to wrong estimation of efficiency and hence the risk for wrong classification of motors. The capability of typical electrical power measurement instruments to accurately measure the electrical power quantities (voltage, current, power, power factor, etc.) also deteriorates when used with VSDs due to presence of higher harmonics in motor input voltages. These requirements put attention on the accuracy calculations of measured efficiency value. For such high efficiency tests objects, calorimetric loss measurement can be an alternative and superior choice for more precise loss measurements, since the accuracy of calorimetric loss measurements is much better as compared to input-output power measurement method. But the use of this method for routine testing will be highly impracticable due to involved complexity for setting up and performing the measurements.

Rather, calorimetric loss measurement method can be used as a validation tool to confirm the accuracy of the test methods based on electrical power measurements i.e., the direct input-output method. This is the main theme of the paper presented, wherein the authors describe their experiences with efficiency measurements related to VSD fed motors using two different methods namely the direct input-output power measurement and calorimetric loss measurements. The calorimetric method has been used to validate the efficiency measurements performed using direct input-output method. It is shown that it is possible to measure motor efficiency within acceptable accuracy limits using direct input-output method. The relative efficiencies at different load conditions are compared with each other, especially the performance of two test methods is compared at partial load conditions, where the measurements have higher measurement uncertainty. Based on the main finding, procedural guidelines and recommendations for accurate measurements of VSD fed motors are presented.

Efficiency classification and measurement standards for VSD fed motors

The standards for IE class definition as well as test procedures for measurement of efficiency of direct on-line (DOL) motors are now well established, while the current focus is more in the field of VSD fed motors and motor drive systems. The standard IEC 60034-30 which describes the efficiency classes (IE- code) for standard line fed single phase and three phase motors is now separated into two separate specifications. Part 1 (IEC 60034-30-1) covers all motors operated direct on-line [4] and part 2 (IEC 60034-30-2), which is under construction, will cover motors operated by VSDs [5]. In line with “IE” class definitions, IEC has also renewed standard for testing the motor efficiency “IEC 60034-2-1 (Ed. 2.0)” which describes test methods for measuring efficiency of DOL motors [7]. IEC 60034-2-3 is published as technical specification which underlines the test methods for determining losses and efficiency from tests for converter-fed AC machines [8]. IEC 60034-2-3 also describes the summary of preferred test methods [7]. The test methods are similar to those underlined as preferred test methods in IEC60034-2-1, for measuring efficiency of DOL motors, except that the calorimetric loss measurement method has been added as preferred method for efficiency determination of VSD motors.

The ongoing work is on defining the efficiency classes for whole power drive systems (PDS), wherein the energy efficiency requirements for complete drive modules (CDM) and power drive systems (PDS) are specified. In this direction, standard EN50598-2, defines the IE classes and provides limits as well as test procedures for their classification [11]. This standard also provides the typical load points for which the efficiency measurements shall be carried out for VSD motors. This is a major difference to the respective standards for DOL motors where the measurements were to be carried out at nominal load point for efficiency classification.

Test methods for IE classification of converter fed motors and motor drive system

Standard EN50598-2 describes the direct input-output measurement method for measuring the losses of converter or converter+ motor combined, whereas calorimetric loss measurement methods can also be used for measuring losses of converter due to much higher level of efficiency of the converters. For measuring the losses of VSD fed motors, it is mainly the guidelines described in IEC 60034-2-3 as mentioned above.

In the input-output method, the measurement of the input power is performed using the electrical power measurements at motor input terminals and output power is measured by measuring the torque and speed at the shaft using torque and speed transducers. The losses are simply the difference between the measured input (P_{input}) and output power (P_{output}) as given in (**1**) below

$$P_{\text{loss,io}} = P_{\text{input}} - P_{\text{output}} \tag{1}$$

The calorimetric method involves the measurement of actual loss in terms of generated heat of the machine, which is very different in principle from other methods described in the above described standards. The heat dissipated in the test objects results in a temperature rise of the cooling medium, which is measured together with the coolant flow inside the calorimetric chamber. By knowing the relative humidity, absolute pressure and temperature rise, the actual heat loss can be calculated, as

$$P_{\text{loss,cal}} = q_{\text{m}} c_p \Delta T \tag{2}$$

where, q_{m} is the coolant flow rate, ΔT the temperature rise in the coolant inside calorimeter and c_p is the specific heat capacity of the coolant. There are many different ways of constructing calorimeters which is mostly governed by the size and type of test objects, required accuracy levels, etc. [15]. The open type calorimeter, which is further discussed in this paper, is simpler, mostly uses air as cooling medium and with proper care for considering heat leakages, accurate results can be obtained. Still calorimetric loss measurements are often considered complex and time consuming tasks [18],[21].

Instrumentation error sources and uncertainty of efficiency measurement methods

The error sources in the input-output measurement arise from accuracy levels of measurement equipment used to measure the electric converter input and output powers and the mechanical power on the shaft. The measurement uncertainty in electric power measurement comes from the instrument accuracy related to actual reading, range and the power factor, related to the power analyzer, current transducers accuracy and torque transducers accuracy. This uncertainty can be calculated using the technical specifications given by the measurement instrument's datasheets provided by manufacturer [14].

In the calorimetric measurement, the error sources are the heat leakages through the chamber, the variation in the fluid (air) properties during the tests and from the temperature measurement. The heat leakage from the chamber walls, mounting arrangements for motor and shaft hole contribute its own share of unaccounted heat loss which needs to be estimated [15][18][21]. Although these heat losses can be estimated appropriately, it adds its own share of uncertainty to the measurement. Thus, the error sources of these two methods and thus the uncertainty of measurement are totally different and totally independent of each other. Therefore, both methods can be used simultaneously to get the results with maximum reliability. The uncertainty is always an estimate and it may or may not present the actual fluctuation of the measurement results. However, it can be used as a measure to compare the reliability of the measurement and highlight the magnitude of the uncertainty of measurement methods.

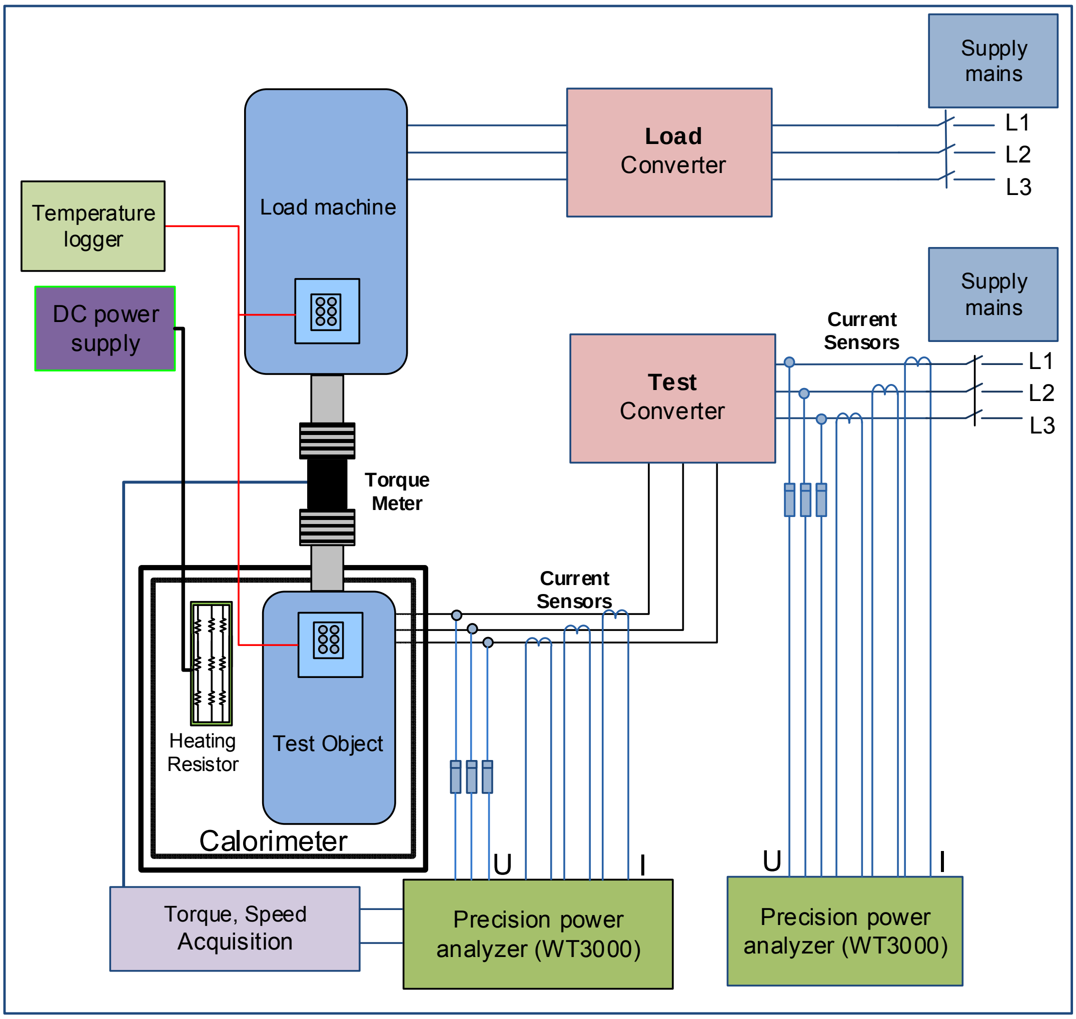

Figure 1: Electrical wiring schematic of measurement setups for simultaneous back-to-back and calorimetric tests

Description of test setups at different lab facilities

This section describes the test setups used at three different lab facilities. The measurements are performed on a VSD fed synchronous reluctance motor of rating 15kW, 1500rpm. The wiring connection schematic of test setups used in different labs are very similar in terms of electrical connections, loading arrangements and instrumentation facility. A typical schematic of the electrical wiring is shown in Figure 1. The mechanical arrangement consist of a test motor coupled to a load machine with a torque transducer in between for measuring mechanical quantities like torque, speed and mechanical power. The load machine is supplied through a VSD (load converter) which is used to apply specific load torque on the shaft. The test motor is either connected directly to supply mains or through a VSD (test converter) depending upon the type of measurements. The electrical and mechanical power measurement data is acquired by the power analyzers since all the measured signals are inputs to power analyzers. Thus the power analyzer is capable of directly presenting the electrical power, mechanical power, motor losses and the motor efficiency from the measured quantities.

Although the three labs use power analyzers from Yokogawa [17], there are variations in the setups at three locations which are significant from the measurement accuracy point of view. The model as well as accuracy specifications of the actual instruments are different in each lab. Also the interfaces of torque transducers with the power meters are different in different labs. For example, Lab 2 uses analog signals proportional to torque quantities, while Lab 1 and Lab 3 uses a digital communication through CAN- or PROFI-bus, which is more accurate and less sensitive to wiring length. Similarly, the current transducers used in three labs are different in terms of manufacturer and accuracy levels.

Labs 1 and 2 uses WT3000 precision power analyzers and Lab 3 uses WT1600 high precision power analyzer from Yokogawa [17].

Description of calorimeters in Lab 2 and Lab 3

The assembly of the calorimeter in Lab 2 is shown in Figure 2. The details about construction, operating principle and test measurements related to this calorimeter were published in [15]. The methodology followed to estimate the heat leakage from different parts like motor shaft, motor mounting bolts (which is negligible in this case as hard fiber bolts are used instead of metal bolts) and the chamber walls of the calorimeter was also described in [18]. The calorimeter in Lab 3 is similar to the one in Lab 2, it's full details are published in [18][21]. However, there are some differences which has influence on the accuracy of the calorimetric loss measurements which are mentioned below. There is no shaft support bearing inside the calorimetric box and the motor support is created with two iron cylinders. The iron cylinders are equipped with two Pt-100 temperature sensors, one at the top of the cylinder and the other at the bottom to measure the heat leakage through the motor supports. The calorimeter is supported by air preheater in the air input circuit to control the inlet air temperature. Also, the air properties variation during the tests has been taken into account by measuring the barometric pressure and air humidity, using the post-processing method given in [21].

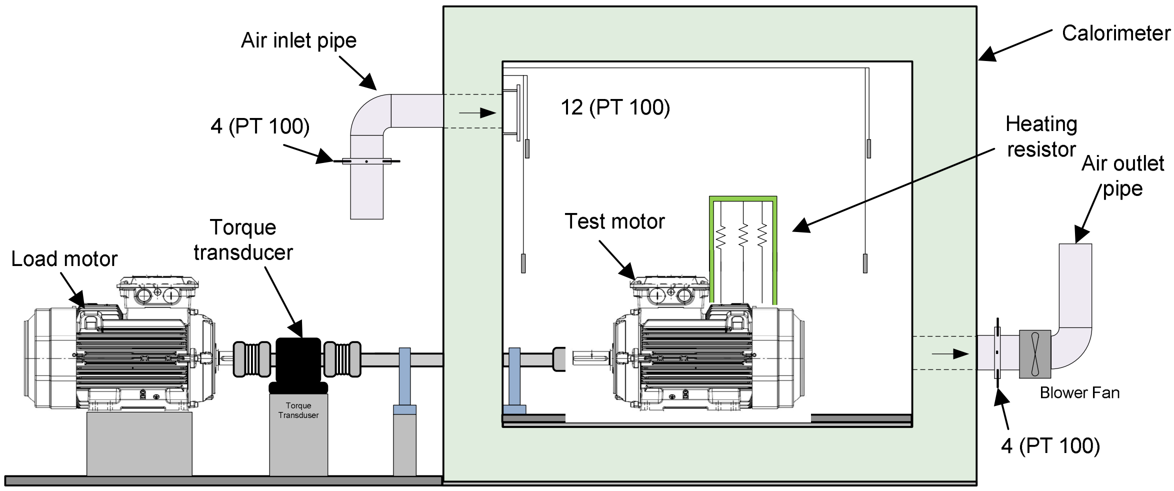

Figure 2: A schematic of the calorimetric loss measurement system

Efficiency measurement tests at different laboratories

The test points were chosen according to the draft European standard EN50598 [11], and can be seen in Figure 3. During the standard development, the measurement points have been modified slightly in the final released version of EN50598-2. The measurement points 1 and 8 are constant torque points that represent the efficiency in constant load torque applications such as lifting gear, extruders and conveyers. The measurement points 1 to 4 are the fixed speed points that represent the efficiency for example in cascaded pump applications. The points 1, 5, 6 and 7 presents the pump/fan curve where the load torque is proportional to square of the speed. The measurement points with 100% frequency reference and 75%, 50% and 25% torque references (points 2, 3 and 4) were only measured in labs 1 and 2.

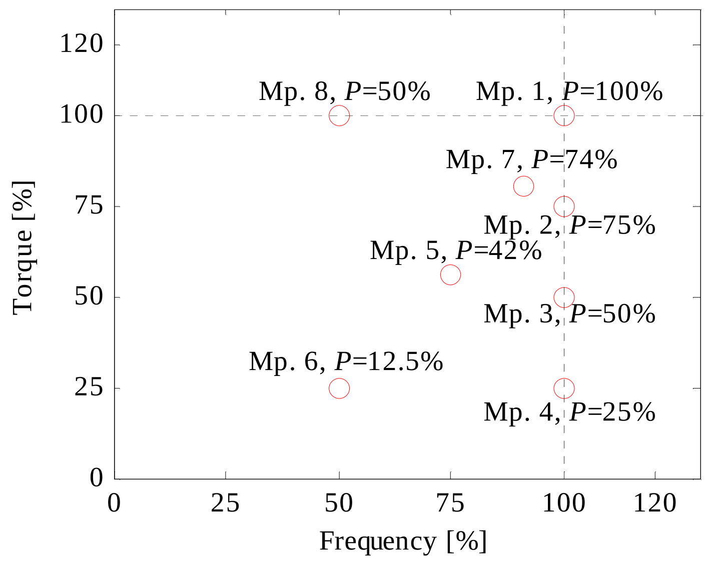

Figure 3: Measurement points in frequency torque plane

Measurement procedure

The test sequence for efficiency measurement are similar in Lab 2 and Lab 3 as described below

- Firstly, the calibration tests are performed at different load points and the calorimeter reference parameters like air flow (blower speed) and temperature gradient are measured. The measurements are performed at thermal equilibrium for each test point. The input and output power measurements from instrumentation setup are also recorded, which are used later to obtain the motor efficiency by direct input-output method.

- The balance test were performed for all test points and the input power to the resistor element to create similar thermal equilibrium is measured, which are used as indicative of motor losses for the respective load conditions.

The test procedure in Lab 1 is slightly different as the calorimetric measurement facility is not available. Here the normal input-output method is used wherein the load conditions as per the test point sequence are applied and input-output power measurements are taken at thermally stable conditions.

Efficiency measurement results

The losses and efficiency for direct input-output method is determined from measured input and output powers during calibration tests. The losses for calorimetric method are determined from the DC power to the heater resistors during balance phase. This loss values together with motor input power during calibration phase is used to determine motor efficiency for calorimetric loss method. The resulting efficiency values for various load conditions are shown in Figure 4 for in all three laboratories, where measurement point is described as [x, y], where x and y are the operation speed and torque values at the test point, respectively. ‘I-O’ stands for input-output method and ‘Cal’ stands for calorimetric method.

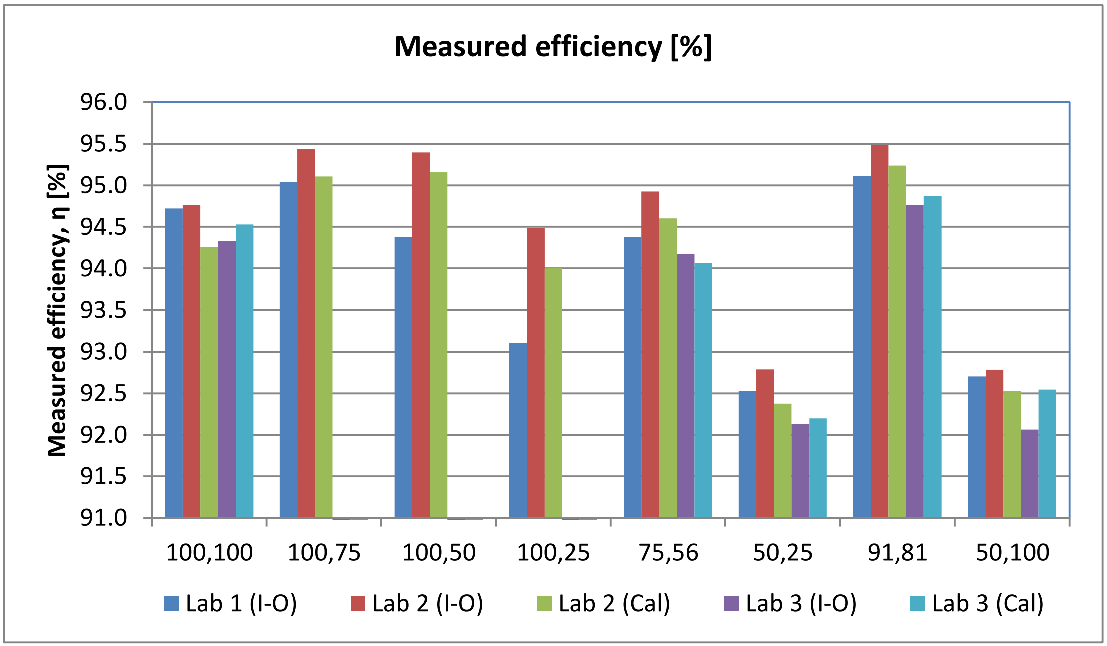

Figure 4: Measured values of motor efficiency for measurements performed in three different labs

It can be seen that the efficiency values measured by different labs at nominal operation points is in close agreement with each other, irrespective of the methods used. The efficiency values measured using direct input-output methods are higher than calorimetric method for Lab 2 at all operating points. On contrary, it is other way round for Lab 3 where efficiency values at majority of test points are higher with calorimetric method as compared with direct input-output method. There is much larger variation especially at partial load conditions, for example 1.5% point at [100, 25] between the results from different labs, which is much larger than corresponding values at nominal load point.

Still some trends can be observed by looking at variation of results. The measurements by two different methods in one lab give results which are in close agreement with each other, although it has larger variation as compared to results from other labs at that particular operating point. This can be due to performance capabilities of the instrumentation used in different labs, especially under lower loads compared to their ratings. This issue of analyzing and comparing performance of instrumentation in different labs at varying loads is discussed in next sections.

Calculation of measurement uncertainty

The accuracy of measurement setup and the test method used become more and more important while testing high efficiency motor drive systems since any slight errors in the measurements can lead to significant deviations in the measured efficiency. This section describes the calculation method followed for estimating the measurement uncertainty for the experimental tests described in previous section.

Accuracy of measuring instruments

A typical setup for measuring motor or motor drive system efficiency includes sensors for measuring electrical quantities like current transducers, voltage shunts together with sensors for measurement of mechanical quantities like speed and torque, where the actual power measurement is done by precision power analyzers. Each of the above sensors are generally combined with their own signal conditioning equipment. For best results, a direct interface of motor current and voltage through power measuring instrument is preferred. Although most of the instruments and sensors used for power measurements available in the market have better accuracy than described in the IEC standard, it does not mean that using such instrumentation would always give the efficiency measurement results within acceptable tolerance limits. The main reasons could be how the settings of the instruments are made, ambient conditions, calibration intervals, wiring connections on power analyzers, grounding, cabling, mechanical alignment in case of torque meters, temperature effects, etc. The power analyzer accuracy levels are function of frequency of supply voltages, often the limits grow linearly with frequency of supply voltages under test. Thus in case of motor efficiency measurement under VSD fed conditions, the uncertainty of the power measurements is often higher, in the order of tens, as compared to the case with sinusoidal supply conditions. This can also be one of the major source for large deviations in measured efficiency values while measuring on any VSD fed motors.

Derivation of uncertainty in measured efficiency

The methodology followed to calculate the total uncertainty of input power, output power and motor efficiency has been detailed in [14],[18]. The procedure involves accounting individual uncertainty of different instruments and sensors involved in the measurement chain of particular parameter and then combining them to calculate the overall uncertainty of the measurement.

The combined standard uncertainties of efficiency measurements are calculated according to [22] by means of an uncertainty budget. In most of the cases, a measurand y is not measured directly, but is determined from N other quantities $x_1 \;\; x_2 \;\; x_3 \; \dots \; x_N$ roughly a functional relationship f

$$y = f(x_1, x_2, \dots, x_N) \tag{3}$$

The combined standard uncertainty $u_c(y)$ is the positive square root of the combined variance $u_c^2(y)$, which is given by

$$u_c(y) = \sqrt{\sum_i^N \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)}. \tag{4}$$

where $\mathrm{u}(x_i)$ is a best estimate of the standard uncertainty of particular measurand, the partial derivatives $\frac{\partial f}{\partial x_i}$ are sensitivity coefficients, describe how the output estimate of y varies with changes in the values of the input estimates $x_1 \;\; x_2 \;\; x_3 \; \dots \; x_N$. In particular, the change in y produced by a small change ∂x_i in input estimate x_i is given by $(\Delta y)_i = \frac{\partial f}{\partial x_i} \Delta x_i$. The combined standard uncertainty $u_c(y)$ is an estimated standard deviation and characterizes the dispersion of the values that could reasonably be attributed to the measurand y as defined by guide the law of propagation of uncertainty.

The combined uncertainty of the measured efficiency for an operating point of the motor can be determined based on the uncertainties of the measured electric and mechanical powers, which are actually calculated based on measurement of voltage, current, motor torque and speed quantities as well as changes in ambient conditions being different than the specifications.

The uncertainty quantities are decided based on the laboratory setup consisting of the power analyzer and torque transducer uncertainty factors. The estimate of the input quantity is multiplied by the uncertainty of the particular measurement instrument to obtain the standard uncertainty. A sensitivity coefficient $c_i = \partial f / \partial x_i$ is needed to achieve the contribution of the above to the combined standard uncertainty $u_i(y) = c_i u(x_i)$. Finally, the combined standard uncertainty u_c of the measurement result is obtained by a root sum square of all the uncertainty contributions.

In direct input-output method, the motor efficiency is determined from input and output powers as given in (**5**).

$$\eta = \frac{P_\mathrm{m}}{P_\mathrm{el}} \tag{5}$$

and the motor losses are

$$P_\mathrm{loss} = P_\mathrm{el} - P_\mathrm{m} \tag{6}$$

whereas for calorimetric method, the actual motor loss is measured and the efficiency is measured using measured loss and input or output power which is measured by power meters separately. Thus when using the loss value, the efficiency can be defined using the electric input power

$$\eta_2 = \frac{P_{\mathrm{el}} - P_{\mathrm{L}}}{P_{\mathrm{el}}}, \tag{7}$$

or the mechanical shaft power

$$\eta_3 = \frac{P_{\mathrm{m.}}}{P_{\mathrm{m.}} + P_{\mathrm{L}}} \tag{8}$$

In the uncertainty budget, the estimate of the input quantity is multiplied by the uncertainty of the particular measurement instrument to obtain the standard uncertainty. The equations above can be used from the equations for loss and efficiency uncertainties, from (**4**) and we get

$$u_c(\eta) = \sqrt{\left(\frac{\partial \eta}{\partial P_{\mathrm{m.}}}\right)^2 u^2(P_{\mathrm{m.}}) + \left(\frac{\partial \eta}{\partial P_{\mathrm{el}}}\right)^2 u^2(P_{\mathrm{el.}})} \tag{9}$$

After differentiating we get

$$u_c(\eta) = \sqrt{\left(\frac{1}{P_{\mathrm{el}}}\, u(P_{\mathrm{m.}})\right)^2 + \left(\frac{-P_{\mathrm{m.}}}{{P_{\mathrm{el}}}^2}\, u(P_{\mathrm{el.}})\right)^2} \tag{10}$$

Similarly, from (6) we get

$$u_c(P_{\mathrm{L}}) = \sqrt{\left(u(P_{\mathrm{el.}})\right)^2 + \left(-u(P_{\mathrm{m.}})\right)^2}, \tag{11}$$

and from (7)

$$u_c(\eta_2) = \sqrt{\left(\frac{P_{\mathrm{L}}}{(P_{\mathrm{L}} + P_{\mathrm{m.}})^2}\, u(P_{\mathrm{m.}})\right)^2 + \left(\frac{-P_{\mathrm{m.}}}{(P_{\mathrm{L}} + P_{\mathrm{m.}})^2}\, u(P_{\mathrm{L}})\right)^2} \tag{12}$$

From (8), we get

$$u_c(\eta_3) = \sqrt{\left(\left(\frac{P_{\mathrm{L}}}{(P_{\mathrm{el}})^2}\right) u(P_{\mathrm{el}})\right)^2 + \left(\frac{-1}{P_{\mathrm{el}}}\, u(P_{\mathrm{L}})\right)^2} \tag{13}$$

It is easily seen in (**12**) and (**13**) that the dominating term in the uncertainty is $u(P_{\mathrm{L}})$ when the efficiency is high. The electrical and mechanical power uncertainties can be estimated using the measurement instruments manufacturer's technical data sheets. The measurement instrument accuracies are usually given as ranges without any information about statistical distribution or confidence level. If the statistical distribution is not known, the best guess is the normal distribution with 95% confidence level.

Comparison of calculated measurement uncertainty for three labs

The above described methodology is followed for estimating the measurement uncertainty of direct input-output and calorimetric method. The uncertainty values from most of the instruments and sensors like, torque transducers, current transducers, power meters, power analyzers are available in technical datasheets of instruments. These are used to calculate the uncertainty of the measurements for direct input-output method from the three laboratories at different load conditions.

Uncertainty of measured motor input power

As described above, the electric power uncertainty $u_c(P_{el.})$ include the phase displacement error, the amplitude error of the current sensors; reading, range and power factor errors of the power analyzer [17]. The estimated uncertainty of input power measured at three labs in absolute values and in percentage are shown in Figure 5(a) and Figure 5(b), respectively.

As expected, there are some differences in the results due to the manner in which the instruments were configured. Lab 1 and Lab 2 use the power analyzers in “auto” scaling mode where the instruments select the best suitable scales for voltage and current measurements, whereas Lab 3 uses “fixed” scale throughout the measurements for all the test points. Also the CT ratios of current transducers in three labs are different as the manufacturers are different and hence are with different accuracy specifications. The power analyzers used in Lab 3 are of higher uncertainty level as compared to Lab 1 and Lab 2, although power analyzers in all laboratories conform to the standard specifications. The above differences have led to differences in the measurement uncertainty in the measured electric input powers at these three locations

- At nominal operation point, Lab 1 has lowest uncertainty due to the use of higher accuracy current transducers and auto scaling mode. Lab 2 uses “auto” scaling mode but has low accuracy current transducer, resulting in higher uncertainty as compared to Lab 1. Whereas, although Lab 3 has higher accuracy current transducers, use of fixed scale causing higher range related errors specific to power analyzers.

- Input power measurements for Lab 1 always have lower uncertainty as compared to Lab 2 for all measurement points, except operation point [75, 56]. This is due to use of current transducers with different CT ratios, the current scale selection of power analyzer results in secondary current which is most optimal for Lab 2 setup. This was unexpected but combination of CT ratio and Auto scale resulted in lower uncertainty for this particular test point for Lab 2.

- For other measurement points, Lab 1 and Lab 2 uncertainty is relatively similar to the nominal point. But the uncertainty of Lab 3 increases proportionally, due to underutilization of the available capacity of the setup by choosing the fixed scale for the power analyzer. The current range related uncertainty contribution is much higher for partial operation points. The worst affected points, as can be seen from Figure 5(b) is operation point [50, 25], where the motor current is very small as compared to the capacity of the setup.

- Use of “auto” range for Lab 3 will result in uncertainty values which are very similar to Lab 1 due to the use of similar current transducers.

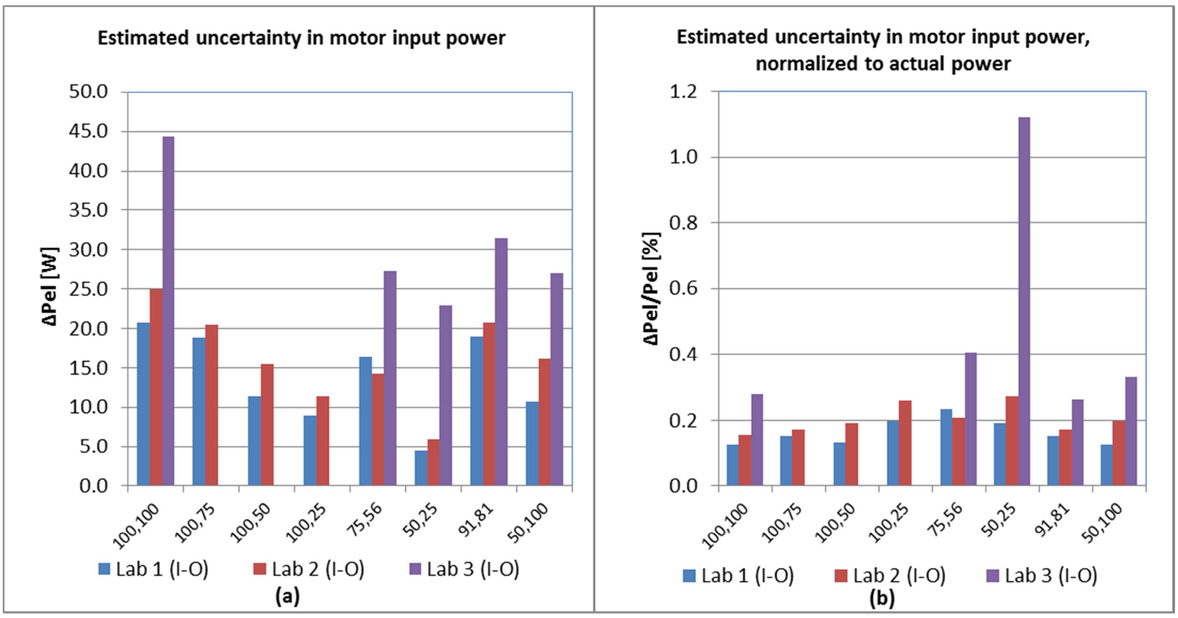

Figure 5: Estimated uncertainty in motor input power

Uncertainty in measured motor output power

The main contributions to the uncertainty in mechanical power $u_c(P_{m.})$ are uncertainties in measured torque and speed measured by the torque transducer and the respective uncertainties of power analyzer while acquiring these signals. Again, the type of transducers and their interfaces to the power analyzers are different for all three labs. The torque transducers used in Lab 1 and Lab 3 are having ten times higher accuracy than the transducer used in Lab 2. Also, Lab 1 uses digital frequency signal representative of actual torque to interface with the power analyzer torque inputs, while Lab 3 uses direct acquisition of torque values over dedicated communications bus to acquisition computer, thus providing most accurate torque information. Lab 2 uses analog output signals representative of torque to interface with power analyzer. The estimated uncertainty in the motor output power is shown in Figure 6. The following observations can be made from the absolute uncertainty values and the respective normalized numbers to actual output power for different labs at various operation points.

- The uncertainty estimation method is different for different torque transducers as described in the datasheets from respective manufacturers.
- Lab 3 uses higher accuracy torque transducer and a direct communication interface to the transducer. Thus uncertainty for this lab is lowest as compared to other two labs. Lab 1 uses digital signals for interfacing to power analyzers, the added uncertainty of this interface results into higher overall uncertainty as compared to Lab 3 for measurement points.
- Lab 2 uses lower accuracy transducer, thus has highest uncertainty as compared to other labs. The exceptions are at operation point [100,25] and [50,25]. The analog signal interface to the power mode is used together with “auto” mode. At the above measurement point, the power analyzer selects best suitable scale thus minimizing the “range” related uncertainty.
- Although, the absolute uncertainty at partial operating conditions are lower as compared to the nominal operation point, relative uncertainty is much higher when normalized to actual power value as shown in Figure 6(b). Under-utilization of the measurement setup results into higher uncertainty or relative uncertainty, similar to electrical power measurement.

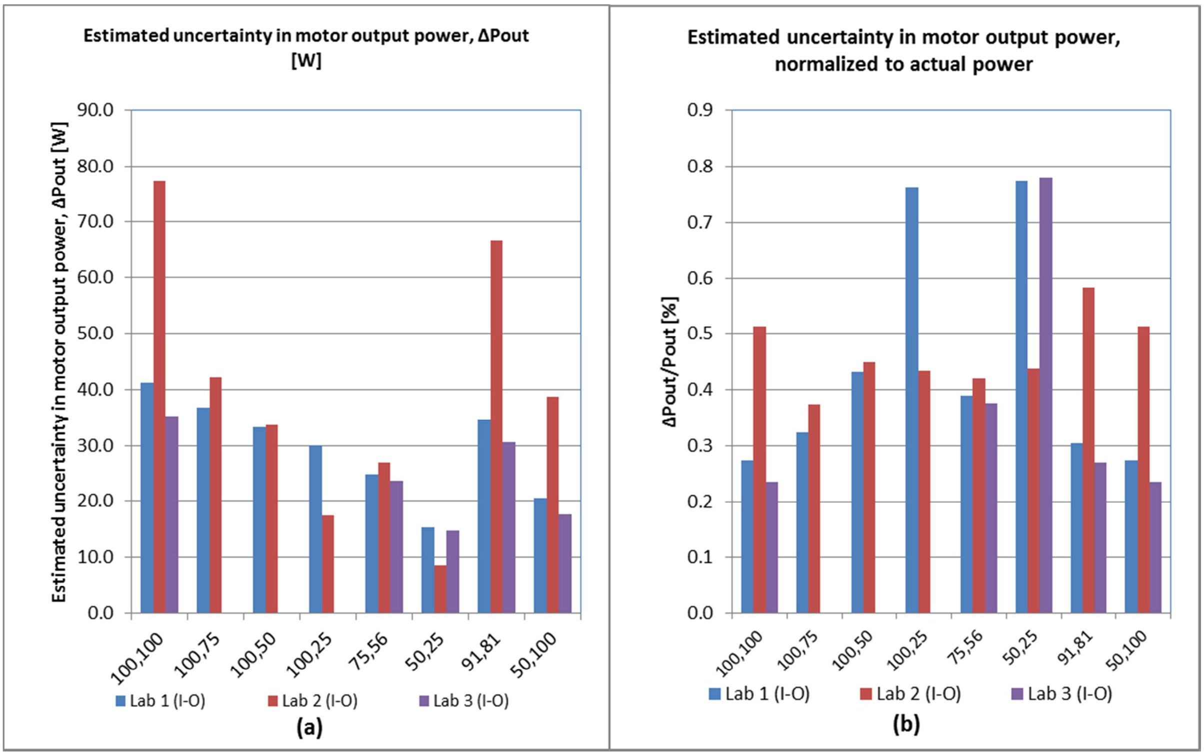

Figure 6: Estimated uncertainty in motor output power

Uncertainty in losses measured using calorimetric method

The procedure for estimating of the uncertainty of calorimetric loss measurement is detailed in [21]. First, the corrections in the measured losses is done by accounting for all heat leakage from different sources like motor shaft, mounting and chamber walls as described in [15] [18]. The uncertainty of the different measurements is considered to estimate overall uncertainty of motor loss measurement. As the calorimetric loss measurements are performed in two phases, first calibration phase: to establish blower speed at set temperature gradient, followed by balance phase to establish the same thermal conditions using the DC power to heater placed inside calorimeter. Assuming that the air qualities is same as that of calibration phase, the DC power to heater is considered as motor losses for similar equilibrium condition of calorimeter. It is straightforward to assume that the heat leakages through chamber walls, motor shaft, motor mounting are similar during calibration and balance phase and minimized by use of special construction techniques [15]. The main contributions to the uncertainty are thus from DC power measurement, friction and windage losses of motor, whereas the uncertainty of temperature measurement, blower speed measurement is ignored owing to two step procedure. The uncertainty in motor losses for Lab 2 and Lab 3 is shown in Figure 7 for different operating conditions. The calorimeter used in Lab 3 has methods to control and correct the inlet air qualities and thus considered more accurate as compared to calorimeter in Lab 2.

Uncertainty in motor losses and efficiency

The uncertainty of motor losses for input-output method is calculated from the uncertainties of the measured input and output powers as described in (**11**). The calculation results are shown in Figure 7 together with respective uncertainties for calorimetric method described above. Similarly, uncertainty in motor efficiency is calculated from respective uncertainty estimates for input and output powers as shown in (**10**). The uncertainty in efficiency for calorimetric method can be derived either using motor output power and motor losses or motor input power and motor losses, as described in (**12**) and (**13**), respectively. As the electrical input power measurement is more accurate as compared to mechanical power measurement (**12**) is used for the calculations shown in Figure 7. The uncertainty estimation in efficiency thus considers the respective uncertainties in the input power measurement during the calibration phase shown in Figure 5 and uncertainty in motor loss shown in Figure 6. The final results for uncertainty in efficiency values are shown in Figure 8.

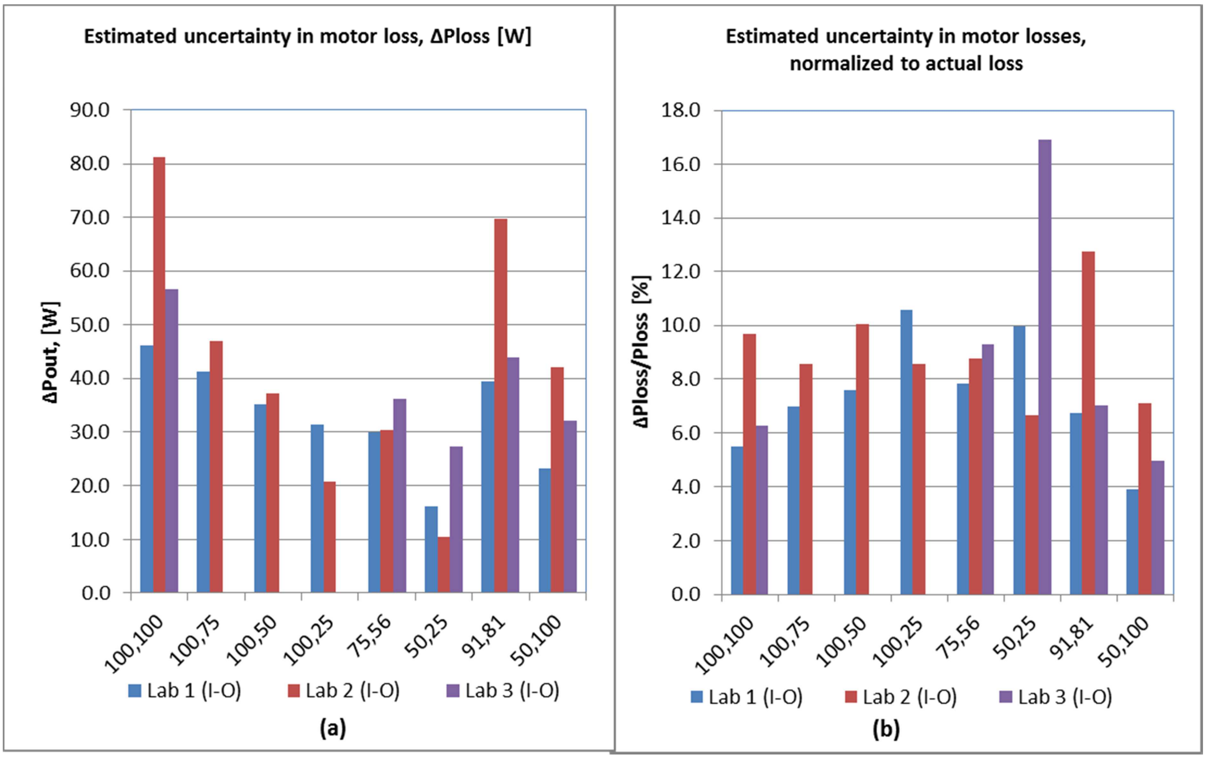

Figure 7: estimated uncertainty in motor losses

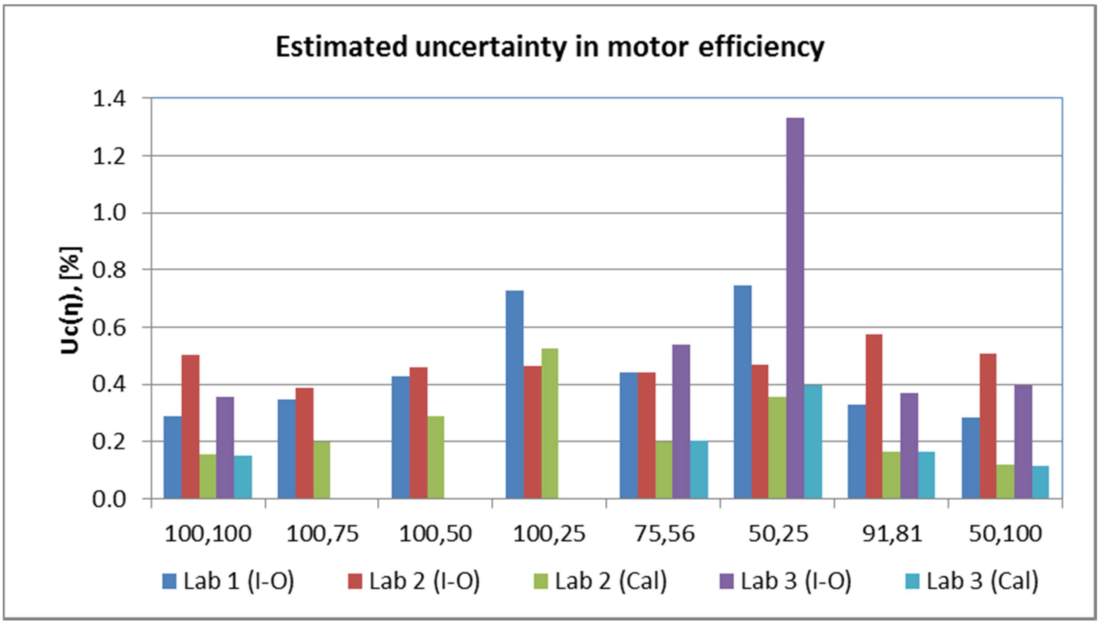

Figure 8: motor efficiency with estimated uncertainty of measurements

In general, the calorimetric method shows lower uncertainty compared to the direct input-output method. Although this is not the case for all the operating points tested. For example at [50,25] operating point, due to auto selection of ranges for electrical power measurement and torque inputs, the results of overall uncertainty in motor efficiency is much lower than respective values for calorimetric method. The motor efficiency values reported earlier in Figure 4 are shown again in Figure 9 together with uncertainty values superimposed as error bars.

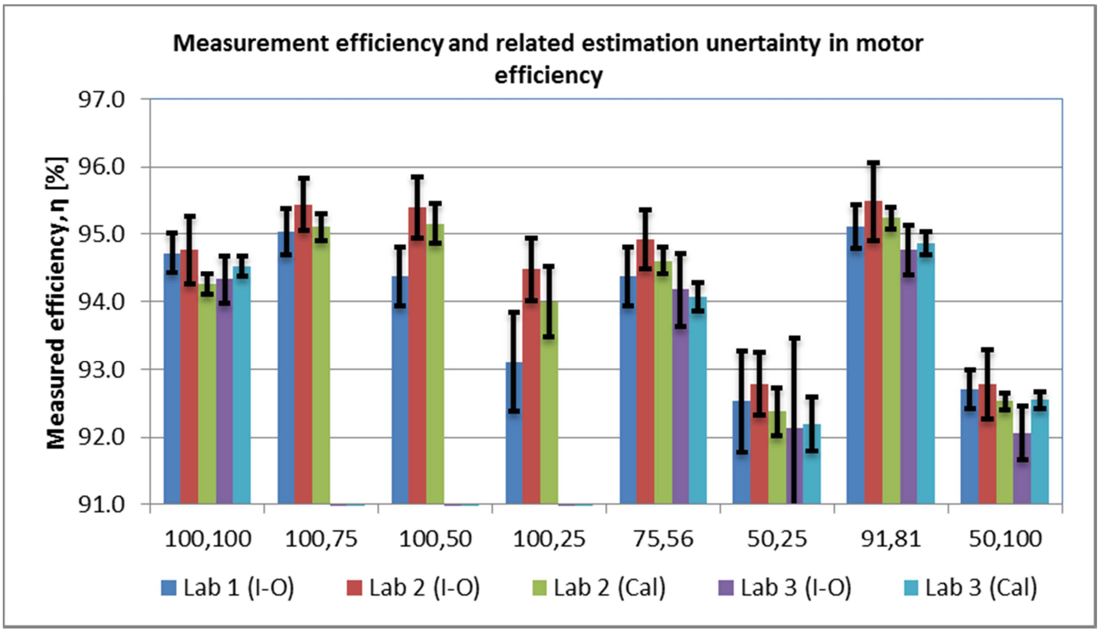

Figure 9: Summarized performance of different labs and measurement methods for motor efficiency measurement

Comparison of measurement uncertainty with manufacturing tolerance levels

In addition to the accuracy requirements for measuring equipment, standards also specify the respective tolerance levels for measured motor efficiency or losses due to manufacturing variations and material property changes. The maximum tolerance as per IEC60034-1 is 15% of the losses (1-η) for a 15 kW motor rating[1]. But standards do not specify the requirements on the overall uncertainty in measuring motor losses or efficiency and how it should be estimated for different test methods. In case of VSD fed motors, the efficiency is required to be evaluated at more than one operation point apart from the nominal load conditions, but the requirements on uncertainty of motor efficiency for such operation points is not yet addressed in the standards. For high efficiency motors, the measurement uncertainty are equally important as the manufacturing tolerances and improper use of measurement methods can lead to large variation in measured efficiency and thus wrong determination of motor IE class.

The estimated uncertainty presented in previous sections can be compared with the manufacturing tolerance levels to make a comparative assessment of the importance of measurement uncertainty. The estimated uncertainty in efficiency is normalized using the actual measured efficiency value at that operation point and the results are shown in Figure 10. The relative uncertainty at nominal operation point is much lower than the 15% value of manufacturing tolerance. As described in earlier sections, $u(\eta)/(1-\eta)$ for Lab 2 is highest as compared to other labs due to a low accuracy torque transducer. Similar agreements are observed at other points except the operation point [50, 25], where $u(\eta)$ for direct input-output method is even lower than the calorimetric method due to auto range selection. It should be noted that the relative measurement uncertainty in efficiency cannot be compared with different operation points due to different efficiency values at these operation points. The calorimetric method is shows much lower uncertainty values as compared to direct input-output method.

The calorimetric methods in both labs performs well where most of the measurements points show measurement uncertainty below 8%, except for one measurement point for Lab 2 where it exceeds 8% of maximum margins. This is due to the higher value of uncertainty in the input power measurement, whereas the actual loss measurement is still with lower uncertainty. The motor losses are much lower than the designed heat capacity of the calorimeter chamber and this leads to higher uncertainty of calorimeter measurements for these operating points.

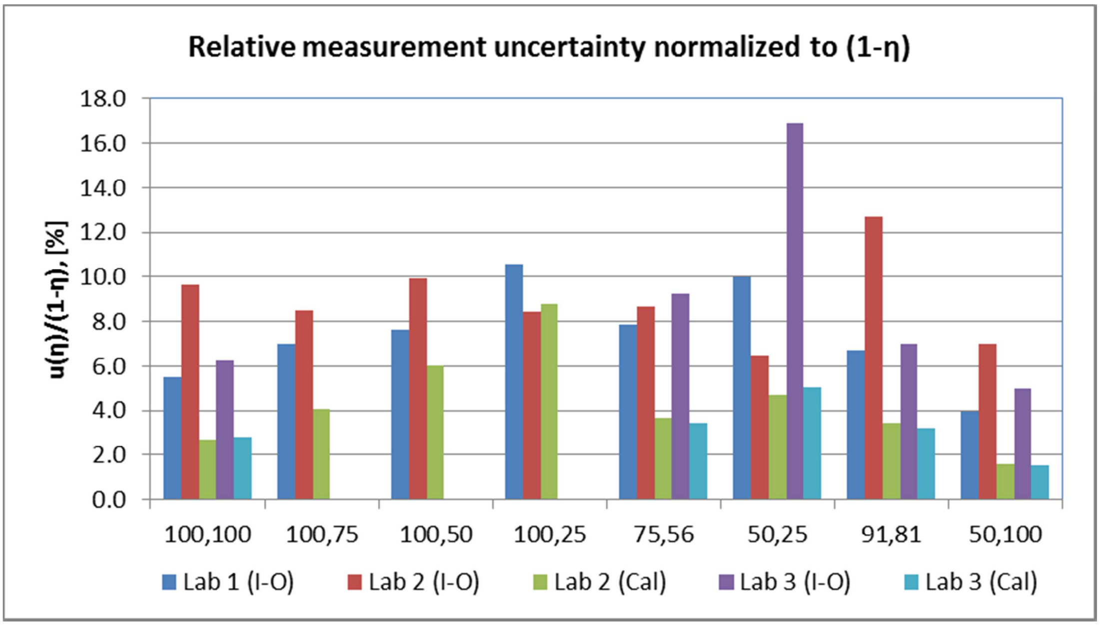

Figure 10: The measurement uncertainty in motor efficiency normalized to actual value

[1] Tolerance is the maximum allowed deviation between the test result of a quantity and the declared value on the rating plate or in the catalogue. As long as test procedures and test equipment according to IEC standards are used, the test result shall not exceed the allowed deviation independent of test laboratory or equipment. Tolerance does not cover the uncertainty of a test procedure, i.e. the deviation between the test result and the true value.

Guidelines on use of instrumentation and measurement procedures

As shown above, the relative uncertainty is often close to respective manufacturing tolerance levels, especially at partial load operation points. The variations in different setups and methods followed in respective labs also gives guidelines on use of instrumentation and measurement procedures.

The use of higher accuracy transducer for Lab 2 can produce equal performance as compared to other labs. Similarly, avoiding fixed range for power analyzers can reduce the measurement uncertainty for Lab 3 in partial load operation points. Another improvements for the lab setups in Lab 1 and Lab 2 can be done with improved interface (Profibus) of torque transducer outputs, similar to the method used in Lab 3. While conducting calorimetric measurements in partial load conditions, bias power using heater resistors can be used so that the calorimeter is always operated with higher capacity, which can minimize the possible errors.

The efficiency in partial load condition shows larger variation when compared to the results obtained from different labs. Partial load condition can also be seen as testing a smaller kW motor on the much higher capacity instrumentation setup. The measurement uncertainty for such a combination will be worse, similar to the partial load conditions of a higher capacity motor. In a typical motor testing laboratory, it is impracticable to prepare measurement setups for all motor ratings. The best judgment should be made based on the available margins left for manufacturing tolerances.

It is also questionable if the nominal speed and torque operation point is the best operation point for specifying the accuracy requirements for VSD fed motor efficiency class categorization. The VSD driven motor is very unlikely to be only used in this one operating point, and the area of operation of VSD motor is generally at lower speed and torque values depending upon the torque characteristics of the load. Thus the main comparison point should be, for example, 75% speed and 75% torque which is in the range of real operation points of the VSD fed machines or area of operating region on speed-torque plane. Similarly, accuracy requirements should be broadly described for different operating points in simplistic manner without losing on reliability.

The efficiency measurement standards for VSD fed motors can be adapted to include specific information on the levels of measurement uncertainty as well as the methods to estimate such measurement uncertainties. This can enable to select best methods to be followed for measuring efficiency of VSD fed motors. It is clearly understood that 15% allowed tolerance in losses stated in IEC60034-1 and measurement uncertainty added to it can easily influence on efficiency class separation (~20% of losses is the separation between efficiency classes) , especially for high efficiency motors. There is also a potential risk that tolerances could be misused, intentionally or unintentionally, which could lead to unfair competition and increased energy consumption from the motor manufacturers to miss utilize the tolerances to claim that their produced motors meet the standards, which is not true.

Hence, one main recommendation from this work is to standardize the test procedures with measurement tolerances limits and also reduce the allowed tolerances to a reasonable level in comparison with manufacturing tolerance levels. For example, the analysis presented in this paper shows most of the measured uncertainty values below 8 %. One proposition can be to allow equal distribution of 7.5 % for both manufacturing tolerances and measurement uncertainty. Also the uncertainty requirements at partial load conditions could be weighted according to the powers involved, thus allowing for higher tolerances at partial loads to conform to the accuracy specifications as mentioned above. Such trade-off can be easily accepted knowing that the motor energy consumption is much lower at partial load conditions and it is very unlikely that the motor will be operated in such operating point for most of its lifetime in actual industrial use.

It should be kept in mind that the uncertainty of the input-output loss determination method is approaching infinity when the efficiency is approaching unity as shown in [27] . Thus, it is going to be even more challenging to use direct input-output method for higher efficiency motors like IE5 or higher. The calorimetric loss measurement method is going to be more accurate for such higher efficiency class VSD motors.

Conclusions

The paper presents the comparison of direct input-output method and calorimetric loss method for measuring the efficiency of a VSD fed SynRM motor. The measurements using these two methods are performed at three different labs for different operating points and a comparative assessment of each method is presented in this paper. The paper presents the detailed analysis of the measurement uncertainty which is estimated using the known accuracy limits of instrumentation for different operating points described in the standard for evaluating efficiency of VSD motors.

A general observation is that the results from direct input-output method are in good agreement with the results obtained from the calorimetric method irrespective of different laboratories where they are tested. A larger deviation in efficiency occurs at partial load conditions between the measured efficiencies in different labs. However, irrespective of the load point, the maximum deviation between the efficiency measured using two methods in same lab is always below 0.5%.

The uncertainty in efficiency measurement at partial loads are higher than at the nominal values for direct input-output method as expected. As described in the paper, standardizing tolerance requirements for different measurement points as well as the accuracy specifications for instrumentation could provide an important base for accurate measurements and effective classification of VSD fed motors. The paper provided specific inputs for describing accuracy requirements of instrumentation setups as a part of related measurement standards. The paper also suggested to adapt the overall measurement uncertainty requirements as a function of operating conditions to allow for higher uncertainties at partial load conditions.

The calorimetric method has been used as a base to compare input-output measurement methods as described in this paper. Although the measurement standard [11], clearly mentions calorimetric loss measurement method to be used for measuring efficiency of converter or converter+motor, it is used in this paper to validate the efficiency measurements of VSD motor performed using input-output method. It is shown that with proper care taken with respect to instrumentation, reliable results are also achieved using input-output method. It can be thus concluded that at the moment, the input – output method with high accuracy instruments is well capable of producing the results needed in type testing and energy efficiency classifications in the range of IE4 machines.

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Testing of Power Drive Systems (PDS)
– A joint test program toward a harmonized standard

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Abstract

During recent years, multiple efforts have been taken toward making standards for testing Power Drive Systems (PDS) e.g. converter + motor. One standard has already been published (Canada), while others are still in the final voting stage (Europe).

Beside this, discussions are well underway in the European community as the next step for motor and converter legislation and inclusion in the eco-design frame of European energy efficiency. One new element of this legislation concerns the converter's efficiency as a separate component. A converter is referred in this context as complete drive modules (CDM).

An important input to these discussions came from independent laboratory efficiency tests conducted on numerous drives and motors in many different combinations and sizes, according mainly to the new published European standard EN-50598-2 and some tests on larger PDS based on the Canadian Standard CSA C838.

This paper presents independent test results based on both standards for motors, converters, different motor/converter technologies and even different combinations of manufacturers.

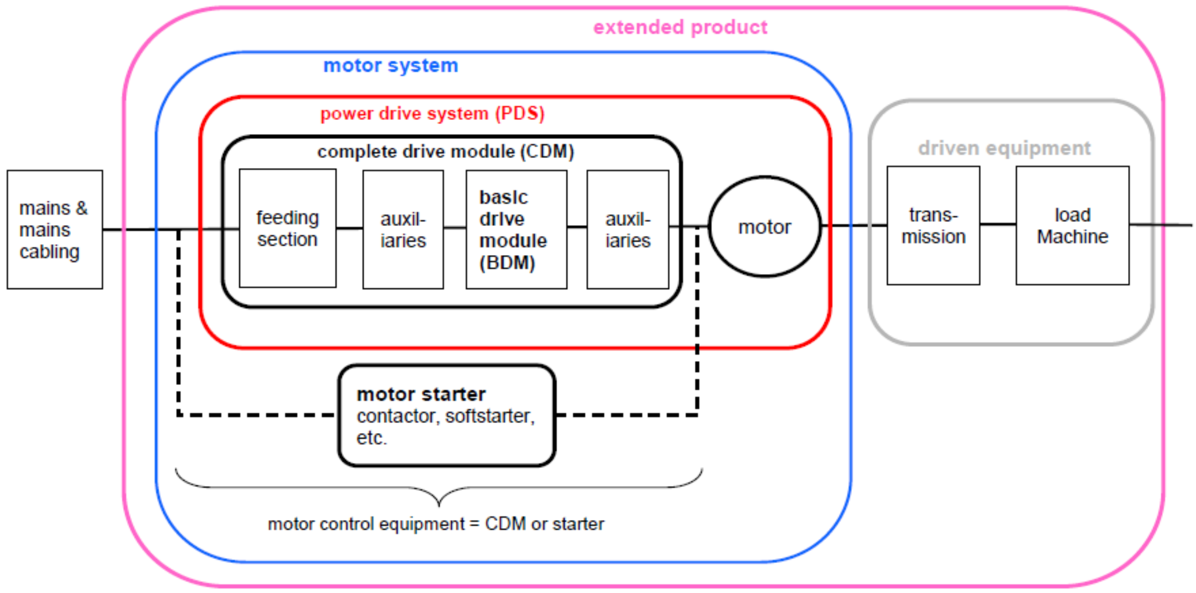


Figure 1: Concept of the extended product as defined in EN 50598-2

Testing according to EN 50598-2

The following paragraphs detail a walkthrough of how to determine efficiency and IE class for a complete drive module (CDM) and a complete power drive system (PDS), according to the European EN-50598-2 standard published in December 2014.

Examples help to illustrate the ambiguities and other open ends within the standard that leave up to the reader many important factors of efficiency determination, thereby making comparison between test labs and manufacturers very difficult.

Following this, the EN 50598-2 standard also creates problems for the European Commission in terms of eco-design regulation on CDM's, as it is questionable how a given CDM is referred inside the regulation itself. Market surveillance will be immensely difficult to perform with the standard and regulation proposed.

Hopefully, the work done on the International level within IEC SC22G Working Group 18 on the upcoming IEC 61800-9-2 standard is aimed to solve these issues.

CDM – IE classification by testing

For this type of testing, a complete drive system has to be selected. In the case of an independent accredited test laboratory, many products of different power sizes and brands are available.

For this example, the CDM system has the following specifications[1]:

- 1.1 kW Frequency converter, found and bought anonymously in a webshop in the fall of 2014, including a display but without other auxiliaries. All tests were performed "out of the box". Specifications of the device as quoted from the nameplate:
  - Input specs: 3x380…500 VAC, 50…60 Hz, 2.8 Amp AC (400V)
  - Output specs: 3x0…Un VAC, 0…599 Hz, 3.1 Amp AC (400V), P = 1.1 kW (1.5 Hp)

  - Calculated kVA as quoted from EN 50598-2:

$$S_{r,equ} = \sqrt{3} \cdot U_{1,r,out} \cdot I_{r,out} = \sqrt{3} \cdot 400 \cdot 3.1 = 2.15 \text{ kVA}$$

Objectives:
- Determine CDM IE class by actual testing
- Determine efficiency in eight pre-defined part load operating points

[1] No manufacturer brand is disclosed by agreement

Step one: Finding an appropriate motor size

For testing, it would be natural to try to connect a same size of motor and CDM. However, in reality this is rarely the case, especially with CDM of smaller sizes.

The EN-50598-2 standard has shown that losses of CDM's are highly dependent of the "torque producing current", which is considered part of the load current that produces torque (as opposed to the magnetizing current).

As it is impossible to measure this current directly on asynchronous machines, the EN 50598-2 standard provided tables with values to guide the user in any given operating point:

Torque producing current / %	Test load current $\frac{I_{out}}{I_{r,out}}$ / % for the apparent power range $S_{r,equ}$ of				
	0,278kVA (0,12kW) to <1,29kVA (0,75kW)	1,29kVA (0,75kW) to <7,94kVA (5,5kW)	7,94kVA (5,5kW) to <56,9kVA (45kW)	56,9kVA (45kW) to <245kVA (200kW)	245kVA (200kW) to <1209kVA (1 MW)
25	0,79	0,58	0,45	0,42	0,39
50	0,81	0,71	0,60	0,58	0,56
75	0,89	0,82	0,79	0,78	0,77
100	1,00	1,00	1,00	1,00	1,00

Torque producing current / %	Test load displacement factor cos ϕ for the apparent power range $S_{r,equ}$ of Fundamental displacement factor in different operating points				
	0,278kVA (0,12kW) to <1,29kVA (0,75kW)	1,29kVA (0,75kW) to <7,94kVA (5,5kW)	7,94kVA (5,5kW) to <56,9kVA (45kW)	56,9kVA (45kW) to <245kVA (200kW)	245kVA (200kW) to <1209kVA (1 MW)
25	0,34	0,38	0,49	0,54	0,57
50	0,51	0,60	0,71	0,75	0,78
75	0,64	0,72	0,80	0,83	0,85
100	0,73	0,79	0,85	0,86	0,87

Figure 2: Tables 2&3 quoted from EN 50598-2

For this test, the CDM requirements of the second column apply and for the 100% torque producing current operating point, a motor drawing 3.1 amps with a fundamental displacement factor of 0.79 (*a deviation of ±0.08 are allowed*) is required.

The standard states that the above tables come from actual measurements on 4p IE2 400V 50 & 60 Hz asynchronous motors, and that this would be a likely but not required load to use. This type of motor is considered as standard motor, and is easily available.

Following many tests of different combinations, a **4p 1.5 kW IE2 motor, 400V, 3.26A** was selected as load for the 1.1 kW CDM under test, as this motor proved most sufficient to apply the required load over a longer period.

Test setup

The test set-up according to EN-50598-2 standard is very similar to the test set-up with other standards as in Figure 3.

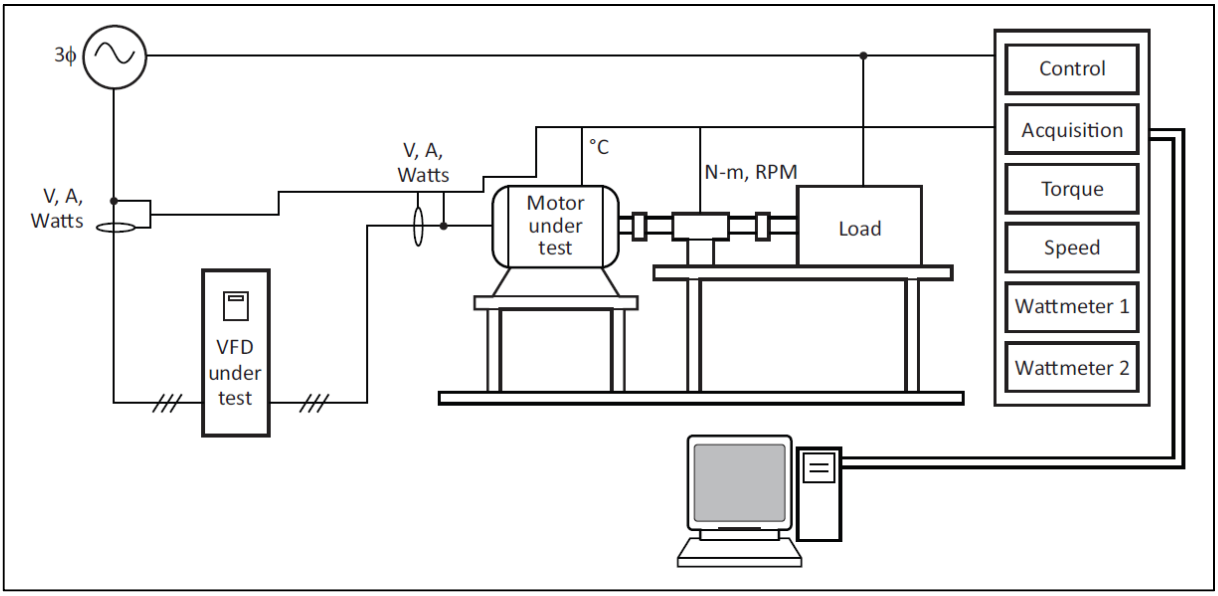


Figure 3: Illustration from Canadian CSA 838-13

A variable transformer ensures constant supply voltage and frequency to the equipment under test, (EUT).

A Zimmer LMG-450 power analyzer is used on the primary side of the CDM (Wattmeter 1) while a Voltech PM3000A power analyzer is connected to the secondary side of the CDM (Wattmeter 2). Both power analyzers use the recommended 3-phase 4-wire wattmeter method with a “star adapter” as described in the Canadian CSA 838-13 standard. The Zimmer LMG-450 power analyzers have a basic accuracy of 0.1%, whereas the Voltech PM3000A have a basic accuracy of 0.05%.

A non-contact torque transducer DR-2412 with a 20 Nm full scale from Lorenz Messtechnik GmbH, Germany measures torque and speed at the motor shaft with a basic accuracy of 0.1%.

A second torque and speed measurement setup is part of the load machine thereby providing a dual independent measurement of these two important parameters.

A 15 m cable (type 3+1 wire 2.5mm^2) is installed between the CDM and the motor as prescribed in EN-50598 standard. CDM input and output electric powers, are measured as close as practically possible to the CDM terminals (< 1m).

All temperature measurements are done by calibrated thermocouples type T including ambient, CDM heat sink & inlet, motor frame, inlet & winding. The accuracy of these calibrated thermocouples are better than ±0.2 °C

The acquisition and control of the test set-up is fully automated under LabVIEW PC environment, which allows the user freely to choose sample time, duration and operating points of the tested system in any given order.

Step two: Warm-up and (90;100) duty point for IE classification

The test CDM was mounted with the selected motor as described above and the system was tuned in to run at 45Hz output (90%) at a current of 3.1 ampere (100%).

The EN-50598-2 standard quotes: “Run until thermal stability has been achieved, with less than 2K rise per hour”, but it is not defined where to measure it.

Experience has shown though that CDM efficiency suffers little or has no change as soon as the conducting IGBT’s and heat sink warm up as demonstrated by many tests performed in the lab. This condition is normally achieved within 30 minutes of full load operating time.

Figure 4 shows an example of a CDM + motor system warming up for approximately two hours.

- The thick yellow line is the heat sink temperature (measured at the heat sink by thermocouple)
  - Stabilized after approx. 15 minutes.
- The thick purple line is the motor winding temperature (thermocouple down junction box)
  - Stability achieved after approx. 2 hours.
- The thick light blue line on top is the directly measured CDM efficiency (input/output)
  - Little or no change in measured efficiency in the entire period.

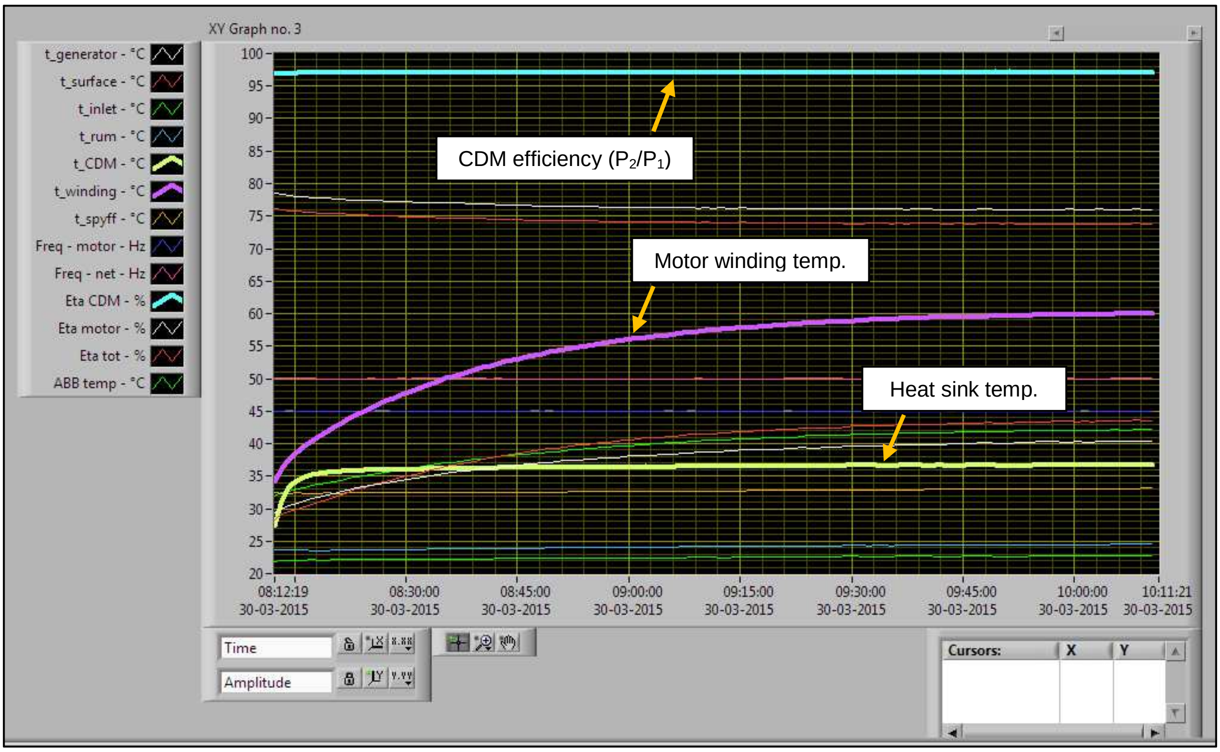


Figure 4: Screen capture of an example 2h warm-up period

After a sufficient warm-up period of the CDM in the (90; 100) duty point the data was collected over a period, averaged and the calculation of IE classification according to EN 50598-2 was performed.

In this calculation, the tested CDM has to be compared to a reference CDM (RCDM) that can be found in a look-up table (20) within the EN 50598-2 standard.

This reference is based on either the calculated or the stated apparent power of the EUT. In this case 2.15 kVA.

Table 20 — Reference CDM losses for IE class 1 definition

P_{rM} / kW	$S_{r,equ}$ / kVA	$I_{r,out}$ / A of the 400V RCDM	$p_{L,RCDM\ (90,100)}$ / % of $S_{r,equ}$	$P_{L,RCDM\ (90,100)}$ / W
0,12	0,278	0,401	35,85	100
0,18	0,381	0,550	27,30	104
0,25	0,500	0,722	21,80	109
0,37	0,697	1,01	16,84	117
0,55	0,977	1,41	13,21	129
0,75	1,29	1,86	11,02	142
1,1	1,71	2,47	9,51	163
1,5	2,29	3,31	8,21	188
2,2	3,30	4,77	7,20	227

Figure 5: ***Extract from EN 50598-2 table 20***

If the specific kVA size are not to be found the next higher shall be used. In this case, this results in a reference CDM of 1.5 kW RCDM with an allowed loss percentage of 8.21% for IE1 class[2].

According to EN 50598-2, the relative losses of the EUT shall always be calculated including the uncertainty of the input/output measurement. This uncertainty is therefore added to the actual measured loss, before the two relative loss percentages are divided resulting in a relative number

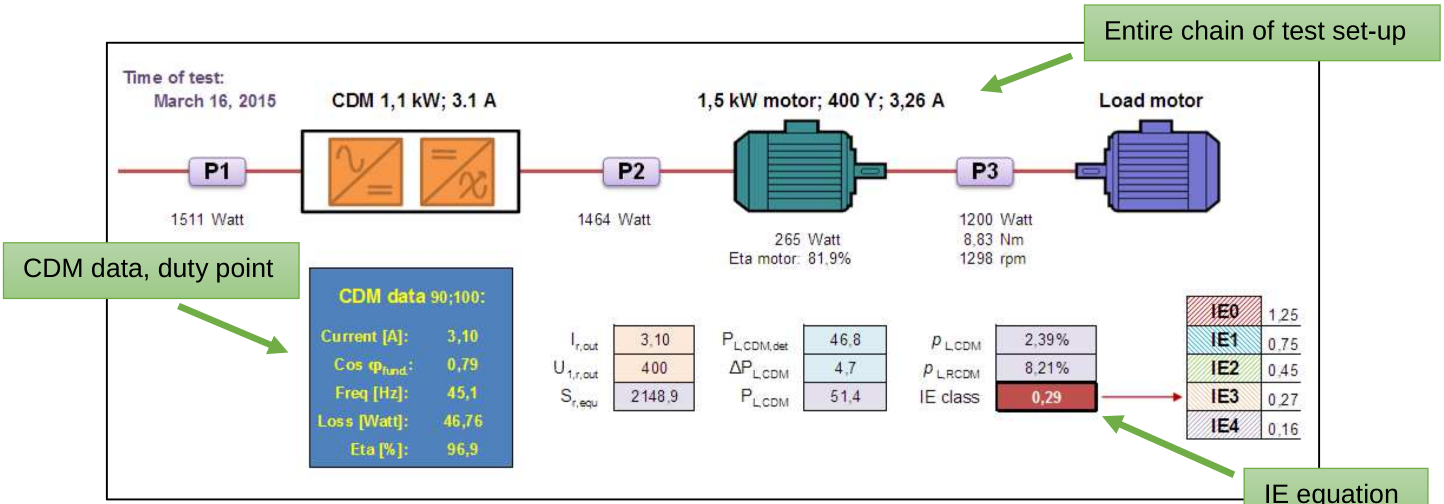


Figure 6: IE classification of 1.1 kW CDM with 1.5 kW motor as described in EN 50598-2

For this CDM, the IE classification figure is 0.29, which would classify it as **IE2** – with margin[3].

The IE scale in EN 50598-2 only includes IE1 & IE2 (IE2 is defined as everything less than IE1 x 0.75).

If one was to extend the classification scale to include also IE3 & IE4 following the same analogy with a baseline ± 25% margin then the tested CDM would be classified **IE3** (0.27 < IE3 < 0.45).

[2] The reference CDM is one power class higher than EUT

[3] Note the fundamental displacement factor in this case is spot on 0.79

Step three: Same CDM – Smaller motor

As described earlier, different motors were tried out with this CDM before selecting the 1.5 kW motor. Figure 7 presents the results with a 1.1 kW 4p IE2 motor.

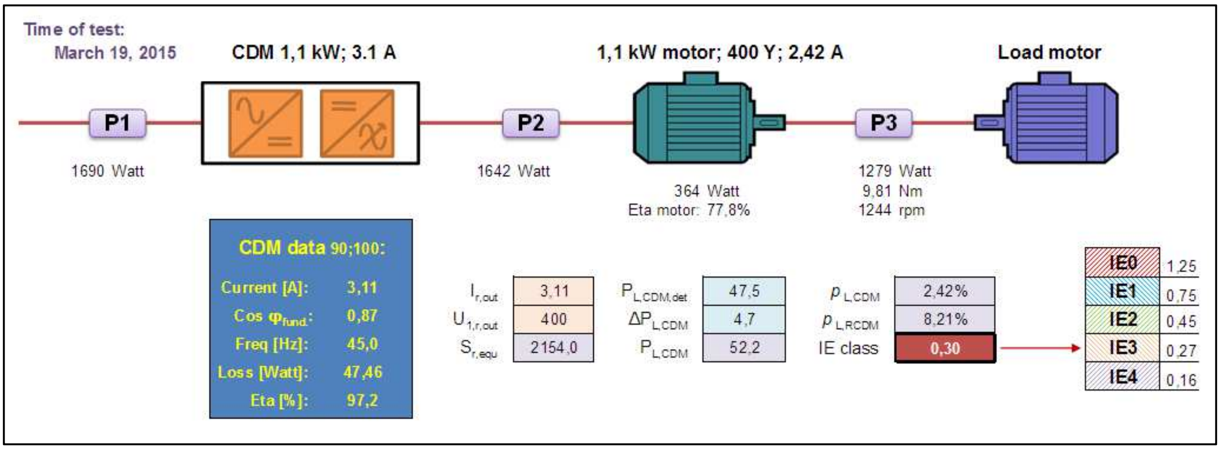


Figure 7: Same CDM with smaller size motor.

However this combination has some problems especially at the (90; 100) operating point. By using a 1.1 kW motor and forcing it to draw 3.1 ampere, the motor is overloaded.

Nominal values of the IE2 motor are:

- 1.1 kW, 400V, 2.42A, 1435 rpm, 50 Hz, PF 0.80 & 7.32 Nm

This means for one, that special action has to be taken in terms of cooling the motor properly during the warm up period, but also that the power factor of the motor is relatively high and indeed much higher than at nominal load.

In this specific case at the (90; 100) duty point the power factor is acceptable according to the EN 50598-2 tables 2-3 (figure 2), but only with full use of the allowed deviation utilizing rounding etc. However, this is not the case for the other seven part-load duty points.

For the IE classification of the CDM in question, this smaller size motor have very little impact on the classification result. The current drawn by the motor, the voltage and frequency send out by the CDM are comparable and almost the same values.

Only real difference is the absolute power delivered by the CDM and the power factor of the motor connected. This raises marginally the efficiency and the power losses in absolute values. The official classification is still IE2 with margin (and IE3 unofficially).

Many of the smaller sized CDM's require motors at least one size larger based on the nominal values, and this could be problematic in terms of comparing complete power drive systems from one supplier to systems where individual components are purchased separately.

CDM – Partial load points by testing

To enable the user to eventually calculate complete motor system losses including partial load efficiencies, EN 50598-2 standard introduces 7 additional load points to complement the reference load point (90; 100) giving a more detailed insight of the losses of the CDM.

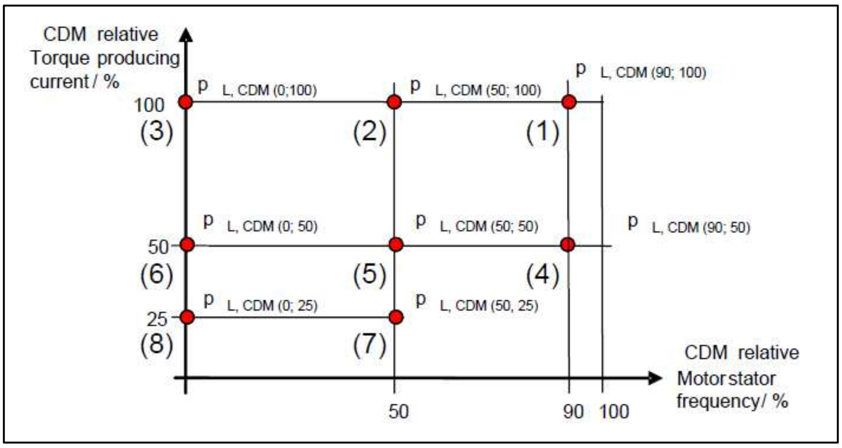


Figure 8: The eight part-load duty points from EN 50598-2

The numbers in parentheses on figure 8 refer to the preferred order of measuring the part load points, which are to be measured "immediately" after thermal stability have been achieved (not well defined in the standard). No requirements are apparently set in terms of duration of each duty point, duration of the entire test or even thermal conditions that needs to be met during the test.

The part-load points numbered (3), (6) & (8) are intended to be measured at 0 Hz output frequency to accommodate special applications as cranes, lifts and likewise, but in practice these are very hard to achieve. This is not new for people working with drives in real conditions. Normally duty points like these would require both encoder feedback as well as special "fine-tuned" software to be able to withstand zero speed / full torque for extended periods.

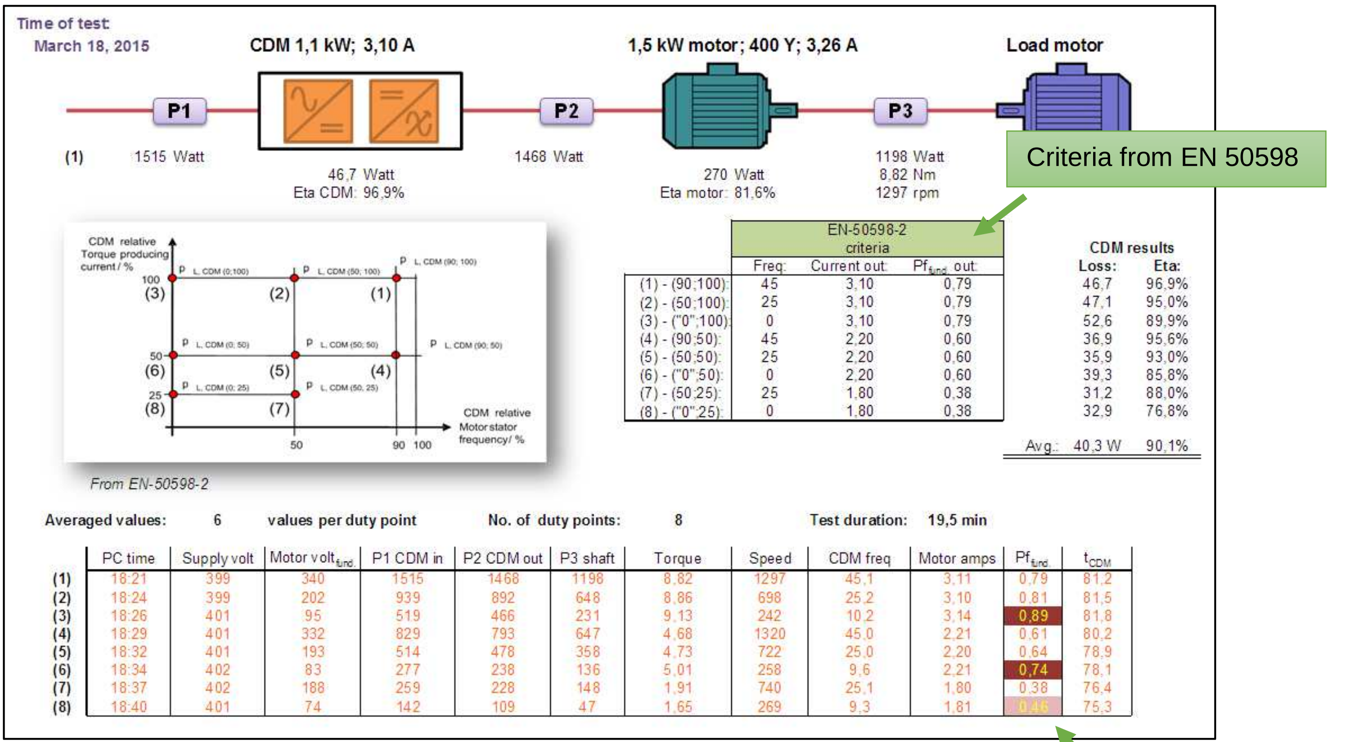
The EN-50598-2 standard therefore allows up to 5 Hz output instead, but even at that frequency the CDM tested collapsed at full load current. For practical reasons the CDM was therefore tested at the lowest possible output frequency, namely ≈ 10 Hz.

After spending countless hours in testing many different motors with this specific 2.15 kVA CDM, it was shown that it was impossible to find a motor that would live up to the requirements of tables 2 & 3 in all eight operating points as required by the standard.

Following the same analogy as described in the CDM IE test above, i.e. re-connecting the 1.5 kW motor, warming up the system and sub-sequentially measuring as described in the EN-50598-2 standard, the 8 point measurement cycle was hereafter performed.

Each of the eight part-load duty points were collected over a sufficient amount of time to average and typically last a couple of minutes, making an entire measurement cycle of 20 minutes.

The measurement results are presented in Figure 9.



	EN-50598-2 criteria Freq:	Current out:	$Pf_{fund.}$ out:	CDM results Loss:	Eta:
(1) - (90;100):	45	3,10	0,79	46,7	96,9%
(2) - (50;100):	25	3,10	0,79	47,1	95,0%
(3) - ("0";100):	0	3,10	0,79	52,6	89,9%
(4) - (90;50):	45	2,20	0,60	36,9	95,6%
(5) - (50;50):	25	2,20	0,60	35,9	93,0%
(6) - ("0";50):	0	2,20	0,60	39,3	85,8%
(7) - (50;25):	25	1,80	0,38	31,2	88,0%
(8) - ("0";25):	0	1,80	0,38	32,9	76,8%
			Avg.:	40,3 W	90,1%

	PC time	Supply volt	Motor $volt_{fund.}$	P1 CDM in	P2 CDM out	P3 shaft	Torque	Speed	CDM freq	Motor amps	$Pf_{fund.}$	t_{CDM}
(1)	18:21	399	340	1515	1468	1198	8,82	1297	45,1	3,11	0,79	81,2
(2)	18:24	399	202	939	892	648	8,86	698	25,2	3,10	0,81	81,5
(3)	18:26	401	95	519	466	231	9,13	242	10,2	3,14	0,89	81,8
(4)	18:29	401	332	829	793	647	4,68	1320	45,0	2,21	0,61	80,2
(5)	18:32	401	193	514	478	358	4,73	722	25,0	2,20	0,64	78,9
(6)	18:34	402	83	277	238	136	5,01	258	9,6	2,21	0,74	78,1
(7)	18:37	402	188	259	228	148	1,91	740	25,1	1,80	0,38	76,4
(8)	18:40	401	74	142	109	47	1,65	269	9,3	1,81	0,46	75,3

Figure 9: 8 x partial load points with 1.5 kW motor

The measurement shows that the 1.5 kW motor, in spite of being merely "perfect" for CDM IE classification at the (90; 100) duty point, is having trouble keeping the desired fundamental displacement factor in two of the eight duty points (3) & (6). In the eighth duty point, it is very close to the limit using the fully allowed tolerance.

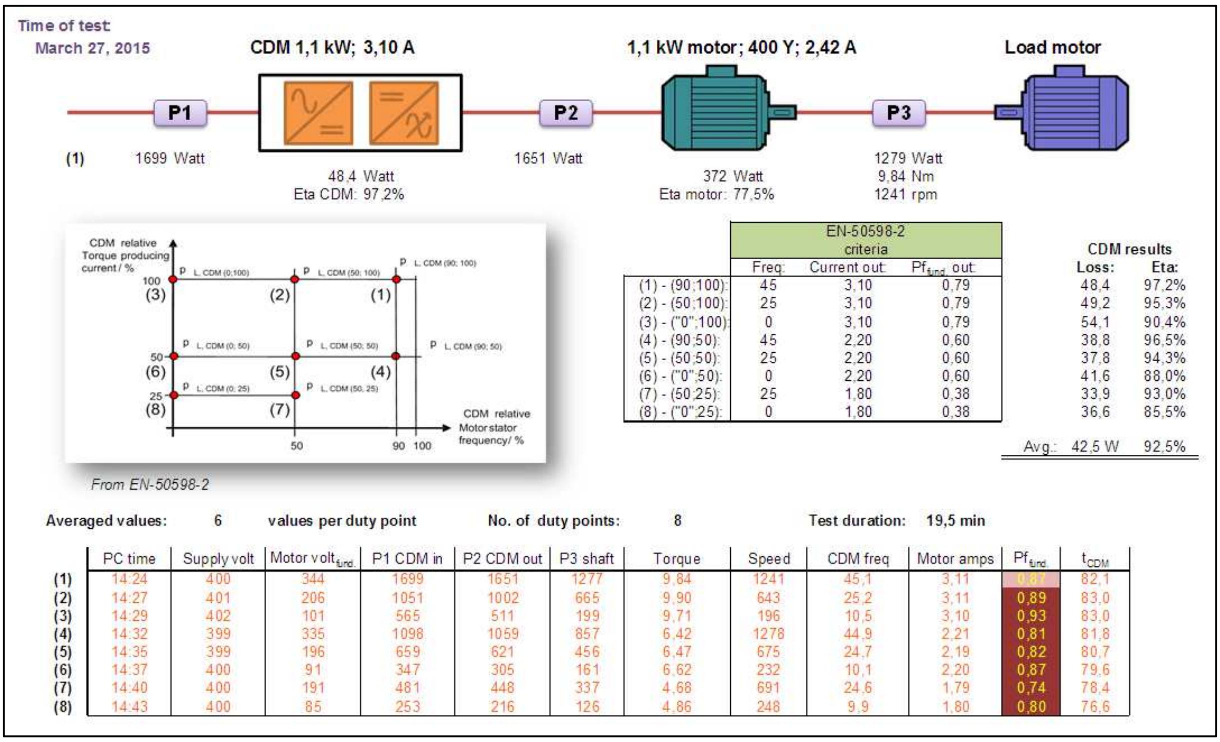
All three "problematic" duty points are at "zero" Hz output frequency.

The efficiency of the CDM is directly computed here as (P_2/P_1) in each part-load duty point, this time without adding the uncertainty. It can be seen from this that efficiency decreases with both reduced speed and reduced load.

An un-weighted average of the eight measured efficiencies comes to 90.1% efficiency with an averaged loss of 40.3 Watt by using the 1.5 kW motor as load, thereby meeting the criteria of the EN 50598-2 standard in five (6) of eight duty points.

Sub-sequentially the same test with the same conditions with the exception that the tested motor was a 1.1 kW IE2 motor (same one as used earlier) was performed.

This resulted are presented in Figure 10.



	EN-50598-2 criteria Freq:	Current out:	$Pf_{fund.}$ out:	CDM results Loss:	Eta:
(1) - (90;100):	45	3,10	0,79	48,4	97,2%
(2) - (50;100):	25	3,10	0,79	49,2	95,3%
(3) - ("0";100):	0	3,10	0,79	54,1	90,4%
(4) - (90;50):	45	2,20	0,60	38,8	96,5%
(5) - (50;50):	25	2,20	0,60	37,8	94,3%
(6) - ("0";50):	0	2,20	0,60	41,6	88,0%
(7) - (50;25):	25	1,80	0,38	33,9	93,0%
(8) - ("0";25):	0	1,80	0,38	36,6	85,5%

	PC time	Supply volt	Motor $volt_{fund.}$	P1 CDM in	P2 CDM out	P3 shaft	Torque	Speed	CDM freq	Motor amps	$Pf_{fund.}$	t_{CDM}
(1)	14:24	400	344	1699	1651	1277	9,84	1241	45,1	3,11	0,87	82,1
(2)	14:27	401	206	1051	1002	665	9,90	643	25,2	3,11	0,89	83,0
(3)	14:29	402	101	565	511	199	9,71	196	10,5	3,10	0,93	83,0
(4)	14:32	399	335	1098	1059	857	6,42	1278	44,9	2,21	0,81	81,8
(5)	14:35	399	196	659	621	456	6,47	675	24,7	2,19	0,82	80,7
(6)	14:37	400	91	347	305	161	6,62	232	10,1	2,20	0,87	79,6
(7)	14:40	400	191	481	448	337	4,68	691	24,6	1,79	0,74	78,4
(8)	14:43	400	85	253	216	126	4,86	248	9,9	1,80	0,80	76,6

Figure 10: 8 x partial load points with 1.1 kW motor

The results show that the 1.1 kW motor is having problem keeping the desired fundamental displacement factor in all of the eight duty points! Only one duty point seems acceptable but again only when utilizing the tolerances of the standard and rounding.

This would off course disqualify the 1.1 kW motor as load in a “real” CDM efficiency evaluation, but it proves a valid point. A 1.1 kW motor cannot be used as load for a 1.1 kW CDM when considering CDM efficiency.

For the same reasons as mentioned above, the CDM appear to have an absolute higher loss, but as it at the same time delivers more active power, the efficiency on average seems higher by as much as 2 percent or more. This tendency is by far much more visible in the latter duty points (6, 7 & 8) going toward zero load and zero speed.

The relatively higher “torque producing current”, and the linked increased heat losses in the 1.1 kW motor can explain this. However, it also emphasizes the importance of the tables 2&3 of the EN-50598-2 standard to keep different loads of CDM’s comparable.

This exercise have shown that the 8 desired duty points required by the EN 50598-2 standard to show losses in the entire valid working area of a CDM, is close to unobtainable by using only one motor as “load” for the CDM. At least for the smaller sized CDM’s.

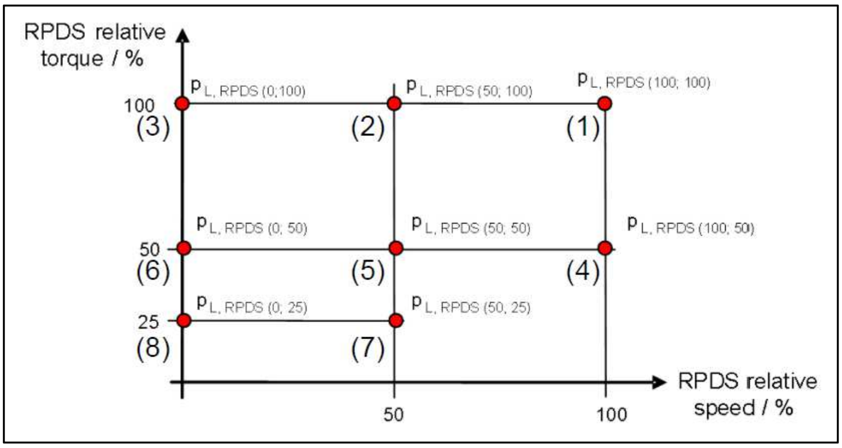
In this specific case the nominal motor (1.1 kW) was a very poor match and the 1.5 kW came close but it was not perfect and a third motor should have been found to accommodate the remaining duty points. An attempt to find one motor that could provide all 8 duty points was made but unsuccessful.

In real conditions, this would mean that testing laboratories doing actual measurements would have to switch to a suitable motor in each duty point during a complete test which is completely unrealistic in terms of duration, reliability, repeatability and costs.

The upcoming International standard on the topic, IEC 61800-9-2, should work to accommodate this problem and define more realistic duty points.

PDS – Power Drive System, partial load points by testing

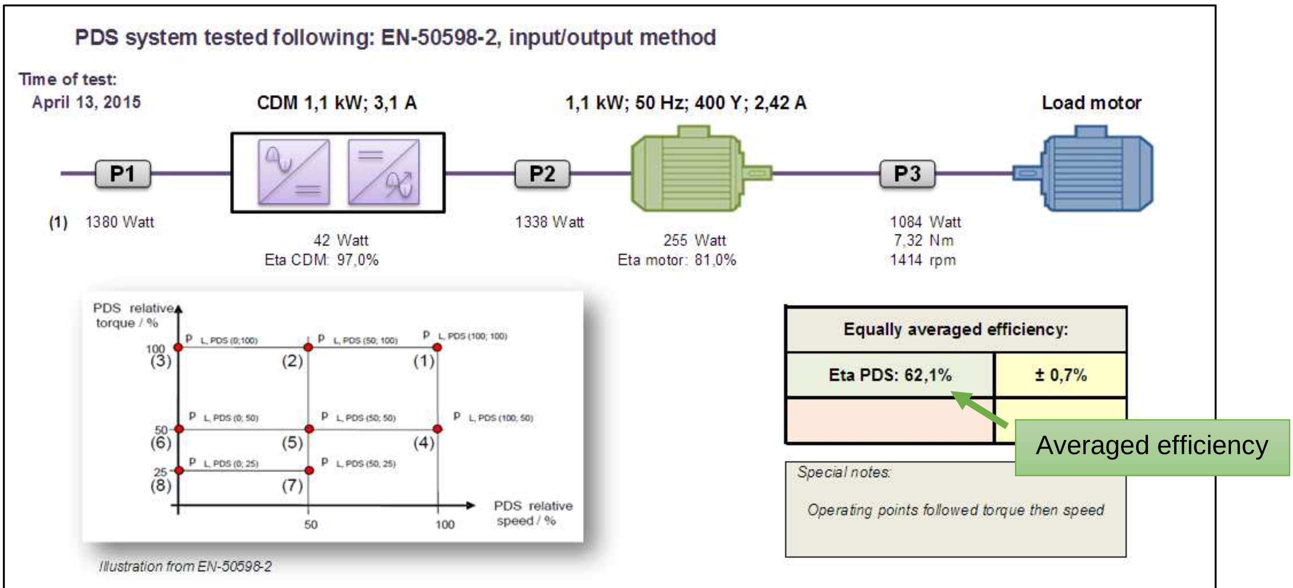
As with the CDM test, the EN 50598-2 standard introduces eight duty points to describe the power drive system in the entire area of operation. As these are based relative speed and torque of the motor connected, the pairing of a 1.1 kW drive and a 1.1 kW motor is now relevant.



Figur 11: The eight part-load duty points from EN 50598-2

The description of the testing conditions when performing a full PDS test is limited in the EN 50598-2 standard. Therefore, as before, it was necessary to adopt details from the Canadian CSA 838-13 standard, in which many testing details are explained thoroughly, when performing this full PDS test. In this way, the insurance of proper, reliable and repeatable results are more likely.

The 1.1 kW PDS system test results are presented in figure 12:



Averaged values: 6 values per duty point No. of duty points: 8 Test duration: 19,5 min

	PC time	P_1 CDM in	Supply freq	Supply volt	Supply curr.	P_2 CDM out	CDM freq	Motor amps	P_3 Shaft	Torque	Speed	t_{Motor}	Eta_{PDS}	$\Delta\ Eta_{PDS}$
(1)	13:21	1380	50,0	403	2,25	1338	50,0	2,55	1083	7,32	1414	40,7	78,5	± 0,4
(2)	13:24	751	50,0	403	1,43	711	25,1	2,40	524	7,32	684	40,5	69,7	± 0,6
(3)	13:26	380	50,0	400	0,82	337	10,1	2,34	182	7,32	240	39,4	47,8	± 0,7
(4)	13:29	718	50,0	400	1,27	686	50,1	1,62	561	3,67	1461	40,5	78,2	± 0,8
(5)	13:32	394	50,0	401	0,81	362	25,0	1,62	275	3,67	719	39,5	69,9	± 0,7
(6)	13:34	197	50,0	401	0,48	163	9,7	1,60	100	3,68	265	37,7	50,9	± 0,8
(7)	13:37	233	50,0	401	0,54	204	25,0	1,36	141	1,83	735	38,1	60,5	± 1,0
(8)	13:40	126	50,0	401	0,34	95	9,5	1,38	52	1,83	276	36,7	41,4	± 1,0

Figur 12: 8 x load points for the entire 1.1 kW PDS system

Detailed results from 8 duty points

The first duty point in figure 12 **(1)**, which is at 100% frequency and 100% torque, is the duty point for the warm up period seeking thermal stability before the actual tests, and also the duty point that can be used to evaluate the IES class of this specific system:

In this case, the losses is not more than 310 Watt including an estimated uncertainty. According to EN 50598-2, the reference power drive system RPDS at 1.1 kW allows 484 Watt losses for IE1 class with a 0.8 factor for IE2 (387 Watt) hence making this specific system **IE2** – with margin.

For comparison, the final exercise prepared for this paper was a "Canadian" measurement of the system in question, namely the 1.1 kW CMD + 1.1 kW motor of two different brands.

The Canadian CSA 838-13 standards approach to describe a power drive system in partial duty include 20 duty points.

When testing a complete drive system the most time consuming details is the physical mounting, the alignment and additionally the "First approach" in the software etc.

Once the system is up and running and the load is well defined, one can take as many duty points as wanted making the Canadian approach unproblematic.

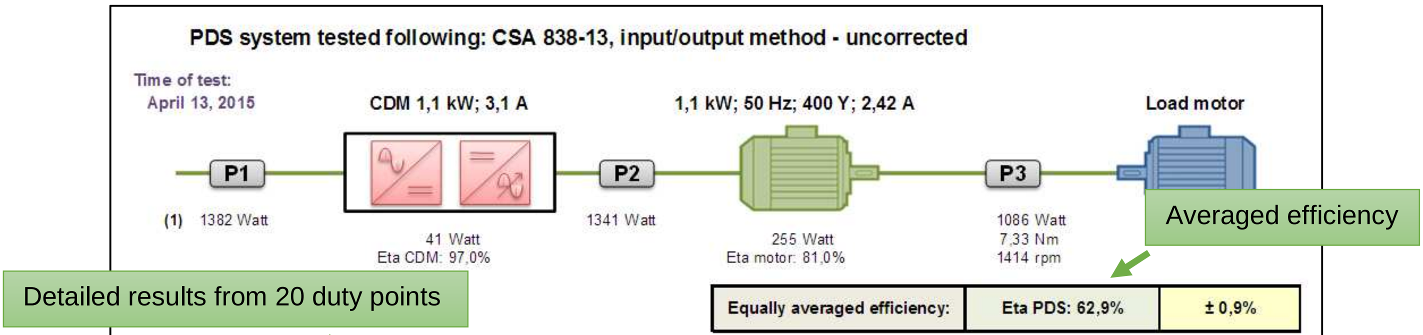
Table 1
Testing points at specified frequency and torque
(See Clause 7.3.3.)

Points	**1**	**2**	**3**	**4**	**5**
Frequency (%)	100	100	100	100	100
Torque (%)	100	75	50	25	10
Points	**6**	**7**	**8**	**9**	**10**
Frequency (%)	75	75	75	75	75
Torque (%)	100	75	50	25	10
Points	**11**	**12**	**13**	**14**	**15**
Frequency (%)	50	50	50	50	50
Torque (%)	100	75	50	25	10
Points	**16**	**17**	**18**	**19**	**20**
Frequency (%)	25	25	25	25	25
Torque (%)	100	75	50	25	10

Figur 13: The 20 defined duty points from CSA 838-13 including order of performance

All conditions when performing the complete PDS test are well defined within the CSA 838-13 standard.

The results can be seen in figure 14.



Averaged values: 6 values per duty point   No. of duty points: 20   Test duration: 51,7 min

	PC time	P_1 CDM in	Supply freq	Supply volt	Supply curr.	P_2 CDM out	CDM freq	Motor amps	P_3 Shaft	Torque	Speed	t_{Motor}	Eta_{PDS}	ΔEta_{PDS}
(1)	17:22	1382	50,0	402	2,24	1341	50,0	2,55	1085	7,33	1414	40,3	78,5	± 0,4
(2)	17:25	1042	50,0	403	1,74	1005	50,0	2,05	829	5,50	1439	40,0	79,5	± 0,6
(3)	17:28	715	50,0	403	1,26	683	50,0	1,61	559	3,67	1458	39,3	78,2	± 0,8
(4)	17:30	403	50,0	400	0,83	375	50,0	1,28	283	1,83	1481	38,1	70,2	± 1,0
(5)	17:33	225	50,0	400	0,57	198	50,0	1,17	114	0,73	1491	36,9	50,6	± 1,7
(6)	17:36	1059	50,0	400	1,82	1019	37,6	2,42	813	7,33	1060	37,0	76,8	± 0,5
(7)	17:39	801	50,0	400	1,42	766	37,5	2,00	619	5,51	1074	37,2	77,3	± 0,6
(8)	17:41	554	50,0	401	1,04	522	37,5	1,63	417	3,65	1093	37,0	75,3	± 0,9
(9)	17:44	320	50,0	401	0,70	291	37,5	1,36	211	1,82	1110	36,3	66,0	± 1,0
(10)	17:47	187	50,0	401	0,49	160	37,6	1,27	87	0,74	1121	35,7	46,3	± 1,6
(11)	17:49	760	50,0	400	1,43	720	25,1	2,43	534	7,43	687	35,5	70,2	± 0,6
(12)	17:52	565	50,0	400	1,09	530	25,0	1,98	405	5,50	704	35,6	71,6	± 0,7
(13)	17:55	394	50,0	401	0,81	362	25,0	1,62	276	3,67	720	35,6	70,0	± 0,7
(14)	17:57	232	50,0	401	0,54	203	25,0	1,36	141	1,83	736	35,3	60,7	± 1,0
(15)	18:00	142	50,0	401	0,38	114	25,0	1,27	58	0,75	745	34,7	40,9	± 1,5
(16)	18:03	435	50,0	401	0,91	393	12,5	2,35	240	7,32	316	34,2	55,3	± 0,7
(17)	18:05	328	50,0	401	0,72	292	12,5	1,95	189	5,49	333	34,2	57,7	± 0,6
(18)	18:08	232	50,0	402	0,55	200	12,6	1,62	132	3,65	350	34,1	57,0	± 0,8
(19)	18:11	144	50,0	402	0,38	114	12,5	1,39	67	1,78	365	33,9	46,7	± 1,0
(20)	18:13	99	50,0	401	0,28	71	12,5	1,32	28	0,74	373	33,6	28,7	± 1,2

Figur 14: The 20 measured duty points when following CSA 838-13 on the 1.1 kW PDS system

When comparing to the EN 50598-2 results the averaged efficiency is higher, but this is due to the presence of the four 75% torque duty points, which by traditional motor tests, often have higher efficiency than the 100% duty points. In the same way, the calculated averaged uncertainty is marginally higher with this test, but again, this can be explained by the presence of more duty points in the lower region toward zero load and zero speed, that traditionally have higher uncertainty and thereby influences the average negative.

Conclusion

This paper has demonstrated how to determine efficiency and how to IE classify a complete drive module (CDM), when following the recently published European standard EN 50598-2. It has also demonstrated how to “map” a complete power drive system (PDS) when following the European EN 50598-2 standard and when following the Canadian CSA 838-13.

Several ambiguities and other problems have been demonstrated with the EN 50598-2, which have under prioritized actual testing of systems.

- On smaller CDM systems, motors of at least one power class higher are needed to provide the necessary load over longer periods still keeping the correct power factor.
- On smaller CDM systems, it is impossible to achieve all 8 duty points with correct power factor using only one load motor. This is unacceptable for testing laboratories.
- The IE classification scale in the EN 50598-2 are incomplete. Many tests performed by several laboratories commercial as independent prove CDM’s with potential IE3 and IE4 levels.
- Description of test conditions, temperature measurements and stability criteria as well as other surrounding factors are too limited in the EN 50598-2. When performing CDM tests and PDS tests it is impossible to complete these, without either close dialog to the authors of the standard or a good solid network of independent testing laboratories for sparring.

The IEC SC22G Working Group 18 has a big task ahead of them. The coming International standard on this topic, IEC 61800-9-2, must accommodate these problems and create a well-defined testing standard in which these issues solved.

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Motors 2

Interpolation procedures for the determination of losses and energy efficiency of electrical machines

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Abstract

This paper is about interpolation of losses and efficiency of three-phase rotating electric machines (synchronous and asynchronous machines) over the whole constant flux torque- and speed-range (base-speed range). An interpolation formula is developed, which takes all relevant loss-effects into account and hence provides a high accuracy. In order to obtain the interpolation coefficients from measurements, just seven operating-points are required.

In a second and optional step, the interpolation coefficients can be improved by a numerical optimization taking 16 operating-points into account. Depending on the measurement quality, this second step may not be required. The decision can be taken based on the determined quality of the interpolation (interpolation stability index), which is also proposed in the paper.

EN 50598-2 introduces 8 operating-points. Five of these points are identical to proposed operating-points of the new interpolation method. The remaining points can be obtained from EN 50598-2 by shifting two points from zero speed to 25% speed.

The proposed interpolation method will be included in the first edition of IEC 61800-9-2. Later, it is envisaged to move the procedure to IEC 60034-30-2 and then remove it from future editions of IEC 61800-9-2.

Introduction

While fixed speed grid operated electric motors have been in the focus of energy efficiency regulations for the last 20 years or so, recent studies have shown the even larger potential of variable speed power drive systems (PDS) [1]. A number of standardization and regulatory projects are currently ongoing with the aim to measure, improve and regulate efficiency of such variable speed power drive systems [2], [3], [4].

Obviously, when calculating total losses of a complex cycle of varying load and speed, a performance map of losses or efficiency depending on load and speed is required (see figure 1).

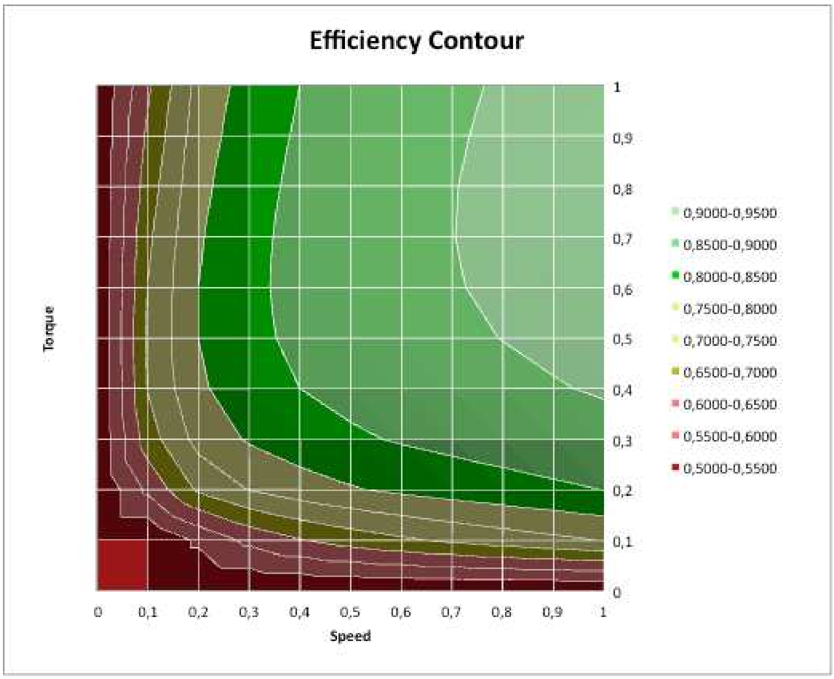

Figure 1: Efficiency contour plot over speed and torque

For economic reasons, such a map cannot be completely derived from measurements, as hundreds or even thousands of operating-points might be required. Instead, only a limited number of points should be measured and the losses of all other operating-points should then be determined by a suitable interpolation.

The question is, how to obtain good interpolation accuracy with the least number of measured points (i.e. with the least amount of measurement cost).

In the following paper, an interpolation formula and suitable operating-points will be presented that give very good interpolation results and require just seven loss tests at different operating-points (load, speed).

The accuracy of the proposed interpolation procedure is validated on a total of 128 different motors. For each motor, the losses at 16 measured operating-points were compared to the interpolated losses at these points. Measurement data was obtained from several sources, including both manufacturers' and independent testing laboratories. The motors are 2-, 4- and 6-pole from 0.12 to 1000 kW of output power and cover all efficiency classes (IE1 – IE4). Included are permanent magnet synchronous machines, synchronous reluctance machines and induction motors.

Losses

In the following, all quantities are related to their nominal values: T = 1 is rated torque, n = 1 is rated speed, f = 1 is rated frequency, η = 1 is 100% efficiency and P = 1 is rated output power.

It is assumed that the machine is operated with constant magnetic flux (U / f = const), i.e. in the base-speed range only (f = 0…1, T = 0…1).

Operation in the field-weakening range (constant power range) (f > 1 with U = const) is not discussed in this paper and must be addressed in further studies.

General motor behavior stipulates that the interpolation can be applied to the overload range (T > 1) albeit with increasing error.

The interpolation formula is based on the frequency f of the supply voltage and on output torque T.

In case of synchronous machines, speed n may be used instead of the supply frequency f without any loss of precision.

In case of asynchronous machines, the supply frequency can be determined from a measurement of the fundamental frequency at the motor terminals. However, when the exact supply frequency at certain operating points is unknown, speed n may be used for interpolation instead of the supply frequency f. As this neglects slip, a slight reduction of interpolation precision will occur. This is usually acceptable in practical applications. EN 50598-2 [4] uses the same approach.

The efficiency of electric motors is influenced mainly by the following loss components:

Stator and rotor winding I^2R losses ($P_{LS} + P_{LR}$)

These losses are independent of frequency and vary with the square of the torque (since current basically varies with the square of the torque). However, there is an offset for magnetizing current (no-load current) that has to be taken into account.

Hence winding losses at any load-point $P_{LSR}(f,T)$ can be interpolated from the winding losses P_{LSR} at rated frequency f_N and rated torque T_N by:

$$P_{LSR}(f,T) = P_{LSR}(f_N,T_N) \cdot \frac{I_0}{I_N} + P_{LSR}(f_N,T_N) \cdot \left(1 - \frac{I_0}{I_N}\right) \cdot T^2 \qquad (1)$$

Iron losses (P_{Lfe})

Iron losses contain two parts:

- Hysteresis losses, which are depending on the frequency and
- Eddy-current losses, which are depending on the square of the frequency.

When the exact distribution of these two parts is not known, an equal distribution (50:50) should give satisfying results in practice.

The later introduced interpolation formula makes no use of the loss distribution of hysteresis and eddy current losses, i.e., the formula is equally accurate for any distribution between the two loss components.

There is no dependency of iron losses on magnetic flux (B-field) in the constant flux (base-frequency or constant torque) speed-range.

$$P_{Lfe}(f,T) = \frac{1}{2} \cdot P_{Lfe}(f_N,T_N) \cdot f + \frac{1}{2} \cdot P_{Lfe}(f_N,T_N) \cdot f^2 \qquad (2)$$

Additional load losses (P_{LL})

Additional load losses are losses in supporting structures (housing, flanges) and losses due to side effects (cross-currents between rotor bars, eddy currents in permanent magnets etc.). They can be separated in two parts:

- Additional load losses, which consist of losses in proportion to frequency and to the square of torque and
- Additional load losses, which are based on eddy current effects and are therefore proportional to the square of frequency and torque.

Since the exact distribution of these two parts is generally unknown, an equal distribution (50:50) is assumed. Again, the later introduced interpolation formula makes no use of this and is equally valid for any distribution between the two components:

$$P_{LL}(f,T) = \frac{1}{2} \cdot P_{LL}(f_N,T_N) \cdot T^2 \cdot f + \frac{1}{2} \cdot P_{LL}(f_N,T_N) \cdot T^2 \cdot f^2 \qquad (3)$$

Friction and windage losses (P_{Lfw})

Friction and windage losses can be split in two parts:

- Friction losses, which are proportional to frequency and
- Windage losses, which are proportional to the third power of speed (frequency).

IEC 61800-9-2 will provide recommended values of the split of these two losses in case the exact distribution is unknown. In case of 4-pole machines, an equal distribution can be assumed. As before, the later introduced interpolation formula makes no use of this distribution, i.e., the formula is equally accurate for any distribution between friction and windage losses.

$$P_{Lfw}(f,T) = \frac{1}{2} \cdot P_{Lfw}(f_N,T_N) \cdot f + \frac{1}{2} \cdot P_{Lfw}(f_N,T_N) \cdot f^3 \qquad (4)$$

Additional harmonic losses (P_{LHL})

The non-sinusoidal power supply by a PWM frequency converter causes additional current and voltage harmonics, which are basically depending on the switching scheme. They can be assumed to be constant over the whole speed and frequency range.

$$P_{LHL}(f,T) = P_{LHL}(f_N,T_N) \qquad (5)$$

Total Losses (P_{L}) and efficiency

Based on the formulas introduced in the preceding paragraphs, the total loss at any operating-point (torque T and relative supply frequency f) is therefore given by:

$$\boldsymbol{P_L(f,T) = P_{LSR}(f,T) + P_{Lfe}(f,T) + P_{LL}(f,T) + P_{Lfw}(f,T) + P_{LHL}} \qquad (6)$$

The efficiency at any operating point can be calculated from:

$$\eta(f,T) = \frac{f \cdot T}{f \cdot T + P_L(f,T)} \qquad (7)$$

Likewise, the losses at any operating point can be determined from the efficiency by:

$$P_L(f,T) = f \cdot T \cdot \left(\frac{1}{\eta(f,T)} - 1\right) \qquad (8)$$

Interpolation formula

By examining formulas (1) to (5) it becomes obvious that the total losses at any operating-point (f,T) can be interpolated by using just seven parameters:

$$\boldsymbol{P_L(f,T) = A + B \cdot f + C \cdot f^2 + D \cdot f \cdot T^2 + E \cdot f^2 \cdot T^2 + F \cdot T + G \cdot T^2} \qquad (9)$$

Even though the constants A … G have no direct physical meaning, they provide a complete and mathematically correct transformation of the physical equations and their constants given in (1) to (5). Interpolation formula (9) is mathematically identical to formula (6).

Any assumptions regarding the distribution of iron losses between hysteresis losses and eddy-current losses and the distribution of friction and windage losses are no longer required, when the five constants are determined from measured operating-points.

Practical tests, however, show significant deviations of measured loss characteristics over speed and torque from the theoretical formula (9).

This can be attributed to several factors. In particular, the fundamental voltage at part load and part speed plays an important role for the losses. In order to keep a constant flux, frequency converters must increase the voltage above the linear U/f ratio at lower speeds to compensate for voltage loss across the stator resistance.

Depending on the control software and parameters, this is not always done in the same way. Quite the contrary: Many frequency converters will instead reduce voltage at part load (and hence reduce the flux) to reduce the current and improve efficiency.

A number of investigations have shown that interpolation accuracy can be greatly improved by adding an additional linear torque term.

Furthermore, investigations have shown that the loss-term attributed to windage losses with the third power of frequency (interpolation coefficient D in (9)) often leads to uncontrolled fluctuations when the measurements are slightly in error. Therefore, this term was removed. It will be demonstrated later that the slight loss in accuracy of windage loss interpolation resulting from this removal is acceptable.

The final interpolation formula for the losses therefore is as follows:

$$\boldsymbol{P_L(f,T) = A + B \cdot f + C \cdot f^2 + D \cdot f \cdot T^2 + E \cdot f^2 \cdot T^2 + F \cdot T + G \cdot T^2} \quad (10)$$

In case of synchronous machines, the relative speed n may be used as a replacement of the relative supply frequency f without any loss of precision.

In case of asynchronous machines, the relative supply frequency f for any given speed can be determined from a measurement of the fundamental frequency at the motor terminals when the shaft is rotating at the desired speed.

However, the relative speed n may also be used for the interpolation instead of the relative supply frequency f, thereby disregarding the slip. This will result in a slight reduction of interpolation precision, which is usually acceptable in practical applications.

Determination of the interpolation coefficients

The seven interpolation coefficients (*A*…*G*) can be determined analytically by solving a system of linear equations when losses at any seven linearly independent operating-points are known.

However, it is unclear which seven operating-points to pick in order to get the most reliable results and a good interpolation.

A thorough study was undertaken based on actual testing laboratory measurements of 128 motors. ABB (Freddy Gyllensten), Grundfos (Finn Jensen), KSB (Michael Koenen), Leroy Somer (Eric Vassent), Quebec-Hydro (Pierre Angers), Siemens (Ulrich Kaumann) and WILO (Michael Maier-Wagner) kindly provided the data. For each motor, measurements at 16 operating-points were available (f = 0.25, 0.5, 0.75, 1.0 and T = 0.25, 0.5, 0.75, 1.0).

In the study, many different selections of the seven operating-points from the 16 available points were analyzed. The following operating-points (table 1, figure 2) were finally selected as they gave the best interpolation results overall:

	f	T	P	Comment
P_1	0.9	1	0.9	Also included in IEC 61800-9-2
P_2	0.5	1	0.5	Also included in IEC 61800-9-2
P_3	0.9	0.5	0.45	Also included in IEC 61800-9-2
P_4	0.5	0.5	0.25	Also included in IEC 61800-9-2
P_5	0.25	1	0.25	
P_6	0.5	0.25	0.125	Also included in IEC 61800-9-2
P_7	0.25	0.25	0.0625	

Table 1: Operating-points for the analytical determination of the interpolation coefficients

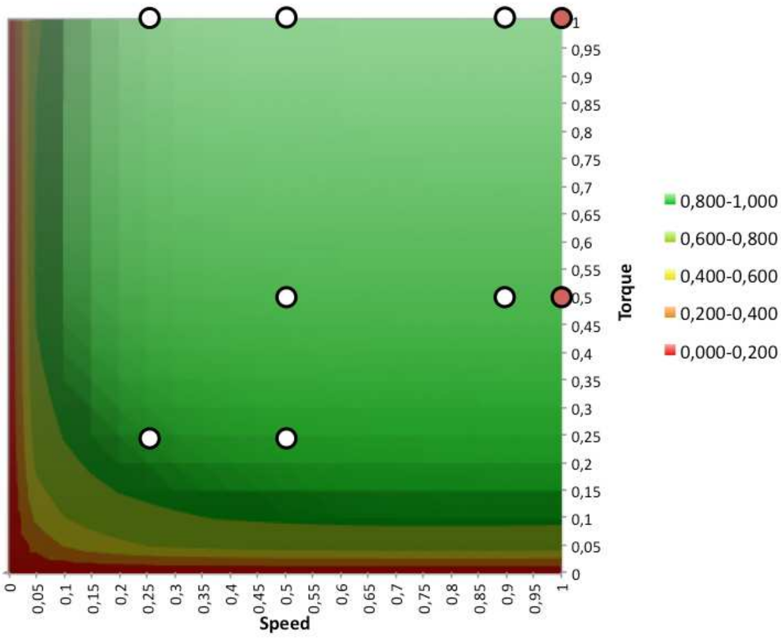

Figure 2: Operating-points selected for the analytical determination of the interpolation coefficients

By using these seven points, a system of equations can be set up to determine the unknown interpolation coefficients $A\ldots G$:

$$\begin{pmatrix} P_L(0.9,1) \\ P_L(0.5,1) \\ P_L(0.9,0.5) \\ P_L(0.5,0.5) \\ P_L(0.25,1) \\ P_L(0.5,0.25) \\ P_L(0.25,0.25) \end{pmatrix} = \begin{pmatrix} 1 & 0.9 & 0.81 & 0.9 & 0.81 & 1 & 1 \\ 1 & 0.5 & 0.25 & 0.5 & 0.25 & 1 & 1 \\ 1 & 0.9 & 0.81 & 0.225 & 0.2025 & 0.5 & 0.25 \\ 1 & 0.5 & 0.25 & 0.125 & 0.0625 & 0.5 & 0.25 \\ 1 & 0.25 & 0.0625 & 0.25 & 0.0625 & 1 & 1 \\ 1 & 0.5 & 0.25 & 0.03125 & 0.015625 & 0.25 & 0.0625 \\ 1 & 0.25 & 0.0625 & 0.015625 & 0.00390625 & 0.25 & 0.0625 \end{pmatrix} \cdot \begin{pmatrix} A \\ B \\ C \\ D \\ E \\ F \\ G \end{pmatrix} \quad (11)$$

This system of equations can easily be solved to determine the seven constants:

$$\begin{aligned}
A &= -\frac{25}{156}\cdot P_1 + \frac{529}{780}\cdot P_2 + \frac{25}{39}\cdot P_3 - \frac{103}{39}\cdot P_4 - \frac{12}{65}\cdot P_5 - \frac{56}{195}\cdot P_6 + \frac{192}{65}\cdot P_7 \\
B &= \frac{25}{26}\cdot P_1 - \frac{599}{390}\cdot P_2 - \frac{50}{13}\cdot P_3 + \frac{50}{13}\cdot P_4 + \frac{112}{195}\cdot P_5 + \frac{1792}{195}\cdot P_6 - \frac{1792}{195}\cdot P_7 \\
C &= -\frac{50}{39}\cdot P_1 + \frac{22}{13}\cdot P_2 + \frac{200}{39}\cdot P_3 - \frac{200}{39}\cdot P_4 - \frac{16}{39}\cdot P_5 - \frac{256}{39}\cdot P_6 + \frac{256}{39}\cdot P_7 \\
D &= -\frac{50}{13}\cdot P_1 + \frac{2542}{195}\cdot P_2 + \frac{50}{13}\cdot P_3 - \frac{50}{13}\cdot P_4 - \frac{1792}{195}\cdot P_5 - \frac{1792}{195}\cdot P_6 + \frac{1792}{195}\cdot P_7 \\
E &= \frac{200}{39}\cdot P_1 - \frac{152}{13}\cdot P_2 - \frac{200}{39}\cdot P_3 + \frac{200}{39}\cdot P_4 + \frac{256}{39}\cdot P_5 + \frac{256}{39}\cdot P_6 - \frac{256}{39}\cdot P_7 \\
F &= -2\cdot P_2 + 10\cdot P_4 - 8\cdot P_6 \\
G &= \frac{25}{39}\cdot P_1 - \frac{181}{195}\cdot P_2 - \frac{25}{39}\cdot P_3 - \frac{287}{39}\cdot P_4 + \frac{192}{65}\cdot P_5 + \frac{1616}{195}\cdot P_6 - \frac{192}{65}\cdot P_7
\end{aligned} \quad (12)$$

With: $P_1 = P_L(0.9,1)$; $P_2 = P_L(0.5,1)$; $P_3 = P_L(0.9,0.5)$; $P_4 = P_L(0.5,0.5)$; $P_5 = P_L(0.25,1)$; $P_6 = P_L(0.5,0.25)$; $P_7 = P_L(0.25,0.25)$

The selection of two points at f = 0.9 with no points being at f = 1.0 seems to be surprising at first.

The reason is the voltage drop at the output stages (IGBTs) of frequency converters. Due to this voltage drop, constant flux can only be maintained up to a frequency of about f = 0.9. There are several control methods (like flat-top modulation) to increase the constant flux speed range beyond f = 0.9. But these methods are manufacturer specific and they never provide full flux up to full rated frequency (f = 1.0).

To avoid this non-linearity, the proposed interpolation method relies on operating-points that all frequency converters can easily control with constant flux.

When the exact efficiency at full-speed (f = 1.0) is required, the additional losses due to this voltage drop can be calculated linear with the missing voltage.

For example, when the frequency converter is able to supply a maximum fundamental voltage of 360 V and the rated motor voltage is 400 V, then the losses at rated speed will increase by 11% (400/360 = 1,11) compared to the extrapolated losses or operation at 400 V fundamental voltage.

For convenience, when load points at full speed have already been measured according to table 2, the formulas to determine the interpolation coefficients are also given (13).

However, it must be remembered that these formulas are not taking the missing flux at full speed into account and will therefore provide less accurate interpolation results compared to the operating points of table 1 and the formulas given in (12).

	f	T	P
P_1^*	1	1	1
P_2	0.5	1	0.5
P_3^*	1	0.5	0.5
P_4	0.5	0.5	0.25
P_5	0.25	1	0.25
P_6	0.5	0.25	0.125
P_7	0.25	0.25	0.0625

Table 2: Alternate operating-points for the analytical determination of the interpolation coefficients

$$\begin{aligned}
A &= -\frac{1}{9}\cdot P_1^* + \frac{28}{45}\cdot P_2 + \frac{4}{9}\cdot P_3^* - \frac{22}{9}\cdot P_4 - \frac{8}{45}\cdot P_5 - \frac{8}{45}\cdot P_6 + \frac{128}{45}\cdot P_7 \\
B &= \frac{2}{3}\cdot P_1^* - \frac{6}{5}\cdot P_2 - \frac{8}{3}\cdot P_3^* + \frac{8}{3}\cdot P_4 + \frac{8}{15}\cdot P_5 + \frac{128}{15}\cdot P_6 - \frac{128}{15}\cdot P_7 \\
C &= -\frac{8}{9}\cdot P_1^* + \frac{56}{45}\cdot P_2 + \frac{32}{9}\cdot P_3^* - \frac{32}{9}\cdot P_4 - \frac{16}{45}\cdot P_5 - \frac{256}{45}\cdot P_6 + \frac{256}{45}\cdot P_7 \\
D &= -\frac{8}{3}\cdot P_1^* + \frac{56}{5}\cdot P_2 + \frac{8}{3}\cdot P_3^* - \frac{8}{3}\cdot P_4 - \frac{128}{15}\cdot P_5 - \frac{128}{15}\cdot P_6 + \frac{128}{15}\cdot P_7 \\
E &= \frac{32}{9}\cdot P_1^* - \frac{416}{45}\cdot P_2 - \frac{32}{9}\cdot P_3^* + \frac{32}{9}\cdot P_4 + \frac{256}{45}\cdot P_5 + \frac{256}{45}\cdot P_6 - \frac{256}{45}\cdot P_7 \\
F &= -2\cdot P_2 + 10\cdot P_4 - 8\cdot P_6 \\
G &= \frac{4}{9}\cdot P_1^* - \frac{28}{45}\cdot P_2 - \frac{4}{9}\cdot P_3^* - \frac{68}{9}\cdot P_4 + \frac{128}{45}\cdot P_5 + \frac{368}{45}\cdot P_6 - \frac{128}{45}\cdot P_7
\end{aligned} \tag{13}$$

Operating temperature

Obviously, all losses depend on the operating temperature. Stator and rotor winding losses are mostly affected. For practical reasons, a temperature stabilization at each of the 16 load points prior to measurement is not feasible. In order to obtain repeatable and useful results with reasonable effort, it is recommended to perform a heat run at full speed and full torque prior to testing. After the temperature has stabilized, the losses at operating point P_1 shall be measured.

Losses at all subsequent operating points shall then be measured in successive order (P_2, P_3, P_4, …) as fast as possible without delay between the operating points. This will ensure a temperature situation at each operating point that is close to the temperature at continuous operation at that point.

Interpolation quality

In order to assess interpolation quality and deviation, measurements at more than 7 operating-points are required, as the analytical formula will always give exact results in the sampling points. Based on the aforementioned study, 16 operating-points are proposed for the determination of interpolation quality:

$P_{L(f,T)}$ with f = 0.25, 0.5, 0.75, 1.0 and T = 0.25, 0.5, 0.75, 1.0

The average interpolation error Q_{ISI} (ISI = interpolation stability index) provides a good indication of the quality of the interpolation:

$$Q_{ISI} = \sqrt{\frac{1}{16}\sum_f \sum_T \left(\frac{P_{L(f,T)}^{measured} - P_{L(f,T)}^{interpolated}}{P_{L(f,T)}^{measured}}\right)^2} \quad (13)$$

Q_{ISI} is the standard deviation of the average interpolation error over all 16 points. Since all quantities are given as related values (0…1), a value of 0.01 means an average interpolation error of 1% at each of the 16 points.

For example, a 75 kW motor with an efficiency of 90% will have 8.3 kW losses at full load and speed. A Q_{ISI} of 0.01 will result in an interpolation error of 83.3 W at P_L(1,1).

The same motor may show an efficiency of 70% at 25% load and 25% speed, resulting in 2.0 kW losses at that operating point. The same Q_{ISI} of 0.01 will then mean an average interpolation error of 20 W at P_L(0.25,0.25).

A Q_{ISI} value below 5% can be regarded as being very good. Q_{ISI} values below 10% should also be acceptable, even though some operating-points may not be determined with high accuracy.

Improving interpolation quality

Interpolation can be improved by taking all 16 operating-points into account in the determination of the seven interpolation coefficients (A…G). In this case, analytical formulas for the determination of the coefficients cannot be given, as the system of equations is over-determined. Instead, a numerical solution must be developed to search for the minimum interpolation error Q_{ISI}.

A suitable solver is integrated in MatLab, Microsoft EXCEL and other numerical software. It is planned to release a self-contained EXCEL-sheet along the publication of the new standard IEC 60034-30-2 that will include a numerical solver in VBA software (macro). This solver should run on all PCs without a requirement for special software or special setups.

It must be noted that the improved interpolation coefficients will result in slight deviations of the interpolated values from the original data in the seven original operating-points. It is therefore recommended that manufacturer give the interpolated losses of the seven operating-points in their catalog data instead of the original losses in order to avoid misinterpretation.

A Practical Example

A 37 kW 4-pole induction machine was tested. Efficiency values according to the points of table 2 are given in table 3:

Torque					
1	0,7950	0,8709	0,9009	0,9131	
0,75	0,8183	0,8786	0,9047	0,9193	
0,5	0,8221	0,8725	0,8967	0,9126	
0,25	0,7678	0,8250	0,8508	0,8729	
	0,25	*0,5*	*0,75*	*1*	**Speed**

Table 3: Measured efficiency values at 16 operating-points of a sample motor

The seven dark shaded fields were used in the analytical determination of the interpolation coefficients (sampling points). The determined interpolation coefficients are:

A=	0,00511
B=	0,04368
C=	-0,01829
D=	-0,00858
E=	0,02300
F=	0,00487
G=	0,04540

The interpolated energy efficiency is given in table 4:

Torque					
1	0,7950	0,8709	0,8989	0,9131	
0,75	0,8111	0,8774	0,9030	0,9171	
0,5	0,8144	0,8725	0,8972	0,9126	
0,25	0,7678	0,8250	0,8541	0,8758	
	0,25	*0,5*	*0,75*	*1*	**Speed**

Table 4: Interpolated efficiency values at 16 operating-points of sample motor, analytically determined from 7 sampling points

As the interpolated is based on the seven dark green points of table 3, the interpolation is exact in those points. All other points show a deviation resulting from the interpolation procedure.

A comparison of the measured losses with the interpolated losses showed the following errors (table 5):

Torque					
1	0,0%	0,0%	2,3%	0,0%	
0,75	4,9%	1,1%	1,9%	2,9%	
0,5	5,4%	0,0%	-0,5%	0,0%	
0,25	0,0%	0,0%	-2,6%	-2,6%	
	0,25	*0,5*	*0,75*	*1*	**Speed**

Table 5: Error of interpolated and measured losses in percentage, analytically determined coefficients

The interpolation stability index (standard deviation of interpolation error) is 0.0231 or 2.31%, which is already very good.

In a second step, the interpolation coefficients were numerically improved by taking all 16 operating-points into account:

A=	0,00637
B=	0,04783
C=	-0,01934
D=	-0,01166
E=	0,02335
F=	-0,00547
G=	0,05419

This improves the interpolation stability index to 0.0192 or 1.92% and gives the following interpolated energy efficiencies (table 6):

Torque					
1	0,7952	0,8708	0,8988	0,9130	
0,75	0,8146	0,8786	0,9033	0,9171	
0,5	0,8193	0,8733	0,8966	0,9114	
0,25	0,7665	0,8199	0,8478	0,8693	
	0,25	*0,5*	*0,75*	*1*	**Speed**

Table 6: Interpolated efficiency values at 16 operating-points of sample motor, numerically determined from 16 sampling points

A comparison of tables 3, 4 and 6 shows a slight deviation of the interpolated efficiency from the measured efficiency even in the 7 original sampling points although overall the interpolation is improved.

The following diagrams give a graphical impression of the interpolation (figures 3 - 6).

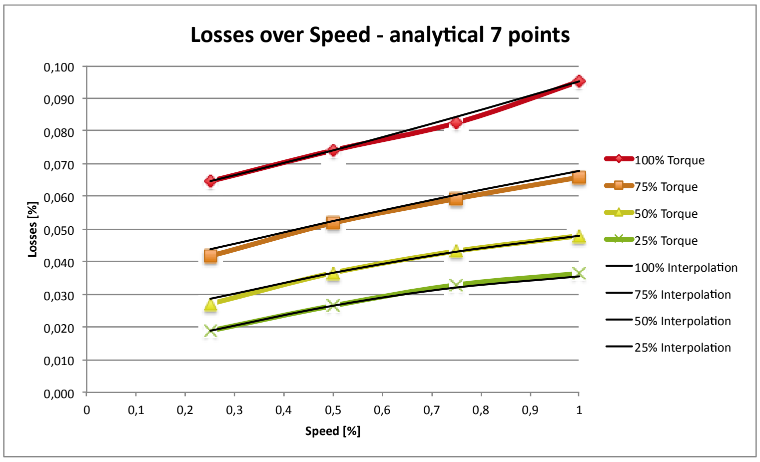

Figure 3: Relative losses as a function of speed; interpolation with analytically determined coefficients from 7 operating-points

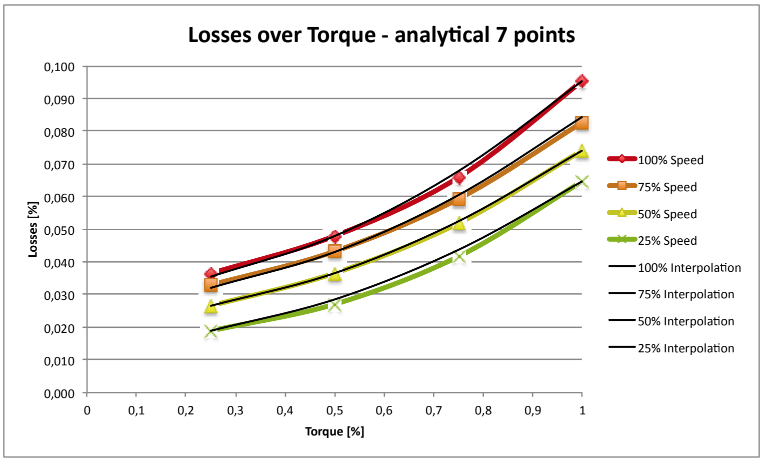

Figure 4: Relative losses as a function of torque; interpolation with analytically determined coefficients from 7 operating-points

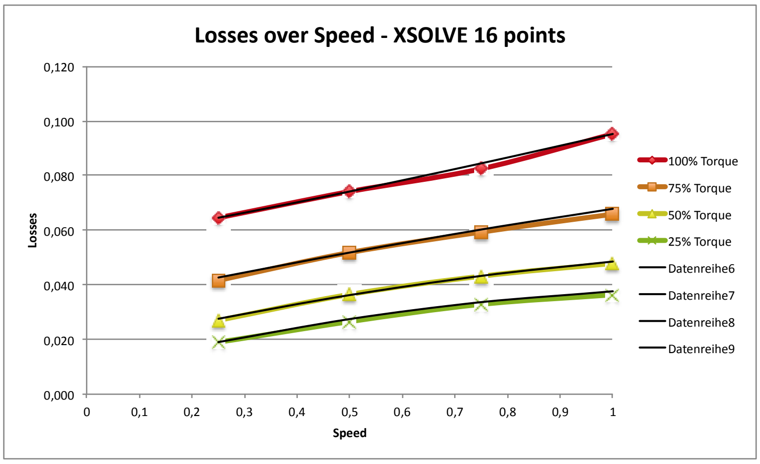

Figure 5: Relative losses as a function of speed; interpolation with numerically determined coefficients from 16 operating-points

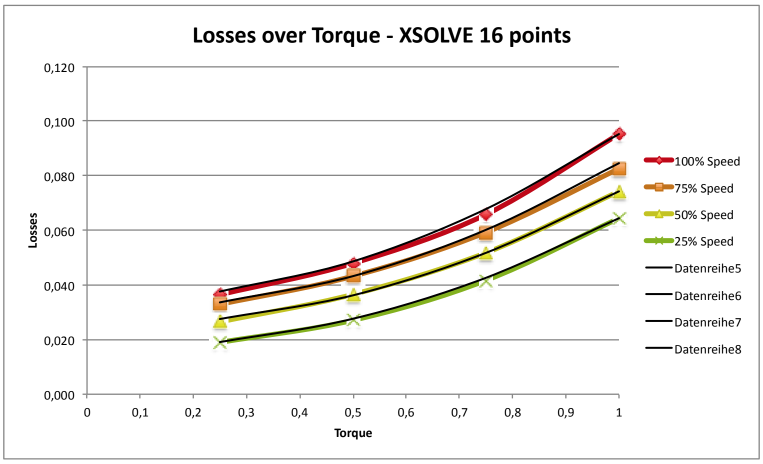

Figure 6: Relative losses as a function of torque; interpolation with numerically determined coefficients from 16 operating-points

Efficiency interpolations in comparison

The European standard EN 50598-2:2013 also contains an interpolation procedure for efficiencies. This two-step linear interpolation is based on 8 load measurements defined in annex G.2.3 [4]. It is basically a linear interpolation between two adjacent points of the 8-point efficiency grid.

Table 7 gives the results of the aforementioned study.

	7-coeff analytical 7 points	7-coeff numerical 16 points	EN 50598-2 linear interpolation
Average error all 128 motors	1,7 %	1.8 %	8.6 %
Max error all 128 motors	7,8 %	10.8 %	20.6 %
Average error 76 IE2 ASM	0.4 %	0.9 %	7.9 %
Average error 32 SynRel	3.2 %	2.7 %	8.7 %
Average error 9 PMSM	4.3 %	4.4 %	11.4 %

Table 7: Average and maximum interpolation error (Q_{ISI}) of 128 motor tests, each at 16 operating-points

Surprisingly, the numerically determined coefficients based on 16 measurement points are not always better than the analytically determined, although those are based on only 7 points. The reason is the limited quality of the visual basic numerical solver macro that was used in the EXCEL sheet. When utilizing the built-in numerical Solver application, lower interpolation errors can be achieved across the board. However, the built-in solver is not available on all computer systems and requires a special software-setup. Therefore, the EXCEL sheet provided by the IEC working group will offer both options: The macro for any system and the solver application for those, which are setup accordingly.

It should be noted that the solver macro will only give worse results than EXCEL's built in solver application when the 16 measurement points are significantly erroneous located.

Summary

It has been demonstrated that the measurement of 7 operating-points in the speed-torque plane is sufficient to interpolate the efficiency of any interesting load-point with good accuracy. The proposed interpolation formula is simple and straightforward. It requires just 7 parameters and can be programmed without iteration or case distinctions.

Based on a thorough study that included many motors of different power ratings and technologies, a set of 7 operating-points is proposed for the analytical determination of the interpolation parameters.

When test results at 16 operating-points are available, the quality of the interpolation can be improved by using a numerical algorithm to determine the interpolation parameters. A formula for the average interpolation error is given.

References

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[2] IEC/TS 60034-2-3 Ed 1.0; *Rotating electrical machines - Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors*; 2013-11

[3] 2/1741/CD; *IEC/TS 60034-30-2 Ed. 1 Rotating electrical machines – Part 30-2: Efficiency classes of variable speed AC motors (IE-code);* 2014-02

[4] TprEN 50598-2:2014-08; *Ecodesign for power drive systems, motor starters, power electronics & their driven applications – Part 2: Energy efficiency indicators for power drive systems and motor starters*; 2014-08

Energy Efficiency related to non-linear waveforms in Generator Systems

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Abstract

The use of rectifiers implies a current demand consisting of non-sinusoidal waveform, and in combination with the upstream impedance this consequently results in a decrease of the supply voltage quality. A large amount of studies were carried out to examine the influence of distorted voltages on induction motor operation. However, if electrical generators such as induction generators or synchronous generators are used, it can be assumed that non-sinusoidal waveforms may inversely affect the operation of these machines. The research presented in this paper will start by an evaluation of the harmonic effects inside induction motors and subsequently will try to translate this knowledge to the electrical generators inside both grid-connected and stand-alone generator sets. As this subject is relatively new, some of the effects will be discussed on a theoretical basis, and some of these effects will be partially validated by measurements.

1. Introduction

Economic and ecological incentives have resulted in an increased awareness of the efficiency of electrical machines. Electrical motors are responsible for 50% of the total electric consumption worldwide. For the industry the electrical machines consume up to 65% of the total electrical energy. Almost 90% of the installed machines that convert electrical energy to mechanical energy are Induction Motors (IM). [1][2] This has led to the fact that a large amount of studies were carried out to examine the influence of distorted voltages on IM operation. [3]-[7] However, electrical machines are also ideal to convert mechanical power into electrical power because of the relatively high efficiency and the high power to weight density. Both Induction Generators (IG) and Synchronous Generators (SG) are often implemented in order to produce electrical power. In this paper the energy efficiency of both grid connected IG and stand-alone SG is evaluated in reference to waveform distortion.

In Section 2 the basic loss mechanisms of IM related to non-sinusoidal supply voltages are elucidated. Although it will be illustrated throughout the paper that this knowledge is not straightforward applicable for generators, this know-how is essential in the analysis of non-sinusoidal waveforms in generator systems. It is obvious that the losses related to harmonic distortion are related to the magnitude of the distortion. However, there is a large difference if generators are coupled to a rigid electrical network, or if the generator supplies power to local islanded grid. From a network point of view, if small-scale generators are integrated into a strong and rigid electrical network the distortion of the supply voltage should be evaluated. In local and small electrical networks, with a high short-circuit impedance, non-sinusoidal current demand will significantly affect the voltage. This will result in complex interactions between distorted current and voltage and will increase the difficulty of analysis drastically. Not only the distortion of the wave-shape is of importance. The losses related to non-sinusoidal waveforms are also related to the type and size of the machine. For grid-connected generators the Induction Generator (IG) is often preferred. IM and IG are the same machine and operate by the same fundamental principles. In stand-alone generator systems SG are preferred due to it's controllable excitation, which can be produced by both Permanent Magnets or with an additional excitation winding.

Consequently, the presented research segregates the analysis into two different sections. In Section 2 the effect of harmonic voltage distortion on grid connected IG is evaluated. In this case a strong rigid grid is assumed. In Section 3 the impact of non-sinusoidal currents is evaluated for SG. This analysis assumes a single generator in feed, a weak grid with very low short-circuit ratio and non-linear loads.

2. The effect of Voltage Distortion on IM

The effects of a distorted supply voltage are numerous as it affects almost every single operational parameter of the machine. A comprehensive overview has been presented in [8], which also lists the basic loss mechanisms due to harmonic voltage distortion inside IM.

1. The total averaged voltage is influenced by the phase of the harmonics, accordingly this influences the magnetizing current. However, this effect is only measureable for low power ratings of machines and at partial loading. Generally a linear induction is assumed and as far as for the voltage harmonics a perfect flux-linkage between the rotor and the stator is assumed.

2. The higher frequencies force the current to flow on the outer rims of the conductor. This effect is known as the "skin effect". For IM with a stator winding, this effect is predominantly present in the rotor bars. This effect is far less pronounced in the stator, due to both the reduced section of the stator coil windings and the relatively low frequencies considered (<40 order of harmonic). The effect results in a reduced active surface area, which leads to an increased current density towards the outer radius. This results in an increase of the rotor bar resistance R_r and is modeled as K_r. Subsequently, the top of the rotor lamination begins to saturate, and results in a decrease of rotor reactance $X_{\sigma\square}$. This is modeled as K_x. [4]

3. The frequency of the induced harmonic rotor currents depends on the relative movement of the rotor in reference to the stator harmonic Magneto-Motive Force (MMF).

$$\Omega_{sh} - \Omega_m = (1 - 6k)\frac{\omega_S}{N_P} - (1 - s)\frac{\omega_S}{N_P} = (-6k + s)\frac{\omega_S}{N_P} \quad (1)$$

With ω_S the synchronous speed at fundamental frequency and N_P the number of pole pairs. Parameter Ω_{sh} is the synchronous speed of the MMF induced by the harmonic current of order *h*. It is common practice to denote harmonic orders in the form of h = 1-6*k*. In this expression, *k* not only denotes out the harmonic order, it also indicates the sequence of the field. If *k* equals 1, a *h* of -5 and the value of -6 + s is obtained. If *k* equals -1, *h* equals +7 and the value of 6 + s is calculated. If *k* equals 0, the fundamental value of s is obtained.

4. Harmonics also result in electro-magnetic power and consequently mechanical torque. Because the actual electro-mechanical torque is located in the far end of the hyperbolical area of the torque speed characteristic, this torque is neglected. Consequently, all harmonic power P_h is assumed to be additional loss in both stator and rotor.

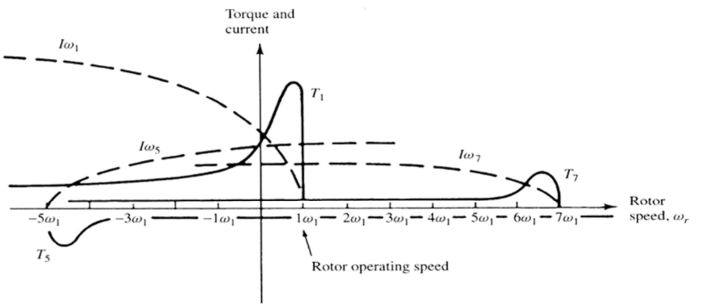

Fig. 1: Electromagnetic torque speed characteristics by supply voltage distortion

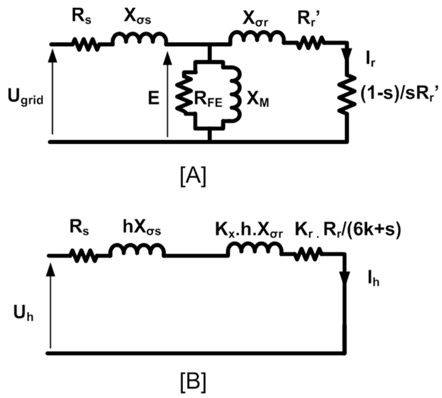

Fig. 2 Fundamental electrical IM equivalent model [A] and harmonic equivalent scheme [B]

In the calculation of the RMS current I_h of harmonic order *h*, the RMS harmonic voltage U_h and the total reactance at harmonic frequency mainly determine the RMS value (2),(3). The corresponding harmonic loss can be calculated by Joule's law (4).

$$|h.X_{\sigma s} + h.K_x X_{\sigma r}| \gg |R_s + K_R R_r| \quad (2)$$

$$|I_h| = {|U_h|}/{|(h.X_{\sigma s} + h.K_x X_{\sigma r})|} \quad (3)$$

$$P_h = 3.R_s.{I_h}^2 + 3.K_R R_r {I_h}^2 \quad (4)$$

Eq. (1) indicates that, in case of IM, every stator harmonic relates to a specific rotor harmonic. Consequently, in order to obtain the overall loss related to all the harmonic voltage distortion P_{h_loss}, simple and straightforward superposition of the individual harmonic losses is allowed.

$$P_{h\_loss} = \sum_{h \neq 1}^{\infty} P_h \quad (5)$$

From (4) it is noticed that for machines with a R_s>$K_r R_r$ the majority of the losses will be induced inside the stator. Contradictory, for machines in which the R_s<$K_r R_r$ the losses will be induced inside the rotor. Generally for IM the majority of the additional harmonic losses will be located inside the rotor, however, for IM and from a thermal point of view the segregation of the loss is of less importance. In case of squirrel cage IM, the rotor is thermally very robust. The heat flux due to the losses has to be dissipated via the stator housing anyhow. The critical temperature is generally located at the end of the stator lamination stack on the drive side of the motor.

3. The effect of Voltage Distortion on grid connected IG

In [8][9] several aspects of harmonic distortion have been addressed specifically related to IG operation. To the authors' knowledge this is the only reference to date addressing such issues. [9] refers to the increased penetration of decentralized small scale power production and consequently illustrated the practical relevance of this specific topic of research.

However, the presented research in [8] did not address the specific loss mechanisms which alter if an identical induction machine's operation shifts from motor to generator operation. The slip *s* alters from a positive value to a negative value and consequently this affects the induced rotor frequencies. This is illustrated Table 1.

Table 1: stator and rotor harmonic frequency for IM and IG

k	Stator harmonic h	Rotor harmonic frequency	
		IM	IG
0	1	s	-s
-1	-5	-6+s	-6-s
1	7	6+s	6-s
-2	-11	-12+s	-12-s
2	13	12+s	12-s

Table 2: skin effect from motor to generator operation

IM→IG	
K_x	↘
X_σ	↘
I_h	↗
K_r	↗
R_{r_h}	↗
P_{h_el}	↗

The skin effect is directly related to the frequency. As the harmonic magnitude in voltage reduces with increasing order, the resulting current is even more damped with increasing frequency due to the mainly inductive impedance of the machine. Consequently, in evaluation of the overall losses related to harmonic distortion, the dominant supply voltage harmonic is assumed to be the fifth.

In relation to the fifth harmonic in the stator, the induced rotor frequency increases in generator mode. This results in a decrease of K_x and an increase of K_R. If the supply voltage harmonic U_h is assumed constant this implies an increased loss effect of harmonic distortion in generator operation in reference to motor operation. However, this effect assumes a perfect flux linkage between stator and rotor.

It is commonly known that IM, which are operated in the generator mode, can work in the saturated area due to the reversed voltage drop over the stator impedance. Saturation in machines is often neglected because saturation results in increased stator joule loss due to an increased magnetizing current, and with a reduced linkage there is a reduction in transmitted power from the stator to the rotor.

However, if in the harmonic model of Fig. 2 saturation is included it can be noticed that saturation results in a reduced linkage from the stator to the rotor. It has been illustrated by Eq. (4) that the majority of the losses are generally located inside the rotor, and although saturation will affect the harmonic current, the reduced link with the rotor can result in a decrease of the overall harmonic losses.

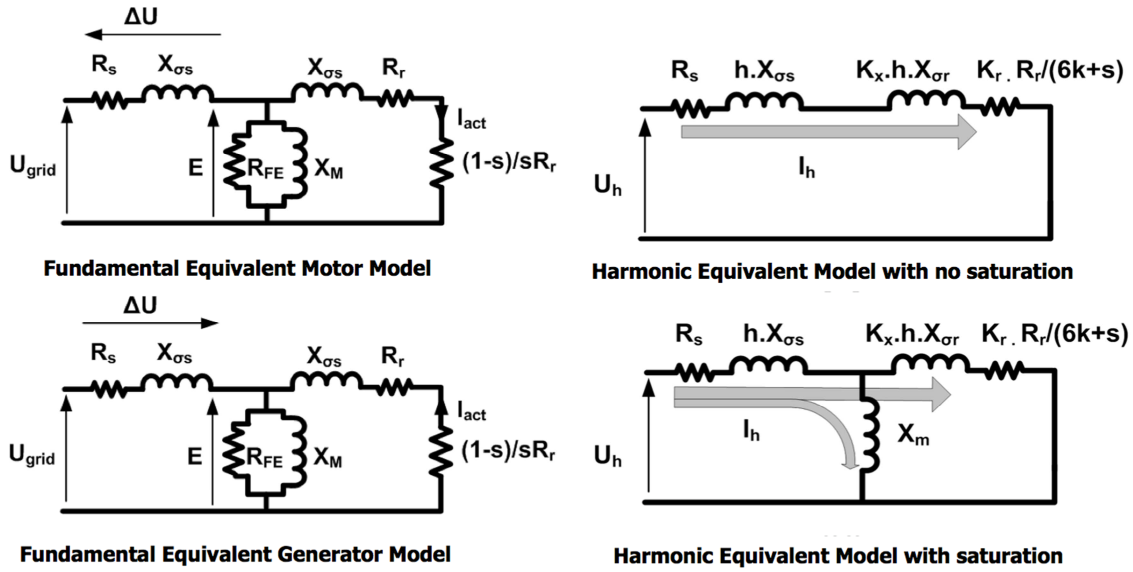

Fig. 3: Fundamental and harmonic model of Induction motor and Induction generator, taking into account saturation.

For the same amount of voltage distortion, it is possible to alter the phase angle *Y* of the harmonic voltage. As the RMS voltage remains constant, but the averaged voltage increases, the machine will work in a more saturated condition and the harmonic loss should reduce. This has been validated on a practical test setup of a 11kW IG. Note that in this analysis a sinus-expansion is used, consequently a Y=0° relates to the highest averaged voltage.

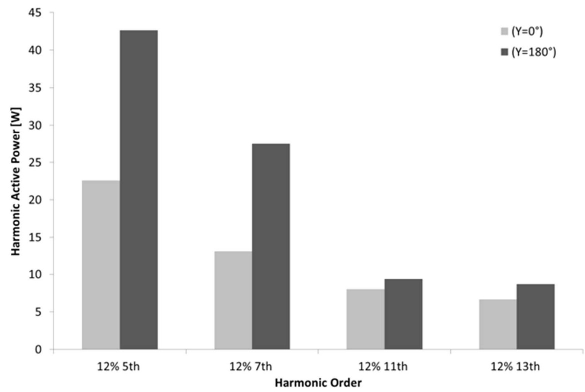

Fig. 4: effect of harmonic frequency and phase angle on harmonic losses for IG

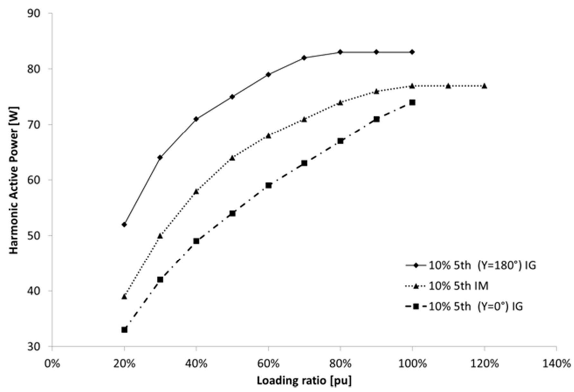

Fig. 5: Comparison of harmonic loss between non- saturated IG, IM and saturated IG operation

4. Introduction to stand-alone electrical generation

Up to this point, the presented harmonic analysis focused towards grid-connected machines. Although the European grid is a very robust grid with an availability of 99,999%, a lot of power is still produced in stand-alone generators. To put this research into perspective, approximately 1,8GW of wind power is installed in Belgium and it is estimated that approximately 1,2GW of stand-alone power is installed. This power is produced in for example remote construction sites, festival areas or as back-up.

In cooperation with the Belgian Sector Federation of local power generator manufacturers, a market survey has been executed. In the analysis the power generators of an installed power less than 7,5kWe have been excluded. From a market survey point of view analyzing sales within this power range is hard to quantify because a lot of these units are bought at very cheap prizes in batches overseas. Subsequently, these units are often sold in local Do-It-Yourself depots.

Table 3: market survey of autonomous power generators for the Belgian market - year 2014

Size	(sold units)	(sold units) (%)	(sold units) (%) (excluding <7,5kWe)
<7,5kWe	>3000	72-79%	/
7,5-30kWe	300-600	8-14%	38-51%
30-75kWe	250-300	6,5-7%	25-31%
75-375kWe	215-245	5,5-6%	21-27%
>375kWe	30-35	1%	3-4%
Total:	3795-4180	100%	100%

It is generally assumed that additional losses are generated inside stand-alone electrical generators due to non–linear loading. And again, to the authors' knowledge no scientific research has thoroughly investigated this effect. From a research point of view it is very interesting to segregate the additional loss into additional loss induced in the electrical generator and subsequently into additional loss linked to the prime mover. Most of these generators use an internal combustion motor as a prime mover, and although it is not the intent to elaborate on the efficiency of internal combustion engines, some basic knowledge is needed. Because it will be validated that, although the additional harmonic loss will result in an increase of active power consumption from the electrical generator, only the prime mover is capable of supplying active power via additional consumption of primary energy.

The operation of the internal combustion engine is called the Otto-cycle, and if the operation is simplified into isentropic and adiabatic processes, the efficiency of combustion engines or turbines is limited to the Carnot efficiency [10]. The efficiency of this simplified machine can be recalculated according to:

$$\eta_{Carnot} = 1 - \frac{1}{({}^{V_1}/_{V_2})^{\gamma-1}} \tag{5}$$

With η_{Carnot} the Carnot efficiency *(V_1/V_2)* the compression ratio and γ the specific heat ratio. An averaged value for a feasible compression ratio is 8 and an averaged value of γ is 1,27. This implies that the theoretical value of the energy efficiency of a stand-alone unit is approximately 40%. This corresponds to a general rule of thumb amongst suppliers of autonomous generators: the fuel consumption in *[l/h]* is equal to the installed capacity in *[kW]* divided by 4. With a fuel energy density of 10 kWh/l, this corresponds to an energy efficiency of 40%.

In case of stand-alone power it is relatively easy to correlate the impact of waveform distortion to primary energy consumption.

5. The effect of Wave Distortion on stand-alone SG

In stand-alone generator systems SG are preferred due to its inherent excitation. This can be produced by both Permanent Magnets (PM) (Fig. 6) or with an additional excitation winding (Fig. 7). A constant output voltage is obtained by controlling the excitation current by implementing an Automated Voltage Regulator (AVR).[11] If a stable output voltage is desired in stand-alone systems with IG, this implies variable capacitor banks, which is practically difficulty feasible.

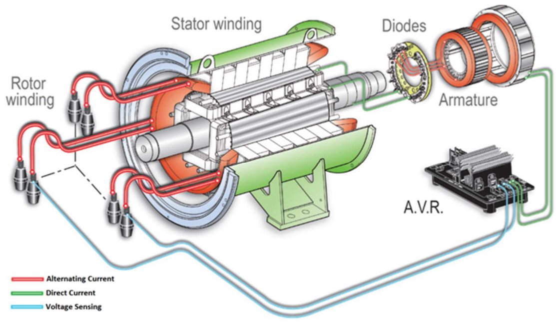

Fig. 6: Shunt excitation of a SG (Courtesy of Leroy Somer)[11]

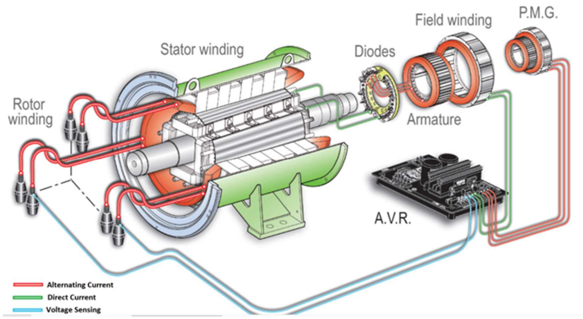

Fig. 7: Permanent Magnet excitation of a SG (Courtesy of Leroy Somer)[11]

Contradictory to IM does the SG operate standard in saturated conditions. Saturation is beneficial to maintain a stable output voltage over a wide load range, as it is far easier to make a controller which operates in a linear magnetization characteristic. Although the saturated operation might result in an increase of iron loss, because the magnetizing power of the rotor winding is delivered via the excitation onto the rotor, this significantly reduces stator joule loss compared to IM. Due to the absence of significant amounts of rotor joule loss and the steep decrease of stator current for identical output power, does the SG achieve higher energy efficiency in reference to IG. For an 11kW 4pole SG efficiencies of >95% are generally achieved.

Several aspects related to both the operational behavior and constructional constraints will result in a very distinctive behavior of SG in relation to harmonic current distortion. As this is an ongoing research some of these effects will be described on more intuitive bases, although some of the effects will be illustrated by measurements.

5.1 Theoretical considerations related to Voltage Distortion on SG

Similar to IM, waveform distortion in SG will affect nearly every single parameter. This section specifically relates to losses in SG. Mechanical losses are generally related to friction and windage loss. Both losses are related to the rotational speed of the machine and not to the mechanical torque. The mechanical speed remains constant because a fixed electrical frequency is one of the constraints to a stand-alone generator. Therefore mechanical losses are assumed independent of waveform distortion.

The output voltage is directly related to the induced Electro Motive Force (taking the stator inductance and resistance into account), and the EMF is directly related to the peak induction. According to the Steinmetz equation, the iron loss is directly related to the peak induction. Because the excitation is controlled to a constant output voltage the iron loss is assumed as a constant loss. In the following analysis the stray load losses are also assumed constant, generally stray load loss is only a minor loss component.

Additionally the harmonic component will induce additional harmonic losses as both stator and rotor joule loss. According to the harmonic loss evaluation in (4) the ratio between stator and rotor resistance determines the additional losses. For induction machines the harmonic rotor joule losses are dominant. However, SG generally operates in magnetic saturation, consequently, the harmonic stator current I_{hs} is partially bypassed via the reduced mutual inductance. This could result in a reduction of the harmonic rotor current I_{hr} and it is possible that the majority of the harmonic losses are no longer generated in the rotor, but that the stator joule loss is now the major harmonic loss component. (8)

$$P_h = 3.R_s.{I_{hs}}^2 + 3.K_R R_r {I_{hr}}^2 \tag{6}$$

$$I_{hs} \geq I_{hr} \tag{7}$$

$$\frac{R_s}{K_R R_r} < 1 \rightarrow \frac{R_s.{I_{hs}}^2}{K_R R_r {I_{hr}}^2} = ? \tag{8}$$

To make the harmonic evaluation even more challenging, it can be derived that there is a specific interaction between certain stator harmonics. In a practical setting harmonic distortion is generally constituted as a summation of a multitude of harmonic components. In eq. 1 the parameter *s* becomes zero, as this is a synchronous machine. Therefore a specific interaction is observed between rotor harmonics of *k=1* and *k=-1*.

Table 4: Interaction of rotor induced harmonic currents

k	Stator harmonic h	Rotor harmonic frequency		
		IM	SG	IG
0	1	s	0	-s
-1	-5	-6+s	-6	-6-s
1	7	6+s	6	6-s
-2	-11	-12+s	-12	-12-s
2	13	12+s	12	12-s

It can be derived that, at synchronous operation, the interaction of rotor-induced harmonics is related to the phase angles of individual harmonics. In function of the phase angle of both the fifth and seventh stator harmonic the induced rotor current of order 6, and the related rotor joule loss, can either be amplified or completely reduced. The full derivation of the analytical equation (9), describing this interaction, has been presented in [14]. Although this reference specifically relates to Line Start Permanent Magnet Machines, the mechanisms resulting in the complex interaction are identical.

$$P_h = 3.{\hat{I}_{r\_RMS}}^2.R_r.K_r.\left(1 - \cos\left(6|k_1|\left(\varphi_{k_2} - \varphi_{k_1}\right)\right)\right) \tag{9}$$

If the losses are generated inside the rotor the phase angle is of importance. In case of a strong grid, with very low grid impedance, it is often assumed that the current distortion is independent of the voltage distortion. However, in this specific case the total impedance is very high. This results in an iterative process between current and voltage distortion. This effect is commonly known as the attenuation effect, and evaluation of this effect will be essential in order to correctly asses the impact of waveform distortion on stand-alone generators.

As will be illustrated in the measurements, the attenuation effect causes significant problems. Due to the large impedance the current distortion affects the voltage. In case of grid connected operation it is assumed that all of the power consumed at harmonic frequency is loss. However, if there is sufficient supply voltage distortion, this assumption is no longer valid. This implies that there is useful active power being supplied at harmonic frequency. Therefore does harmonic analysis of the power no longer suffices to obtain an indication of the overall loss caused by the waveform distortion.

The effect in which large non-linear loading affects the supply voltage from the electrical generator is well known to the suppliers of generator sets, however, the corresponding additional loss has not yet been their main concern. Their focus is to achieve a robust and stable output power, and voltage distortion may affect the voltage feedback loop in the AVR. New technologies such as the Auxiliary Winding Regulation Excitation Principle (AREP), which imply the use of auxiliary windings and control strategies, are being developed to obtain a stable generator in case of waveform distortion.[11] However, next to all of the already indicated losses, does the harmonic distortion add loss via both the excitation winding and it's control. Simple parameters such as controlling towards either a fixed average voltage or a fixed RMS voltage may significantly affect the losses inside the electrical generator.

5.2 Practical measurements related to Voltage Distortion on SG

In the previous section the effect of waveform distortion on SG has been addressed pragmatically. Although from a scientific point of view it would be interesting to elaborate on these items on a more theoretical basis, it is not the intent of this paper. Before this effort is performed, it should be more interesting to validate these effects in a practical setting. Consequently, different measurement setups are currently constructed, modified and used for detailed analysis.

In this paper a small 4kW SG is used for detailed analysis. In this case the prime mover was a DC motor, which inhibits accurate electrical measurements of both in and output power. The generator has been loaded with linear loads (LL) and subsequently with non-linear loads (NL). Some elementary results are plotted, such as the impact of non-linear loading on generator and prime mover efficiency, stator joule loss, excitation loss and the difference between the power present at harmonic frequencies and the overall power loss.

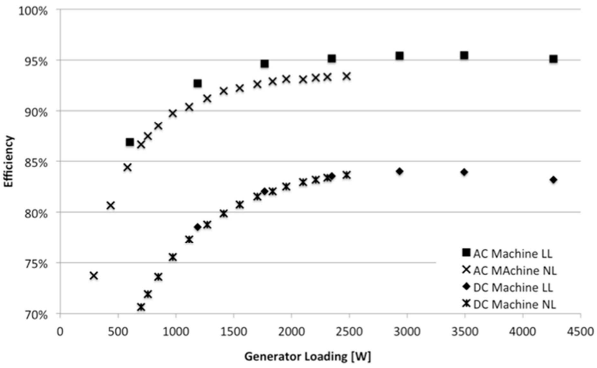

Fig. 8: Impact of non-linear loading on generator and prime-mover efficiency

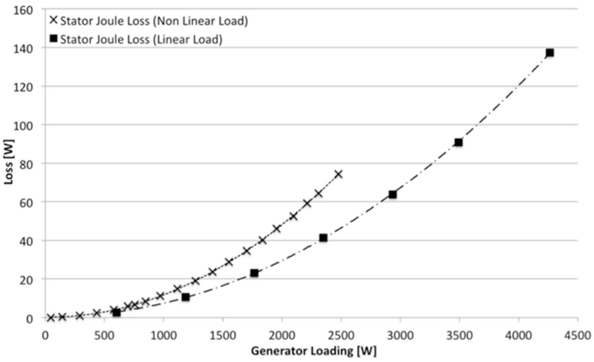

Fig. 9: Impact of non-linear loading on stator joule loss

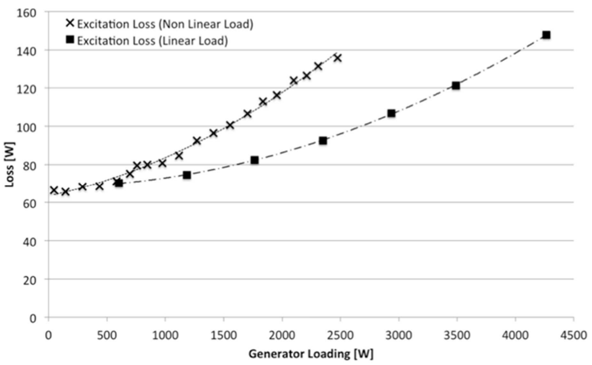

Fig. 10: Impact of non-linear loading on excitation loss

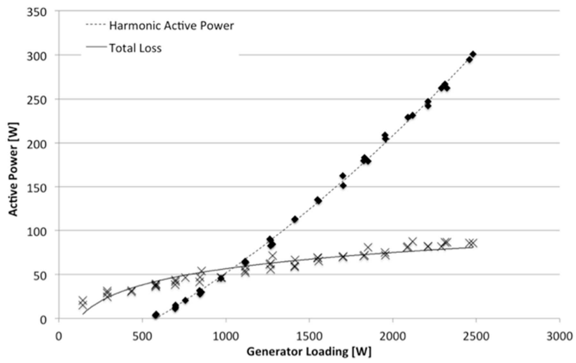

Fig. 11: Difference between harmonic active power and total power loss in stand-alone generator

In Fig. **8** the efficiency is obtained based on the IEC60034-2 method for both the synchronous generator and the DC-motor. The used method is the indirect method based solely on measurements of electrical parameters and the efficiency is derived by the segregation of individual losses. Although the additional power consumption due to harmonic loading may affect the operation point of the prime mover, the measurements indicate that the efficiency of the prime mover is hardly affected by harmonic loading.

In terms of additional losses due to waveform distortion, a very steep inclination is noticed for both the stator joule loss and the excitation loss. The excitation has been adjusted manually to obtain a constant RMS output voltage. Maybe the most relevant picture in the framework of the analysis is Fig. **11**. This figure illustrates a significant difference between the total loss due to waveform distortion and the total amount of harmonic power.

Consequently, comparison of both powers indicates that a large portion of the harmonic power is not to be considered as loss, but harmonics are actively transferring power from the electrical generator to the load. This conclusion increases the difficulty of evaluating the harmonic losses inside SG.

5.3 Future research

Several hypotheses, some of which have been suggested in the paper, should be validated by measurements before a comprehensive and accurate analysis of the effect of harmonic distortion is possible. Maybe the most relevant question is the increase of primary energy due to waveform distortion. This question is a currently ongoing research in which the main drawback is the accurate measurement of fuel consumption. Standard low-cost flow meters do not suffice, as these devices do not achieve the envisioned measurement accuracy.

In the measurements presented in Fig. **8** - Fig. **11**, the evaluated machine has a relatively high stator resistance of 1,4Ω and a large airgap, which implies a relatively low mutual inductance. Because both the influence of saturation, as ratio of stator to rotor resistance, are machine dependent, several sizes of SG will be evaluated.

[A] [B] [C]

Fig. 12: [A] 4kW test setup with internal combustion engine and accurate flow meter device, [B] 15kW test setup with GPRS synchronization between fuel consumption and electrical measurements, [C] 40kW test setup, in construction.

Several aspects will also affect the behavior towards harmonics, which have not yet been discussed in this paper. For example :

- Some of the SG are fitted with a startup/damper cage, which assist in start-up and dampens mechanical oscillations due to load variations. This cage is generally constructed with a reduced cross section in reference to IM cages, since this cage is not intended to provide nominal torque. The altered construction of the cage will affect the skin effect, and therefore application of generalized skin-coefficients for IM will not be valid.
- the influence of magnetic saliency of the generator has not been discussed, however, it can be validated that a difference between the direct and quadrature magnetic axis will severally affect the overall loss.
- In terms of the attenuation effect, not only the overall impedance is of interest, but one should carefully analyze the R/X ratio of the total network impedance.

6. Conclusions

This paper started out by presenting some of the generally accepted knowledge concerning the behavior of induction motors in relation to waveform distortion. Several aspects inherent to IM operation result in a simplified harmonic model. Some of these simplifications are: the absence of saturation, the straightforward superposition of losses and the assumption that all of the harmonic power is to be considered as loss.

The elimination of the saturation effect is no longer valid for induction generators. By shifting the harmonic phase angle the generator can operate in more or less saturated conditions. Measurements illustrated that increased saturated operation results in a decrease of the consumed harmonic power, which proved to be beneficial in terms of excess harmonic loss.

As linear harmonic modeling already seemed impossible for IG, this is most certainly the case for SG. Next to the saturation does the absence of slip result in a specific interaction of rotor-induced harmonic currents. Consequently does this prohibit simple superposition methods to recalculate the energy efficiency of SG in case of supply voltage distortion. Due to the attenuation effect, the possibly large distortion of voltage results in the phenomena in which some of the active power is being supplied at harmonic frequencies. This increases harmonic evaluation drastically.

To conclude, the effect of harmonic distortion on induction motors is generally marginal, except in situations of severe voltage distortion. But in case of synchronous generators, there might be an increased susceptibility towards waveform distortion. Especially since these losses have to be supplied via a low efficient prime mover, there is a possibility to directly relate additional primary energy consumption in relation to waveform distortion.

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Modular Electric Motor-Generator Technology Associated with Electric Gears

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Quantum Electric Ltd is proud to introduce modular electric motor and generator with a wide efficiency range. This is achieved with multi phase speed controller technology associated with *'Electric gears'* (EG). The new EG speed controller technology is practical for all electromagnetic motors and generators. The introduced Electric Gears technology includes:

- Wide Efficiency Range Technology (WERT)
- Universal Voltage Operation (UVO)
- Modular Multi-Phase Operation (MMPO)

EG advantages are further increased with another novelty, the *Modular Multi-Phase Operation* (MMPO) for synchronous motors and generators. Multi-Phase Operation allows combining high efficiency, compact size and low weight of brushless 3-phase synchronous motors with smooth drive and ease of control of multi-pole universal current brushed motors. Further, EG adds to these a new property, the *Universal Voltage Operation* (UVO).

An EG speed controller works simply by connecting sectors of phase coils of motors and generators in series, parallel and combinations of these during operation. In this way it extends motor efficiency range up to several times. EG also increases motor peak electric power. Effect of EG operation is similar to adjusting motor voltage. Actually, the nominal voltage of the motor is adjusted, by EG connections of coil segments.

This paper summarizes the latest developments of modular electric motor technology including mechanical system and component architecture of a modular motor, principles of an electric gearbox system, ANSYS simulation results of the electromagnetic power units and comparison of computer simulations and testing data of a modular EG motor prototype.

Measuring Motor Introduction

The prototype synchronous permanent magnet motor of figure 1 was used for measuring and testing *Modular Multi-Phase Operation* with *Electric Gears*. It has a rotor with twenty permanent magnets and six sets of phase coils on an axial flux configuration. For tests, it was connected first for 3-phase operation, and next for 6-phase operation for comparison.

For experimental optimization, this modular motor was built to allow all parts related to magnetic flux to be either easily changed or adjusted. For example, the air gap between rotor magnets and iron cores was adjustable. The rotor itself was built replaceable to measure and test a variaton of permanent magnets of different sizes. Different conducting and inslulating rotor materials were compared. Phase coil sets were constructed to be modularly replaceable, too.

Prototype motor stators were built as two independent 3-phase modular coil sets in front of and behind the rotor. The motor frame was built to allow rotating these two 3-phase coil sets so that their phases overlapped to create a 6-phase drive for *Modular Multi-Phase Operation* measurements. Because no 6-phase synchronous motor Electronic Speed Controllers (ESC) were yet available, the measuring prototype was realized with two separate standard 3-phase ESC's, each controlling one of the two overlapping 3-phase modular coil sets.

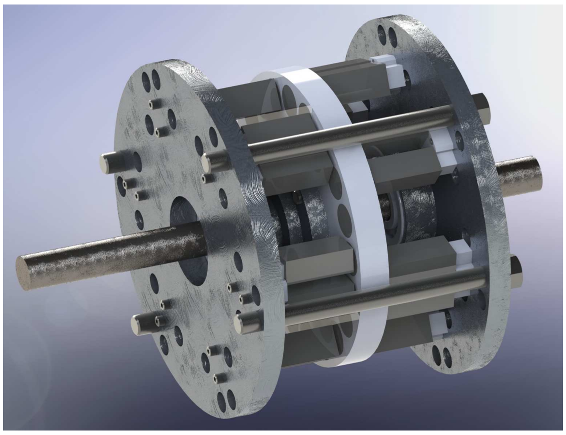

Figure 1: Full CAD model of the measuring prototype modular electric motor and generator

The rotor in figure 2 is rotated by switching current and changing current direction in the phase coils. One of the main features is the use of segmented windings with flat wires for U-shaped phase coils. That allows us to simplify the wiring in manufacture where complex automated systems are used.

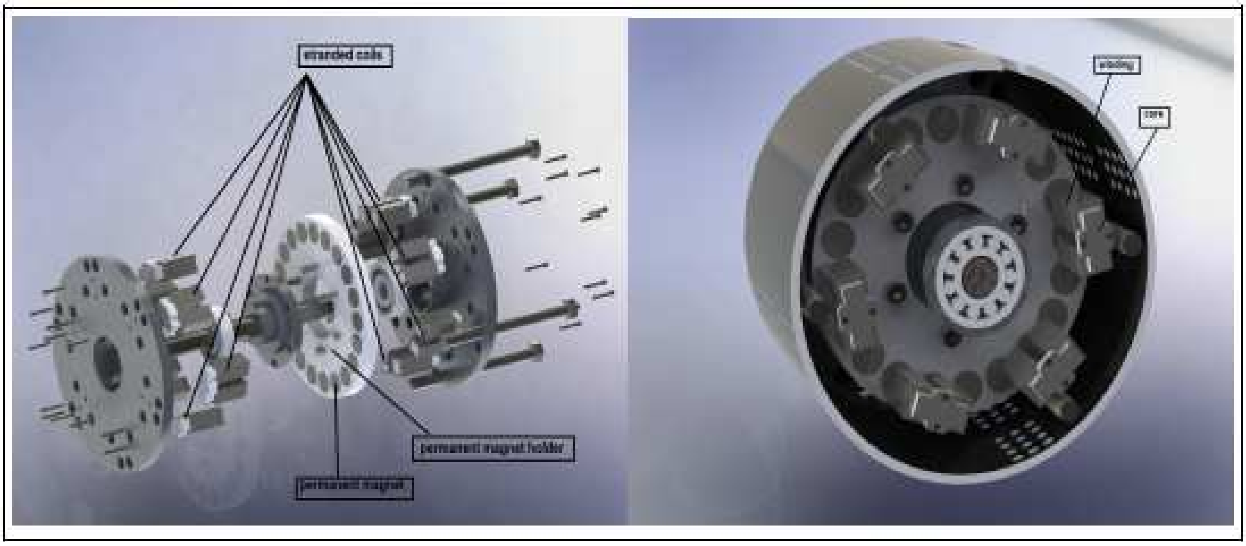

Figure 2: Exploded view and sectional view of the measuring prototype

The second aspect is the possibility of applying a stronger current compared to traditional electrical motors. The construction properties of the power unit allow us to scale the size and output torque both ways: traditional - by increasing construction parameters of the motor - or by adding equal modules in the longitudinal direction.

The electromagnetic unit described can be used for manufacturing of electric motors, generators and integrated generator-motor units associated with electric gears technology. The novelty of that feature is electrical switching of connections with electromagnetic components during drive for taking advantages from each type of the circuit at a particular speed regime.

It is known that electrical components connected into series, parallel or combination of those behave differently in the sense of energy consumption and output power, as well as that an electrical motor could have a lack of torque at one regime and waste a certain amount of power at another. In a traditional control systems where conventional frequency converter or electronic speed controller technology are used this leads to a very limited efficient rpm-range of modern electrical drives. A method to change connections between other basic electromagnetic components during drive facilitates a totally new electric gearbox technology with no rotary or moving parts for that purpose.

Heat Resistant Winding Allowed

Traditional electric motors usually allow using enamel insulated round wire only for coil windings, or at best limited use of enameled flat wire, making them vulnerable to damage even in brief overload situations. The introduced new technology is particularly suitable for Direct Drive (DD) high torque motors for applications requiring exceptionally high short term regular overload.

This new property is realized by modular coil architecture, which allows using flat wire or even foil materials for very effective heat dissipation from inside the winding. Flat foil windings allow using high temperature resistant insulation, making modular coils resistant to unusually high peak temperatures for handling repeated high acceleration peaks. Ruggedness in overload situation makes modular coils ideal for regular intensive acceleration in the case of different vehicles, working machines and aircraft.

Electric Gears Technology

One of the main novelties of the power unit presented is using connections of segmented phase coils or sets of phase coils to electrically extend motor or generator range of optimal efficiency for significantly wider range of power and rotational speed. That corresponds to the effect of a mechanical gearbox in some aspects. The usage of these electrical connections to adjust motor or generator performance is called 'electric gear' or 'electric gears' (EG).

Contrary to usual mechanically or electro-mechanically controlled gearboxes such as Electric Variable Transmission (EVT), the 'electric gears' operate completely electronically without any moving mechanical parts, which EVT and similar gearboxes still have.

The “shifting” is realized by utilizing a modular construction of an electronic speed controller so that each module electronically switches interconnections of phase coil segments of a motor or a generator. The performance differences to mechanical gears is that EG do not increase the maximum torque of an electrical drive, but control the output power directly .

An operational advantage of the invented means of speed control with EG function is that it allows to shift “gears” smoothly and automatically during full power drive, without any need to reduce power for clutch and gears operations required with traditional mechanical transmission.

Usual Means of Speed Control

Usual means of speed control with common three phase electronic speed controllers are by switching its phase currents with a much higher cyclic frequency than its phase frequency using pulse width modulation (PWM) for electric power adjustment.

High PWM cyclic frequency of traditional speed controllers helps us to achieve smooth functionality, but it also significantly increases motor eddy current losses as a function of switching frequency, and it increases switching losses within the speed controller. Additional side-effect of high frequency PWM control is an audible whining or howling noise during motor drive.

Another common way of power control is via Pulse Amplitude Modulation (PAM). There is no need for separate PAM function in the speed controller with the presented technology of using EG, because each electric gear adjusts input voltage of motor by steps.

The same result as PAM of adjusting effective input voltage is achieved with the invention in the motor end, by controlling phase coil voltages using variations of their parallel and series connections, with EG function. The modular controller introduces a more efficient alternative for controlling electric motor or generator power, it reduces the high frequency eddy current loss and switching loss problems by performing main power adjustment using combinations of connections for coil segments.

Efficient Phase Width Adjustment (PWA)

Due to usage of more than three phase drive, the mentioned technique enables motors and generators to be driven smoothly and silently using simple low frequency *Phase Width Adjustment* (PWA) speed control. The required switching frequency is reduced down to phase frequency, which is the lowest frequency that a motor or can be operated with.

However, using high frequency PWM control is possible, but a need for that is only at low electric power operation conditions where the losses that PWM inflicts are minimal. So instead of the traditional three-phase ESC that causes extra losses by means of PWM chopping each half-cycle of phase current with high frequency, the current multi-phase controller simply adjusts the width of each half-cycle of phase current by PWA, preserving this way switching frequency to lowest possible, to restrict harmful and squandering eddy currents and to keep switching losses at minimum.

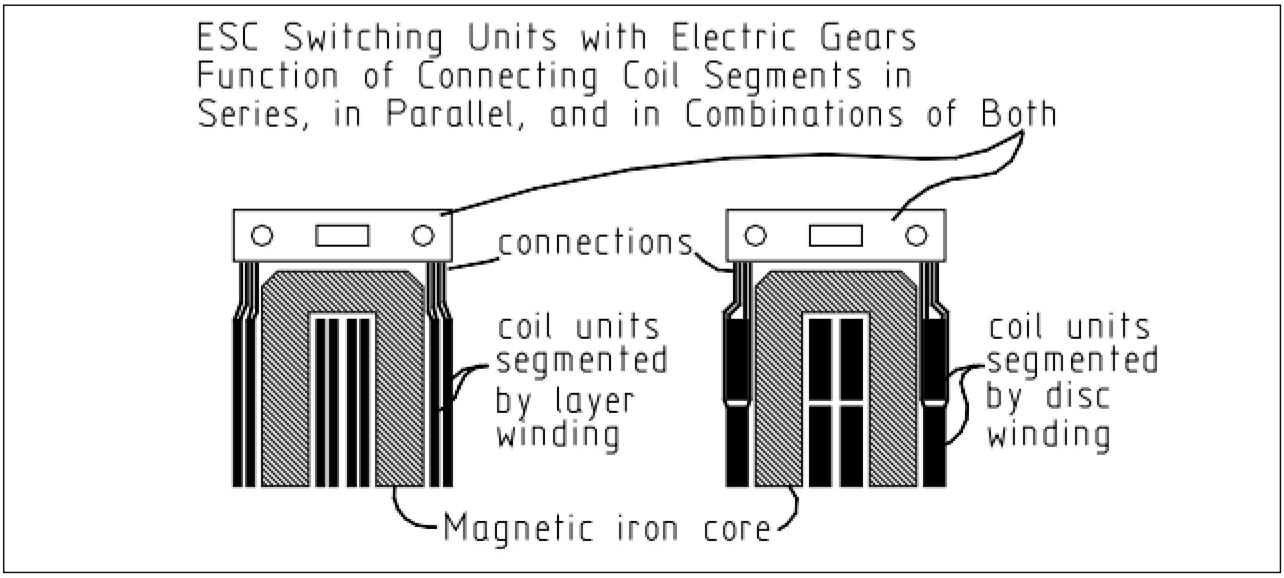

Figure 3: Representation of power unit with segmented coils and EG function

The coils of the power unit (figure 3) are divided into a number of sections or segments, which are connected together in combinations by controller modules, each handling segments of windings of a certain phase coil, or a set of certain phase coils. The number of these internal coil segments in each phase set of coils determines how many electric gears they may be connected to.

Each electric gear means a variation of coil segments of each phase winding connected either in series, or in parallel, or in combination of series and parallel. The more coils or coil segments are connected parallel by the electric gear function, the higher is the motor electric power and torque. Switching phase coil parallel connections step by step for more series connections with the EG function reduces electric power and torque, and increases motor efficiency with low electric power. Correspondingly, for braking action and generator use, highest braking power is attained with all coils or coil segments in series, which also provides most efficient braking energy recovery with low rpm's.

One way to illustrate the efficiency increase implemented by the EG is to think of the motor characteristic efficiency-torque curve. When using the electric gears parallel-series connection function of phase coils or coil segments, the characteristic efficiency-torque curve of a motor or generator is shifted to higher or lower electric power. If we plot the characteristic curve as an efficiency-electric power curve instead of the usual efficiency-torque characteristic, the electric gear effect becomes visible. When a motor is switched for in series connections the efficiency curve of the motor slides towards low electric power.

In case of more parallel connections for power units, the motor characteristic curve slides towards high electric power. The electric power increasing effect is usually limited by maximum allowed power loss, by torque limit and by maximum rotational speed of the electrical drive.

Universal Voltage Operation

One of the crucial features that the current technology provides is an 'Universal Voltage Operation' (UVO) property of EG controlled electric motors and generators. It results directly from EG functionality. EG speed controller varies motor or generator windings during its operation.

For instance, when a traditional motor or a generator is wound for high voltage it delivers its full power with this voltage. Still higher voltage will overheat or even damage the motor, and lower voltage will rapidly decrease its axle power output. EG operation of phase coil segment connections adjusts axle power without adjusting input voltage.

When connecting half of the segmented coil parallel with the other half, also motor nominal operating voltage is divided by two. Now the motor or generator operates with its full power and performance with half of the original operating voltage of a traditional fixed winding motor. With EG means of speed control, number of motor windings are switched for optimal performance and efficiency for any operating voltage and axle power required.

If each of the coil segments are further divided to two segments and connected in parallel again, the operating voltage of the motor is halved by each step of the parallel connection. This is the way the EG function of speed control manages motor phase coils and/or phase coil segments or sections.

The number of available 'Electric Gear' combinations and variations is defined by the number of phase coil segments or sections. The tested prototype has four winding segments in every U-shaped coil, two with series connection and two with parallel. The first gear illustrates the state when every winding is connected in series (gear I). Second gear is a parallel-series combination (gear II). Third gear means that all coils are set parallel (gear II).

The maximum number of allowed phases is the number of phase coils or phase coil sets that the motor or generator is constructed with. In other words, multi-pole construction of a motor or a generator allows more phases to be used for their control, compared to motors with a low number of magnetic poles. Such multi-pole synchronous motors and generators are favored for direct drive applications, because of their high torque.

EG speed controller allows motor or generator may be used with a range of operating voltages, without need to manufacture a separate motor model for each operating voltage. Further, Modular Multi-Phase EG speed controller allows motors be driven from and generators be synchronized with both DC and single phase or polyphase AC mains. So the EG 'Universal Voltage' feature includes 'Universal Current' property, too.

Practical Experiments and Measurements

The prototype presented in the article was investigated both directly and using modern numerical methods. The first approch focuses mainly on circuit variations, current and speed regimes and testing different materials, while the second one pursues optimal construction parameters of a general design and helps to avoid financial losses by identifying best geometrical combinations of the components. Real measurements can be classified into several testing categories.

The starting experiments were basic strength tests, that were measured by means of static moment, with a torque as a function of current and power connected to one coil set at a time. In the following 50 Hz, three-phase experiments, the same parameters were tested with sinusoidal three phase input. These tests were needed to determine the basic properties of an experimental motor in standard 3-phase use.

One of the most crucial tasks was to calculate possible directions for improvement of efficiency, for example using other materials for winding than aluminum alloy coils. As it is shown in Figure 4, general improvement of prototype performance is still possible with simple design decisions which are still not yet present on the market.

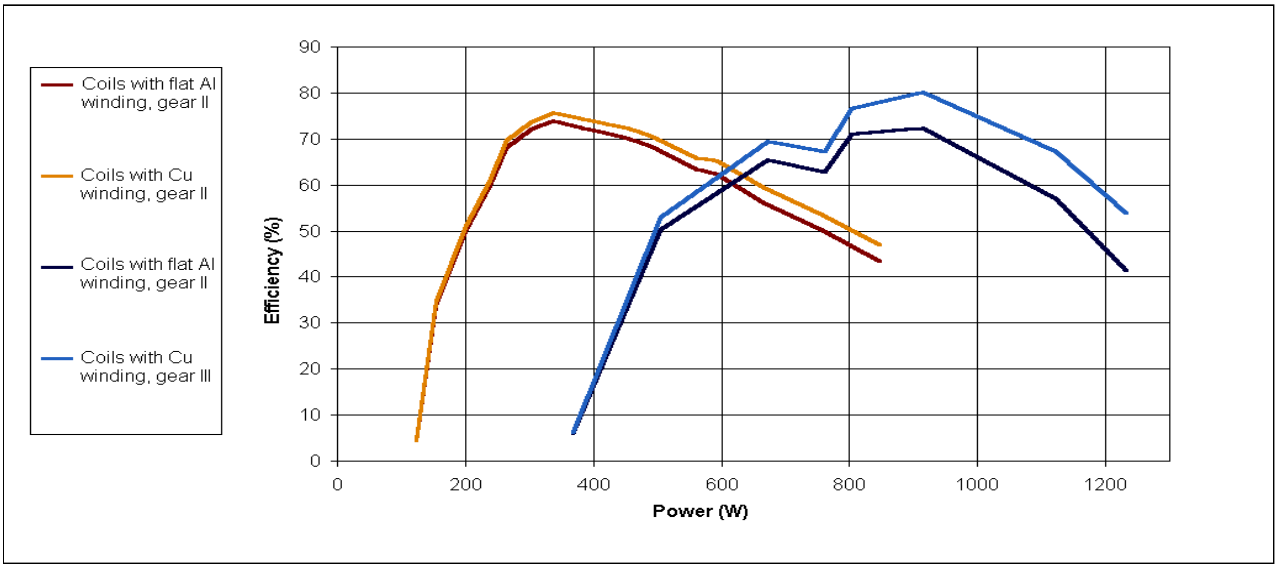

Figure 4: Winding material efficiency calculation

The next stage was to compare three-phase and six-phase drive properties of the measuring motor. Changing the amount of phases is taken into account in such a way that the tested prototype was divided into two equal halves, which were mechanically rotated relative to each other. Directly comparable results for both three-step and six-step operation were obtained. The advantage of six-phase configuration is smoother, softer and quieter drive and braking action. The main goal of using multi-phase configuration is to obtain better drive control of the motor. It is a tool for EG technology.

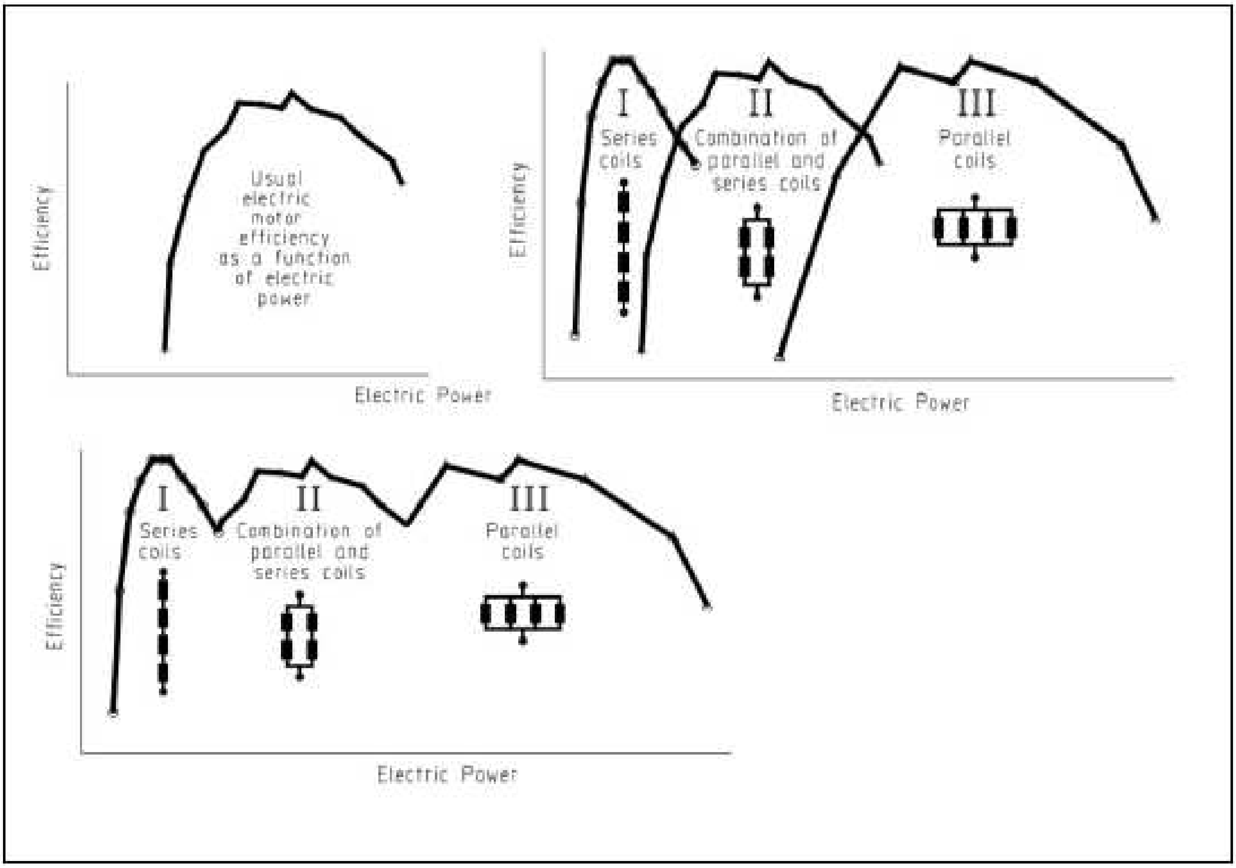

Figure 5: Efficiency curves of an ordinary motor compared to an EG equipped one

Wide Efficiency Range

The most valuable results obtained illustrate several significant possibilities emerging from using EG. The efficiency curve of a traditional electric motor is represented with the first curve of Figure 5. With common undivided coils the curve is typically rather narrow in terms of axle power and speed range.

Conducting a number of experiments with the prototype by dividing its coils into segments and connecting them either in series, in parallel, or in a combination of these, an extended range of efficiency in the second curve of Figure 5 both towards high and low electric power was achieved.

However, it was empirically proven that while the range of efficiency extends to one direction, it narrows from the other. As it is shown with the last curve of Figure 5, if series and parallel EG connections are switched during motor operation, peak efficiency could be extended both towards high and towards low electric power.

The third plot of Figure 5 shows step-by-step how EG extends the efficiency range of an electric motor or generator. A coil divided into four segments is used for that example, with simple schematics of the three electric gear connections under each efficiency curve, representing each of the three example electric gears, marked I, II, and II. In practice, any number of coil segments may be used, depending on optimal number of electric gears for each application.

Figure 6 illustrates a typical measured electric motor speed of rotation of the three previously described example electric gears as a function of motor torque. Electric gear III of parallel coils provides highest speed of rotation, while electric gear I of series coils is ideal for low speed. The combination electric gear II fills the gap between the previous two. The example motor used for this measurement was a synchronous permanent magnet motor with 6-phase drive and a rotor of 10 pairs of neodymium permanent magnets. As it is seen, the effect of electric gears is similar to changing motor power source voltage.

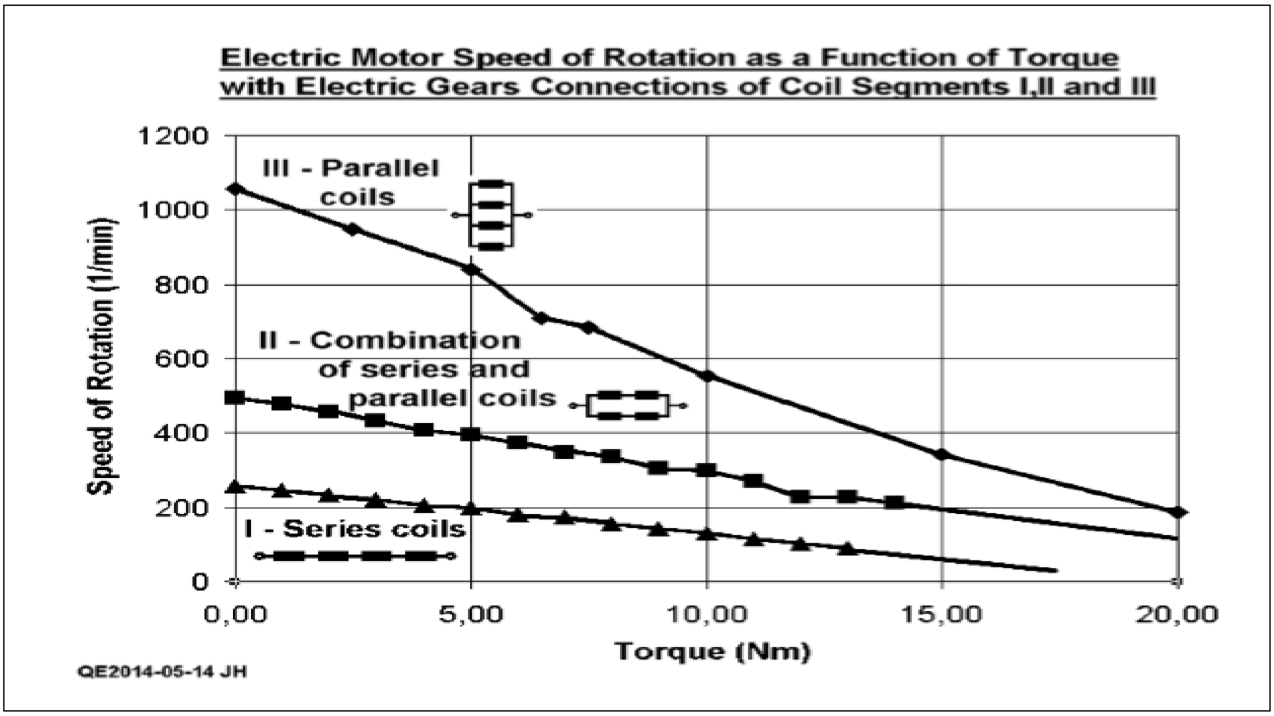

Figure 6: Torque-rpm dependency with Electric Gears I, II and III

Virtual experiments

The design of an electromagnetic motor is a crucial and demanding problem for manufacturers that requires material, construction and control tests to pursue the production of the most efficient device possible with given specifications. Every motor model needs its own tooling and manufacturing arrangements. This causes losses for the manufacturer in both time and money.

To reduce these important losses, different simulation techniques are used. One of the most powerful available is the Finite Element Method, or FEM. Nowadays, such FEM codes as ANSYS Multiphysics can solve great many problems in physics virtually by simulation and that provides a way to decrease the expenses in the process of adjusting the real model to achieve the desired performance. The full model of the current electrical motor was simplified by its geometric symmetries due to rotational symmetry of the processes up to one stranded coil set and from one to four permanent magnets depending on the analysis type.

Simulation was done in several steps, starting from the test model, with a rough shape and approximate physical constants and model parameters, towards a complicated faithful model with the exact dimensions and input data. The first, static analysis, was performed with the geometry simplified up to the set of iron core and two coils. It became possible to estimate the magnetic flux density of the core and magnetic field intensity of the coil. That configuration allowed us to make a number of tests with different geometry parameters to find an optimal set with maximum magnetic flux density.

Further evolution of the model (figure 8) was to add permanent magnet components to the code of the program. This leads to a chance in the estimation of tangential force between the coils and permanent magnets. In that case we are able to perform the analysis to build the dependency of tangential force from the position of the magnets. Four permanent magnets are present in the model (Figure 8 left).

Rotation of the shaft and motor construction illustrates the significant interaction with only four permanent magnets for the time of one cycle and for one set of electrical spools. The pattern, which consists of one coil set is one twelfth part of the motor, which consists of twelve equal reel sets and twenty permanent magnets.

The geometry in the program code was simplified due to independence of the behavior of every equal part. The resulting force can be multiplied by a symmetry coefficient, which is six and then by the coefficient, that states the power increase in the case of another six coil sets on the opposite site of the permanent magnet holder. The static case is equal to very low rpm mode of the motor in the sense of power loss induced by polarity switch of the charge on the reel set.

The results of the current simulation work were obtained using static, transient and harmonic low-frequency electromagnetic analyses. Different constructive and physical parameters were investigated. The most crucial pieces of information about power, efficiency and working regimes of the motor were generated numerically. The experimental values were compared to real measured data of the prototype.

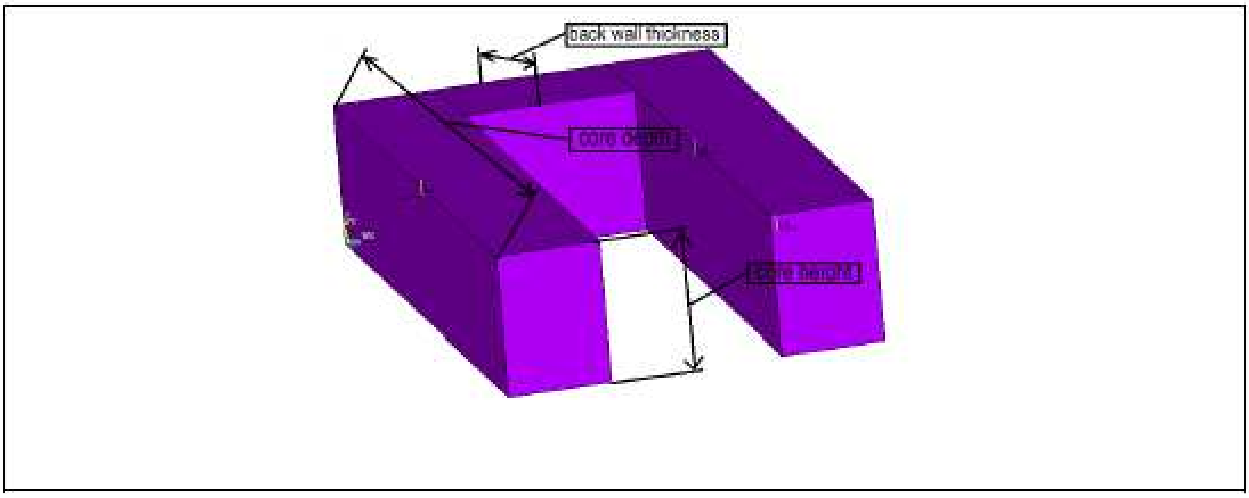

Figure 7: Variation parameters

The first test configuration was used to evaluate the influence of relative change of constructive parameters on the magnetic flux density. To test the influence of configuration changes, we take the average of the magnetic flux density of sliced surfaces of the core. The resulting magnetic flux density is averaged over mentioned zones.

The constructive variables (Figure 7) to vary are the back wall thickness, height of the core, depth of the core and the distance between outer surface of the core and the permanent magnet. All the virtual experiments were considered to maximize magnetic flux density and to check the influence on the tangential force.

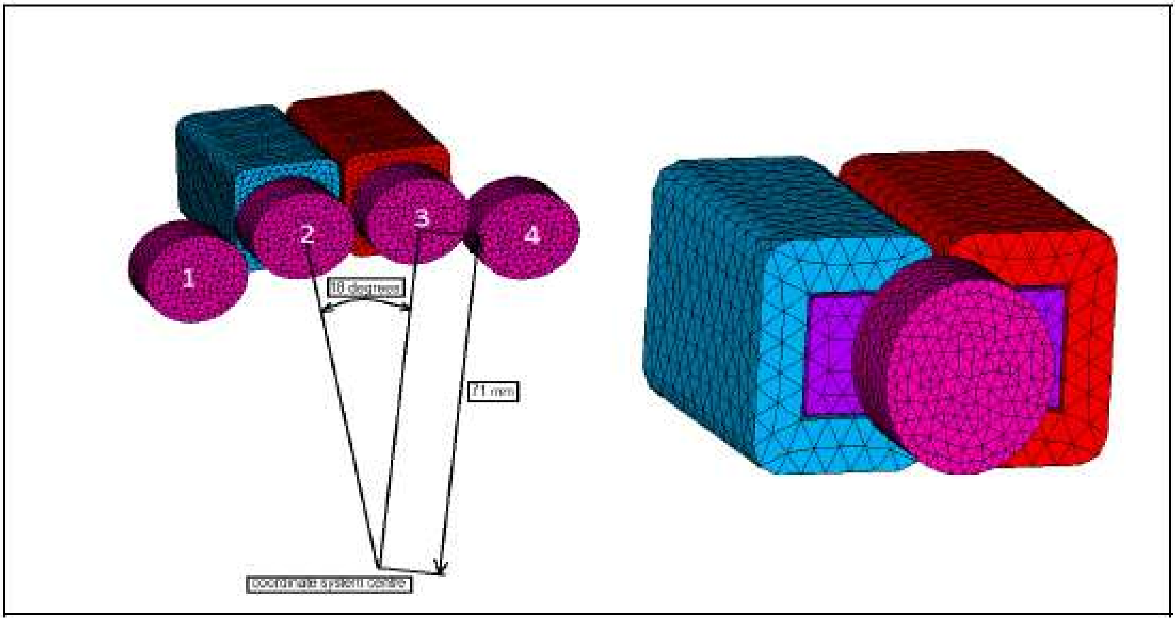

Figure 8: FEA models in use

The following model (Figure 8, left) consists of one core, two coils and four permanent magnets. Magnets are rotating clockwise from 0 to 18 degrees from their initial position. In the initial position of magnets 2 and 3 are in front of the left and right coils, respectively, and have opposite polarity with them.

The magnets are rotating in a cylindrical coordinate system with a distance from the center of the coordinate system to simulate their position and motion as in the prototype. The magnets are numbered as in the picture. Every solution of that type is a series of a hundred static simulations with iterative change of permanent magnet positions.

At every step, the resulting tangential force for each magnet is estimated and the relations between the force and position are constructed in that particular way for every permanent magnet and the total cooperation sum. The tangential forces were measured for each magnet and their sum calculated for a wide range of currents. The resulting tangential force is averaged to obtain absolute force magnitude at each load and build the force (current) dependency.

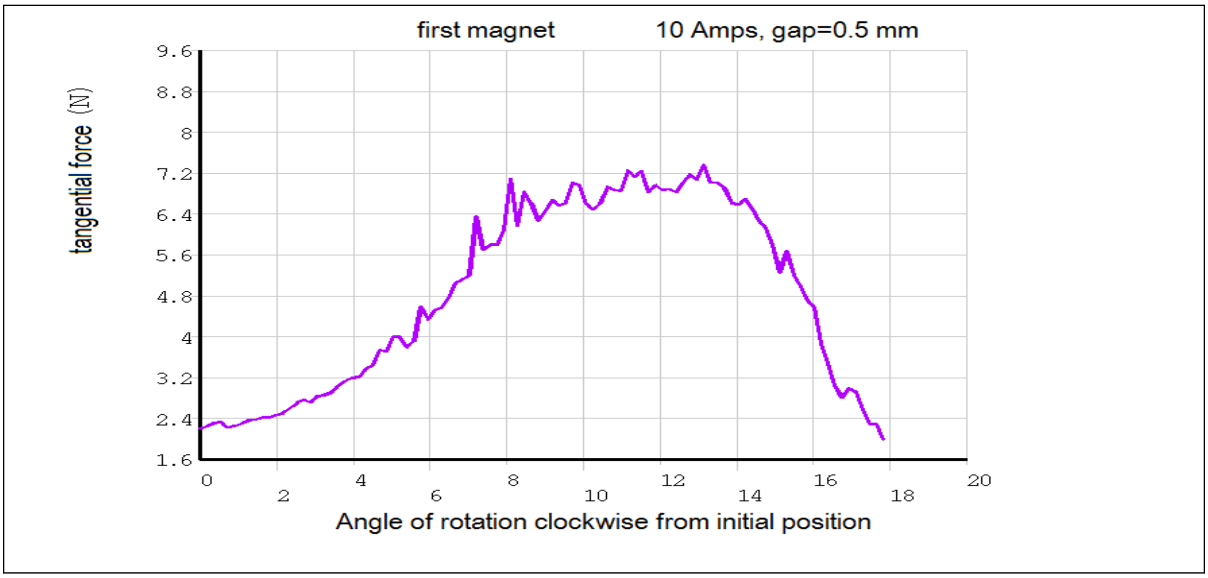

Figure 9: Example of tangential force dependency on the magnet position

The next model (Figure 10, right picture) was conceived in order to understand the effects of air gap thickness change between the core and the permanent magnet, and the effect of permanent magnet thickness change (Figure 10, left picture) on tangential forces.

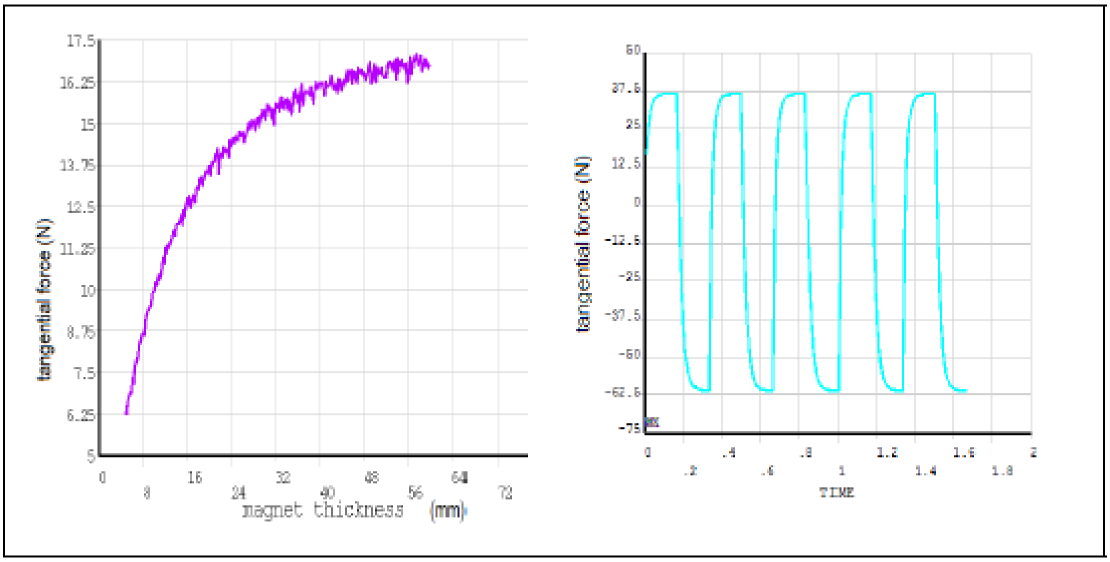

Figure 10: Example results of the second FEA model

The magnet is fixed between the cores, and the right coil is pulling the magnet, the left one is pushing it. That model was taken as the basis to extend the possibilities towards a transient model.

Further, the FEA model (Figure 10, right picture) was assumed to be dynamic in the sense of electrical boundary conditions. The problem considered in the static analysis was extended. The solution of the transient problem pursues the aim to estimate losses with increasing motor speed.

The problem is considered as a series of transient solutions in the sense of electrical conditions, but with a static position of the permanent magnet. The output data is different in the time-dependent case, as seen in Figure 10 (right picture), and quantities are averaged to obtain global dependencies. Using the mentioned scheme, it is possible to obtain the magnitude of tangential force depending on time for every speed regime of the motor. An example is presented at the figure above.

Obtained data is being averaged for each case independently and the information of the power loss is summed up. It is assumed, that at the rpm close to zero, the static model and dynamic results are identical.

Taking the data from the static simulations with the four permanent magnet set, we assume the starting point at rpm near zero and using the information about losses. It then becomes possible to build force, momentum (Figure 11, left), power (Figure 11, right) or efficiency curves with their dependency on rpm. To improve the model, a nonlinear model of the saturation curve was implemented into the model.

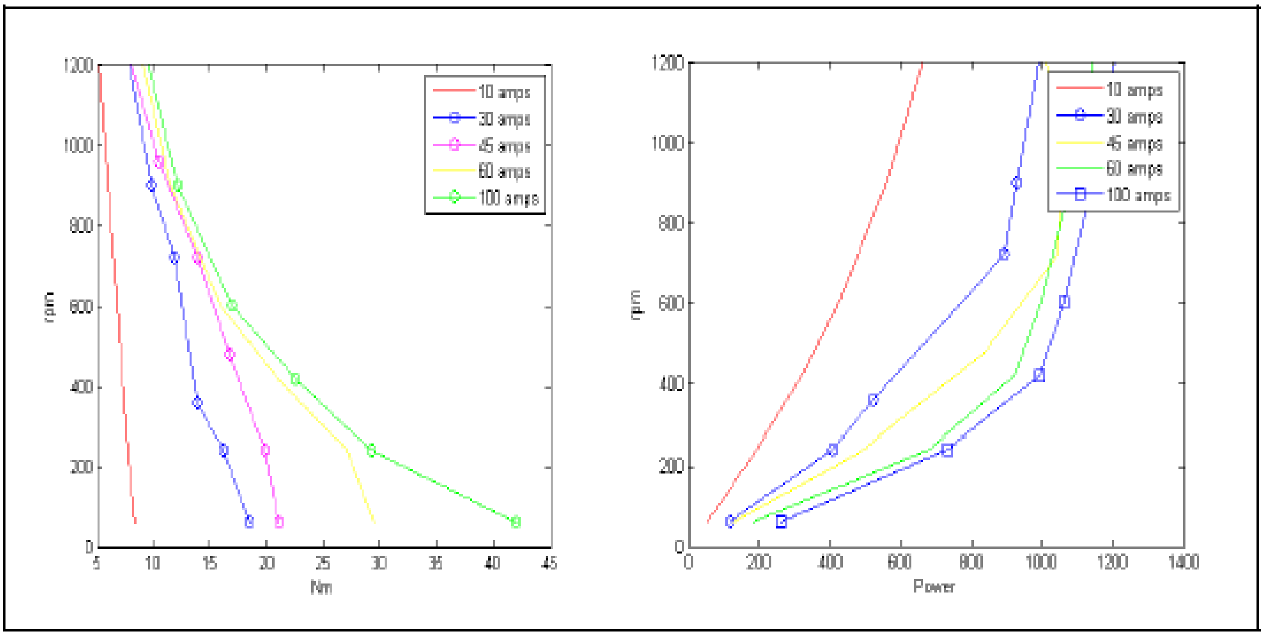

Figure 11: Momentum-rpm and power-rpm dependencies

The accuracy of obtained results depends on several factors: on the number of finite elements, on the correctness of the physical constants used, on boundary conditions and on the amount of dots on the range of detail movement or time step considered. The last two factors are extremely important for the solution time and, therefore it is a crucial task to find a balance between required preciseness and time consumption.

Conclusions

The unique features in the design and technologies used make the presented concept attractive in many industrial applications such as starting motors for turbines, jet engines and heavy machinery, electric motors for elevators, servomotors for heavy industrial robots and electromagnetic brakes to be used in heavy transportation and railway system applications.

Modular construction is lightweight, highly reliable, has a long life and an easily expandable modular construction and requires minimum maintenance. The system is fault-tolerant since even in the case of failure of one power module the other modules continue operating independently of a failed one.

Electric gearbox switching during generator or motor operation brings several advantages such as extended power and efficiency curve, which gives more torque and power over a very wide rpm-range of the motor or generator in comparison with traditional drives. Using few basic components, it is also possible to manufacture many motor or generator models with different operating voltages and power levels which is an advantage to any motor manufacturer.

Electromechanical or electronic switching of electromagnetic components or power units into series or parallel and combinations of these during generator or motor drive allows the design of 'supermotor' construction with extremely high torque and efficiency even with extreme power levels. Production costs for traditional electric motors are expensive, with high cost of stator die tools. Complex winding of stator is a time consuming part of production, requiring either hand winding or expensive special robot.

Modular coils skip traditionally expensive production steps like winding. Coils of each module can be wound separately in a simple, fast and inexpensive winding machine. A complete coil is joined with iron core. No more need for slow manual winding or expensive winding robots. Modular electric motor technology saves initial costs of production, reduces number of different components needed, cuts time and expenses for new model design, and streamlines manufacturing.

The new Multi-Phase Wide Efficiency Range Electric Gears Technology works with motors and generators as well with DC as single and polyphase AC power. It introduces the first practical means for Universal Voltage and Current Operation. These properties combined with unlimited Modular Multi-Phase Controller, the new technology is next step of evolution since Tesla Polyphase system.

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Development of IE5 High Efficiency Motor with Iron-base Amorphous Magnetic Cores

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Abstract

This paper presents an IE5-level efficiency 11kW axial flux permanent motor with ferrite magnets and amorphous laminated stator core. The motor has two 10-pole rotors and one 12-slot amorphous cored stator. The prototype machined achieved 96% efficiency at full load operation after temperature arise is stable. In this paper, the concept of motor structure selection, the properties of amorphous stator cores are introduced. The structure and magnetic properties of amorphous cores are described. The detail of the 11kW prototype machine and the test results are introduced.

1 Introduction

Electrical motors are used in nearly everything, from industrial machines to home appliances. The primary electricity consumption in Japan is more than 1 trillion kilowatt-hours (kWh) every year [1]. Motors are responsible for more than 50% of the primary electricity consumption. In recent years, high efficiency electric machines have been in high demand due to increased attention being placed on energy conservation and environmental concerns. Furthermore, more and more functions were added to products for home appliances, industrial machines, and automotives to meet customer needs, which leaves less overall space for motors within the target product. Smaller size can also alleviate motors' cost pressure due to the increasing cost of nature resources. On the other hand, the International Electrotechnical Commission (IEC) published standard IEC 60034-30/31 to define motor efficiency levels. With the publication of IE4 in March 2014, the development and application of higher efficiency motors in the global marketplace will gain a higher level of importance in the near future.

The high efficiency motors available today are permanent magnet synchronous motors using rare-earth magnets which contain neodymium and dysprosium. Over the past 30 years, electrical machines, equipped with neodymium-iron-boron permanent magnets, have been used in a wide variety of industries. However, the cost of neodymium and dysprosium has risen erratically over the last few years and the supply of these metals is increasingly uncertain. Given the increased costs and limited availability of rare earth metals, suitable replacements or alternative methods must be employed to increase motor efficiency. The purpose of this research is to develop high efficiency permanent magnet synchronous motors without using rare earth magnets.

In this paper, the concept of choosing motor structure for a rare-earth-free motor is introduced. Amorphous magnetic alloy is chosen as the soft magnetic material for the new motor. The structure and the manufacture methods of the amorphous core are introduced. Furthermore, the measuring system for amorphous cores is introduced. The properties of amorphous cores are compared with the no-oriented magnetic steel cores. A 10-pole 12-slot axial flux permanent motor with ferrite magnets and amorphous cores is designed and manufactured. The motor achieved 96% efficiency at full load operation. The details of the motor are introduced in this paper.

2 Motor Structure

There are two main approaches to increase the efficiency of a permanent magnet motor: 1) increase the motor output; or 2) decrease the power losses. Since the coercive force of non-rare earth magnets, such as ferrite or ceramic permanent magnets, are typically 50% to 70% weaker than that of rare earth magnets, increasing the output of a motor using these weaker magnets is extremely difficult with conventional motor structures without increasing the size of the motor.

An electrical motor can be constructed in two ways according to the direction of the main magnetic flux interacting between the rotor and stator. Fig. 1 shows the structure of a radial-flux permanent-magnet machine (RFPM). Fig. 2 shows the structure of an axial-flux permanent-magnet machine (AFPM). “Radial-flux machines” refers to a motor with a magnetic field in the radial direction and an air gap that is parallel to the rotational axis. “Axial-flux machines” refers to a motor with a magnetic field in the axial direction and an air gap that is perpendicular to the rotational axis.

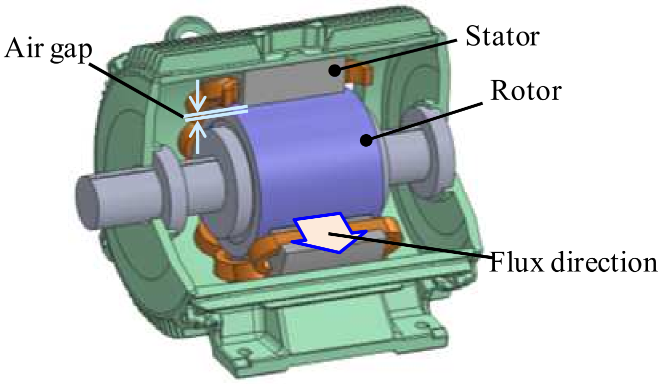


Fig. 1 Radial-flux permanent-magnet motor.

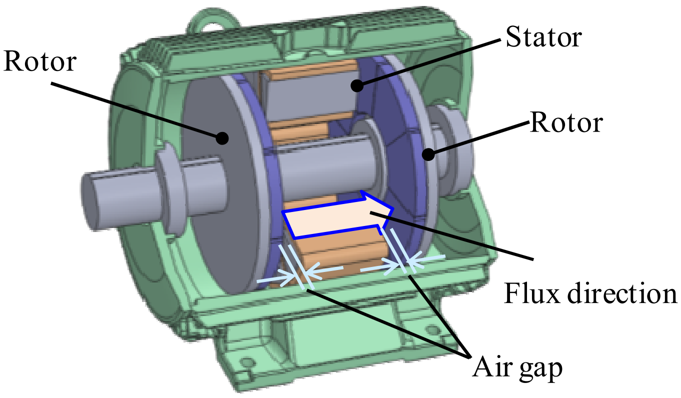


Fig. 2 Axial-flux permanent-magnet motor.

Many scientific publications have outlined comparisons between RFPM machines and AFPM machines [2]-[5]. The general advantages of AFPM machines over RFPM machines include higher torque density, an adjustable air gap, and better heat removal. In a dual gap AFPM with a double-rotor and a single-stator, the area of the effective air gap for the torque production can be expressed as:

$$S_A = 2 \times \frac{\pi D^2}{4} \tag{1}$$

where D is the outer diameter of the motor.

In a RFPM motor, the area of the air gap can be expressed as:

$$S_R = \pi d L \tag{2}$$

where d is the diameter of the rotor and L is the axial length of the rotor.

With the same dimensions, the air gap area of a dual gap AFPM is larger than that of a RFPM motor. The output torque is proportional to the area of the air gap in permanent magnet motors. Therefore, a larger output can be obtained without increasing a motor's size by employing a dual gap AFPM structure.

In previous developments [6] and [7], authors proposed a double-rotor single-stator axial flux permanent magnet motor (APFM) to make up for the insufficient magnetic energy produced by ferrite magnets. This structure provides a motor with more than three times the output torque than that of a radial flux machine with the same volume, which guarantees that the same motor power density can be obtained even with ferrite magnets. Stator cores made from iron-based amorphous magnetic material (AMM) were employed to reduce stator core losses in the motor. The 6-pole 9-slot 200W prototype machine delivered 93% efficiency [7]. Furthermore, skewed magnets were used to decrease the cogging torque. With these developed techniques, an 11kW industrial motor [8] with 8 poles and 12 slots was developed. That motor delivered 93% efficiency at full load, which places the motor in the IE4 level in the efficiency standard IEC60034-30, as published by the International Electrotechnical Commission (IEC).

3 Iron-based Amorphous Magnetic Alloy

There are two major sources of power losses in an electric motor, copper loss in the stator windings and iron loss in the magnetic cores. An optimal winding structure design such as windings with short end-windings can reduce copper loss dramatically. However, iron loss is affected by many factors such as the penetrating flux density, the excited frequency determined by the rotating speed of the motor, and the waveform of the excited voltage. The techniques used to decrease iron loss in motors with conventional magnetic materials has already reached a breaking point.

The most efficient method to reduce iron loss is to apply low iron loss magnetic materials to electrical motors. The iron-based amorphous magnetic alloy has features of extremely low iron losses, high magnetic permeability and high fracture toughness. Table 1 shows the basic properties of the iron-based amorphous alloy and non-oriented magnetic steel in the shape of thin sheets as provided by the manufacturers [9]-[10]. Compared to the non-oriented magnetic steel, iron-base amorphous produces less eddy current loss when the material is subjected to an alternating magnetic field due to their high electric resistance. The amorphous magnetic alloy also produces low hysteresis loss due to their disordered atomic structure.

Commercial amorphous metal is typically processed as 0.025mm thick ribbon. Amorphous ribbon is very hard and brittle, which makes stamping or pressing difficult. Therefore, amorphous metals have not been applied to electrical machines due to the difficulty and high cost of processing the metals for the use in complicated stator cores. Furthermore, the iron loss characteristics of amorphous cores have not been thoroughly investigated. Thus, the proper core design and necessary core loss data for motor applications are required for amorphous application in rotating machines.

Table 1. General properties of non-oriented magnetic steel (35A300) & amorphous magnetic alloy (2605SA1)

Material	Si-Fe sheet	Amorphous
Grade	35A300	2605 SA1
Thickness (mm)	0.35	0.025
Mass density (kg/dm^3)	7.60	7.18
Magnetic permeability	≥ 1000	≥ 10000
Saturation induction (T)	≥ 1.64	≤ 1.63
Resistivity ($\Omega \cdot \mathrm{m} \times 10^{-8}$)	52	130
Core losses (W/kg, V10 at 1T,50Hz)	1.11	0.05
Hardness (HV)	187	900

4 Motor Design

4-1 Motor Specifications

Table 2 shows the requirements of motor specifications. The motor is developed for industrial fan or pump applications. The rated power is 11-kW (3000 r/min, 35 Nm), corresponding to two poles of an induction motor. The targeted motor volume is smaller than conventional induction motors using a bracket number of 160M, and the targeted efficiency is higher than 95%. The targeted temperature increase at the coils is lower than 75 K, corresponding to the maximum temperature increase of class B insulation. The insulation class is the same with a conventional induction motor.

In the previous developments, skewed magnets were applied to reduce the cogging torque. Due to the difficulty associated with the manufacturing process and increased cost, non-skewed magnets are preferable. Therefore, the magnet pole-arc to pole-pitch ratio is designed to be 100% in the new motors. A 10-pole, 12-slot structure results in a fractional number of slots per pole structure and is used to reduce the cogging torque. On the other hand, a fractional number of slots per pole structure is well-known to cause an eddy-current rotor loss increase due to MMF harmonic waves [11]-[12]. Therefore, a wound core made from Si-Fe magnetic steel is applied to the rotor to reduce rotor losses. The AMM laminated cores coupled with concentrated windings are applied to the stator. Fig. 3 shows the 3D drawing of the new motor. Table 3 shows the designed motor specification.

Table 2. The target specifications of motor design

Parameter	Target
Capacity	11 kW (3,000 r/min, 35 Nm)
Volume	≦Bracket number 160M
Efficiency	≧95% (IE5)
Temperature increase	≦75 K (Class B insulation)

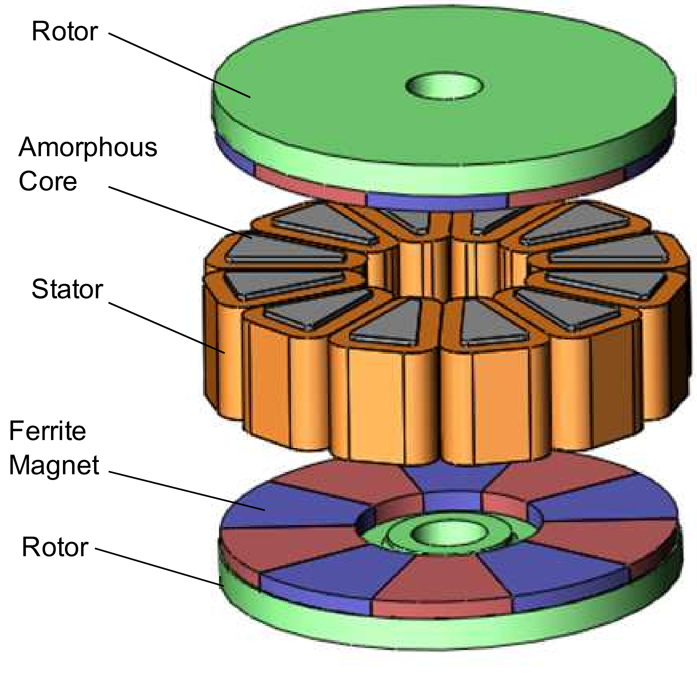


Fig.3 3D model of the axial flux permanent magnet motor.

Table 3. Specifications of designed axial flux permanent magnet motor

Number of Poles	10
Number of Slots	12
Rated Speed	3000 r/min
Rated Output	11kW
Rated Torque	35N・m
Input Voltage	200V
Housing	160M

4-2 Amorphous Stator Core and Iron Loss

The geometry of a core made from amorphous metals is considered one of the most difficult challenges when applying amorphous metals to a motor. Ease of manufacturing and having a structure that produces low iron loss are the major concerns when designing amorphous cores. Basically, the core structures can be divided into two types: the wound core and the laminated core. The wound core always has a lower manufacturing cost than the laminated core since it does not require a lot of cutting or punching. However, due to the difficulty of insulating the amorphous metal, eddy current is produced even when the magnetic flux penetrates the laminated layers. This is the major reason that limits the efficiency of the AFPM motor [5].

In order to reduce the core losses, laminated cores are applied to the motor. Fig.4 shows the manufacture process of amorphous laminated cores. Fig 4a) shows the lamination direction of the core. The amorphous tape is cut into pieces with different widths, and then laminated automatically with the machine. The amorphous core has a trapezoidal cross section, which is shown in Fig 4b).

Amorphous metal's magnetic properties change greatly with the manufacturing process. In order to evaluate core losses properly for electrical motor applications, the cores must be measured under an alternating field with different frequencies. Furthermore, the measurement method must be able to detect the differences between cores with different structures and processing methods.

In this research, an exciting current measuring system is developed for amorphous cores. Fig. 5 shows the configuration of the developed measurement system. This measurement system employs two auxiliary yokes and two test specimen to form a closed magnetic flux path. The H-coil excites an alternating field with the current from AC power. This field travels through the test specimen and search yoke, and then excites voltages in the B-coil. The developed system evaluates the iron loss based on the measurement of the induced voltage of a B-search coil and the exciting current. The power loss in this system can be calculated with Eq. (3)-(5), where is the core mass density; B and H are magnetic flux density and magnetic field intensity respectively; e is the induced voltage of the B-coil with Nb turns, Nh is the number of turns for the H-coil; and l is the length of the magnetic path.

Fig. 6 shows the measurement sample with 6.5% Si steel laminated yokes. The 6.5% Si steel yokes are also annealed to reduce hysteresis loss. Fig. 7 presents the measured core losses of laminated amorphous cores and l non-oriented magnetic steel sheet cores with 400Hz alternating field. The iron loss produced by the non-oriented magnetic steel sheet cores is much higher than that of the amorphous cores. The core loss difference between the two types of cores increases as the flux density increases. According to the measured results, the core loss of the non-oriented magnetic steel core is almost 5 times that of the amorphous cores under a 1T magnetic field. Fig. 8 shows the measured B-H curve of two cores. The amorphous cores are magnetized with lower current than magnetic steel cores due to the high permeability of amorphous metals. This also contributes to the lower iron losses of amorphous metals.

$$P_{Loss} = \frac{1}{\rho T}\int_T \vec{H}(t)\cdot\frac{d\vec{B}(t)}{dt}\,\mathrm{dt} \tag{3}$$

$$B(t) = -\frac{1}{N_b A}\int_0^t e(\tau)d\tau \tag{4}$$

$$H(t) = \frac{N_h}{l}i(t) \tag{5}$$

a) b)

Fig. 4 Amorphous laminated core.

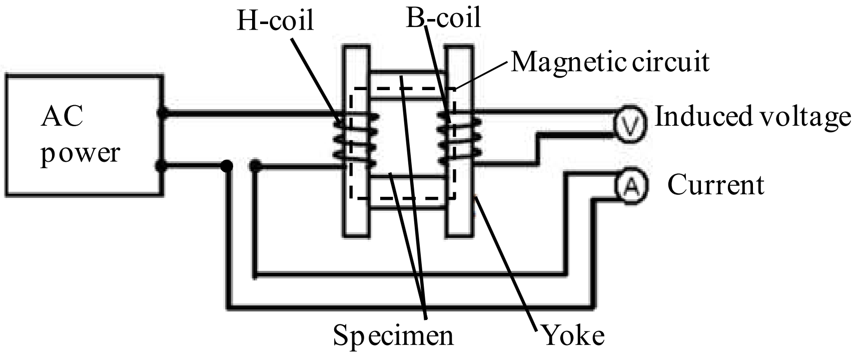


Fig. 5 Amorphous core loss measurement system.

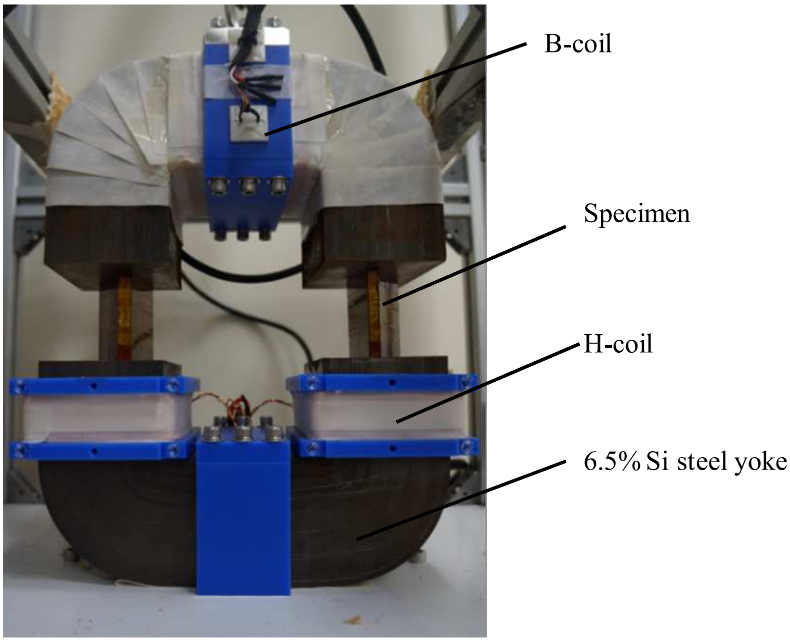


Fig. 6 Core loss measurement sample with 6.5% Si steel yoke.

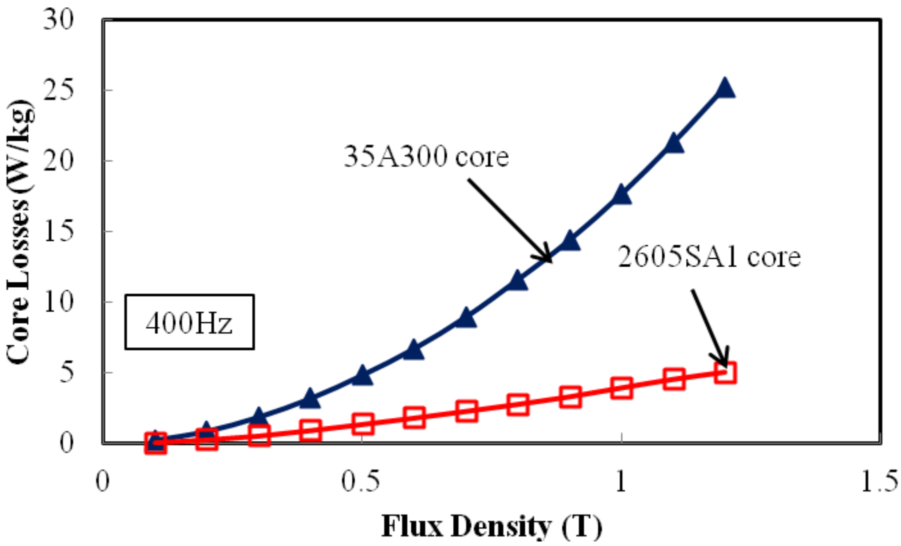


Fig. 7 Measured iron losses of the non-oriented magnetic steel (35A300) laminated core and the amorphous (2605SA1) laminated core in a 400Hz field.

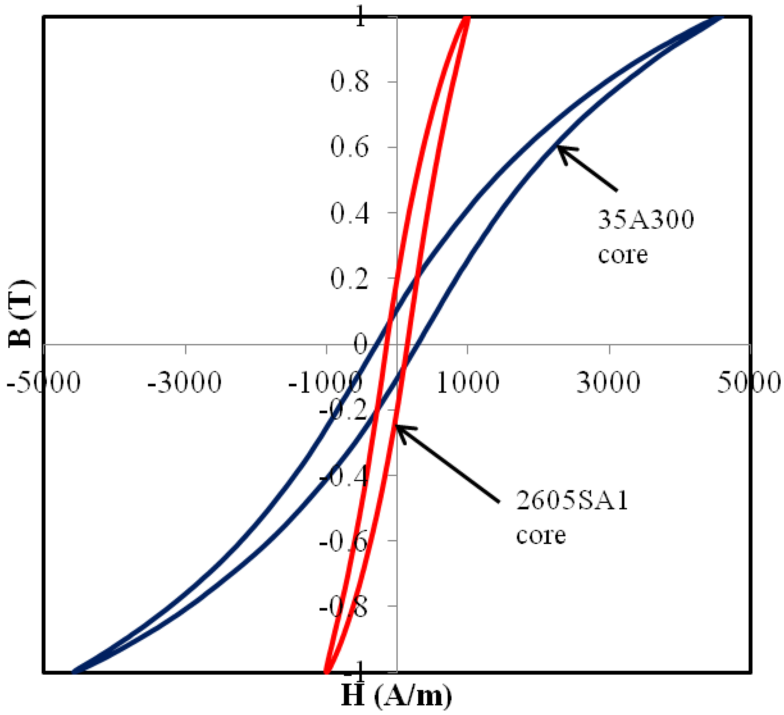


Fig. 8 Measured B-H curves of the non-oriented magnetic steel (35A300) core and amorphous (2605SA1) cores.

5 Trial Motor and Tests

5.1 The Prototype Machine

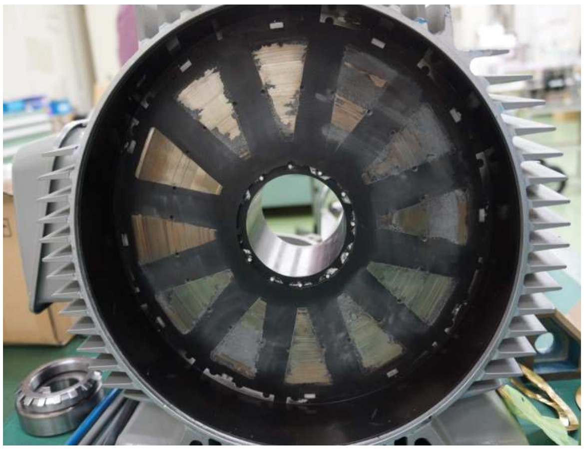
The prototype machines have been built according to the design shown in Table 3. Fig. 9 shows the prototype's components. Fig. 9 (a) shows two rotors with a shaft. Ring-shaped ferrite magnet is fixed on a 0.35mm non-oriented wound magnetic steel core. The ferrite magnets and the wound core are arranged in an iron yoke. Fig. 9(b) shows the amorphous laminated core and concentrated winding. The stator windings made from 2-parallel wound round copper wire to reduce the skin effect. The insulator is placed between the stator core and the coil. The stator teeth and coils are assembled with the housing using a resin mold, which is shown in Fig. 9(c). The two rotors are assembled on two sides of the stator. The assembly of a motor is shown in Fig. 9(d).

5.2 Motor Test

Fig 10 shows the motor test. The prototype motor is coupled with a torque detector. The thermocouple is fixed on the housing during the load tests. The winding's temperature increased 65K after heat-run tests. The magnet's temperature increased about 50K. Fig. 11 shows the measured torque-current relationship after motor's temperature arises is stable. The motor was tested when drives a 120% load and iron saturation did not occur in the prototype motor. Fig. 12 shows the measured motor efficiency. The motor's efficiency is over 96% with 35N･m full load, which meets the design goal

(a) Two rotors with a shaft

(b) Stator cores with coils (2 slots)



(c) Stator mold with the housing

(d) The IE5 prototype

Fig. 9 The prototype of 11kW axial flux permanent magnet motor.

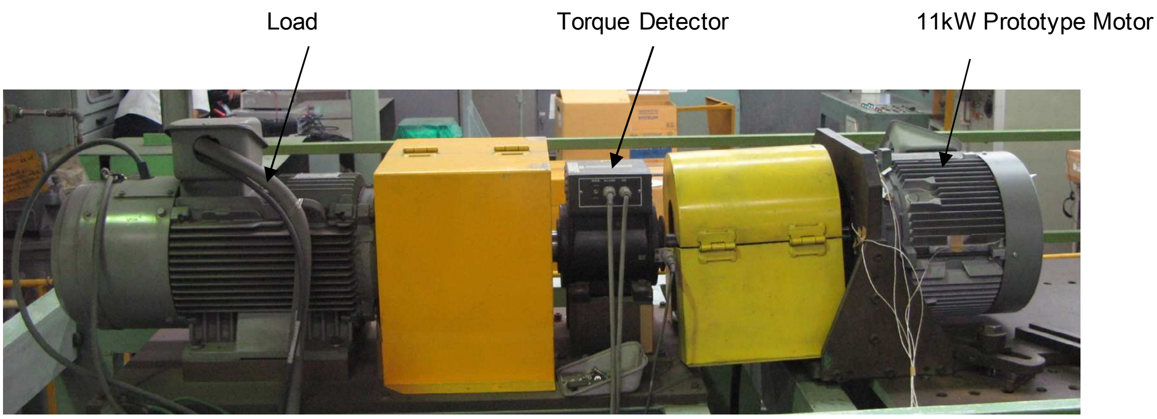


Fig. 10 Motor test.

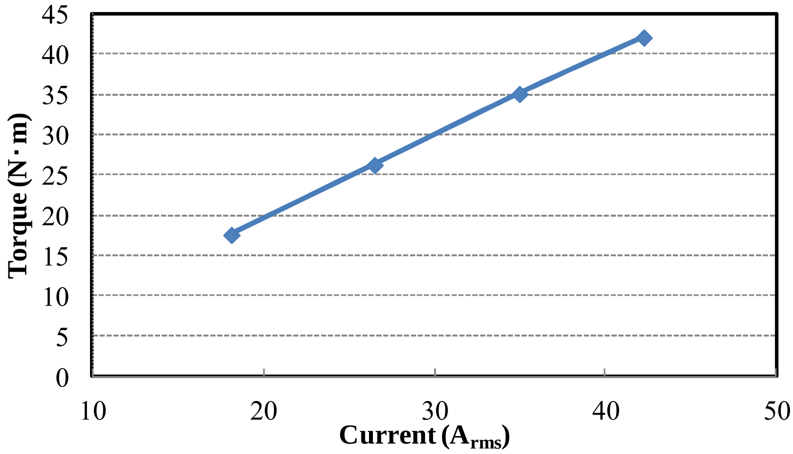


Fig. 11 Measured motor torque with current.

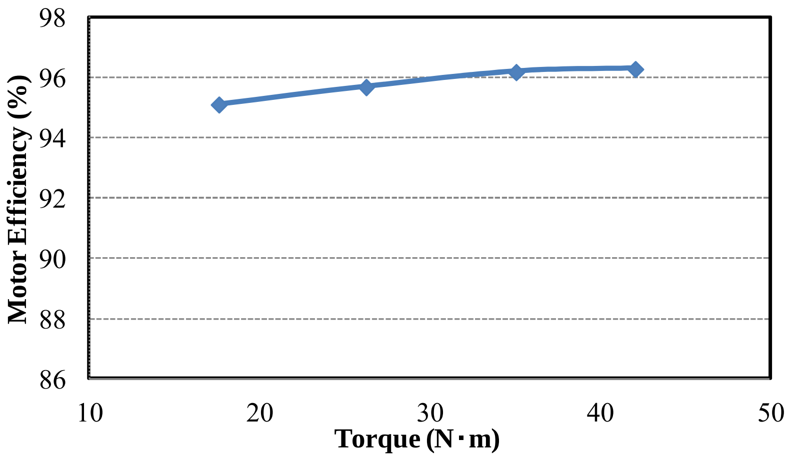


Fig. 12 Measured motor efficiency with torque.

6 Conclusion

An 11kW double-rotor single-stator axial flux permanent magnet motor with ferrite magnets and amorphous cores has been introduced. The concepts of design a high efficiency motor without using rare earth magnets are introduced. Amorphous magnetic alloys are chosen as the low iron loss magnetic material for the stator. With the developed structure and manufacturing, amorphous cores exhibit much lower iron losses than the conventional magnetic material. An 11kW prototype motor has been manufactured. The full load tests are carried out to measure motor's performance. The motor temperature arise is within the design value. The motor provides a 96% efficiency at full load, which demonstrate the design concepts by using axial flux structure and amorphous cores.

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Policy 1

Swiss Competitive Tenders for Promoting Efficient Motor Systems

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Abstract

Following the tragic incident in Fukushima, Japan, in March 2011, the Swiss government decided to adopt a nuclear phase-out strategy. In its new "Energy Strategy 2050", it is proposing to replace nuclear power plants with, inter alia, renewable energies and to reduce consumption by implementing measures to increase efficient electricity use through regulations, promotion and incentive programmes.

This paper outlines the competitive tenders that financially support the implementation of the above measures. The tenders are funded by a surcharge on the Swiss electricity grid. Funding is granted on the basis of an auction process focusing on the cost efficiency of the measures. Only those programmes with the lowest cost efficiency, which is expressed in euro cents per saved kWh, will be supported until the limit of the allocated budget has been reached.

Since 2010, over 70 programmes for the implementation of measures to increase efficient electricity use have been selected, including those relating to motor systems. The total amount of the subsidies up to and including the fifth round (2014) is 76.6 million euros for an accumulated reduction of electricity consumption by 3.0 TWh (which is equivalent to 5 percent of Switzerland's total electricity consumption in 2013), resulting in a cost efficiency of 2.2 euro cents per kWh. This paper presents three practical examples focusing on the promotion of efficient motor systems and it concludes with a brief summary of lessons learned for the promotion of efficient motor systems.

1. Introduction

The Swiss electricity production mix mainly comprises hydropower and nuclear power (58 and 37 percent respectively) [1]. The remaining 5 percent is produced in conventional thermal power plants (gas, oil and non-recyclable waste incineration).

In 2011, the Federal Council and Parliament decided that Switzerland is 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 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 has developed a long-term energy policy ("Energy Strategy 2050") based on the revised energy perspectives [2]. And at the same time, it has produced an initial package of measures aimed at securing the country's energy supply over the long term.

In order to initiate the implementation of "Energy Strategy 2050" without delay, it was decided to launch a first package comprising nine measures. These include increasing the production of electricity from renewable energy (wind, photovoltaics and biomass), expanding the electricity grid and promoting energy research and efficiency.

This initial package of measures contains three instruments for the promotion of energy efficiency: 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 competitive tenders relating to the voluntary measures with subsidies, the main objective of which is to reduce electricity consumption (i.e. promote efficient electricity use).

This paper contains a brief description of energy efficiency and electric motor systems and then addresses the framework conditions of the Swiss competitive bidding procedure. It presents four practical examples in greater detail, and describes the impacts of competitive bidding since it was introduced in 2010. It closes with a brief summary.

2. Energy efficiency

In Directive 2009/125/EC, the European Union defines *energy efficiency* as "the ratio of output of performance, service, goods or energy, to input of energy." It has also formulated other definitions which are of relevance to this paper:

Energy savings	Amount of saved energy determined by measuring and/or estimating consumption before and after implementation of an energy efficiency improvement measure;
Energy efficiency improvement	Increase in energy efficiency as a result of technological, behavioural and/or economic changes.

In other words, energy efficiency refers to the reduction of the consumption of energy through a change in the behaviour of consumers and/or the use of energy efficient systems and processes (in order to reduce demand). Energy efficiency applies to the three main forms, namely fuel oil, combustibles and electricity. As already mentioned, this paper focuses on electricity and its efficient use.

3. Electric motor systems

Electric motor systems account for up to 43 percent of Switzerland's total annual electricity consumption [3]. The average savings potential has been estimated at between 20 and 30 percent [4]. This means that at least one-third of the output from nuclear power plants can be substituted by consistently implementing electricity efficiency improvement measures in electric motor systems. In other words, electric motor systems are one of the major factors for the successful implementation of "Energy Strategy 2050".

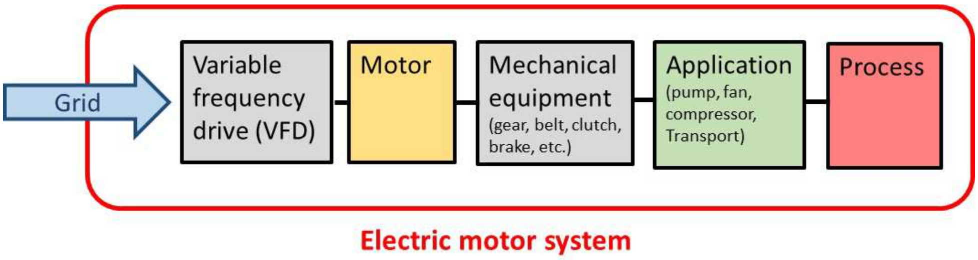

Figure 1: Diagram of an electric motor system [5]

An electric motor system is not just a pump, fan or compressor. It encompasses everything from electricity input through to mechanical output (the process), as depicted in Figure 1.
Significant electrical energy savings can only be achieved by optimising all components of a system (including their interactions). In order to exploit and maximise the savings potential, a set of nine groups of improvement measures has been defined (cf. Table 1).

Table 1: The nine groups of electricity efficiency improvement measures and their typical savings potential in percent [6]

Description of group	Typical electricity savings potential
Recuperation of mechanical process energy by special drives (e.g. centrifuges, elevators)	10-50%
Optimisation of the overall process (e.g. re-dimensioning of a ventilator system and pipes, suppression of leaks in compressors, etc.)	5-50%
Adaptation of the operation of the installation to genuine needs (e.g. switching off the installation at night when not in operation, speed regulation using a VFD)	15-40%
Increase/improvement of efficiency in motor systems (pumps, fans, compressors, etc.)	2-20%
Correct dimensioning of electric motor and drive systems	6-9%
Reduction of mechanical losses in motor systems (e.g. through maintenance)	3-7%

Increase in the efficiency of load carrying elements (e.g. belt, clutch)	3-7%
Improvement of motor efficiency (e.g. higher efficiency class)	1-9%
Optimisation of electricity supply	1-5%

These groups have been used as the basis for projects and programmes in the competitive bidding procedure.

The level of electricity efficiency that can be reached depends on two main factors: the initial state of the system (how efficient was it before any measures were implemented?) and the depth of the analysis and subsequent implementation of the improvement measures. Changing an electric motor to a higher efficiency class only results in a minor improvement (from 1 to a maximum of 9 percent in the best case) compared with process optimisation in combination with re-dimensioning of the system with regulation (savings of up to 90 percent). In other words, the complete motor system has to be analysed in order to maximise the energy savings and minimise the payback time, since up to 97 percent of the life cycle costs of motor systems are attributable to electrical energy.

4. Competitive tenders

4.1 Legal framework

The implementation of energy efficiency improvement measures is strongly influenced by a variety of players (manufacturers, industrial users, electricity supply companies and standards organisations), as well as by national policies. Switzerland's energy efficiency policy is based on three main instruments as defined in the initial package of measures for "Energy Strategy 2050":

1. *Regulation*, by defining mandatory energy performance standards and monitoring compliance with them;

2. *Voluntary measures without financial incentives*, in order to raise awareness;

3. *Voluntary measures with financial incentives*, in order to initiate and accelerate the implementation of energy efficiency measures.

The regulatory measures are specified in the relevant legislation in the form of mandatory energy performance standards. The voluntary measures without financial incentives are implemented in the federal government's "SwissEnergy" programme, the main objective of which is to raise awareness through information, consultancy, education and training.

Competitive tenders, which are also part of a federal government programme focusing on efficient electricity use (i.e. the reduction of electricity consumption) form an integral part of the voluntary measures with financial incentives. The framework conditions for competitive tenders are defined in Article 7a, sections 3 and 4d of the Federal Energy Act:

The Federal Council may regulate competitive tenders for efficiency measures, in particular for the efficient use of electricity in buildings and companies;

Competitive tenders are financed through five percent of the surcharge on transmission costs on the high voltage grid.

Article 4 of the Federal Energy Ordinance regulates the implementation of competitive tenders:

Each year, the Swiss Federal Office of Energy shall call for competitive tenders for temporary efficiency measures relating to electricity consumption;

The objective of the efficiency measures must be to reduce electricity consumption, especially in buildings, vehicles, equipment and in industrial and services companies, as well as to accelerate the market penetration of new technologies, with the best possible cost-benefit ratio;

Applications for projects and programmes may be submitted by private or public sector entities;
Only projects or programmes that could not be realised without the financial incentives may be considered.

4.2 Projects

Projects have to incorporate measures that induce electricity savings in equipment, installations, vehicles and buildings that are in the possession of the project owner(s), and must also be linked with investments.

Projects also have to meet the following requirements that are defined in the conditions governing the submission of projects [7]:

- Projects must be realised in Switzerland;
- Projects must ensure additionality;
- Projects must not be bound by any legal obligation to implement the measures;
- Participation in other incentive programmes (in the public or private sector) is prohibited;
- Measures should not induce the substitution of electrical energy with any other form of energy that is not renewable;
- The maximum duration of projects is 3 years;
- Funding should amount to at least 20,000 euros, and a maximum of 1,000,000 euros;
- Funding should cover between 20 and 40 percent of the creditable costs, depending on the payback time (cf. Figure 2);
- The cost efficiency of the funding should not exceed 15 euro cents per kWh;
- Multiple submission of a specific project in the same year is prohibited.

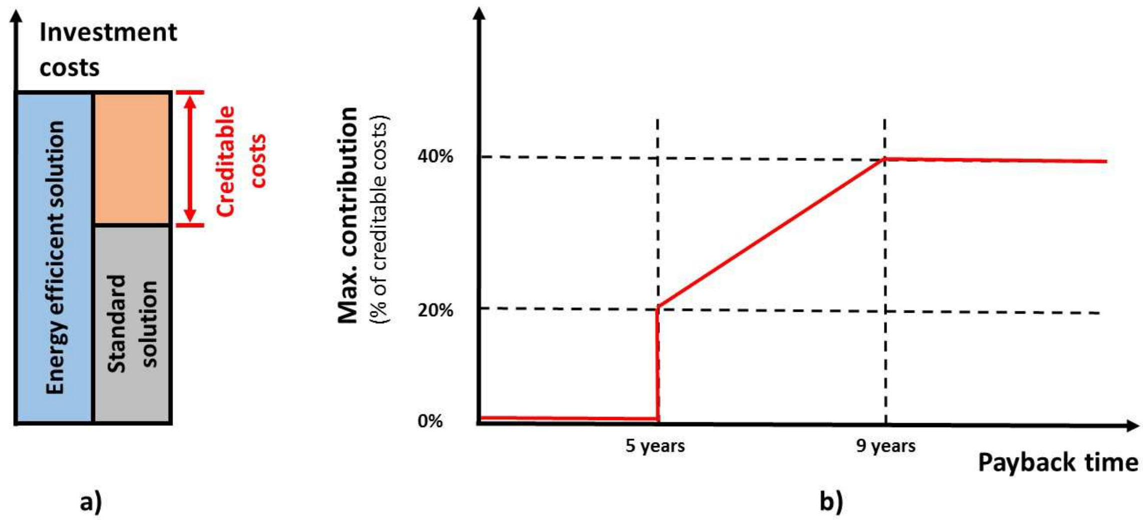

Figure 2: Financial framework conditions for projects: a) Creditable costs for renewal of existing installation or investment in a new one, and b) maximum financial contribution (towards the creditable costs) as a function of the payback time.

For projects, the principle of additionality is based on the payback time, which must be at least 5 or 9 years for measures with a recordable time of up to or over 15 years respectively.

The selection of projects to be granted financial support is effected via an auction procedure in which all the accepted applications are included. Those projects with the best cost efficiency will be granted support until the budget for projects has been exhausted. The cost efficiency is calculated as follows:

Cost efficiency = received subsidies / (annual electricity savings x duration of the efficiency measures)

4.3 Programmes

In the same way as projects, programmes have to include measures aimed at reducing the electricity consumption of equipment, production facilities, vehicles and buildings that programme managers are implementing for third parties. In general, programmes should target a large number of people with a single measure (e.g. the replacement of electric water heaters with heat pump water heaters in households) or propose a series of improvement measures adapted to a specific sector or company (e.g. optimisation of electric drives).

Programmes may be submitted and implemented by private or public sector entities. These may be companies, private individuals, government bodies or interest groups.

Like projects, programmes also have to meet certain requirements, most of which are identical to those for projects. However, the following requirements are specific to programmes [7]:

- Funding must be at least 150,000 euros (up to a maximum of 1,000,000 euros);
- Product placement is prohibited;
- The payback time of the measures should be at least 2 years (compared with 5 years for projects).

The duration of programmes is limited to three years. However, under certain circumstances and for valid reasons (e.g. lengthy decision time for investments), the duration may be extended by at least one year following an evaluation of the case in question.

Table 2: Financing framework for programmes

<table>
<tr><th colspan="2">Financial contribution</th><th>Description</th><th>Type of costs</th></tr>
<tr><td rowspan="3">Max. 40% of the financial contribution</td><td>Max. 15% of the financial contribution</td><td>General administration, administration per dossier, programme concept</td><td>Programme management</td></tr>
<tr><td rowspan="2"></td><td>Communication, education, consulting, tools (e.g. software)</td><td rowspan="2">Accompanying measures</td></tr>
<tr><td>Monitoring</td></tr>
<tr><td rowspan="3">Max. 60% of the financial contribution</td><td>Max. 100% of costs of the preliminary analysis</td><td>Preliminary analysis (to indicate the potential)</td><td rowspan="3">Financial contribution to end users</td></tr>
<tr><td>Max. 50% of the detailed analysis</td><td>Detailed analysis (specific measures with cost efficiency rate)</td></tr>
<tr><td>Max. 20 to 40% of the realisation costs</td><td>Realisation</td></tr>
</table>

In the same way as projects, programmes are also subject to an auction procedure until the budget for programmes has been exhausted. However, the criteria for their assessment relate not only to cost efficiency (although this accounts for 70 percent of the assessment), but also to the probability of realisation based on a risk assessment regarding the financing of the programme, the feasibility of electricity savings and uncertainties relating to the organisation, the acquisition of participants, the available human resources, the management of the programme and the implementation of the improvement measures.

The financial framework for programmes is more complex than that for projects (cf. Table 2). Funding is divided into two parts. The first part, which represents a maximum of 40 percent of the financial contribution, covers the costs relating to the management of the programme and the accompanying measures (communication, training, tools, etc.). The second part, which represents at least 60 percent of the funding, goes directly to the end user for: a) *the preliminary analysis* in order to demonstrate and estimate the electricity savings potential (financial contribution up to 100 percent of the costs), b) *the detailed analysis* in order to identify specific improvement measures together with their cost efficiency (financial contribution up to 50 percent of the costs, paid only if the measures are realised), and c) *implementation* of the improvement measures (financial contribution up to 40 percent of the costs).

As already mentioned, in the same way as for projects the financial contribution for the realisation of the measures depends on the payback time. Here, a major difference versus projects is that programmes can financially support improvement measures that have a payback time of 2 years (compared with 5 years for projects), and the maximum rate of the financial contribution (40 percent) is already reached at a payback time of 6 years and more (compared with 9 years for projects).

4.4 Evidence of electricity savings

For both projects and programmes, evidence of electricity savings has to be provided once the efficiency measures have been implemented. The causal link between a project or a programme and the evolution of electricity consumption has to be demonstrated. In principle, the realised electricity savings should be demonstrated through monitoring. If this is not possible (e.g. for financial reasons or due to the seasonal fluctuation of the results), the reduction in electricity consumption is estimated on the basis of calculations using a proven and recognised method. The calculation of electricity savings also has to be based on conservative assumptions.

5. Practical examples

The following three examples, which cover some of the major applications (electric motors, compressors and pumps) in the field of motor systems, have been selected in order to illustrate how the competitive tenders procedure works:

- Efficient electric drives programme
- Efficient compressed-air systems programme
- Energy check programme for water supply installations

Each of these three programmes is briefly described below in terms of their objectives, structure, cost efficiency and improvement measures, as well as the reduction in electricity consumption that they have induced (or at least committed to).

5.1 Efficient electric drives programme [8]

This programme ("Effizienz für Antriebsysteme" or EASY for short) promotes the implementation of more efficient electric drives in industry, infrastructure facilities and building technology systems. The replacement of old and inefficient drive systems is often considered, but various obstacles exist that prevent or at least slow down their replacement, including the complex and expensive preliminary analyses, without which the changeover to more efficient systems cannot take place. For this reason, the main objective of the EASY programme was to accelerate the replacement of inefficient systems through financial contributions, particularly for supporting preliminary analyses, as well as detailed analyses in industrial companies with an annual electricity consumption of at least 10 GWh. This programme was managed by a private organisation in cooperation with other partners, including major traders, planners (engineering companies), energy producers, a mechanical engineering association, etc. The programme's approach was based on a methodology called "motor check", which comprises the following four steps:

1. A *preliminary analysis* based on a software tool which estimates the savings potential with the aid of the key data of the company, plus the potential rate of replacement of old electric motors by more efficient models;

2. An *"intelligent motors list"*, in order to refine the findings of the preliminary analysis. Here, all the company's motors are listed and sorted by age, nominal power, hours of operation and application (pump, ventilation, compressor, etc.). This list indicates which motors need to be examined more closely in a detailed analysis (e.g. older motors with high nominal power and long hours of operation);

3. A *detailed analysis* based on the results of the list. The motor systems that are shown in red in the list need be examined more closely through measurements on site in order to evaluate their efficiency;

4. *Implementation* of the improvement measures for at least 25 percent of the electricity savings potential.

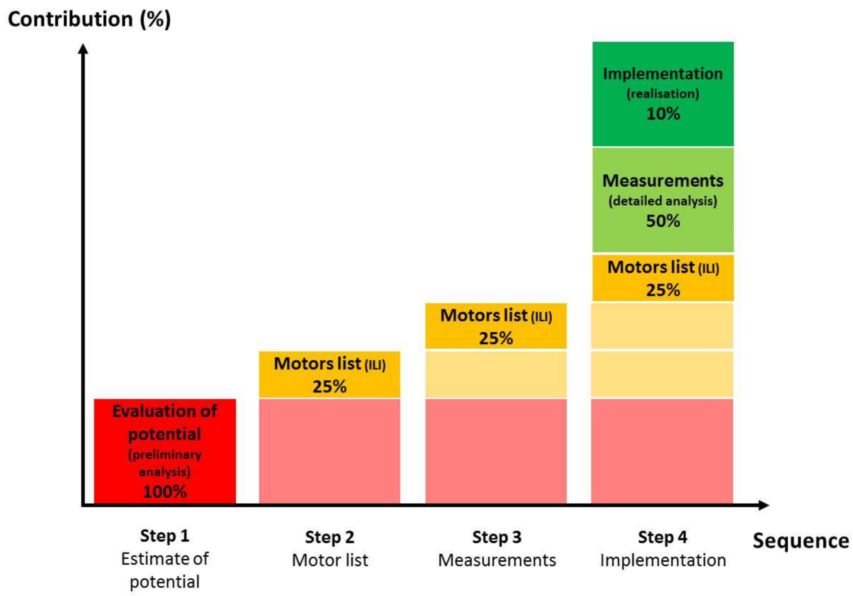

Figure 4: Funding model for EASY (efficient electric drives programme)

The EASY programme committed to savings of 6.3 GWh per annum over a period of 11 years (average life cycle of the improvement measures). It was granted funding amounting to 1.0 million euros, which means that its cost efficiency is 1.45 euro cents per kWh saved over the 11-year period (= 1.0 million euros / (6.3 GWh p.a. * 11 years) * 100). The contribution covered the programme management (12.5 percent) and communication (2.5 percent) costs, while the remainder (85 percent) was used for partially or fully covering the costs of the analyses and subsequent implementation of the measures (cf. Figure 4).

Fifteen companies participated in this programme, and more than 4,000 electric motor systems were analysed. The programme was launched in November 2010 and concluded in December 2014. It exceeded its target of 7 percent. Although it was successful, it only addressed around 6 percent of companies with an annual consumption of ≥ 10 GWh [9]. In view of the success of the EASY programme and the identified remaining potential, a follow-up programme called SPEED (Smart Procedure for Efficient Electric Drives) was launched in August 2014 and is currently ongoing.

5.2 Efficient compressed-air systems programme [10]

The aim of this programme (Programm Energieeffiziente Druckluftanlagen, or ProEDA for short) is to promote the efficiency of compressed-air installations. Compressed air is a transversal technology, which means that little attention is paid to it by the companies that use it, and very little is undertaken to improve its efficiency, as long as it still functions. The objective of the programme is to attract the attention of compressed-air users through financial contributions, and to concentrate on installations with an output greater than 18 kW in order to make the savings count. The programme was managed by an energy consultancy company together with compressed-air installation manufacturers as technology partners, and with a private sector organisation representing the Swiss industry as communication partner. Like the EASY programme, it defined three steps:

1. A *preliminary analysis* involving a visit to the company (approximately 2 hours) resulting in an estimate of the potential electricity savings and the formulation of recommendations.

2. A *detailed analysis* in the form of an evaluation of the consumption and annual costs based on measurements carried out during one to two weeks. The outcome is an investment proposal with a calculation of electricity savings.

3. *Implementation* of the measures defined in the detailed analysis, involving new investments the company needs to make.

The ProEDA programme committed to savings of 3.7 GWh per annum over a period of 10 years (average life cycle of the improvement measures). In order to achieve its target, it was granted a financial contribution of 0.8 million euros, which means that its cost efficiency is 2.1 euro cents per kWh (= 0.8 million euros / (3.7 GWh p.a. x 10 years) x 100). The fixed costs (programme management and communication) accounted for 10 percent of the funding, while the remainder (0.72

million euros) was used to fund the analyses and as a financial contribution towards the required investments:

- 50 percent of the costs of the preliminary analysis;
- 25 percent of the detailed analysis (including measurements and analysis of the compressed-air consumption);
- Max. 20 percent of the investment costs.

Table 3: Overview of the electricity savings potential for compressed air in Switzerland [11]

Description	**Savings potential (GWh p.a.)**
Need for reduction for compressed air (process optimisation)	93
Leakage reduction outside production time	31
Leakage reduction during production time	47
Optimisation of compressed air production	75
TOTAL	**245**
ProEDA electricity savings	5.6
Total savings potential induced by ProEDA	**2.3%**

The ProEDA programme was launched in July 2011 and concluded in June 2014. It was very successful in that it exceeded its target by more than 50 percent. However, it addressed less than 3 percent of the total savings potential (cf. Table 3). In view of the success of the first programme and the identified remaining potential, a second ProEDA programme was launched in July 2014 and is currently ongoing.

5.3 Energy check programme for water supply installations [12]

Infrastructure facilities, including cleaning and sewage, waste disposal, water supply installations, etc. account for an annual electricity consumption of up to 1.3 TWh (which is equivalent to around 2 percent of Switzerland's total consumption), of which 30 percent is attributable to water supply facilities.

Although the electricity savings potential is high, water supply companies have barely addressed this problem (mainly due to a lack of awareness), because their main focus was on securing water quality and the operation of their facilities. The objective of this programme was to make water supply companies aware of their savings potential and, with the aid of an instrument called "energy check", to encourage them to implement efficiency measures. The programme was managed by a private sector umbrella association incorporating Swiss water supply companies. Like the other programmes, it defined three steps: preliminary analysis (estimation of the potential energy and cost savings), detailed analysis and implementation of the measures identified in the detailed analysis.

This programme committed to savings of 5.2 GWh per annum over a 20-year period. It was granted funding of 1.0 million euros, which means that its cost efficiency is 0.96 euro cents per kWh (= 1.0 million euros / (5.2 GWh p.a. x 20 years) x 100). Its fixed costs were fully covered by the programme management as a personal contribution, so that the full amount of the funding was allocated as follows:

- 100 percent of the cost of the preliminary analysis;
- Up to 60 percent of the cost of the detailed analysis (only if the efficiency measures are implemented).

No financial contribution was allocated for investment, because all the measures are highly cost-effective with a short payback time.

The programme was launched in March 2011 and was scheduled to be concluded in February 2014. However, due to the lengthy implementation time of the efficiency measures and the time required for taking the investment decisions, the programme has not yet achieved its savings target and has been prolonged for at least a year. Like the other programmes, it will also address only a small proportion of the overall savings potential (less than 7 percent) [13].

6. Impacts of competitive tenders

Since its introduction in 2010, the competitive bidding procedure has induced accumulated electricity savings (over the average life cycle of the respective measures) equivalent to 5 percent of Switzerland's annual electricity consumption, with funding totalling 79.6 million euros, resulting in a cost efficiency of 2.6 euro cents per kWh. Table 5 shows the evolution of accumulated electricity savings for projects and programmes over a five-year period. The programmes have accounted for three-quarters of the savings.

For 2015, three main improvements have been introduced in order to strengthen the effectiveness of the competitive bidding procedure by increasing the number of projects and programmes:

- Two subscription rounds for projects (one in winter and one in summer) instead of only one per annum (in winter);
- Introduction of a web-based tool for the subscription of projects (simplification of the subscription procedure, especially for small and medium-sized companies, in order to increase the rate of subscription for projects);
- Introduction of sector specific programmes that have a higher budget, broader scope and a stronger impact.

Furthermore, the budget for 2015 (42 million euros) has been almost doubled versus 2014 (22 million).
Although the competitive bidding procedure has had a positive impact by promoting and encouraging (through financial incentives) the implementation of measures aimed at increasing efficient electricity use, the projects and programmes nonetheless only address a small proportion of the overall potential (well below 10 percent). In other words, competitive tenders are more of a promotion tool than an extensive implementation instrument.

Table 5: Evolution of the accumulated electricity savings through projects and programmes since the introduction of competitive tenders in 2010 [14]

Competitive tenders	**Projects**			**Programmes**			**TOTAL savings***
	Number	GWh	Euro cents per kWh (average)	Number	GWh	Euro cents per kWh (average)	
1st round (2010)	18	113	2.3	8	457	1.5	570 GWh
2nd round (2011)	32	99	4.5	13	548	1.7	647 GWh
3rd round (2012)	67	242	3.2	9	276	2.4	518 GWh
4th round (2013)	35	167	4.1	23	421	2.9	588 GWh
5th round (2014)	61	191	3.7	21	509	3.2	700 GWh
TOTAL							**3,023 GWh**
Switzerland's annual electricity consumption in 2013							**59,323 GWh**
Proportion of Swiss consumption							**5.1%**

* Accumulated potential savings over the creditable duration of the projects and programmes.

7. Sector specific programmes

As mentioned in the previous section, sector-specific programmes have been introduced for the 6th round (2015). The aim here is to broaden the scope of programmes to encompass a whole sector. One of the programmes that will be launched concerns the replacement of circulating pumps in the industry and services sectors. It will be subject to technical as well as implementation requirements. The main differences versus standard programmes are as follows:

- Budget up to 5.0 million euros (instead of 1.0 million), 85 percent (instead of 60 percent) of which has to be used as a financial contribution to end-users;
- In the reference development (additionality) for determining the potential savings, the natural replacement cycle has to be taken into account (-2.5% per annum);
- The financial contribution has to cover at least 15 percent of the creditable costs (pump and installation costs);
- National coverage;
- Only highly qualified personnel are authorised to replace circulation pumps;

- As an additional quality assurance measure, the Swiss Federal Office of Energy will conduct on-site spot checks in order to assess the quality of the installation and the energy savings.

Sector-specific programmes will also be subjected to an auction procedure, together with all the other submitted programmes, in order to preserve the competition aspect. Furthermore, sector-specific programmes also have to ensure that they are additional. Consequently, free riders will not be granted a subsidy. These programmes also have to meet the required minimum energy performance standards and fully support the investment costs.

8. Summary

Terms such as energy efficiency, energy savings and energy efficiency improvement are defined in EU Directive 2009/125/EC. Energy efficiency concerns the three main energy sources: fuel, combustibles and electricity, whereas of course efficient electricity use only concerns the reduction of electricity consumption.

An electric motor system is more than just a motor. It comprises several components, ranging from electricity input through to the end process, each of which has an influence on the efficiency of the entire system, both individually and through their interactions. A high level of efficiency improvement can only be achieved by combining measures over several components of the system. As energy costs account for more than 95 percent of the life cycle costs of a motor system, energy savings have a strong impact in terms of reducing the payback time of measures to increase efficiency.

Switzerland’s energy efficiency policy is based on a set of three instruments: regulation, voluntary measures with financial incentives and voluntary measures without financial incentives. Competitive tenders correspond to voluntary measures with financial incentives in order to initiate and accelerate the implementation of measures aimed at reducing electricity consumption. The framework conditions governing competitive tenders are specified in the relevant legislation. The detailed conditions for the submission of a project or programme are defined separately. The financial support (between 20 and 40 percent of the creditable investment costs) for the implementation of improvement measures depends on their payback time (at least 5 years for projects, but only 2 years for programmes). The selection of projects and programmes takes place via an auction procedure, in which only those with the best cost efficiency (and the lowest realisation risks for programmes based on a grading system from very low up to very high risk with a 30% weighting over the cost efficiency) are selected.

Competitive tender programmes are mostly based on the same structure as projects, namely three steps: 1) a preliminary analysis to identify the energy savings potential, 2) a detailed analysis, which may also include some measurements on site, in order to fine tune the quantification of the savings potential estimated in the preliminary analysis and to establish a list of detailed improvement measures, including their cost efficiency, and 3) the implementation of the measures. The financial contribution may cover up to 100 percent (preliminary analysis) and 50 percent (detailed analysis) of the costs. Coverage of the costs for the implementation of the measures varies between 20 percent (payback time at least 2 years) and 40 percent (payback time at least 6 years).

Since 2010, the competitive bidding procedure has induced accumulated savings equivalent to 5 percent of Switzerland’s annual electricity consumption, with a cost efficiency of 2.6 euro cents per kWh. The programmes have realised 75 percent of these savings. For the 6th round in 2015, some changes have been introduced (2 rounds for projects, web-based tool for project applications, sector-specific programmes), and the budget has been increased. In spite of their success, the projects and programmes only address a small proportion of the overall potential.

Sector-specific programmes are similar to the other programmes, though they have a broader scope with a focus on an entire sector, a higher budget (up to 5 million euros), national coverage and an enhancement of quality assurance. They are subjected to an auction procedure in the same way as all the other programmes.

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A system approach to improving energy efficiency in industrial electrical motor systems – experience from Sweden using the MOVE-model

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Keywords: energy efficiency, methods, behavior, improvements, electrical motor, motor system efficiency

Abstract

Improved energy efficiency in industry constitutes one of the important means of hindering global warming together with decarbonizing electricity generation and behavioral changes to reduce energy demand. Improved energy efficiency is also one of the means for achieving energy sustainability; locally, regionally, and globally. 65-70 percent of the industrial electricity use emanates from motor systems. Industrial motor systems have a large potential to be improved in terms of its energy use and this has traditionally been done by focusing on improved motor efficiency. Standards for more efficient motor systems are pushing manufacturers towards further improvements on a single electric motor level. However, it has been shown that the major efficiency potential is found on the higher system levels – in the system the motor serves, such as ventilation or hydraulic system. This insight calls for new approaches in improving industrial motor systems, with a wider system boundary. This paper presents the results of development and industrial testing of an innovative analytical methodology for identifying and addressing energy efficiency improvement opportunities to existing and new industrial electric motor systems. The methodology is developed within the project MOVE (Method for optimizing system efficiency in electric motor systems). By applying this methodology, information acquired and knowledge gained by industrial personnel working with energy issues, maintenance, and production processes can be immediately used for improvement suggestions. These suggestions include localizing improved system designs as well as optimizing the current ones. The paper describes the analytical system methodology and findings from an industrial case study.

1. Introduction

Improved energy efficiency in industry constitutes one of the most important means of hindering global warming together with, for example, decarbonizing electricity generation and behavioral changes to reduce energy demand [1]. Improved industrial energy efficiency is also one of the pivotal means for achieving energy sustainability; locally as well as regionally and globally. Electric motors account for about 65-70% of the total electricity consumption globally and thus present a very important sector where a significant potential to energy efficiency improvements can be found. Waide and Brunner [2] categorized the EMDS in three levels:

1. Electric motor
2. Core motor system
3. Total motor system

According to Waide & Brunner [2], it has been estimated that the major potential to energy efficiency is found on higher levels of motor systems (Total motor systems) – in the systems that electric motors serve, such as the core production process, ventilation system or the hydraulic system. However, the work on improving energy efficiency in EMDS has traditionally been done by focusing on improved efficiency of an electric motor, investing in new more energy-efficient motors or upgrading existing ones. Stricter regulations for more efficient motor systems have also been pushing manufacturers towards further improvements on a single electric motor level.

In addition to that, Backlund et al. [3] have shown that the extended energy efficiency potential is spread beyond technical systems and can be reached by applying energy management practices in companies. Empirically, this extended potential (practices to operate the motors and behavioral actions) has been shown to be considerable [4]. However, the extended energy efficiency potential is not taken into consideration by Waide & Brunner's categorization. Neither does the categorization cover the aspect of the industrial processes in which an electrical motor adds value to a common costumer.

In the 90´s, the Department of Energy in the US (DOE) developed several tools which have been used to analyze EMDS in order to assess the potential to energy efficiency in the motor systems as well as to suggest measures on improving energy efficiency [5]. The examples of these tools are Energy Performance Indicator Tool, Fan System Assessment Tool, MotorMaster+, Pumping System Assessment Tool, etc. These kinds of tools focus mainly on a technical assessment aspect. Research shows that the measures proposed by technical assessments are realized only by 50 percent [6]. In support, DOE stays the potential to energy efficiency in EMDS to be high only in combination of technological solutions, training, and energy management practices. DOE offers various workshops aiming to educate industrial personnel in motor operation practices, management practices of motor systems, guidelines on selection of optimal motor size, inventory of motor equipment, etc.

The Swiss experience of work with EMDS expressed implicitly in the results of the Audit Program Easy run between 2010 and 2014 [7]. In the scope of this audit program, a method was developed to identify where in electrical motor systems the highest energy efficiency potentials are found. For that the motor inventories of different industrial facilities were performed followed by the testing and implementation phases of the proposed improvement measures. The program was subsidized by the Swiss Energy Agency. The insight and experience from Switzerland show good consistency with Waide and Brunner´s estimations of the energy-efficiency potentials in EMDS' three system levels. It was shown that the replacement of an electric motor would result only in small energy savings. Moreover, the results show that a lot of motors exceed the average life expectancy, and are often over-dimensioned running at 50-60% of the installed capacity.

Overall, the recent international experiences have shown that a known way for improving energy efficiency by investing in new energy-efficient technologies or to upgrade existing equipment is not enough to achieve significant energy savings. Energy efficiency measures should include not only technical solutions at the component level but also the combined actions embracing the entire motor systems. Conducting management practices in combination with tools and technology is accepted to be crucial in order to achieve higher system efficiency potential. However, an approach that would improve overall efficiency in EMDS taking into account the extended energy-efficiency potential is lacking. Thus, the methods are needed that would expand and push the abovementioned actions one step further and help not only define energy efficiency improvement opportunities on higher system levels but also help to assure their implementation. These insights call for development of new approaches for improving industrial EMDS with a wider system boundary, i.e. an analytical system approach which includes a system perspective and covers the extended energy efficiency potentials. Such kind of methods should take into account energy management practices e.g. adapting of more energy efficient routines and energy conservation activities.

The aim of this paper is to present a novel method for optimizing system efficiency in electric motor systems. The method is developed within the project MOVE (Method for optimizing system efficiency in electric motor systems).

2. Improving energy efficiency in EMDS

In order to improve EMDS' energy efficiency on higher system levels, the industry is in need of more explicit knowledge about the actual demand for electric motors as well as the knowledge of electric motors operating as an integral part of the industrial processes. A system approach in the industrial applications thus should be applied in order to show the interaction of EMDS beyond Waide and

Brunner's third level (Total motor system). This would also help to show how EMDS add value to a product in an industrial process [8].

2.1. Value added by EMDS

Cronemyr and Danielsson [9] describe a single "process" as a network of repeatable activities which create value for a "costumer". The definition of a costumer can be different, depending on the system boundaries. In all kind of processes there is always a costumer because otherwise there is no necessity to deliver and add value to different products, functions or services. In theory, the costumer can be external (end-user) and internal (an intermediary) [10]. Internal costumers are located inside the organization and can be represented by staff, operators, products or technical systems. Depending on where a process delivers its function, there can be several internal costumers within the processes [10]. These internal customers are affected by the products or processes. From this perspective, an EMDS can be seen as a value-supplier to the manufacturing process' internal costumers. One example is a washing process of a driveshaft where the driveshaft represents such an internal customer. In this example, the value is created through the pumping process. By means of pumping, the industrial process gets mechanical power from an electric motor to transport a certain amount of washing fluids to clean the driveshaft from oil and other impurities. In order words, any electric motor delivers a function to a system and a process which contributes to adding value to a costumer. Visualization of an electric motor as an integral part of industrial systems helps to understand how it adds a value to an internal customer which is not possible without applying a system approach.

2.2. Long-term systematic energy efficiency work

Energy efficiency actions can be represented by two types of energy-related behavior [11]:

1. Efficiency behavior (when one makes a single action, for example, buying an energy-efficient motor)

2. Curtailment behavior (when one performs repetitive actions on improving energy efficiency)

In order to obtain positive results it is not enough to do discrete actions, both types of energy actions are necessary [11]. However, many businesses are in need of external support to perform long-lasting energy-efficient work because of different barriers to energy efficiency [4], [12], [13], [14], [15], [16], [17[, [18], [19], [20]. This can also be aggravated by insufficient abilities or knowledge to streamline their own industrial processes [21]. Also, the lack of clear structure and discipline when performing energy efficiency activities makes it difficult to apply long-term perspective in energy management practices.

Deming [22] introduced empirical studies of the crucial role of leaderships in process management and continuous improvement in order to achieve an organization with qualified knowledge of successful improvement. This research has been confirmed over the years [23]. The main area addressed there is Total Quality Management (TQM) but can also be applied to other areas [24]. The central idea in Deming's work is that an organization should achieve a state when it obtains qualified knowledge for successful improvement work, so-called "profound knowledge". This is also supported by Senge [25] who addresses the aspect of "profound knowledge" in so-called "learning organizations". In order to become a learning organization there is a need to develop system thinking inside the organization. System thinking thus is the fifth discipline connecting the other four disciplines such as [25]:

1. Mental models – for creation of particular mental models, knowledge is needed to be able to interpret while extending framework interpretation of reality is very important.

2. Personal mastery – personal growth and learning are incredibly important to achieve learning on organizational level.

3. Learning in group – knowledge should become mutual in order to improve processes.

4. Shared vision – affection and willingness to work together help to achieve mutual visions of a group which stimulates new ways of thinking and acting.

What Deming and Senge have in common is system thinking being a core element in their models. Applying system thinking to a long-term energy efficiency work provides in-depth knowledge of industrial processes, systems and its potential and contributes to see the whole picture and create knowledge about the organization [26], [25].

Further contribution of system thinking is an ability to visualize how actions at different system levels can be prioritized for obtaining the maximum energy efficiency potential and how they should be selected according to the "right" and "best" action criteria. This can be done by studying the system's overall efficiency which is, as Ahlmann [27] argues, the combination of external and internal efficiency. Understanding of energy use and (or sometimes subjective) description of the process' requirements is done in "External efficiency". External efficiency describes a creation value for a customer and answer the question "Why is energy used?". Descriptions and facts documented in the external efficiency are the entry requirements to the technical systems which are built in the next stage called "Internal efficiency". Internal efficiency describes the best technology and methodology to meet the requirements and answer the question "How is energy used?". Combining external and internal efficiency makes the vision of high overall efficiency possible (Ahlmann, 2002). The efficiency potential will be lower if the technical systems are optimized separately from, or perhaps even without knowing, customer's requirements [27].

It is important, however, to have a costumer in the center. The costumers' requirements are the fundamental reason why energy is supplied to a particular process. The requirements are different depending on which process or the system boundaries are chosen and are directly affecting the energy demand of the process. However, the energy demand is often not seen as an important part in the core industrial process [28]. To understand the costumer's requirements affecting the energy usage, and thereby the EMDS efficiency, management practices must be exercised. Combined with the methods that take into account the entire system efficiency, management practices can enable prioritizing the benefits that each used kWh provides.

3. Method

The original idea is to develop a method to identify possible savings in EMDS on the basis of theoretical research to further validate it by means of practical case studies. This is to be accomplished through testing, continuous development and adaptation of knowledge from methodologies dealing with flow efficiency, technical solutions, and the role of successful management and leadership in the improvement process. The method is intended to be applied by Swedish manufacturing industries and should have a user friendly configuration and a logic flow.

3.1. Categorization of existing energy-efficient measures

The starting point was the categorization of earlier suggested electric motor system measures in order to investigate on which system levels the highest improvement potential is found. The measures are extracted from the energy-efficient measures database for the Program for energy efficiency in energy-intensive industries (PFE) in the amount of over 1250 measures resulting in savings of around 900 GWh/year. The basis for the categorization of motor measures was the three levels of EMDS described by Waide and Brunner [2]. Within this project, an additional category, called Level 4 (Extended motor systems) was introduced in order to also include the operational measures and measures related to energy management. These actions are found outside the overall motor systems in the sense that they do not directly lead to changes in the technical system, but consists of changes in procedures or methods of operation. Level 4, thus, includes the measures that affect how the operators interact with motor systems. The most obvious action is when it clearly implies that a man should do something, such as "introducing a new procedure for stop of a machine". Also, the measures that require modifying a driving procedure, adjustment, turning off, monitoring or optimization are included in Level 4.

In overall, over 800 measures with potential savings of over 630 GWh were categorized as motor-system related. Most of the measures suggested belong to Level 2. The number of actions on Level 4 is two times less than on Level 2, however, the potential for electrical efficiency is about the same for those levels. These results served as basis to work further with the development of the method for system efficiency improvement.

3.2. Method development

Swerea SWECAST (the Swedish foundry branch’s institute for research, development, education and training) is a project manager and run the project in collaboration with DynaMate Industrial Services (a consulting company offering technical services in production and property maintenance) and Linköping University. The method was developed in four steps. The outline of the method was developed as a first step based on the theories of EMDS, value stream mapping (VSM) and insights from a national industry training program called LEAN energy. The first version was tested in a pilot study and the obtained experiences fed the method with new and modified contents. The updated version was trialed in case studies whereas each of them was followed by further modifications coming from the new gained results. The final third version was tested, evaluated and validated in a third case study.

Summarized, the method has been evaluated and verified in three different companies with significant use of electric motors. Workshops were performed with the industry representatives after each version’s update in order to follow up the modifications done and get feedback from the participants. The companies participating in the case studies represent three different Swedish manufacturing sectors: foundry, iron and steel, and medical sectors in order to make a method more generalizable. The case studies have been done in close collaboration with corporate representatives. This is a direct benefit to the companies to participate in identification of opportunities and measures for energy saving. The case studies serve as an indirect educational activity and the internal knowledge of the methodology, processes and systems reach a higher level when the case studies are conducted. This would give the involved companies the possibility to perform qualified energy efficiency work with electric motor systems after the project end, with or without external support.

Working groups are represented by members of the project management group and industry representatives. The industry representatives should be cross-functional since different parts of the method should involve various functions within one company in order to achieve a complete understanding of the studied objects. The composition may vary depending on a case study. If external experts are working at a company with an efficient energy use, involving them would increase understanding of the processes. In some cases, an energy auditor should get insight into the company's processes before the work.

Throughout the project, the core working group is collaborating in order to develop a methodology and system models. Since MOVE is not an implementation project but a method development project, the focus is not on obtaining the quantified results. In turn, by means of try-and-error approach, continuous improvement of the work methodology, testing in a pilot study and verifying in case studies the method underwent several modifications. User-friendliness is in focus for paving the way for a future high implementation rate in organizations.

4. Results

In this part, the results of development and industrial testing of an innovative analytical methodology for identifying and addressing energy efficiency improvement opportunities to existing and new industrial electric motor systems (MOVE) are presented in one case study.

4.1. The MOVE method

The method, called MOVE, is a four-step chronological model. The steps represent the full content of the method and what must be carried out to perform MOVE. The methodology aims at gaining facts and knowledge about a particular industrial process, the demands and requirements which drives the energy usage as well as the energy efficiency potential of the system. There are no criteria for choosing an industrial process rather than it should have potential for improvement. A simple energy audit may be needed in order to define possible areas for improvements. However, it is not a requirement and MOVE can serve as a method to initiate continuous work on different areas within a particular industrial activity. Figure 1 shows the process flow of the method.

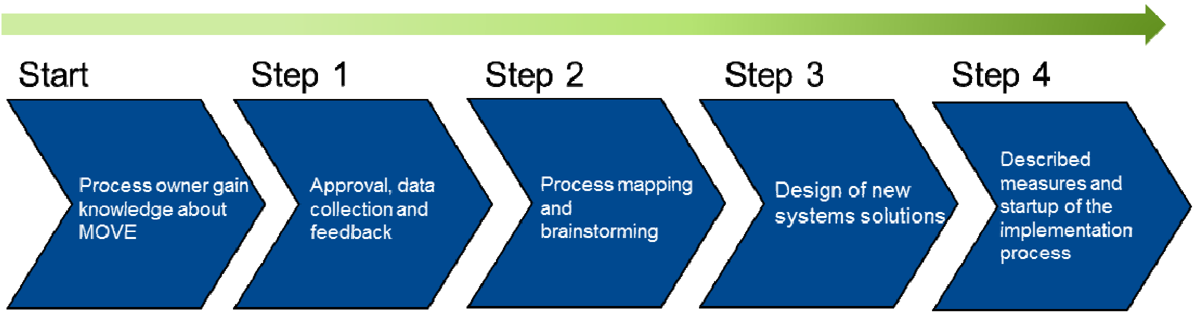

Figure 1. The working process of MOVE

Start
First startup phase is a preparatory lecture when the external process leader is supplying a process owner from the company with overview knowledge about the methodology. The role of the external process leader is to coordinate the team throughout the implementation of the method. In this particular case study the task of the external process leader was carried out by a management consult who was a partner in the project group. The process owner is defined as a person who is employed within a manufacturing company and has formal main responsibilities in the chosen manufacturing process.

Step 1
In step 1 (Figure 1), the company organizes and sets up a case study team, collects critical data for the chosen manufacturing process and determines an internal strategy to carry out the activities in the following steps. The collected data are summarized and analyzed by the external process leader. This is followed by a feedback procedure involving the process owner and experts.

Step 2
Steps 2-4 take place during two days at the company in a location close to the selected industrial process or technical system. The process mapping, as well as the other activities is led by the external process leader which gathers information from the team assembled by the process owner. The team should consist of at least 4 persons in addition to the process leader. However, the number of attending operators is not the critical issue while the personnel's field of knowledge and expertise is the critical parameter. As mentioned, the process mapping design is similar to value stream mapping in combination with new innovative designs developed in the project (Figure 2). The scope of the process mapping is to visualize the process requirements affecting the energy usage, the product value flow and how it contributes to internal customer satisfaction. An example of a requirement can be a purity of a product, and an internal costumer could for example be a following manufacturing process which is outside the system boundary. The mapping process represents the work with "External efficiency" which was described in the theory chapter. During the process mapping, the most interesting requirements will be sorted out to be overall criteria to fulfill when new energy efficiency measures are identified.

The process mapping step is followed by a simplified brainstorming activity which stimulates innovation and creation ability of the team members. The brainstorming has two important functions: involve all the participants and make sure to capture efficiency measures which are outside the system boundary.

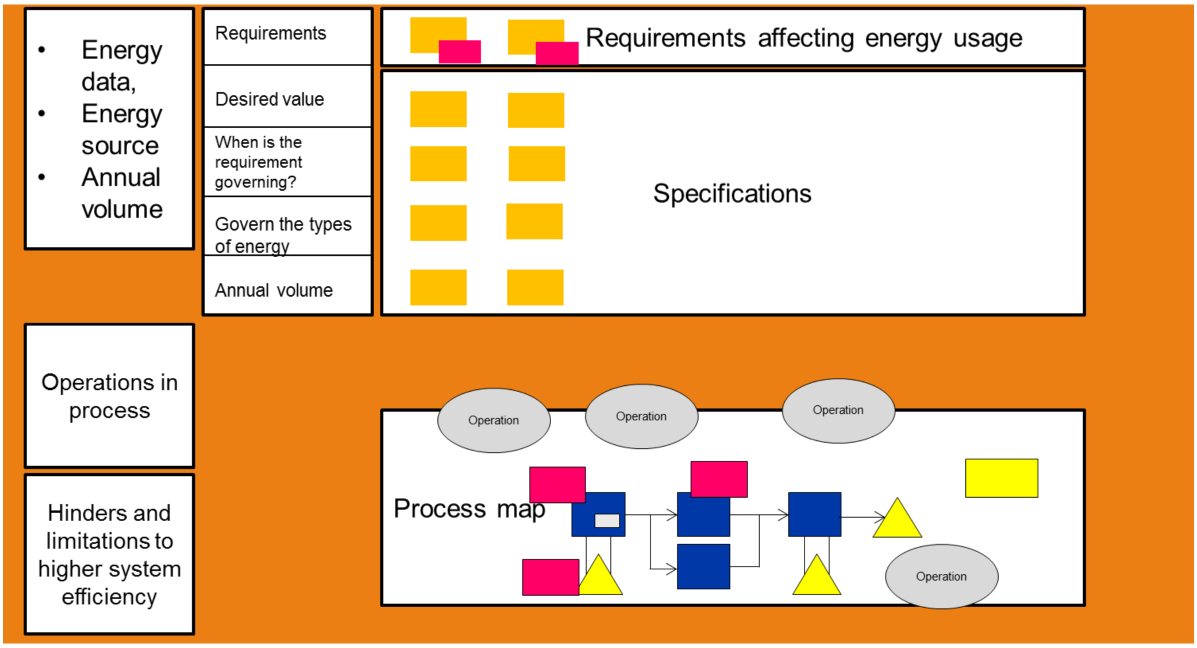

Figure 2. Step 2 - Process mapping design (External efficiency)

Step 3

The described requirements from step 2 are the overall criteria in step 3 when energy efficiency measures are being proposed. However, the first activity in step 3 is to collect data to describe the current system routines, automations control and technical components and sort them out into seven motor system levels according to Figure 3 (numbers 1-7 are system levels). This categorization has been extended from Waide and Brunner's categorization within the method development. See table 1.

Table 1. Motor system levels: extended categorization.

System level	Category	Description and content
7	Human factor	Behavior, "way oF work", instructions, common routines
6	Automation	Control systems, data measurements and collection, ability to take actions
5	Production philosophy	How the resources are used to create costumer value: supplied as much as required when required, supplied when a product is manufactured, supplied all the time
4	System solutions	Overall system design: centralized or decentralized, continuous flows or batch, type of energy supply (boiler, district heating, hot water or steam)
3	Whole motor system	Type of pumps, fans, etc.,

		heat exchange
2	Core motor system	Use of variable speed drives, direct coupling or use of belt drives
1	Electric motor	Type of motors

The existing system is described and the data are evaluated into three categories of energy efficiency where the left category is more efficient and the right category is less efficient. Improvements proposals are described and also specified to a correct level of the system matrix as well as judged according to efficiency category. In overall, step 3 represents the work with internal efficiency by choosing best technology and methodology to meet the requirements identified within external efficiency (Figure 3).

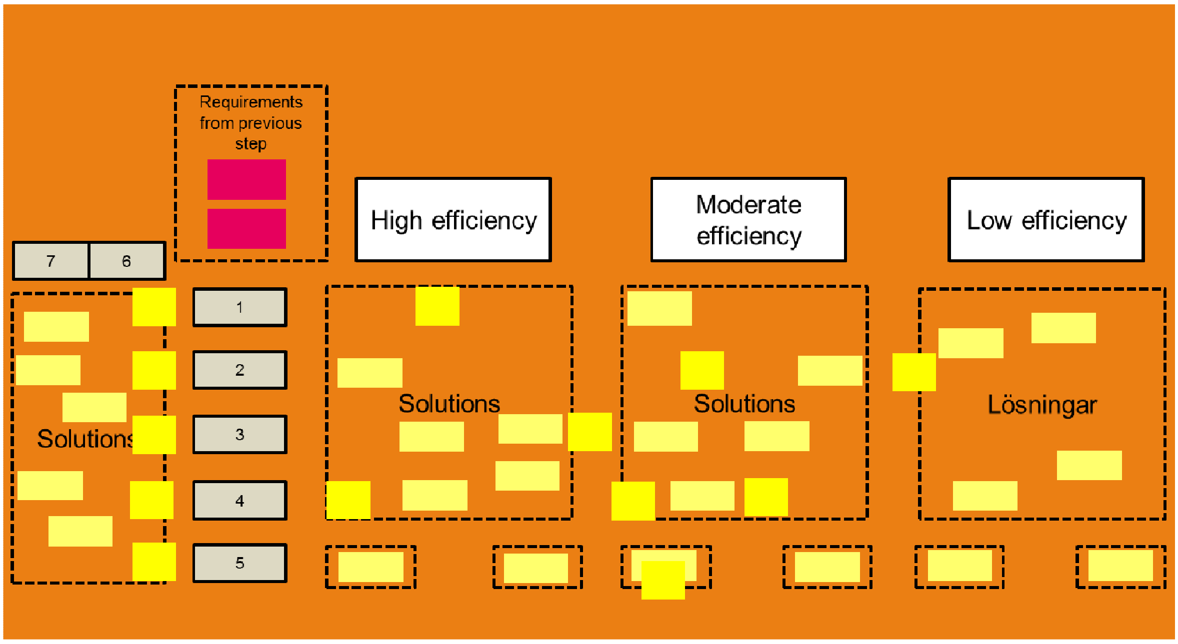

Figure 3. Step 3 - Finding energy-efficient measures (Internal efficiency)

Step 4

The final step 4 aims to combine the level-specific solutions from 7-1 into a list of summarized energy efficiency measures. The measures are then analyzed, evaluated and placed on an evaluation matrix. Notice that measures from different levels are combined to create new system solutions, meaning improvements from multiple levels are merged into system efficiency measure. The matrix considers two important aspects: the effect of an energy efficiency measure and its implementation complexity. Finally, the measures are voted for and the highest-rated measures represent the area for a further implementation process.

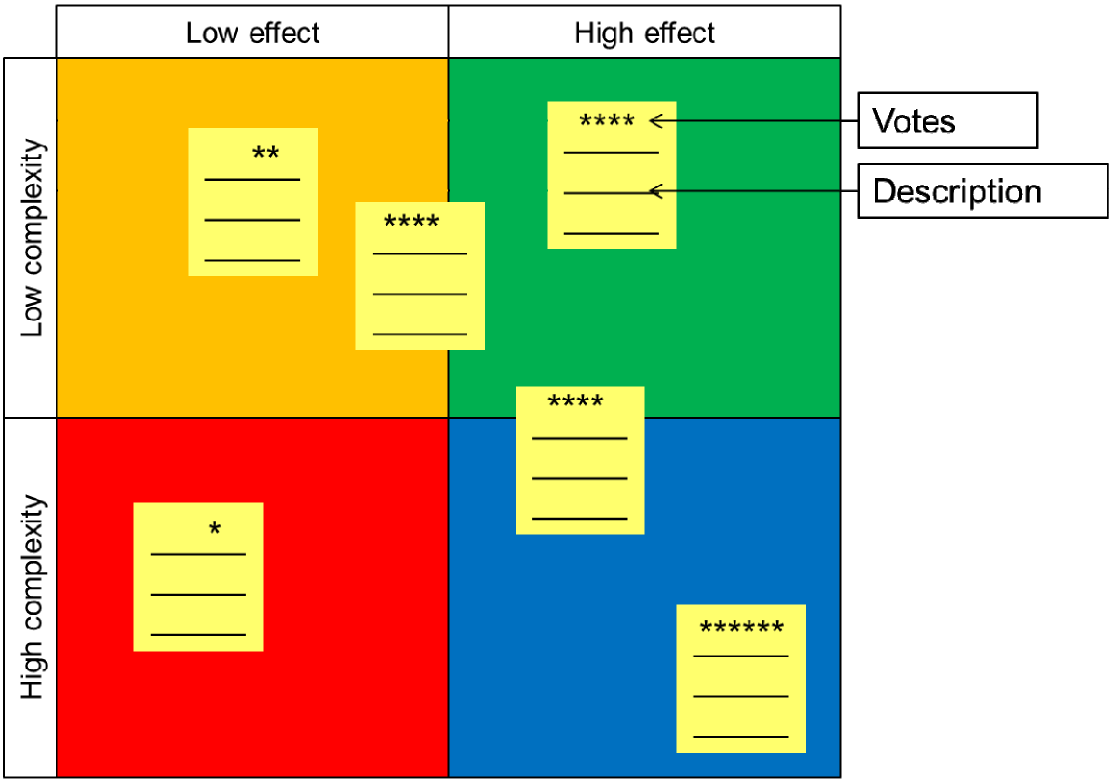

Figure 4. Step 4 - Priority matrix

4.2. A case study, identified measures

The method was first tested in a pilot study. Later on two case studies were performed where several modifications in the methodology were improved along the project. The following part is a result of the second case study performed on a heavy trucks manufacturing company. The object chosen for the case study was a hot water system within a driveshaft painting process. Thus, the aim with the case study was to test a method and at the same time to improve the washing process. The hot water system serves the driveshaft washing and painting process and delivers 4000 MWh per year. There are many pumps and heat exchangers in the system supplying heat to washing water in a washing machine, tanks and water treatment step. In the drying tunnels, the heat is supplied by hot water through the heat batteries and transferred to air in order to dry driveshaft after washing and painting steps.

Firstly, the process data were collected (start phase). The basic data include the description of the process in form of flowcharts, energy carriers and their yearly use, process' customers and process' requirements. The day before the workshop, the external process leader and the process owner studied the chosen process in order to obtain the knowledge about it as well as to create the blueprint for the process mapping (step 1). The following day, the process mapping was performed by the working team with the help of the external process leader and the most interesting requirements were chosen (step 2). Seven important requirements were mentioned but only two of them were chosen to be included in the further work on internal efficiency. The two requirements were:

- The requirement to prevent bacteria and mold growth in washing step and tanks;
- Temperature in washing step to meet the purity requirements.

These requirements were considered as the governing parameters that affect energy use to a significant degree and thus affect the system efficiency.

During the brainstorming, the good ideas from the participants were selected in order to proceed to the work with internal efficiency. The improvement suggestions were summarized and combined on a white board. It became clear during this activity that some suggested solutions were outside the selected system boundary. Even these proposals were documented to ensure that they are available in the future. After that the group agreed that it would be interesting to explore the possibility of lowering the temperature of the defatting and rinsing water.

Further, during the work with internal efficiency, the current system structure was mapped and improvements were identified. There were several assumptions:

1. The system is divided into seven levels (Table 1) in order to form a complete system with components, control systems, methods and work approaches;
2. The requirements should be satisfied in a most efficient manner;
3. The requirements shall govern efficient energy use and the best available technology and methodology are to be used.

In step 3, the existing system to wash and rinse drive shafts was mapped in the 7-level-model to determine which important components it contains and how they are used to reach the purity requirements and limited bacterial and mold growth. The present system was evaluated from the point of view of its effectiveness (high, moderate, low efficiency) in order to propose improvements in the various system levels. In the current case study the working team had a good understanding of which solutions had higher, moderate or lower efficiency. The solutions in the different levels were summed up to a number of energy efficiency measures (step 4). The solutions were described, categorized and prioritized according to the priority matrix from such aspects as how difficult the measure is to implement and how large the potential for energy saving is. Then each participant got two votes to recommend the measures. The measures are then described in a table, sorted out with the highest voting rate as number 1.

The improvement proposals could dependent on each other, which could lead to an implementation of a specific action could reduce or eliminate the need for another. This should be considered before deciding on the implementation of an action. Assessment of the raw energy efficiency potential was made as well. The measures are presented in Table 2 according to the company's voting and priority.

Table 2. Overview of improvement measures.

Priority	Measure description	Involved systems	Strategy of measure	Energy savings, MWh
1	Decrease temperature (42◦C) in washing step in order to replace hot water to district heating (can cause replacement of some chemicals)	High-temperature hot water system Defatting and rinsing processes	Long-term, requires pre-study	1500
2	Decrease volume in defatting and rinsing tanks that are pre-heated in the beginning → lower power consumption and decreased preheating time (can affect the cleaning system)	Hot water system Defatting and rinsing processes	Short-term	100

3	Use the information from the control system about the exact location of the shafts in the washing machine for the control of the pumps in different washing steps	Hot water system Defatting and rinsing processes (possibly also in drying zone)	Short-term	
4	Increase the time interval with a lower temperature in the rinsing step. Try to find a suitable interval that prevents mold and bacteria growth in the washing step	Hot water system Rinsing tanks	Short-term	200-300
5	Check if "Energy efficiency mode" is activated on all VSD	All relevant pumps with ”Energy saving mode”	Short-term	50-100
6	Install pressure sensor for hot water system to enable the supply pressures driven by need	Hot water system	Short-term	
7	Use the information in the control system to subdivide nozzles so that the drive shafts can be sprayed individually. Complete with VFD for defatting and valves for nozzles	Defatting and rinsing processes (washing machine)	Short-term	
8	Measurement method for identifying bacteria and mold to enable lowering the washing temperature and increase when needed	Washing machine Washing process		
9	Measurement method for identifying bacteria and mold growth. Lowering only rinsing temperature and increase when needed	Rinsing processes		
10	Replace electric heating with district heating	Electricity Washing process		

The energy saving potential of highest rated measures are summed up and presented in Figure 5. The figure shows a correlation between cost saving potential and system saving potential. The case study showed a total energy saving potential to be 42% of the present hot water usage in terms of energy, which has a value of 115 000 euro. Notice that this is only the energy saving potential. The complete saving potential, including such resources as water and chemical savings are not described in the current case study. By carrying out the method, the energy saving from the system solutions can achieve 42% in comparison to 20% savings if system thinking is not applied.

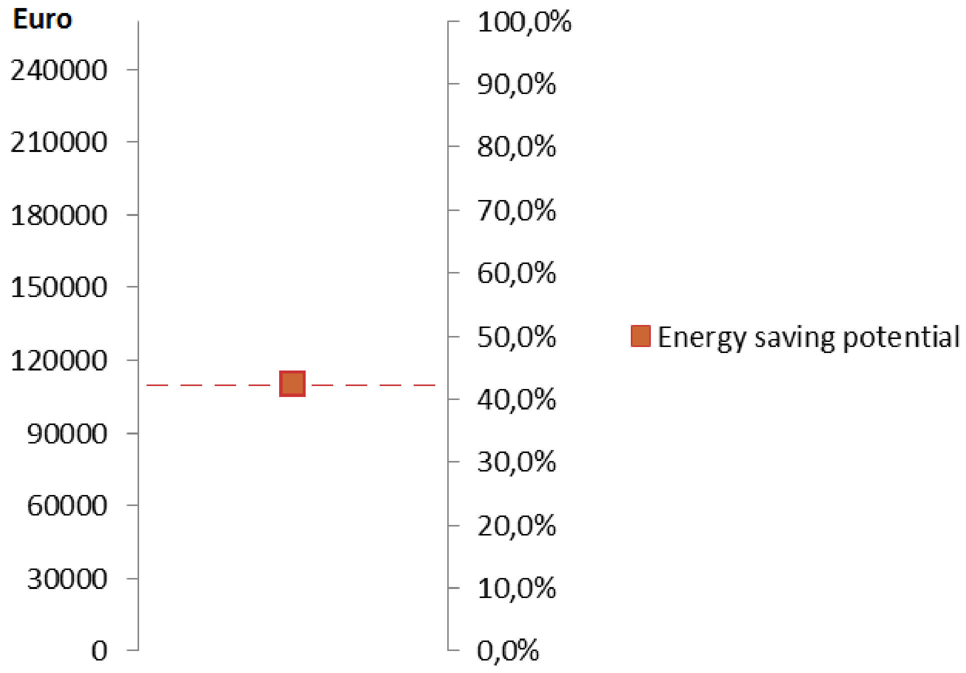

Figure 5. Energy saving potential for the highest rated measures proposed in the case study

Besides the measures, the result of the work with external efficiency was the participants gained knowledge about how the washing and heating process operate and which requirements have the highest effect and thus delimit the system efficiency. Also, describing of the requirements was questioned by the team members and became more visible due to the process mapping. The top result of internal efficiency was the list with the improvement measures evaluated according to their effect and implementation complexity. The suggested measures have effect on both the hot water system, the usage of water, chemicals as well as to which extent the pumps are used. With the help of MOVE, different parameters were taken into accounts that are affected by the hot water system. Thus, the process leads to establishing of mutual learning process and systematic energy work within organization. It was noted as a positive factor that the participants with different expert skills could share their knowledge about the process' sub-systems.

5. Concluding discussions

The method presented in this paper supports Senge's model and proves that a group during the work with MOVE underwent a joint learning process and developed shared visions. The method involves a "train the trainer" concept which implies that corporate and process managers are trained by the project manager leading MOVE workshops. In this way, the knowledge stays available within the company at the end of the project. The method contributes to that the individual competences become collective expertise and that participants learn to think in system terms and see the bigger picture. To take into account the entire system efficiency is not possible without applying management practices. Including management practices in such methods as MOVE help to identify energy efficiency solutions on higher levels of industrial EMDS. Moreover, management practices help to understand costumers' requirements affecting the energy usage. All this enables prioritizing the benefits that each used kWh provides. Further contribution of the method is an ability to visualize how actions at different system levels can be prioritized for obtaining the maximum energy efficiency potential, how they should be selected according to the "right" and "best" action criteria. Properly chosen actions at higher system levels can further contribute to behavioral changes by means of introduction of new procedures and ways of working, development of greater competences within organizations and better control over processes. All this helps to shift from only efficiency behavior to curtailment behavior as in Breukers et al. [11].

The development of the MOVE concept has so far met expectations and the case studies indicate interesting results and data. The case study identified energy saving measures corresponding to 42% of energy in the analyzed systems. The method had direct effects on increased knowledge of the technical systems by the participants. During discussions in the case study, several “myths” and untruths about the process were challenged and corrected. MOVE also provided a natural platform for exchange of experiences and reaching consensus on how the process operates and what measures can be considered appropriate to implement. As a whole, the participants gained a more deeply understanding of the manufacturing process. The documented results in the case study can serve a powerful decision support for prioritizing further investments. The results can also serve as a basis for evaluation of selected technology solutions and strategies in the participating company.

Thus, the outcomes of the method are:

1. Mapping and identification of requirements that govern energy use;

2. Increased knowledge about the industrial process and EMDS;

3. Identifying energy efficiency solutions on higher system levels;

4. In a long run the energy saving aspect becomes an integral part of the overall continuous improvement process.

The novelty of MOVE is that it involves visualization, mutual learning, knowledge and experience sharing and can be implemented for identifying continuous improvement actions. Such innovative methods of work with energy efficiency work support system thinking instead of simply focusing on installation of new more energy-efficient technologies. Experience shows that it is much easier and more attractive to replace technology in form of components instead of combining technology measures with active work, commitment and creative actions. Such an approach is not given priority despite that there is a higher potential to energy efficiency in this kind of actions. The fact is, however, that this is what creates a cultural change in a long run. It is worth to repeat that a long-term systematic approach deepens understanding of processes, systems and potentials and gives the opportunity to see the whole. Applying these two important components (system thinking and repetitive work on energy efficiency) can help to change organizational culture of a particular company and establish successful energy management practices inside the organization. This can also help to track and change the patterns in the staff behavior which also contributes to inefficient energy use.

It is wrong though to consider MOVE a substitution to technical energy audits. In contrary, audits can be used as a prior step to indicate the improvement opportunities on a particular manufacturing facility. However, it is not a requirement and once established within the company, the method can be continuously used for optimizing the processes. Thus, energy efficiency measures implementation rate would be much higher. Also, the list of measures would not only consist of the actions proposed in a single audit and thus limited to the expertise of a particular energy consultant.

Running MOVE during three days helps to concentrate external and internal expertise on a particular process and results in identifying a significant energy saving potential for this process. However, applying MOVE as such for small and medium sized enterprises (SMEs) can be problematic. This is due to the lack of time and information (energy efficiency barriers typical for SMEs. It may be quite problematic to assure a group of several persons working on the method under these days due to SMEs do not always have resources for that. However, a solution can be a simplified method developed for SMEs, so called MOVE Light. The focus then probably would be on external skills and expertise.

To conclude, the core components can be mentioned which present the value added by MOVE compare to other countries’ experiences:

- MOVE have wider approach which does not allow systems’ integral components to be separated from processes’ requirements.

- The participating employees’ skills become a means for improvements on the organizational level.

- Knowledge exchange and learning in group become a vital part of the method as the employees are the actual operators of the manufacturing process.

- In a decision-making process, companies could use the results of MOVE to reduce the risk of sub-optimization of their processes.
- The results of MOVE thus become a powerful decision support via mutual learning process with weighted improvement suggestions.
- Integrating external and internal efficiency, the approach allows connecting customer values and organizational core activities in order to drive market change.

The system approach has shown to be an important concept to investigate further and is vital for the research of industrial methods for improving energy efficiency. In this sense, the MOVE method can launch development of industrial excellence and contribute to establishment of efficient, committed and long-term oriented work on energy efficiency that should become an integral part of an everyday agenda within organizations.

However, there is a further work need to be done within the MOVE framework. Firstly. the method can be further supported by new audit tools to enable a more time-effective way of identifying objects with low system efficiency. Secondly, it is worth to repeat that MOVE was not initiated as an implementation project but as a method development project and thus, the aim was not on obtaining the quantified results. Moreover, in this work only one case study is presented. Therefore, the actual impact from all case studies should be verified in future work. Thirdly, a deeper analysis is needed to be done in order to understand how MOVE contributes to fulfillment of end users' quality requirements. These results can be further needed to enable the development of a business model for the method with the aim to provide new energy services.

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Industrial Motors and Drives: Global Market Update

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Abstract

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. 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 ten global suppliers and thousands of regional suppliers, it is the only industrial machinery market that is governed by energy-efficiency legislation in all three regions. New amendments to existing MEPS in both the EU and North America will have a significant influence on the market's sales of higher-efficiency, low-voltage motors and VSDs[1]. The discussion will also include new 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.

Introduction

This update includes an overview of the worldwide low-voltage motor and drive markets in 2014, with projections from 2015 to 2019. The global market for low-voltage motors and drives, with a combined value of almost USD$26.7 billion in 2014 according to the latest data from IHS (NYSE: IHS), experienced weak growth for the year. Total market revenues grew by less than 1.0% for the LV motor market and a lackluster 2.4% for the LV drive market last year, but revenue growth is expected to stabilize slightly in 2015. IHS predicts that total revenues for LV motors and drives will grow by slightly less than 3.5% in 2015. This consecutive annual slow performance of the markets can be attributed to the fact that sales of these products are heavily dependent on demand for machinery as well as the state of energy-intensive industry sectors. The sudden decline of the oil and gas industry had a sharp negative impact on the motor and drive markets in 2014 and will continue to hinder these markets' growth in 2015. Furthermore, global machinery production is forecast to increase by only 1.6% in 2015[2], which does not bode well for suppliers to these markets. Of course, slow growth in China's economy, coupled with political unrest in the Middle East and Russia and the CIS countries, lessened the markets' growth potential for 2015 and has resulted in tepid investments, which have undoubtedly reverberated into the year. Generally, manufacturers have reported that they have adopted a "wait-and-see" attitude regarding investments and manufacturing decisions. In many cases it remains to be seen what impact the upcoming Minimum Energy Performance Standards (MEPS) will have on the respective regions in which they are implemented, but all signs point to an increase in sales of higher-efficiency equipment. On the other hand, Chinese leadership that continues to focus its efforts on stimulating economic growth, a projected improvement in the fiscal performances of Europe and Japan, and the steady resurrection of oil prices and investor confidence are factors which should lead to more stability, all of which are expected to benefit the global LV motor and drive markets in 2015.

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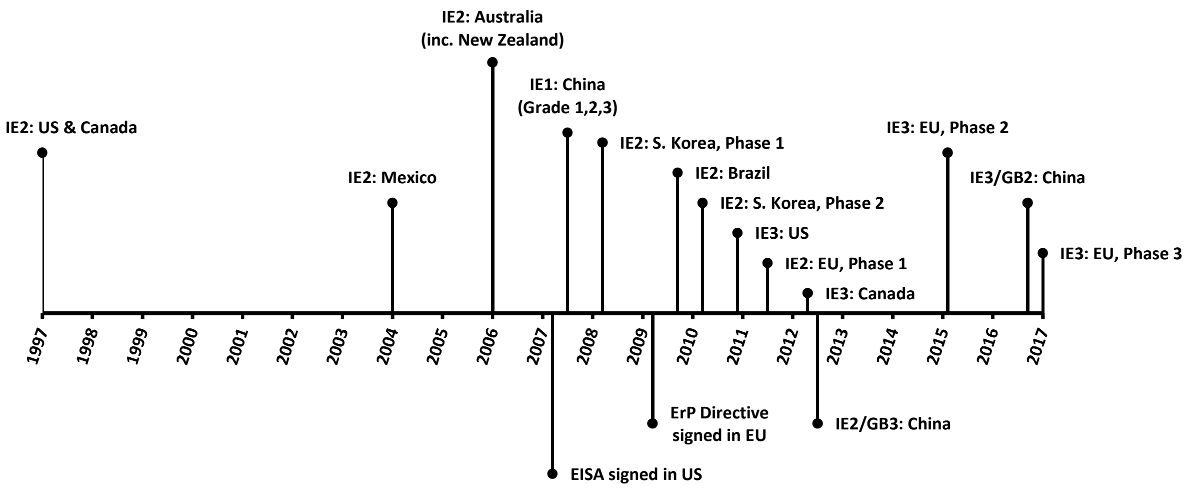
[1] IHS collects data from the leading LV motors suppliers in every region and publishes data on the impact of LV motor MEPS in most key countries.

[2] IHS Economics and Country Risk publishes quarterly GDP, Industrial Production and Machinery Production data by country.

Low-voltage Motor Market Update

In the case of low-voltage motors, a market that was valued at $14.2 billion in 2014, revenues have grown more rapidly than unit shipments due to various motor efficiency legislations being enacted around the world (Figure 1). As a result of these legislative initiatives, motors that are more energy efficient and more expensive are being mandated by government entities to manufacturers, original equipment manufacturers (OEMs) and end users alike. This will substantially inflate the revenue growth of the low-voltage motor market over time, particularly when compared to other industrial automation product markets. Low-voltage motor revenues increased by more than 5.0% in 2013 as the market continued recovering from the recession. The revenue growth was bolstered by the continued transition to IE3 (Premium efficiency) motors in North America and the sustained shift in Europe to IE2 (high-efficiency) motors, which went into effect mid-2011. However, 2014 low-voltage motor sales revenues were mostly flat due to the economic difficulties associated with falling oil prices, political uncertainties and a 6% contraction in the Chinese low-voltage motor market. Though IHS initially believed a full transition to higher-efficiency motors would be recognized immediately, this has simply not been the case in most countries and regions. In the United States in 2016 a new round of regulations will be introduced with the intention of pushing motor efficiency standards that are stricter and eliminate myriad loopholes that have been exploited throughout the past five years. IHS does expect this endeavour to result in a further increase in average selling prices (ASPs) in North America due to a larger percentage of this market selling higher-efficiency LV motors. The market's revenue growth will continue outpacing unit growth as future updates to the various regional initiatives continue increasing motor efficiency requirements, thereby resulting in higher motor prices. However, as advanced technologies such as permanent magnet motors gain popularity, IHS expects that the ASP of this equipment will actually decline steadily over time. Because of the low percentage of permanent magnet technology (Figure 2), however, price declines will not occur for at least a decade.

Figure 1



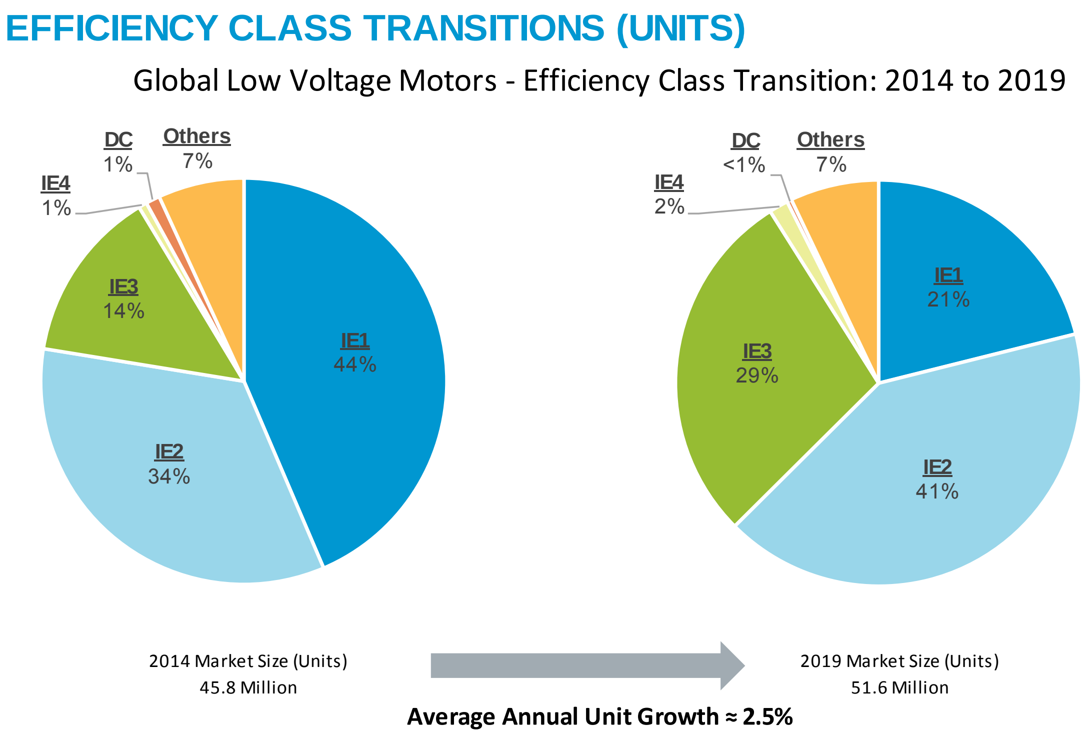
After accounting for 55% of the market's revenues in 2013, IE1 (Standard Efficiency) motors made up an estimated 51% of the market in 2014 and are expected to comprise less than 25% of market revenues by 2019 (Figure 2). These products are sold mainly in the emerging markets that have yet to adopt any type of efficiency regulations; however, many leading suppliers are still successfully selling these motors in developed countries such as the United States and Germany. IE2 motors represented an estimated 19.5% of market revenues in 2014, but are expected to account for more than 45% of total market revenues by 2019. The main market for these motors through 2012 was that of North America, but since then both Europe and China's transitions significantly increased demand for these motors. IE3 motors accounted for only 2% of global revenues in 2010, but made up 15% of market revenues in 2014 and saw another rapid uptick in demand during the first half of 2015 due to the

European Union's move to implement the next phase of its motor efficiency legislation. This efficiency regulation in the EU was mitigated, however, due to the scope of this policy[3].

The world market for industrial IE4 low-voltage motors is estimated to have been worth $159.2 million in 2014 with nearly 300,000 units shipped. This was almost triple the amount of revenues and more than quadruple the amount of units in 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 20% in 2015 to $191 million with nearly 20% 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 2010. However, this segment grew to slightly more than 1% of revenues in 2014 and is forecast to represent more than 2% of all sales by 2019. Although sales of IE4 motors are expected to grow faster than the overall market, rare-earth magnet prices and supply concerns are expected to persist. Coupled with how expensive these motors are, IE4 LV motor sales will be limited in the short term.

Figure 2

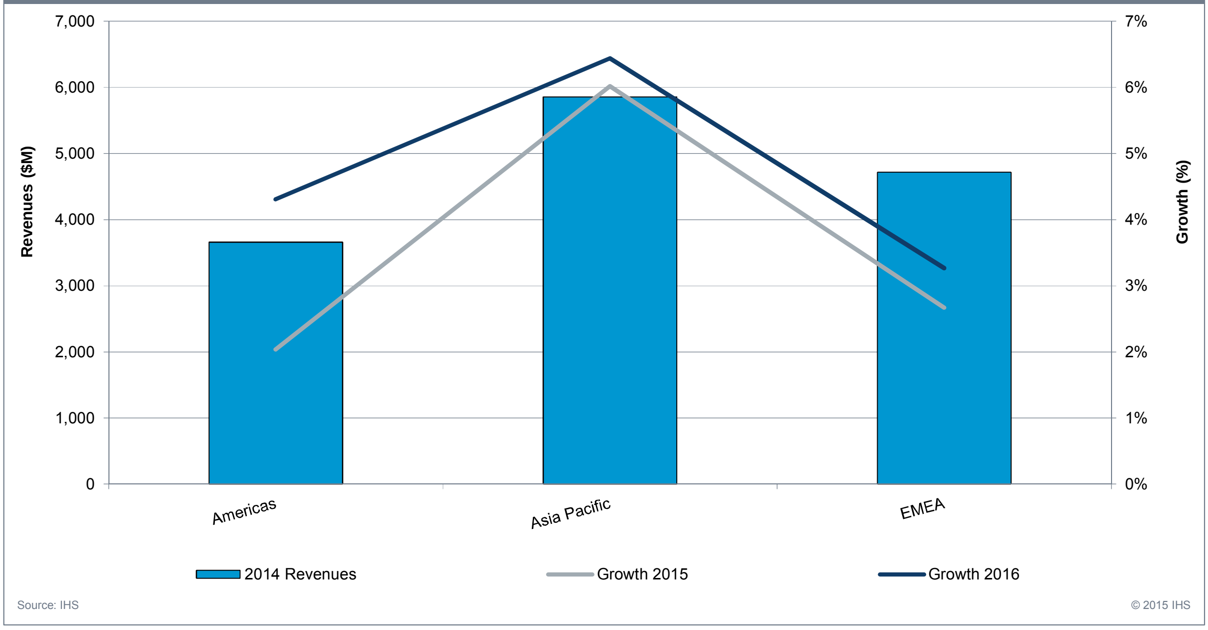


The low-voltage motor markets in North and South America accounted for 26% of global revenues in 2014 (Figure 3). China was the largest individual country market for low-voltage motors in 2014, with revenues accounting for almost 21% of the worldwide total. The European, Middle Eastern and African (EMEA) region comprised approximately 33% of global revenues during 2014. Although the Chinese market experienced a very difficult year in 2014, contracting by more than 6%, it is expected to resume growth in 2015, though not at a fast pace. China currently has a large share of the IE2 LV motors market, and IHS expects that a transition to IE3 class motors will be implemented by 2017. With China, Asia comprised roughly 41% of global revenues in 2014, a share that will remain fairly constant through 2019.

Figure 3

[3] The second phase of the EU LV motor efficiency transition mandates the use of LV motors operating above 7.5kW, which accounted for only 12% of LV motor shipments in 2014.

Figure 3 The World Market for Low-voltage Motors By Region - Market Breakdown and Growth



The top industry sectors for LV motors in 2014 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 (including Baldor), Siemens, Regal Beloit, WEG, TECO, Leroy Somer, Toshiba, Hyosung and Nidec.

Low-voltage Drives Market Update

The world market for LV motor drives experienced strong growth in 2011, similar to that seen in the LV motor market. However, 2012 was a relatively flat year for the motor drives market, mainly due to reduced growth in machinery production. Total 2013 LV motor drive revenues are estimated to have been more than $11 billion, reflecting stable growth from 2011 to 2013. The year 2014 was a very difficult year for the same reasons, hindering 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. In the future, it will also more directly benefit from the second and third phases of the European legislation. The year 2015 has seen the EU mandate requiring the use of either an IE3 efficiency motor or an IE2 efficiency motor coupled with a variable frequency drive for motors with a power rating of 7.5kW or more. While it is still unclear whether end users will prefer the IE3 or IE2 + VFD configuration, IHS expects that it will be split relatively evenly. Starting in 2017, the legislation will apply to motors between 0.75kW and 7.5kW, which accounted for nearly 90% of all unit shipments in 2014. 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.

VFDs have been around since the 1970s and have been gaining widespread acceptance due to the energy efficiency benefits that they provide. The drives market is expected to continue to be one of the fastest-growing industrial automation equipment markets in the future. Applications where motors are typically running at full speed on continuous duty cycles, but could benefit from variable speed operation, representing opportunities where return on investment (ROI) is most quickly realized and becoming high-growth markets for drives. These applications include blowers, compressors, fans and pumps. In addition, motor drives are increasingly being designed with a focus on controlling different types of motor technology, including traditional AC induction motors, squirrel-cage PM motors and servo motors.

Conclusion

The year 2014 featured weak performances by the low-voltage motor and drive markets, but 2015 is poised to be a year of stable, rebounding growth. 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. To counter that, large projects, particularly those involving engineering, procurement and construction (EPCs) or contractors, will continue to struggle on account of the low oil prices. This is not expected to reverberate as long as many project, though, as new technologies and efficient production techniques will continue to grow in popularity. Historically, as energy prices decline so does demand for energy efficient technologies; however, government-mandated regulations will negate this effect. In the short term, it is difficult to forecast the effect that these regulations will have on the motor and drive markets because it often takes 4-6 years for a transition to complete. In the mid to long term, however, energy savings via LV motors and drives are expected to be quite significant, driving revenues and stability for these manufacturers throughout the foreseeable future. This will present many opportunities for suppliers of both LV motors and drives in such a rapidly evolving environment.

SPiCE³ - New industry Platform to boost energy efficiency in chemical SMEs

Sami Nikander - Kemianteollisuus ry

Abstract

The aim of the **Sectoral Platform in Chemicals for Energy Efficiency Excellence** (SPiCE³) was to foster uptake of energy efficiency measures in SMEs across the EU as a whole and specifically in the countries represented by a consortium of 11 formal country partners (and 2 informal country partners) which together represent around 80% of all the EU chemicals industry. In total, the expected energy savings delivered through the project were expected to be in excess of 10M€ per year (approximately 300 GWh/a). In the original project proposal to the EC it was stated that the chemicals sector is committed to the goal of SPiCE³ beyond the funding period from the Commission.

Executive Summary

The Sectoral Platform in Chemicals for Energy Efficiency Excellence (SPiCE³), a project co-funded by the European Commission, was launched in 2013 with the aim to boost energy efficiency across the European chemical industry, particularly in small and medium-sized companies (SMEs[1]). Chemical SMEs constitute a significant part of the European chemicals supply chain, which offers an important potential for energy efficiency improvements.

SPiCE³ brought together 11 national EU chemical federations with the aim of supporting companies to make energy savings. These organisations came from Belgium, Bulgaria, Czech Republic, Germany, Finland, Greece, Italy, Netherlands, Poland, Sweden and UK and were supported in their activities by the European Chemical Industry Council (Cefic), energy consultancy Challoch Energy, online communications agency ExtraMile Communications Ltd, and RVO, a division of the Dutch Ministry of Economic Affairs.

Each SPiCE³ partner was a member of a specific Group within the project.

- Group 1 partners (BE, CZ, DE, IT) were committed to organising 8 national workshops, carry out on-site trainings and contribute to the online platform.
- Group 2 partners (FI, NL, PL, UK) 4 national workshops, and contribute to the platform.
- Group 3 partners (BG, GR, SE) contributed to the platform and communication activities.

SPiCE³ supported the chemical industry through the following tools:

- Online platform: a website (www.spice3.eu) available in 12 languages was developed to act as a first-stop shop for energy efficiency information
- Workshops: local level events organised to raise awareness of energy management tools, best practices and energy efficiency measures among chemical SMEs
- On-site trainings: aimed to provide chemical SMEs with concrete and case-specific technical support to better tap their energy efficiency potential
- Energy efficiency award scheme: run in parallel with the Responsible Care[2] awards, this award recognises and promotes SME efforts in the field of energy efficiency
- European level events: were used to present, and discuss achievements of the project

After 27 months (between April 2013 and June 2015), the project has achieved the following results:

- More than 6,500 chemical companies were reached
- The project made chemical companies aware of the importance of energy efficiency measures, and encouraged them to take positive action in improving their energy use

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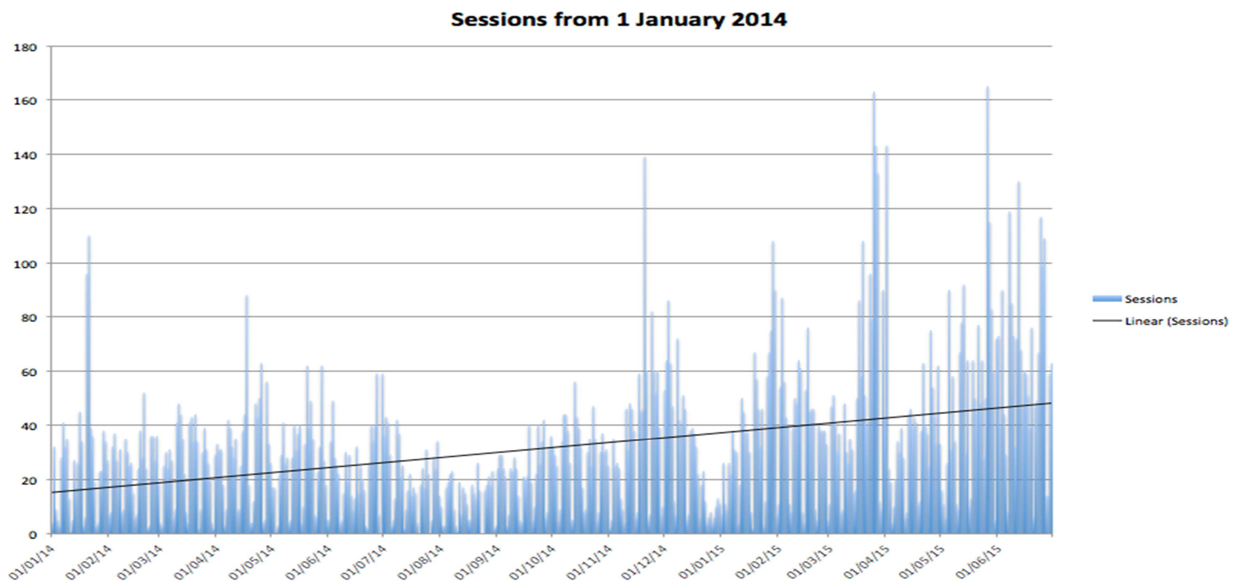
[1] Definition of SME: http://ec.europa.eu/enterprise/policies/sme/facts-figures-analysis/sme-definition/index_en.htm

[2] Responsible Care® is the global chemical industry's unique initiative to improve health, environmental performance, enhance security, and to communicate with stakeholders about products and processes http://www.cefic.org/Responsible-Care/

- Chemical companies were provided with multiple access points to learn more on how to save energy
- The project’s online platform has evolved into an extremely useful tool for European chemical companies seeking to become more energy efficient

Figure 1: The use of the platform has constantly increased since the beginning of the project (18,849 sessions by June 2015)



- The platform has also showcased industry success stories and presented best practice examples
- SPiCE³ has been able to encourage energy efficiency investments by companies worth more than an estimated € 23 million
- 8 editions of the SPiCE³ newsletter were delivered. Each edition highlighted interesting and useful energy efficiency stories from both large and small chemical companies

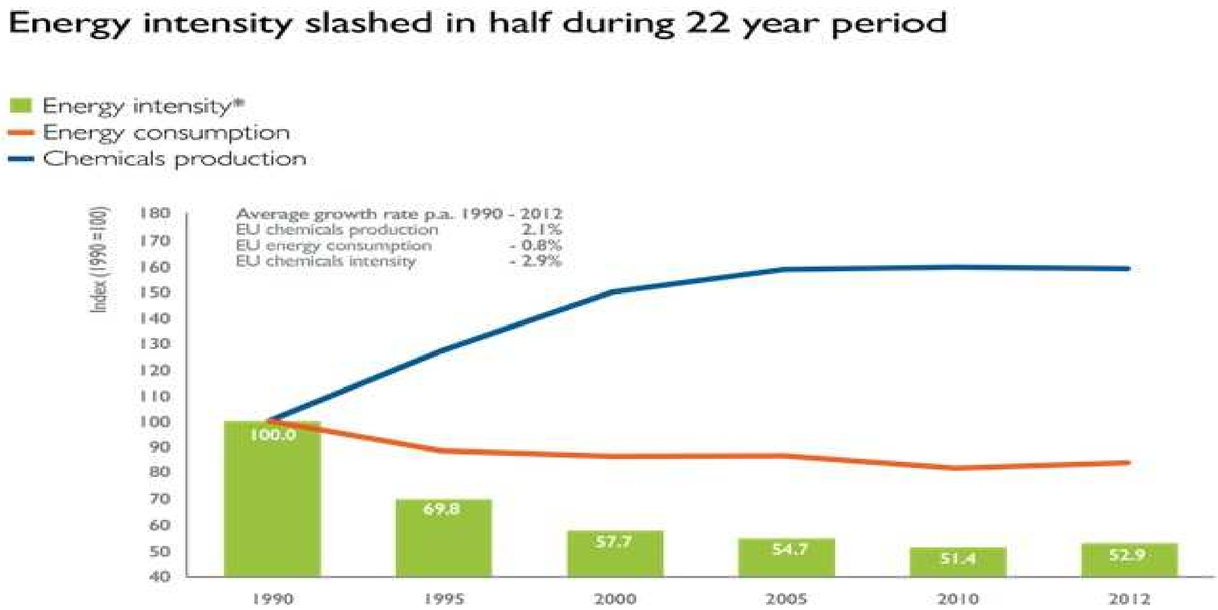
Introduction

SPiCE³ aimed to boost energy efficiency across the European chemical industry, particularly in SMEs. It is mostly these companies that hold a substantial untapped energy management potential, estimated by Cefic to be at 10-15%.

Over the last twenty years, the EU chemical industry has significantly improved its energy efficiency. Between 1990 and 2005, energy use per unit of production decreased by more than 40%. Much of the sector's engagement has been through voluntary and sector-led initiatives, such as the global chemical industry's Responsible Care initiative and the CARE+[3] energy efficiency project.

Figure 2: A reduction in energy intensity in the chemical sector over the past 25 years has led to a reduction in energy consumption and helped lead to increased competitiveness.

[3] http://www.cefic.org/Policy-Centre/Energy/Energy-Efficiency/CARE-/



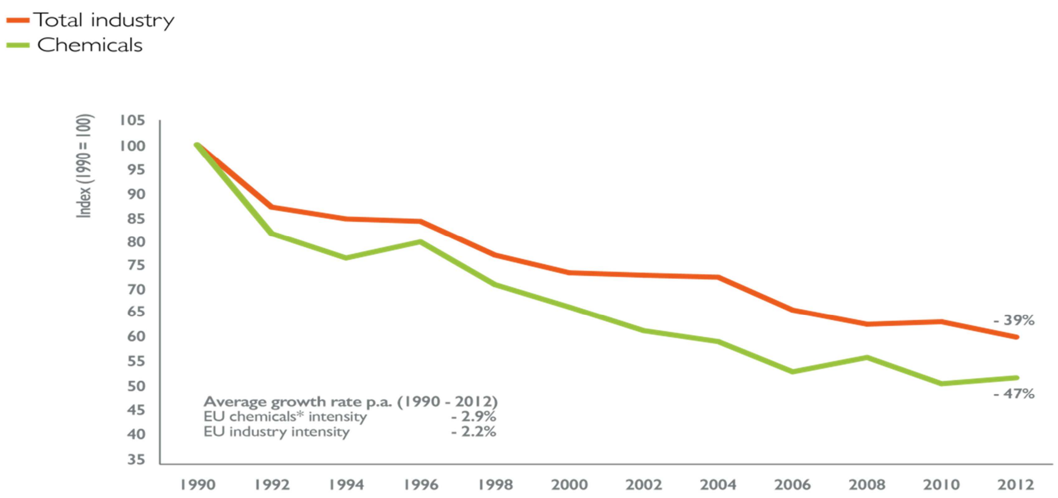
However, it is evident that large improvement potential exists for chemical SMEs. SMEs are an important target for energy efficiency efforts, as they make up a substantial part of the European chemical industry. 96% of the 27,000 chemical enterprises in Europe are SMEs, and account for 30% of sales and 37% of employment in the sector. The challenge for the project partners was to help overcome the barriers for smaller companies which include a lack of appropriate knowledge, tools and financial and human resources needed to effectively control their energy use and implement energy efficiency measures.

The SPiCE[3] project brought EU-wide, coordinated industry specific and industry-led action to support companies by showcasing best practices, sharing of success stories and linking larger companies as 'mentors' to small businesses. The project also developed a coordinated support approach using both top-down (the online platform) and bottom-up (country level workshops and onsite trainings) measures. It is designed specifically to help chemical companies improve and reduce their use of energy. Reaching out to SMEs is a long-term task, and the chemicals sector is committed to this goal. Although the project came to a formal end in June 2015, the partners are committed to build on the initiative and continue their work.

Energy efficiency in the European chemical industry: it's good for the climate, and business!

Energy efficiency is at the heart of the European chemical industry's energy and environment policies, because it can make a significant contribution to improving both environmental sustainability (climate change) and competitiveness (energy security, energy supply, energy costs).

Figure 3: EU chemicals energy intensity cuts deeper than manufacturing sector average

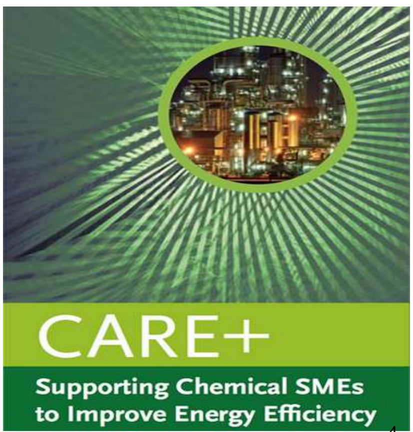


Sources: Cefic Chemdata International (2014), and
Eurostat and European Environment Agency (EAA)
* including pharmaceuticals

Unless specified, chemical industry excludes pharmaceuticals
Unless specified, EU refers to EU 28

The chemical industry is an energy-intensive industry, using coal, oil products, natural gas, electricity and renewables both as raw materials, i.e. feedstock, and as power and fuel. The sector accounts for 12% of total EU energy demand and one third of EU industrial energy use. Since energy costs represent up to 60% of the industry's production costs, European chemical companies have every reason to focus on energy efficiency to succeed in the face of global competition.

For many years, larger EU chemical companies have voluntarily implemented energy efficiency improvements and realised there is an important business case in doing so. However, it has only been in the past few years that the EU chemical sector has made more direct efforts to support its companies through the EU co-funded project CARE+, and more recently SPiCE³.



The CARE+ project (2008-2011) looked to facilitate energy efficiency improvements in SMEs by identifying energy saving opportunities for SMEs that lacked experience with energy audits. CARE+ was started in three target countries and is now adopted after the end of the Intelligent Energy Europe (IEE) support funding by a further 6 countries so far. Activities following CARE+ continue on a voluntary basis, but the scope is very focused on a specific energy efficiency enablement tool.

Global demand for chemicals has been growing in the past decades but with the development of industry elsewhere in the world European companies have found the market increasingly competitive. In Europe, comparatively high energy and feedstock costs have resulted in the chemical sector needing to find ways to become more competitive (EU wholesale gas prices are more than twice as high as in the US, and electricity prices are 30% higher)[4]. One such way, has been through the implementation of energy efficiency measures that save energy and therefore reduce costs.

[4] EC Energy Union Communication, 2015 http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2015:80:FIN

For many years, the EU's chemical industry has made strenuous efforts to improve energy efficiency through its products, processes and research capabilities. Between 1990 and 2005, energy use per unit of product decreased by more than 40%.

A series of factors have recently heightened the continued need to focus on energy efficiency, not least EU and national legislation in this area, along with climate and energy goals for 2020, and 20230.

There are however, limits to deeper efficiency improvements as the larger chemical companies have almost reached the maximum level of energy efficiency potential in many of their processes. To achieve further gains, the chemical sector therefore needs to focus on:

- Initiatives to boost research and development, the development of new technologies and cogeneration and a level playing field for the stimulation of plant replacement;
- Chemical products, which help increase energy efficiency throughout society and in all sectors;
- Spreading energy efficient technology/culture to SMEs….

…unleashing further improvement potential in SMEs

99.8% of the 21.7 million enterprises in Europe are SMEs, making up around 2/3 of all employment in the EU. 50% of these companies consist of one person, though on average a company employs 5 people.[5] Cefic estimates that energy in chemical SMEs can be up to 25% of their total costs, and unlike larger companies, small and medium sized enterprises are more likely than not paying the market rate for their electricity and gas supply.

SMEs are an important target for energy efficiency efforts, as they make up a substantial part of the European chemical industry but they often require specific assistance and guidance to become aware of the issue and develop the know-how to implement measures leading to a lower energy bill. As most SMEs have little control of their energy consumption costs (i.e. the price they pay for energy), hands-on support can be a key driving force for efficiency improvements.

Objectives, Impacts and Performance Indicators

The SPiCE[3] project aimed to drive energy efficiency excellence, and effect positive change in the European chemical industry, particularly SMEs, by:

- Facilitating access to existing information, tools and support schemes
- Enabling companies to take up tools and actively participate in existing initiatives
- Promoting best practices and success stories
- Establishing and strengthening contacts between energy efficiency actors to create a network for learning and exchange
- Offering a communication platform for SMEs and large companies
- Providing technical support on energy efficiency

At the start of the project in 2013, the expected energy savings that could be delivered through the project were in excess of €10 million per year for the EU chemical industry.

This figure was broken down so that it was expected that for SMEs involved in the country-level on-site trainings they could save 10% of their energy consumption. In addition, a similar level of savings could be achieved from the SMEs taking part in the workshops.

Likewise, the project had longer-term strategic objectives in-line with those of the European Commission's 2020 strategy. The project coordinators conservatively estimated that around 15% energy reductions could be achievable through the application of generic energy efficiency measures. These measures include: insulation; monitoring and targeting; buildings efficiency measures such as lighting; motors and drives; and in some cases

[5] Figures are from UEAPME as presented at 3rd EU Level Event, 13 May 2015
http://www.spice3.eu/index.php/UK/news/353-spice%C2%B3-conference-drawing-together-the-results

the use of cogeneration. Further savings are available in process improvements, but these are very dependent on the processes used and thus are less widely applicable.

In particular the project consists of the following components:

- **The SPiCE^3 online platform** acts as a first-stop shop for energy efficiency information to help companies across Europe access the tools and advice they need to implement energy efficiency improvements. The multilingual online platform includes information on European energy efficiency initiatives (e.g. EUREM.NET), national initiatives (e.g. voluntary agreements such as the Benchmarking Covenant in Belgium), energy efficiency tools (e.g. CARE+), and case studies and success stories. It also provides opportunities for networking and exchange among industry experts.

  The platform is available in 12 languages, and with 14 country specific sections.

- **Workshops** organised at the national local level by the Group 1 and 2 project partners. The workshops enabled SMEs to learn about energy efficiency tools and initiatives. Workshops have covered topics such as good housekeeping or energy management, concrete tools available for SMEs, and local initiatives, funding schemes and tax exemptions for energy efficiency investments, among other topics. In addition to SMEs, the workshops often involve large chemical companies and energy expert organisations with the objective of facilitating the sharing of knowledge and experience throughout the sector. These activities have generated case studies, best practice examples and other materials that are disseminated through the online platform.

- **On-site training** organised at the national level by Group 1 project partners they targeted around 20 SMEs in each participating country. They often included half-day site visits and follow-up support was offered by energy experts chosen by the national chemical federation. The purpose of the on-site training was to provide SMEs with concrete technical support to help them take steps towards improving their energy efficiency and give recommendations on how they can better tap their energy efficiency potential by using existing tools or participating in relevant initiatives.

- An **energy efficiency award scheme**, run in parallel with the European chemical industry's Responsible Care awards, recognises and promotes SME efforts in the field of energy efficiency in order to showcase good examples and encourage further companies to take up energy efficiency measures.

- **Three events at the European level** brought the online platform to life and offered the 150+ participants at the events the opportunity for networking and exchange of experience including lessons learnt and good practices identified throughout the project.

The SPiCE^3 project was designed to have long-term sustainability in mind. The Chemical industry undertook this initiative to begin a process of deep and long-term improvement in the sector.

Specific Objectives for the Project
The SPiCE^3 project aimed to drive energy efficiency excellence and effect positive change in the European chemical industry, particularly SMEs, by:

- Facilitating access to existing information, tools and support schemes
- Enabling companies to take up tools and actively participate in existing initiatives
- Mobilising large companies to mentor SMEs and stimulate involvement in the project
- Promoting best practices in energy efficiency
- Providing support to the European chemical industry in strengthening their knowledge and know-how on energy efficiency
- Gathering success stories and showcasing them through different channels

- Establishing and strengthening contacts between energy efficiency actors to create a network for learning and exchange
- Demonstrating possibilities and potentials for transforming energy management
- Offering a communication platform for SMEs and large companies
- Providing technical support on energy efficiency
- Involving countries covering some 80% of the EU chemicals manufacturing volume
- Improving the EU chemical industry networking with SMEs on energy efficiency
- Using large companies' expertise and best practice cases to educate chemical SMEs through the online platform, workshops, on-site trainings, awards scheme and EU level events on energy management
- Improving energy efficiency of SMEs and the international competitiveness of the sector
- Reaching out to at least 5,000 SMEs

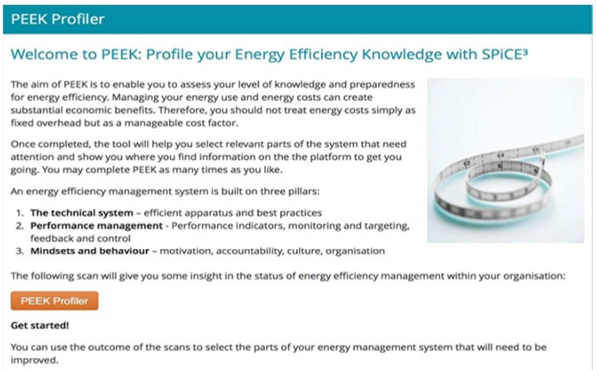
A key overarching objective of the project was to effect change in SMEs on energy. This is why we set a challenging target for investments in energy efficiency.

Achievements

The Platform www.spice3.eu

On developing the concept for SPiCE³, it was particularly evident that what was lacking for the chemical industry was an easy to access online resource centre which could transparently connect users to the information they required on energy efficiency.

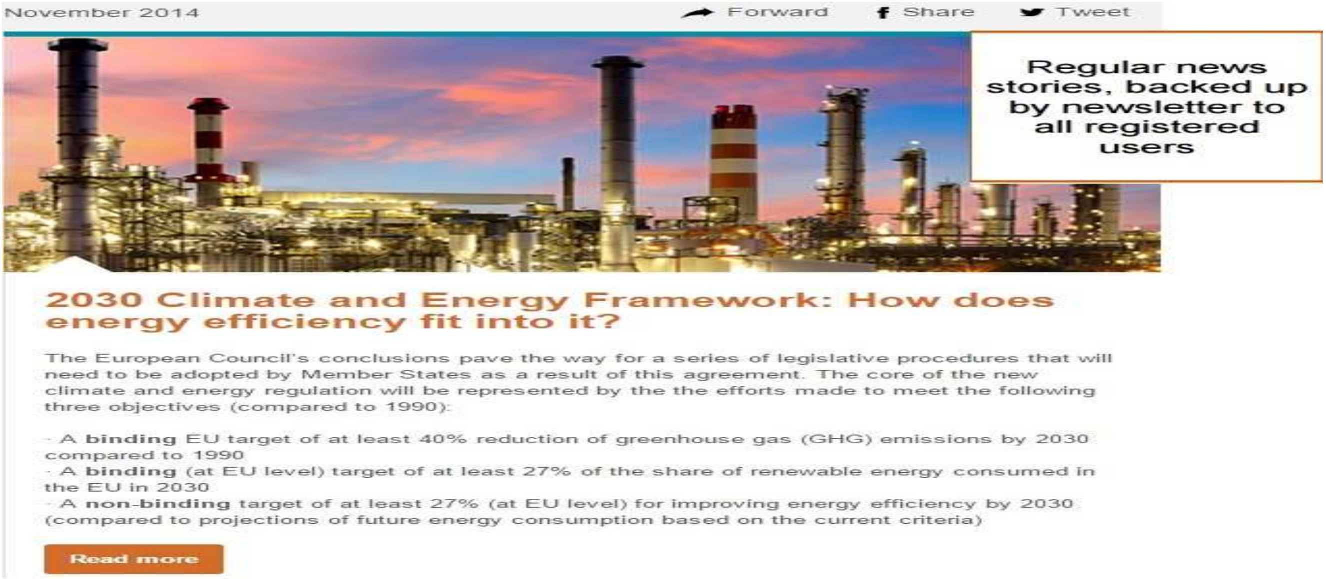
To respond to this need, the project's consortium decided to design a unique multi-language online platform that could function as a first-stop-shop for energy efficiency, including detailed information on European and national energy efficiency initiatives, energy efficiency tools for companies, case studies and a large number of reports and articles on best techniques and methods for energy savings specifically relevant for the chemical industry. It was considered very important to make the resources more accessible to a larger number of companies, hence the decision to develop the platform in 12 languages. This has allowed for a tailored service to local users across the 13 countries which participated in the project.



In order to better help SMEs in their journey towards energy efficiency, it became evident that SMEs should be provided with a means to determine their level of awareness of energy efficiency. In this regard, the Profile Energy Efficiency Knowledge (PEEK) section of the platform was conceived and put in place. This tool enabled companies to assess their level of knowledge and preparedness for energy efficiency measures and thus significantly facilitated their take-up.

Newsletters

The project e-mail newsletter drew content from the online platform and encouraged readers to visit and use the platform. The 8 newsletters published during the project highlighted new case studies, new best practices, EU-level news and other content published on the platform as well as informing readers of upcoming events and initiatives (such as workshops, and on-site trainings). Each newsletter followed a template format that allowed adaptation for the different country audiences in terms of language and country context.



Workshops

The objective of the workshops was to give SMEs the necessary tools and advice for them to achieve concrete energy efficiency improvements. The workshops provided companies with information and training on existing tools (such as CARE+) knowledge on how to implement an energy audit, local country level information related to access to funding and national energy efficiency measures, amongst other topics.

An overview of each workshop was carried out including its content, presentations and conclusions and these were uploaded to the online platform, allowing for sharing of information not only to companies in the country where the workshop was organised, but across borders to any user accessing the information.

The workshops were an essential part of the project as they allowed the partners to reach out to SMEs and large companies, establish personal contacts, exchange views and to overall strengthen the links between companies within the EU chemical sector.

The workshops were specifically conceived and organised to attract a consistent number of SMEs (20 to 30) and promote the participation of larger companies, so these latter could share their knowledge with the SMEs and act as their 'mentors'. Moreover, partners also invited to the workshops representatives of local authorities, energy agencies, academia and think-tanks. Having a broad-range of participants assisted in the exchange of information, knowledge and experiences.

On-site Training

The ultimate objective of the on-site training was to provide the SMEs assisted with a good overview on the energy status of their facility and to recommend the use of existing tools (available on the online platform and elsewhere) to help them become more energy efficient. The training provided concrete, tailored hands-on support to companies, and was a key first step for them to make an energy audit. The trainings were designed to help trigger appropriate actions and investments in energy efficiency in the participating companies.

Each of the on-site trainings was envisaged as a visit by an energy expert, after which each company would be given a post-visit 'priority list' with possible follow-up measures together with an estimation of their energy efficiency potential. It was deemed important that the energy expert mainly focused on giving good housekeeping advice but could also add advice specific to the individual company's situation. To encourage SMEs to take part in the on-site training, the initial visit and follow-up report were made free of charge.

EU Level Awards

Another success of the project was the development of a new energy efficiency award scheme, which ran in parallel with the European chemical industry's Responsible Care awards. The awards scheme aimed to recognise efforts of SMEs in the field of energy efficiency and to promote examples of good practice and encourage companies to take up energy efficiency measures.

The call for entries and the submission process was coordinated by Cefic with the support of the SPiCE³ national federation partners. Each entrant was assessed and the winner selected by an independent panel of invited stakeholders broadly representative of the sector and from different countries. Further information can be found later in this paper.

Energy efficiency tools and case studies
Content-specific sections of the SPiCE³ platform were designed in order to provide visitors with a selection of relevant materials that pertain to the chemical industry and the situation of the each SME.

Visitors were encouraged to browse through these sections looking at the case studies, tools and other useful materials. All this set of information has enabled many SMEs to start or continue improving their use of energy and reduce their energy footprint and business costs.

Results, impacts and achievements

Investments, energy savings and CO_2 emissions reduction

The table below summarises the project's achievements in terms of:

- Cumulative investment made by European SMEs in sustainable energy as a result of project activities
- Primary energy savings achieved by chemical SMEs involved in the project:
- Reduction of greenhouse gas emissions (tCO_2e/year)

	Cumulative investment (€)	Primary energy savings (ktoe/a)	Reduction of GHG emissions ($ktCO_2$/a)
Total	33,713,284	51.8287	186.82361

Workshop Statistics
Total Number of Workshops Group 1 partners: 32
Total Number of Workshops Group 2 partners: 16
Total Number of SMEs Participating in Workshops: 650+

Platform Statistics
Number of case studies: 50
Number of best practices: 20

Number of unique visits: 18,849
Total number of unique users: 12,538
Number of registered users: 670
Number of Newsletters published: 8

On-site Training Statistics
Number of SMEs Assisted: 63

Results of Actions Carried Out at Country Level

Group 1 Partners (Workshops, On-site Trainings, Communication, and Platform)

-Belgium - (essenscia)

Workshops
8 workshops were organised in Belgium: 6 in Flanders and 2 in Wallonia, a fair balance related to the distribution of the chemical industry in the country. In Flanders, the topics were subdivided in two categories: energy efficiency projects (good energy housekeeping, ISO 50001 and demand response, Economic evaluation of energy saving projects) and technology specific energy management (compressed air, heat and networks). In the Walloon Region, the workshops combined a morning session on energy management and technology specific energy optimization. In this region, the local government also participated at two workshops by presenting financing opportunities and local initiatives. Overall and when possible, the workshops were combined with a site visit. The workshops combined both theory and practical examples of best practices with the participation of larger chemical companies sharing their experiences. Each workshop was promoted on the SPiCE³ platform and through the essenscia newsletter. Invitations were also sent by email to member companies. After each workshop a report was published on the platform.

On average, there were 23 participants at each workshop and in total 48 SMEs participated. At the end of each workshop participants were asked to fill in a questionnaire covering content, accommodation and communication.

On-site Trainings
A number of successful on-site trainings were run in Belgium. Due in part to the other initiatives in the country also offering a similar service, which proved a challenge for essenscia in reaching and attracting SMEs to this part of the SPiCE³ project. However, using subcontractors for the on-site trainings ensured an excellent level of knowledge and technical experience was shared with those SMEs who profited from the trainings.

Platform and Communication
Essenscia contributed to the development of the website and in particular for the Flemish and French speaking Belgium specific pages on the platform. Feedback from users of the platform enabled Belgium to understand more the content needs of the target audience. During the duration of the project, essenscia had several meetings with local governments where the SPiCE³ project was discussed and broadly welcomed and appreciated. Additionally, essenscia cooperated with other energy efficiency initiatives in Belgium.

-Czech Republic – Association of the Chemical Industry of the Czech Republic (SCHP)

Workshops
In launching the project in the Czech Republic, SCHP found that many SMEs they spoke to lacked information and experience needed to undertake energy efficiency measures. SCHP reached out to inform companies of SPiCE³ and to explain the concept of the project and how it could help them. Given that the project was offering free-of-charge workshops and advice, SCHP managed to convince companies of the importance of energy-saving efforts.

By the end of the project 8 workshops with a participation of more than 150 companies had been organised. For a number of the workshops the day was broken down in to issue specific sessions. Firstly, participants were introduced to the positive aspects of energy efficiency. Following this, they were informed more on the project, including a presentation of the platform and available tools. Finally, the workshops looked at national and European legislation, energy management systems, case studies and financing investments in energy savings.

On-site Trainings

Through intensive promotion, SCHP were successful in organising 17 on-site trainings. SMEs were attracted to the trainings through promotion during the workshops, by email and telephone and also through an article published in a national newspaper. An energy expert took contact with each of the companies, who filled in a simple questionnaire looking at the type of energy the company used, the basic processes of production and other data. After this the expert visited the company for an onsite visit, followed by a brief report in which the expert defined the most significant savings opportunities, including a rough estimate of the anticipated savings in energy costs and greenhouse gas savings.

Platform and Communication

SCHP ensured information from the Czech Republic related to national initiatives in the field of energy efficiency were recorded on the platform. SCHP contributed national level information for each of the 8 SPiCE³ newsletters published. At the national level contact with SMEs and larger companies helped to generate interest and participation in the project workshops and onsite trainings. SMEs were initially hard to persuade that the project could assist them, and even that energy efficiency should be a part of their business plans, however, a great deal of momentum has been built on the issue which can be carried-forward in the future.

-Germany – German Chemical Industry Association (VCI)

Workshops

The VCI (German Chemical Industry Federation) organised eight one-day workshops all over Germany. The sites were Düsseldorf (25 SMEs participated), Hannover (20 SMEs participated), Ludwigshafen (30 SMEs participated), Munich (20 SMEs participated), Schkopau (25 SMEs participated), Magdeburg (20 SMEs participated), Stuttgart (40 SMEs participated) and Düsseldorf II (26 SMEs participated).

The workshops were closely organised with the local *Lander* associations and located close to the sites of large chemical companies as they hosted the workshops. The presence of large companies in a region attracts SMEs, so the workshop participants were often located close by.

Workshops invited regional speakers from energy agencies/companies and in general each followed a similar programme. The majority of workshops looked at the current legal situation for the SME in Germany; provided further information on the SPiCE³ project and tools; and gave an introduction to energy management systems, standards, certificates, opportunities, implementation and funding programs. Finally case studies, best practices and practical experiences from participants such as larger companies (e.g. Bayer, DOW, Wacker, Evonik) as well as SMEs were shared.

Some workshops also included more specific technical information related to energy efficiency in engines and pumps, refrigeration, compressed air, heat generation/recovery, and lighting systems.
Large chemical companies played the role of mentoring SMEs giving useful feedback during the workshops. The workshop in Ludwigshafen, was supported by four state ministries of economics and the one in Stuttgart was complemented by a short welcoming speech by the principal of the department Energy Efficiency in Homes and Businesses of Baden-Wuerttemberg.

On-site Trainings

The on-site trainings started at the end of 2013 and VCI organised 20 in total. SMEs were often attracted to receive trainings having participated in a workshop where companies were able to mark their interest on a feedback form which resulted in around 2-3 interested companies per workshop indicating their interest to be helped further.

The person involved from the company in the training was generally the technical manager, commercial manager, or a member of the board. The trainings themselves were perceived very positively by the companies.

Platform and Communication
Many German chemical companies which are members of the VCI are connected all over Europe and therefore they were glad to have a single online platform where they could find such a wide range of information about energy efficiency, regulations, legislation and support like funding for different countries. Feedback from other industries which had visited the platform was also positive. The platform is a well-known address for energy efficiency information in the chemical industry in Germany.

-Italy – SC Sviluppo Chimica (SC)

Workshops
SC organised 8 workshops at the national level, all of which were extremely well attended with on average 70 participants at each event. The majority of participants were from larger companies, though SMEs were represented. Local authorities attended some of the events particularly when the topic of the workshops included the Energy Efficiency Directive (which was a recurring topic at numerous events).

On-site Trainings
An external energy expert was assigned to provide on-site training to 20 SMEs, who themselves were identified and selected by SC Sviluppo. Some of the SMEs assisted were daughter companies of larger chemical companies, but due to the operational nature of their facility can be classed as small-medium sized companies. The trainings provided the companies with insight and valuable guidance on the current state of their energy efficiency potential. They were recommended to follow the SPiCE³ platform best practice section, and encouraged to look at the appointment of an energy management system in their organisation. The assistance consisted of a half-day site visit by the energy expert, and afterward the expert reported back to the SME with an analysis report.

Platform and Communication
SC Sviluppo promoted the project through a number of communication actions. In particular a SPiCE³ specific section on their website was constructed, 3 articles were published in the newsletter of SC Sviluppo's mother organisation Federchimica. Likewise, and brochure was created in Italian language dedicated to the project. All such activities helped in drawing a great amount of interest in companies to participate and profit from the services being offered through SPiCE³.

Group 2 Partners (Workshops, Communication, and Platform)

-Finland – The Chemical Industry Federation of Finland (Chemind)

Workshops
Chemind worked closely together with a subcontractor Motiva (a company promoting efficient and sustainable use of energy and materials in Finland), to ensure that the workshops were delivered to the needs of the target audience. The partnership with Motiva was crucial, when planning and putting together the technical details of workshops (which attracted more than 110 participants). It was evident from the satisfaction rates from participants (which were on average above 88%) that this was very successful approach.

Chemind organised a joint workshop with IKEM (Sweden) which was a great success and good example of sharing best practices between two country projects.

Communication (tweeting) activities during the workshops and follow-up web articles were well-received well and gave extra visibility to the project. The willingness of larger companies to participate formally and informally in the events was a key success as networking between larger and smaller companies was valued greatly.

Platform and Communication

Chemind gradually built up a well-functioning Finnish section of the platform, which is widely appreciated among its member companies and especially with other stakeholders such as national and local authorities.

Finland contributed to case studies, tools, information on funding, good practice and advised on best practice guides. A good amount of material was available from other sources that was readily adapted in to the SPiCE³ platform. This is particularly true for industry case studies that have been highly regarded and a source of inspiration for smaller companies.

-Netherlands - Association of the Dutch Chemical Industry (VNCI)

Workshops

VNCI's first workshop (which was attended by 12 companies) covered the purpose and benefits of the SPiCE³ project and platform. The topics for the remaining 3 workshops were based on the feedback received from participants at the first. The second workshop focused on efficient motor-drives and welcomed 17 companies. For both of these workshops VNCI cooperated with RVO (the national energy agency of the Netherlands) in the organisation and in securing the right technical experts to present /discuss on the topic of motor-drives.

VNCI organised another 3 workshops together with regional partners in the Netherlands. Because of this cooperation, and because the events were carried-out in specific strategic regions the workshops were all very well attended and companies were able to network with other businesses in their direct neighbourhood.

All three of the workshops focused on 'best practices and operational experience' exchange. However, at the first of this series of workshops (held in Rotterdam) the focus was on new technologies related to high efficiency and energy efficient equipment. This particular workshop was organised by VNCI, Deltalinqs, PlantOne and welcomed 30 participants.
The second regional workshop was held in Groningen in cooperation with SBE (Samenwerkende Bedrijven Eemsdelta) and was attended by 28 participants.

The final workshop took place in Geleen in the west of the country. It was organised in cooperation with Chemelot (an industrial park housing many chemical companies) and welcomed 36 participants.

A good number of larger Dutch chemical companies contributed to the SPiCE³ workshops through their attendance at events, and by sharing advice and best practices. Regarding other sectors, VNCI invited companies from the NRK (Dutch federation of Rubber and plastics) who also agreed to share information with their members about the SPiCE³ platform.

Platform and Communication

VNCI actively participated in the development of the PEEK section and played an important role in the development of the 'Resources/Best Practice' section, as well as contributing in other areas. The SPiCE³ website has been well received in the Netherlands. Overall companies approached to evaluate the platform indicated they were content and declared they consider visiting it again.

-Poland – Poland Chamber of the Chemical Industry (PCCI)

Workshops

PCCI organised 4 country workshops which were attended by more than 150 companies. Two of the workshops were sponsored by chemical companies and the remaining ones by PCCI. The workshops differed in content. For example, one was focused on energy management, and another on practical information. PCCI learned that workshops focused on practical information and legislative aspects are the most popular in SMEs. In total the workshops welcomed 48 SMEs.

The first workshops organised started with more general topics of interest, whilst the last workshop was devoted to practical aspects of energy efficiency. Overall the workshops covered a variety of issues including legislation, management systems in energy, energy efficiency in practice and, sources of financing activities in energy efficiency. Two of the workshops were organised in cooperation with large chemical companies – acting as mentors to the participants. Likewise, PCCI had very valuable support from the Ministry of Economy. After each of the events, a survey was distributed to the companies to ask them their satisfaction level and the interest in the topics.

Platform and Communication
PCCI worked to promote the platform including through the preparation of several media articles. Also the PCCI had meetings with the Polish Ministry of Economy and sought to establish close cooperation with the national 'CO2 Forum' and 'FOEEiG' (Polish Forum on Electricity and Gas) - two organizations playing important role in Poland due to their scope of activity in a number of PCCI member companies. PCCI also had good cooperation with KAPE (National Agency on Energy Conservation).

- United Kingdom – Chemicals Industry Association (CIA)

Workshops
CIA organised 4 workshops which were attended by over 150 participants. The willingness of larger companies to participate formally and informally in these events was a key success as networking between larger and smaller companies was valued greatly.

The 4 workshops were run in the two main regions of chemical industry activity – the North West and North East of England. The first set of workshops in these two regions included talks and exhibitions on tools techniques and case studies given by larger companies who had experience in these areas as well as specific energy and equipment specialists.

The second set of workshops in each area was more practical and participative (and based on feedback from the first workshop focused on the basics). Topics included energy management systems, auditing and energy Kaizens (how to make the most of employees to improve energy efficiency). These workshops were run with the assistance of CIA's member Cofely. Feedback from the first event also showed an interest in ISO 50001, which was subsequently included as a topic.

Platform and Communication
Due to their existing work on energy efficiency, CIA were able to supply a significant amount of information for the platform on case studies and the general regulatory regime.

The English version of the platform has proved very successful with 'hits' from the UK being at consistently high level. CIA and some of its members have contributed case studies, tools, good practice and advised on best practice guides. Industry case studies have been highly regarded and considered a source of inspiration for smaller companies.

Group 3 Partners (Platform, and Communication)

-Bulgaria – Bulgarian Chamber of the Chemical Industry (BCCI)

The BCCI provided content to the SPiCE³ platform and contributed to its promotion. They used the platform as a way to inform their members about new energy efficiency legislation, funding, training possibilities in Bulgaria and as a means to promote and report on the different news and energy events in Europe and Bulgaria.

The BCCI found that the only way for Bulgarian SMEs to effectively profit from the platform content was to translate most of it in to Bulgarian language and a lot of effort and resources were put in to achieving this.

Contributions were made to the platform by providing versions of the 3 guidebooks developed under the CARE+ project and were relevant for the SPiCE³ project. BCCI also submitted two case studies of successful implementation of energy efficiency in Bulgarian chemical companies, along with an overview of the legislation in Bulgaria related to energy efficiency. Information on financial and funding sources for increasing energy efficiency was likewise provided.
BBCI also built a strong network on energy efficiency and also organised a workshop, combined with on-site trainings at their own expense. Together with HACI (GR), Federchimica (IT) and in cooperation with Cefic, they organised a regional workshop in Thessaloniki. The aim was to promote the SPiCE³ platform, but also to exchange best practices and present the ISO 50001 standard to the attendees.

- Greece – Hellenic Association of Chemical Industries (HACI)

HACI's work in the project was focused on the platform, and communication. The Greek section of the platform was visited by more than 300 Greek SMEs. A fair amount of work was spent in translating other topical sections of the website from the local language in to Greek for the benefit of national companies.

Information about the platform and its capabilities were communicated to HACI members and other SMEs of the chemical sector which are not members of the Association. This has been achieved through emails, direct contracts and workshops at the national level. For example, direct mails shots were sent to some 2500 contacts in the HACI database.

It is often the case that chemical industries communicate with HACI asking about energy management systems (related to ISO 50001 and DIN EN 16247-1) and looking for trainings about energy efficiency.

To complement this, HACI and BCCI organised a workshop in Thessaloniki on 2 June, 2014. The workshop 'Energy Efficiency Management in Chemical Industry Sector', welcomed industry professionals from Greece and Bulgaria who were informed about the SPiCE³ platform, EU energy policies, SPiCE³ approach, 2030 energy roadmap, energy management systems and useful tools derived from the project.

HACI also sought through the project to also establish a link with local authorities responsible for industrial energy policy and energy efficiency. In May 2014 HACI organised an open meeting with prospective members of the European Parliament where energy efficiency policies were at the top of the agenda. As a result of the meeting, the Minister of Environment, Energy and Climate Change announced an initiative to reduce energy costs for Greek enterprises in the context of the development of the European energy and climate policy.

-Sweden –Innovation and Chemical Industries in Sweden (IKEM)

IKEM is a well-known and established organisation and trusted partner (to government, public authorities, etc) on issues regarding energy in Sweden. During the SPiCE³ project, IKEM has been active in the discussion on the development of existing and future programs for energy efficiency in both large energy intensive process installations and SME. In that context IKEM informed about the SPiCE³ project and the efforts done by the wide range of countries within the project.

IKEM found that interviewing SMEs for case studies about their experiences on energy efficiency activities and describing the main hurdles and positive take-aways from those, has been a good way to spread the word about SPiCE³ and energy efficiency in a national policy angle. These proved popular for Swedish companies.
Regarding communication, in cooperation with the Linköping University and the Swedish Energy Agency IKEM supplied important tools and contributed to the best practices section of the platform.

IKEM also used its database of 1400 member companies to promote the project and the newsletter as well as posting on the IKEM home page and presenting SPiCE³ through a dedicated section on the website.

Exemplary Cases from SMEs Assisted During the Project

-Worlée-Chemie GmbH

Worlée is a paint and coatings supplier that develops, produces and distributes resins, binders, additives, pigments and raw materials for the cosmetic industry. With three sites in Germany, the company has continually sought to reduce its energy consumption in every business area of the company. During the last 10 years, they have been able to increase energy efficiency by 20%.

Worlée's energy management has been certified according to ISO 9001, quality management ISO 14001, environmental management ISO 50001 and energy management BS OHSAS 18001. There have also been a significant number of investments, in for example, compressed air, heat recovery and process heating.

Its site at Hamburg, Lauenburg, Lübeck in northern Germany, counts 240 employees and has implemented the following energy efficiency measures:

Thermal Insulation reactor heads and installation of high-speed gates at the warehouses

- Investment: € 140,000
- Energy savings: 3,456,000 kWh/a
- Heating energy savings: 18%
- Energy cost savings: 103,680 €/a
- Return on equity: 74%
- Additional effects:
- Improved working conditions and occupational safety

Renewable energies

- Biogas
- Biomass-kettle
- Photovoltaics
- Solar thermal (with storage)
- Geothermal (by use of heat pump)
- Small wind turbines

Combined heat and power

- High energy efficiency
- Very reasonable with regard to climate protection
- Legal framework hinders development of CHP in Germany in case of not optimal heat use

-GSK Pharmaceuticals

(Responsible Care Awards 2013 - Energy Efficiency Award Category Winner)


The GSK Pharmaceuticals site in Irvine, Scotland – the largest energy and water consumer of the group's 80 manufacturing sites worldwide – operates large scale fermentation, extraction and solvent recovery processes to produce antibiotics. The 2020 goal of the GSK site – a large energy and water consumer company – is to take it off grid. In this regard, investments in renewable technology, continued implementation of energy efficiency projects and other initiatives all play an important part. Some 50 projects have been implemented since 2009, and in the past five years, the site's sustainability programme has delivered a 24% reduction in carbon from energy. Currently £ 20 million is being invested in two major projects: wind turbines to supply a projected 12% of electricity needs; and anaerobic digestion of fermentation waste which will produce methane to power a combined heat and power plant and take waste water treatment off-grid.

The company is utilising a tri-pronged plan focusing on carbon reduction, environmental stewardship and regulatory/cost benefits. The Irvine sustainability programme was introduced in 2008 and performance has improved on many fronts. In the period 2006 to 2011, CO_2 emissions have fallen by 24% with around 50 projects implemented since 2009. In the same period (2006-2011), water use is 26% lower, volatile organic compounds down by 64%, landfill has been reduced by 76% and there has also been an impressive 99% cut in hazardous waste.

The company has also completed the construction phase of its initial renewable technology projects – the installation of a £ 10 M anaerobic digestion plant and the first of two 2.5 MW wind turbine generators also costing £ 10 M. It is forecast that the anaerobic digester will save 6,000 tonnes of CO_2 and supply 5% of the site’s electricity requirements. When the planned four wind turbines are running they are expected to save 12,000 tonnes of CO_2/year and deliver 12% of the site’s electricity.

- Emerald Kalama Chemical BV
(Responsible Care Awards 2014 - Energy Efficiency Award Category Winner)

Emeralda Kalama Chemical BV, a business group of Emerald Performance Materials, is an organisation focused on toluene oxidation chemistry in Rotterdam, The Netherlands.

Google Maps® view of the company's site:

Emerald Kalama Chemical manufactures a complete line of food and beverage preservatives, flavour and fragrance intermediates, plasticisers and other initiatives – all with a focus on quality, reliability and innovation. Emerald Kalama Chemical is the leading global producer of benzoic acid, benzaldehyde, benzyl alcohol, sodium benzoate and performance additives such as K-FLEX® dibenzoate plasticisers. The company's business is focused on 3 product segments:

- Benzoates and Intermediates
- Aroma Chemicals/Flavour and Fragrance
- K-FLEX® Non-Phthalate Plasticisers

Emerald Kalama Chemical BV, together with Rotterdam-based grid manager Stedin and waste processor and energy supplier AVR, has completed a key project in the new energy cooperative supporting the Rotterdam Climate Initiative.

The project aimed at helping to develop an energy-efficient grid for the city of Rotterdam that distributes steam generated from non-recyclable household waste rather than fossil fuels. This supplies much 'greener' high-pressure steam to the company's toluene-based production processes. The construction of the project started in the end of 2012 and finished in April 2013. The steam pipe is in operation since May 1st 2013.

The steam network began operating in 2012 and has enabled users to:

- Reduce their carbon dioxide emissions by 25,000 t/a
- Cut the amount of natural gas they burn each year by 15,000,000 cubic metres
- Potential further reduction of CO_2 emissions by up to 400,000 t/a

The project had a collaborative nature, which combines energy exchange between industrial partners and strong use of industrial ecology by harnessing waste as a resource.

-Huntsman Pigments
(UK Low Carbon Award Winners 2011)

Huntsman Pigments is a division of Huntsman Corporation, a global manufacturer of differentiated chemicals. The division operates a titanium dioxide manufacturing site at Greatham, Teesside, UK.

Manufacture of titanium dioxide pigments is an energy-intensive process and to compete in the global market, UK manufacturers must ensure their energy use is as low as possible. Many of the tools and techniques used by Huntsman are applicable across all chemical operations. Key to their success has been: management backing and setting a strategy and goal setting, clear assessment of where energy is used and what potential savings where achievable, prioritisation of projects and involvement and buy-in of all staff.

Energy consumption has been an important issue at the Greatham plant for many years. Over the past decade a rigorous management process has been in place, which has reduced the specific energy consumption for the site by 30%.

In the late 1990s the EU IPPC legislation set best available technology (BAT) targets for the titanium dioxide industry which have acted as key drivers for the energy management of Greatham. The Best Available Technique (BAT) target for the chloride process operated on this site was set at 16-20 GJ/t, and by 1998 site specific energy consumption was above the range.

The site introduced a strategy that would address the issue of energy costs and BAT compliance and by the end of 2002, specific energy was below the 20Gj/t threshold.

This strategy included:

- Appointment of a site energy manager, part of the site leadership team
- Introduction of a multifaceted specific Energy Reduction programme

As a result of the strategy, in 2003 the site arranged a Government funded audit conducted by external consultants Enviros. This raised a series of recommendations that led to projects and improvements.

Some of the actions involved simple common sense issues that were addressed by day-to-day housekeeping practices. The major project options were evaluated using a 6-sigma technique, a methodology that has been developed across Huntsman and which is still used today at Greatham.

Networking between divisional and site expertise has been critical, and it has helped greatly to have an integrated supporting management structure. Energy, specifically steam, gas and electricity, has always been a significant component of the site budget. However, consideration of other sustainability parameters such as environmental impact and efficient use of resources has increasingly featured in recent years.

Huntsman Pigments introduced an enhanced sustainability programme in early 2010. The programme was supported by the company president and the divisional leadership team and is integrated as a key element of our business strategy.

At the core of the programme is a sustainability framework which aggregates different activities into four common themes, described below, that help the company to prioritise and focus its work and guide its choices.

1. Being responsible
Ensuring that associates, local communities and wildlife habitats are treated with respect

2. Reducing our carbon footprint
Making the best use of the energy we consume

3. Minimizing waste and use of resources
Reducing the use of raw materials and efficient use of resources

4. Innovating
Helping customers to reduce energy and improve their own sustainability performance

Carbon footprint and energy reduction are critical components of the framework which has helped reinforce the work conducted at Greatham. For example, a carbon footprint evaluation for the entire value chain of the site (cradle to gate) was carried out in 2010. This places the business in an excellent position to improve further - not only within its processes, but also upstream with the company's suppliers.

The site has been invited to participate in a number of externally funded and supported projects that bring mutual benefits, for example:

- Waste heat boiler project that won an award
- One North East supported a programme involving the Carbon Trust to use Greatham as a pilot site to reduce power from waste heat

Best Practices Available on the SPiCE³ Platform

There is a large number of reports and articles on the best techniques and methods for energy savings that are relevant for the chemical industry. The SPiCE³ Platform provides a way to get easy access to a large number of these documents through its “Best Practice” section.

The “Best Practice” section gathers information from different national authorities, large chemical companies and sector-specific European associations.

Visitors to the platform are provided with detailed articles for each best practice and links to available related documents. The information is organised by topic and portrays the most important facts and “common truths” of a specific technology or technique.

By the end of the first 27 months of the project, the number of technology-specific best practices available on the platform amounted to 20:

Discover Best Practices for operations within your company:

Cleaning in place	Insulation	Pumps
Climate control	Lighting systems	Solid drying
Compressed air	Liquid/solid separation	Steam systems
Cooling systems	Membrane Technology	Unit Operations and Equipment
Distillation	Monitoring energy use	Vacuum systems
Energy management	Motor drives	Ventilation and dust control
Heat recovery	Pinch analysis	

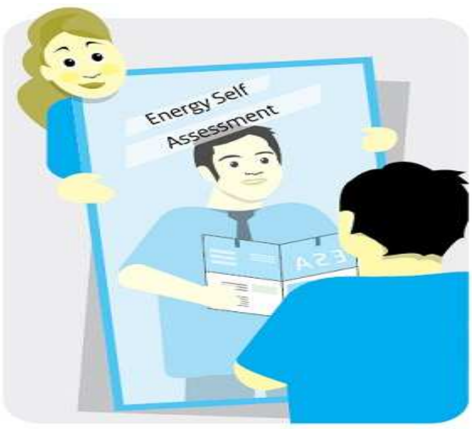
In addition to this, the section offers guidance documents on the following issues:

How to convince upper management to invest in energy efficiency
Often, industrial facility managers must convince upper management that an investment in system efficiency is worth making. The problem is that sometimes communicating this message can be more difficult than the actual engineering behind the concept. A corporate audience usually responds more readily to cash flow impacts than to a discussion of best efficiency points. By adopting a financial approach, the facility manager can relate system performance and efficiency to corporate goals and "win over" the senior management who make the final decision on capital investments in system upgrades.

In order to overcome the obstacles often encountered in the process of convincing upper management that a given investment in energy efficiency is worth making, you should consider the following points:

1. Gain some insight on/understand corporate priorities
2. Measure the cash flow impact of the system efficiency
3. Present the finances of system improvements
4. Relate system efficiency to corporate priorities
5. Approach: how to make a proposal attractive

How to reduce energy costs in a structural way
Developed by SPiCE[3] partner RVO, the Energy Self Assessment (ESA)® is a powerful and cost-effective tool for SMEs. It leads them through the analysis of their own energy



performance and helps them to determine their energy points for further improvement related to: policy, organisation, performance management, communicating, investment and training.

RVO's tool addresses the organisational aspects of a company's energy management system. Furthermore, ESA helps SMEs identify energy saving measures that could be implemented including costs and return on investment. An external facilitator normally provides substantial added value, especially when a company executes the ESA for the first time, as they streamline the assessment process and brings in insights from other assessments.

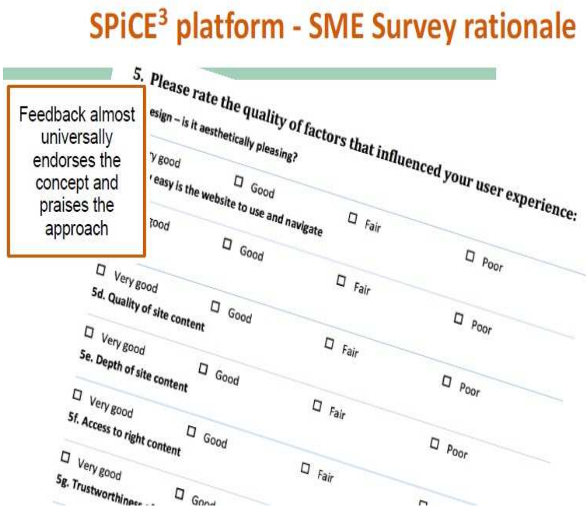
For both SMEs and large companies, ESA results in improved insight in to their organisation of energy management, and realisation of more energy saving measures and projects. There is money to be made in undertaking energy savings projects, and the ESA can show how such measures can be in line with a company's strategic business needs and requirements.

Feedback from SMEs

Workshops & On-site trainings
The workshops and on-site trainings were an essential part of the project as they allowed the partners to reach out to SMEs and large companies, establish personal contacts, exchange views and to overall strengthen the links between companies within the EU chemical sector.

These contacts with SMEs helped to generate interest and participation in the project and, most importantly, enabled partners to better understand the needs of the target audience. In some cases, national associations had meetings with their local governments where the project was discussed and broadly welcomed and appreciated. In some other cases, partners cooperated with other existing energy efficiency initiatives in their countries.

Questionnaire: Asking SMEs about their experience on the Platform
Since the beginning of SPiCE[3] the project partners have honed their communications strategies and efforts in achieving the objective of engaging as many SMEs as possible. Bearing in mind this imperative a survey template was prepared and sent to a handful of SMEs in each partner country.



The idea of the survey (or questionnaire) was to evaluate the usability of the website from the perspective of the SME, focusing on their experience as a user of the platform as well as the reasons and likelihood of them coming back to the site. This simple but useful exercise was designed to provide the project partners with a better understanding of the project website's strong and weak points, and most importantly, which are the areas that could and needed to be improved.

The questionnaire was a positive experience. Undertaken by the country partners (totalling 27 filled-in surveys), it helped the partners to understand what was working well for the SMEs and what further could be done in order to deliver the project's objectives.

European Level Events

Three events were organised during the course of the project. The events provided a great opportunity for different stakeholders to get to know each other, network, exchange views and discuss experiences.

The first took place in December 2013 in Amsterdam and served as a kick-off launch event for the www.spice3.eu platform. Organised in cooperation with Responsible Carethe event was attended by more than 80 participants from industry, governments and media and featured a high level speaker from the Dutch State Secretary for Infrastructure and the Environment, and a Dutch Green MEP.

The SPiCE³ launch conference in Amsterdam also put great emphasis on sharing best practice from the Responsible Care award winners. In addition to presentations and interactive sessions, all the Responsible Care Awards winners demonstrated their good practice showcases. Videos are available both on the Cefic and the SPiCE³ website and news stories can be found about both – the SPiCE³ EU level event and the special Responsible Care Awards ceremony at the Cefic annual general assembly in Munich, October 2013.

In June 2014 Responsible Care and SPiCE³ held a joint Forum to show how Responsible Care can better address energy efficiency through the SPiCE³ initiative. Experts from Poland and Germany provided local insight into their work with SPiCE³, and showed how SMEs often lack knowledge and financing to become more energy efficient. They argued that sharing of best practices between both large and smaller companies can be a compelling way to inspire other companies to invest. At the Forum first discussions were held between SPiCE³ and water management initiatives 'Water Matters!' about how it might be possible in future to integrate the initiatives in to Responsible Care.

Hosted at the Cefic offices in Brussels in May 2015, the third EU-level event provided an opportunity for the project partners and audience members to share experiences with an array of expert speakers coming from external organisations such as the European Commission, UEAPME, Eurochambres, BASF, and Akzo Nobel. Many insights were offered in to what a SME in Europe looks like and the limitations such small companies often have in terms of financial and human resources. Discussion touched on how SMEs need trusted and tailored assistance to help them become more energy efficient. Ultimately, a clear message which came through was that in order to encourage companies to become more energy efficient they have to be shown the positive financial benefits of doing-so.

Conclusions from the SPiCE³ Project

SPiCE³ has delivered added-value support to the European chemical sector in making companies aware of the importance of energy efficiency and in providing tools which help in the implementation of energy saving actions:

- SPiCE³ delivered a project by the industry for the industry which combined a genuine bottom-up approach with hands-on support directly to companies through workshops, on-site trainings and EU-level events
- The unique and vital SPiCE³ platform acted as a support resource hub which brought to life and gave exposure to the work carried out during the project, at the local and EU level.
- The project's online platform proved to be an essential source of guidance for companies seeking to tackle energy efficiency: it has made it possible to showcase industry success stories and present best practice examples

- SPiCE³ has effectively helped the EU reach its energy targets by 2020 and overcome the present challenges in terms of energy security
- The project has encouraged SMEs to become more energy efficient: being more energy efficient means lower energy consumption, which ultimately translates itself into fuel savings and CO_2 emissions reduction
- SPiCE³ has raised the visibility of the consortium as trusted partners to companies seeking to become more energy efficient
- Through its support to companies in energy efficiency matters, the project has led to cost and energy savings in the long-term, boosting the competitiveness of the sector
- Embarking on SPiCE³ ensured the sector could build on the success of CARE+. This helped ensure that the message of the importance of energy efficiency is still being delivered, and that more and more companies are looking to achieve efficiency measures

There is still potential for further energy efficiency improvements in many chemical companies across the European Union and it is therefore important to continue supporting their efforts. This is the main driver behind the commitment from project partners to continuing actions under SPiCE³ far beyond the project's formal period (at least a further 2 years). This project was initially launched in order to begin a process of deep and long-term improvement in the sector and it is not only coherent, but also beneficial for the industry that it is extended.

It is foreseen that the core of the project will be maintained and enhanced (i.e. support to the EU chemical industry sector in becoming more energy efficient), whilst a new dimension would be added, to use the SPiCE³ online platform as a vehicle for the proactive promotion of the achievements made by our industry in the area of energy efficiency in order to share our good practices and case studies with other industries and the general public.

With two successful projects under its belt, Cefic and its partners feel confident to carry the message of energy efficiency forwards and will strive to ensure this in the long-term.

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Drives 2

Efficiency measurement campaign on gearboxes

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Abstract

The last decade, new concepts of electrical motors with promising efficiency have entered the market. Such an electric motor is connected to the load machine often by means of a transmission system. Considering the energy efficiency of transmission systems, there is a lack of available information on the market. In contrast to electrical motors and drives, there are very few mandatory regulations imposed on these components. Information on efficiency can be occasionally found in catalogs but accepted test procedures are not available. As a result, the reliability of these efficiency values is low and comparison between brands and technologies is impossible.

Regulation on energy efficiency on the other hand evolves towards a total system approach. The new European fan directive 327/2011 is an example of such an approach where overall efficiency is considered. Information on the efficiency of mechanical transmission components such as gearboxes and belt drives will be required to assess and optimize the overall system efficiency.

Due to the lack of reliable information on energy efficiency of these components, a measurement campaign was set up to test a series of gearboxes. This paper discusses the results of this measurement campaign. Because of the wide variation in types and sizing, the measurements where done on a flexible designed input-output gearbox test bench [1].

Available information on gearbox efficiency

Standards concerning measurement methods and energy efficiency of electrical motors have a long history. In previous research projects at the Ghent University the knowledge of speed regulated motor efficiency was expanded by measurements in the entire working range and made visible by means of iso efficiency maps [2,3]. Nowadays, some innovating manufacturers already make this efficiency information available for some motor types in the form of efficiency maps [4].

In contrast to this, the availability of efficiency information on commercial gearboxes is extremely limited. Information on the mechanical and/or hydraulic losses of a single gear wheel pair is available [5-8], but a complete gearbox consists of several gear pairs and other parts. This means the total losses are a combination of different losses such as bearing losses, seal losses, churning and windage losses as illustrated in figure 1.

Few research projects and therefore few publications pay attention to the total gearbox efficiency. Moreover, the gearbox manufacturers manuals provide few efficiency information. In most catalogs efficiency is generally stated as depended on the number of gear stages. In this way one efficiency value is given for a whole range of gearboxes. For example, gearbox catalogs [9-12] states that a helical and parallel shaft and a helical-bevel gearbox have an efficiency of 97% when they have a 2-stage setup. There is no information on the effect of the ratio, the rated power or the speed and load of the gearbox on the efficiency. Only worm gear units form an exception as their nominal efficiency is given as a function of the power and ratio. However, even for these gearboxes, the effect of the torque and speed on the gearbox efficiency is not mentioned.

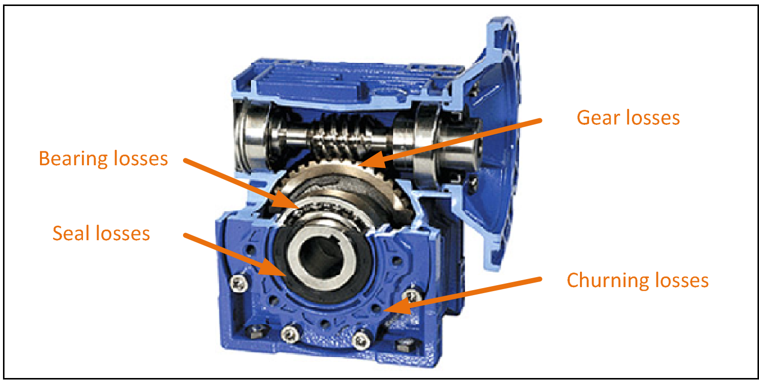

Figure 1: Typical gearbox losses

Another issue about the catalog efficiency is that no efficiency measurement procedure information is given. Some catalogs mention that the nominal efficiency is reached when the gearbox reaches its nominal operating temperature, but a value for this temperature, which is highly dependent on the surrounding ambient temperature, is not given. Various contacts with different manufactures show that the efficiency information is obtained in different ways. Some use measurements while others use mathematical models to determine efficiency values.

The lack of efficiency and measurement information on gearboxes can be partially explained due to the absence of any efficiency standard or measurement standard. In contrast to numerous standards on electrical motor drives no applicable standards can be found for gearboxes.

To optimize the total drive train efficiency, the efficiency values or losses for each part of the drive train need to be known. Because manufacturers use different methods to determine the gearbox efficiency a designer cannot objectively compare different brands. To learn more about the gearbox efficiency in different load points and for different gearbox types a flexible gearbox test bench was designed [1].

Gearbox test bench and measurement flowchart

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. With the gearbox test bench it is possible to test a large scope of these types in a power range up to 15kW and a load torque up to 1000Nm.

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 ‘dual range’ torque sensors with an accuracy of 0.1% full scale. The speed is measured using incremental encoders. The measurement principle is shown in figure 2.

The aim is 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. The flexible design of the test bench allows different shaft heights and dimensions of the test gearbox. The drive side can rotate 90 degrees to test straight and right-angled gearboxes. The testing room is temperature controlled to stabilize the temperature dependent losses. With the gearbox test bench it is possible to drive gearboxes up to 15kW and 3000rpm at input and load the gearbox up to 15kW and 1000Nm at output.

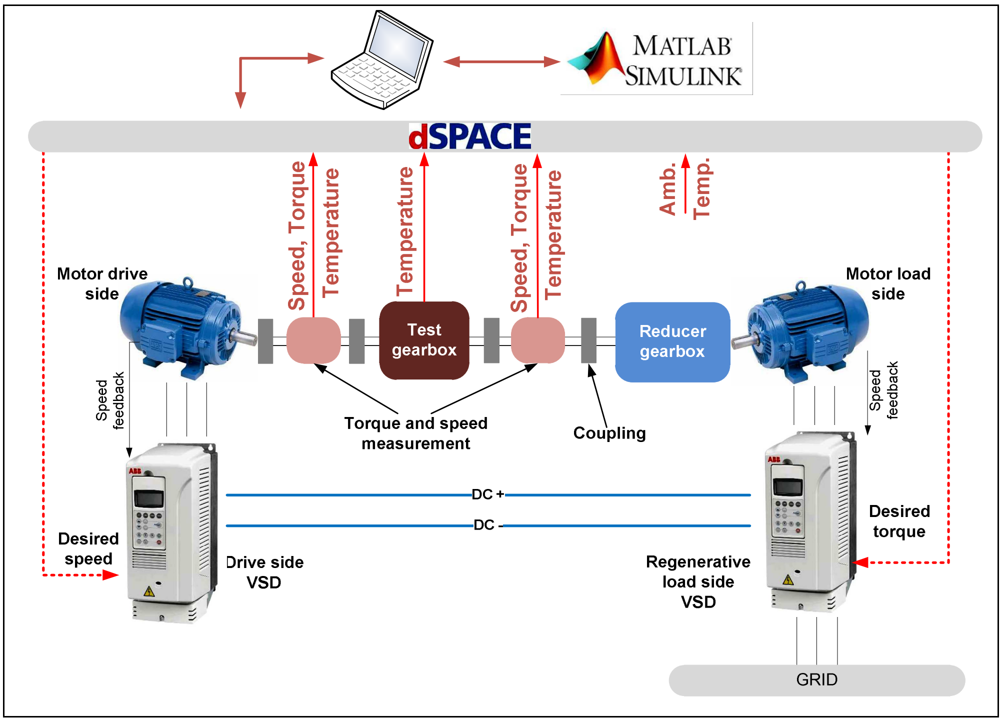

Figure 2: measurement principle gearbox test bench

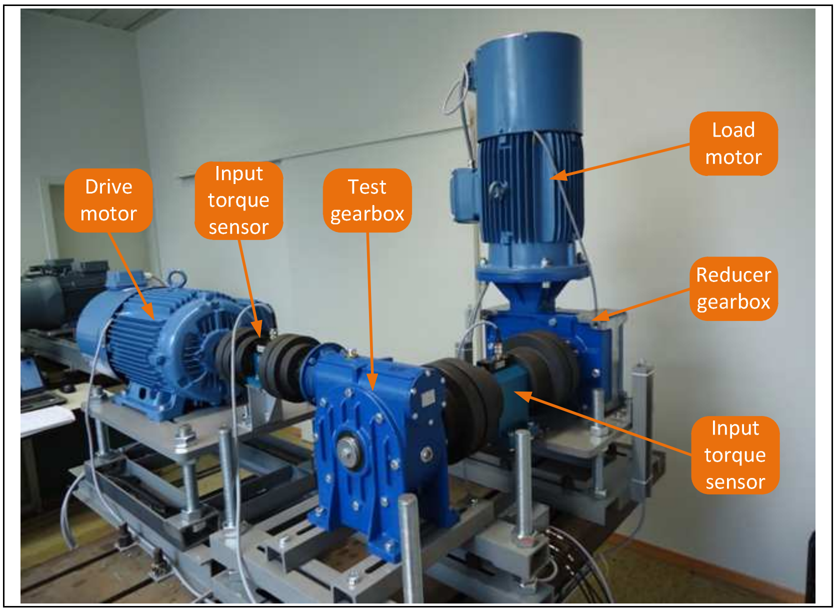

Figure 3: Mechanical design gearbox test bench

As stated before an efficiency measurement standard does not exist for gearboxes. In order to guarantee reproducibility and obtain accurate measurements, a measurement protocol has been setup. After mechanical installation and alignments, the gearbox is tested in three steps as shown in figure 4.

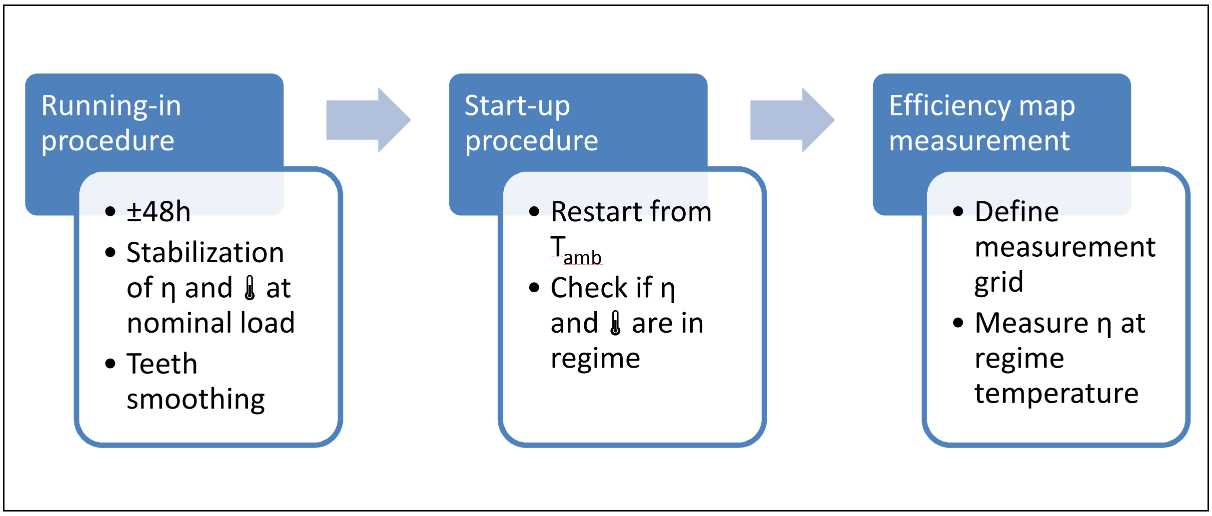

Figure 4: measurement protocol flowchart gearbox test bench

During the initial step the new gearbox is driven and loaded at nominal conditions until it reaches stabilized efficiency and temperature values. By this test, the gear teeth get smoothed. Most gearbox catalogs indicate that a gearbox reaches its nominal efficiency after 24 to 48 hours. Thereafter, the gearbox is stopped and cooled down until ambient temperature before being driven and loaded again at nominal load. If the same stabilized efficiency value is reached during this second test this means the gearbox has run in completely. This step insures the repeatability of the measurements in further steps. In the last step the efficiency is measured in the total working area by means of a predefined measuring grid. The test room temperature is controlled and monitored and during all steps, the device temperature is also monitored because of the high impact of temperature on the losses.

Measurement campaign

Overview

During the research project, 13 gearboxes have been measured resulting in many possible comparisons. The basic properties of each gearbox are summarized in table 1. In this paper the most important results will be discussed.

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	Straigh t	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 (kW)	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
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%

Catalog versus measured efficiency

In figure 5 the catalog efficiency, measured efficiency at rated power and the difference between them are displayed for all the tested gearboxes listed in table1. The depicted efficiency values are measured at nominal speed and torque.

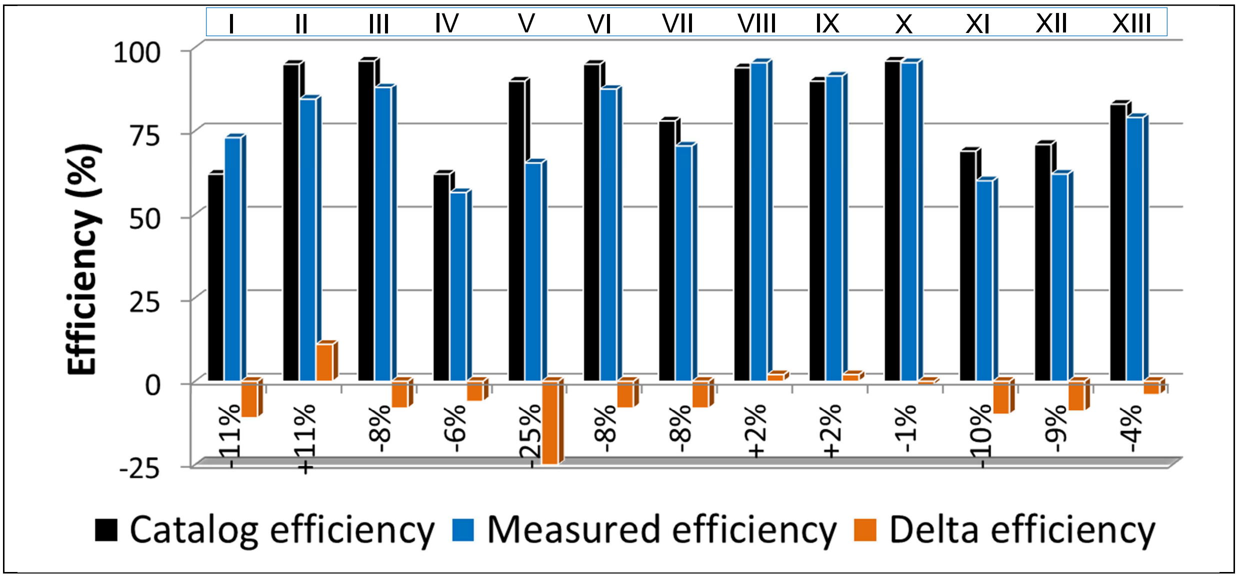

Figure 5: comparison of catalog efficiency versus measured efficiency at rated power for 13 tested gearboxes (points efficiency).

The comparison shows a significant difference between the efficiency mentioned in the catalogue and the measured efficiency for almost all the gearboxes. In most cases the catalogue efficiency is higher than the measured efficiency. It is difficult to determine straightforward conclusions because of the large variety in gearbox parameters. Gearboxes VIII, IX and X show the smallest efficiency difference. These gearboxes have a low ratio and high power compared to the other gearboxes in the measurement set. For higher ratios, such as gearboxes III to VII, the efficiency difference is about 8%. In this comparison the type of gearbox (straight or right-angled) or technology does not seem to have an influence on the difference between catalog and measured efficiency.

The difference between catalog and measured efficiency can be explained by some factors. Since there are no measurement standards, the measurement conditions of different manufactures can vary, which leads to differences. Some manufactures use models to estimate the efficiency, others use measurements and calculations. This means comparing gearboxes from different brands is difficult. To confirm our statements and to learn more about these differences some manufacturers were contacted during the project. In figure 6 the difference between stated catalogue and model based calculated efficiency is shown for a 200Nm and 800Nm gearbox range based on internal manufacturer information.

With increasing ratio the efficiency difference between catalog and model based efficiency enlarges for both gearbox power ranges. When the torque, which is proportional with the power, increases the efficiency difference drops. When the ratio is low, the catalog and model based efficiency match well. These conclusions also match the test bench results during the measurement campaign in the research project (table 1).

It is remarkable that the efficiency data in catalogs (green line) is not equal to the more correct model based efficiency although it is known by the manufacturer. Because there are no standards the manufactures are not obliged to state how the efficiency is measured or obtained so they can choose themselves. From a commercial point of view, manufacturers are reluctant to indicate lower efficiency values.

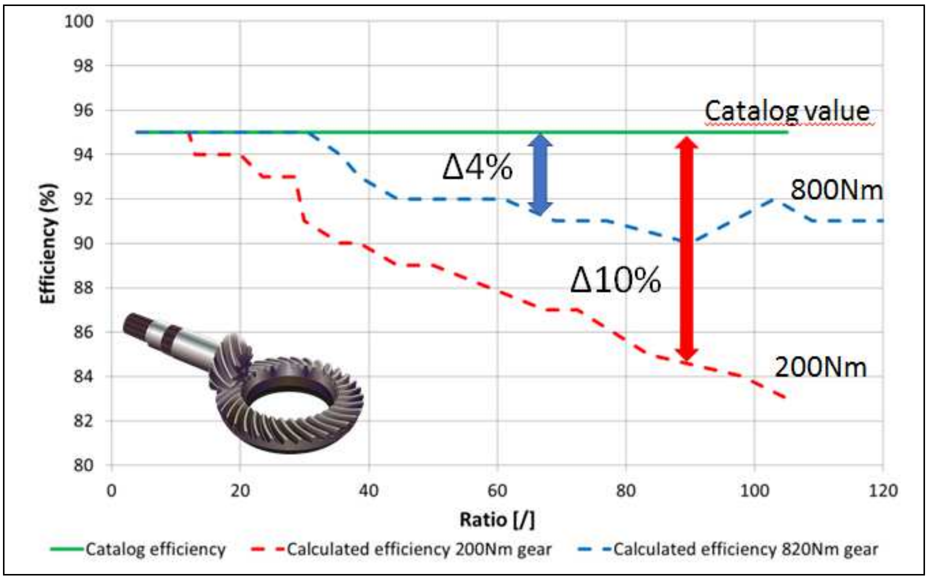

Figure 6: comparison between stated catalog efficiency versus model based calculated efficiency helical bevel gear

Efficiency of gear boxes in part load conditions

In gearbox catalogs, the efficiency value is only stated at nominal conditions. Figure 7, which is an efficiency map of a tested helical bevel gearbox, clearly shows that the efficiency is not equal in the entire working area. Particularly the load torque has an impact on the gearbox efficiency. The highest efficiency is measured at the nominal load torque. When the load decreases the efficiency decreases too. Speed variations have a rather small impact on the gearbox efficiency.

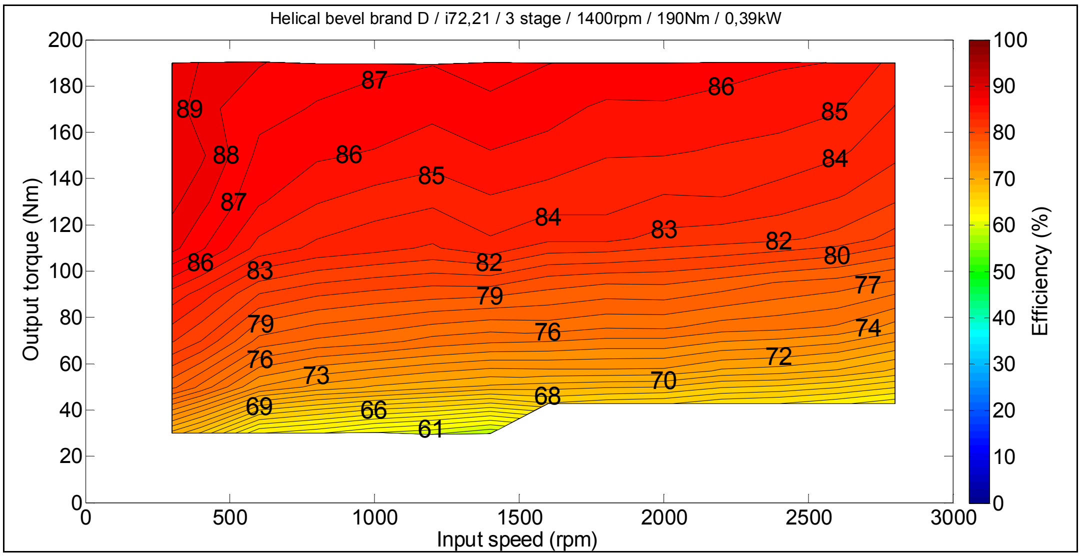

Figure 7: efficiency map of a helical bevel gearbox

Identical conclusions as for this helical bevel gearbox can be found for all gearboxes. All the tested gearboxes show a similar shape of efficiency map. For gearboxes with a high ratio the efficiency decrease is sharper compared to that for gearboxes with lower ratio. This is shown in figure 8 for a helical bevel gearbox with ratio 72. The efficiency drops 8% at 50% of the nominal torque. The efficiency from the gearbox with ratio 11 only drops 1,5% at 50% of its nominal torque. Again, the mainly independent effect of speed variations on the efficiency can be found in these figures.

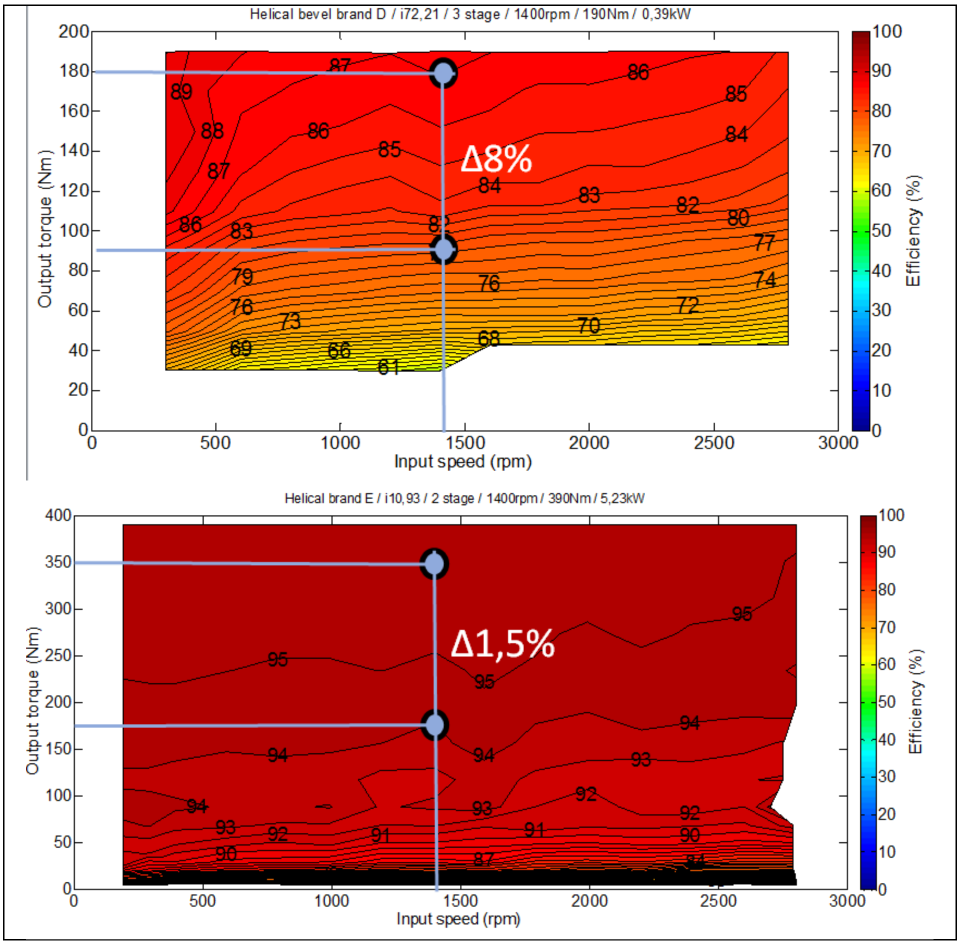

Figure 8: load dependent efficiency variation for different gearbox ratios

Power dependency of gear box efficiency

As with induction motors the efficiency of a gearbox is power dependent. This is confirmed by the measurement campaign. Also in figure 6 it is clear that the 800Nm gearbox power range always has a higher efficiency than the 200Nm range. Although the needed power or torque range is linked and determined by the application, it can be important to keep this in mind when designing a drivetrain.

Ratio dependency of gear box efficiency

The ratio of a gearbox has an important impact on the gearbox efficiency. In most worm gearbox catalogs this efficiency variation due to the gear ratio is already stated and the efficiency is given for each different ratio. A decreasing efficiency while ratio increases can be found. These catalog values only apply for nominal speed and load. However figure 9 shows a measured delta or difference efficiency map of two worm gear units with same power but different ratio. The map shows a rather constant efficiency difference in the entire working area.

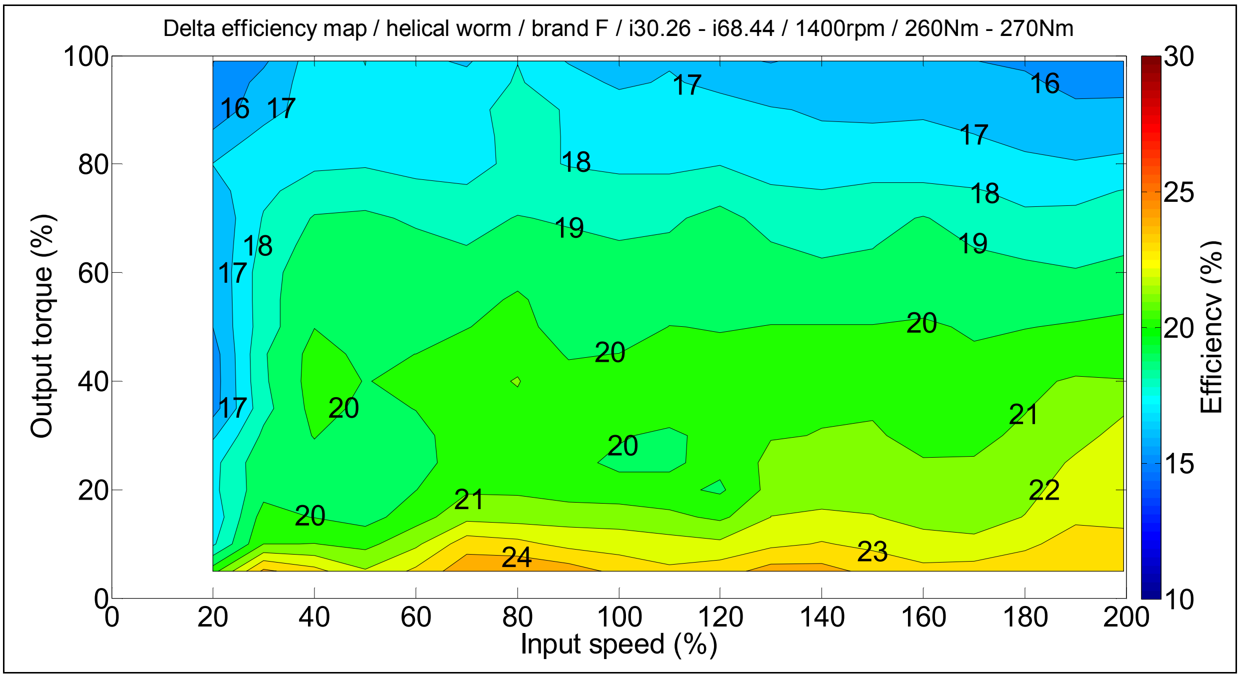

Figure 9: delta efficiency map of two helical worm units with ratio 30 and 68

In the case of helical and helical bevel transmissions the ratio dependency is not clarified in commercial catalogs. These catalogs only describe the effect of the number of gear stages on the nominal efficiency. This effect is also clearly represented in figure 6. When the ratio gets higher, the efficiency drops. This effect enlarges when the power or torque range decreases.

Type dependency (straight vs. right angled) of gear box efficiency

In many industrial cases the space requirements or space limits are an important design factor. Therefore it can be interesting to know whether or not this choice influences the efficiency of the drive line. For example three measured gearboxes during the campaign, two right-angled and one straight, with comparable specifications are considered. The properties are summarized in table 2.

Table 2: straight vs. right angled gearboxes

	Brand E	Brand E	Brand E
Type	Right angled	Right angled	Straight
Technology	Helical bevel	Helical worm	helical
Stages	3	2	2
Ratio	11,41	11,67	10,93
Torque (Nm)	434	373	390
Power (kW)	5,58	4,7	5,23
Measured efficiency (%)	95,5	91,5	95,5
Price (%)	147	98	54

The nominal efficiency of gearbox number 1 (right-angled) and 3 (straight) is comparable. However, the efficiency of number 2 (right-angled) versus number 1 and 3 (straight-angled) drops about 4% at nominal conditions. This difference is mainly technology dependent (helical bevel vs. helical worm). On the other hand, a much larger difference can be noticed at the gearbox price. The straight gearbox only costs half of the price of the helical worm gearbox and merely one third of the price of the right-angled helical bevel gearbox. If the installation space allows for a straight gearbox, this could reduce the costs of a drive train solution while maintaining or even raising the overall efficiency of the drive train.

Technology dependency

It is commonly known that a traditional worm gear unit has a lower efficiency compared to a bevel gear unit. In a lot of low power drive systems where the operating hours are rather low this worm gear proves its usefulness. Also where self-locking is required worm gears show their advantage. Moreover, this paper shows that the bevel gears do not always reach the stated catalog efficiency. One could wonder if the efficiency difference compared to a worm gear is still worth mentioning. Additionally manufactures use new design solutions to optimize the worm gear efficiency. For instance, to enhance the overall gearbox efficiency, an extra gear stage with helical gears is introduced in the worm gear in order to reduce the ratio of the worm-worm wheel itself.

A second consideration can be found in figure 7. Here it was concluded that the efficiency of helical gear units drops with decreasing load. A comparison with a helical worm gearbox can reveal if the efficiency difference between a helical worm and helical bevel gearbox is constant in the entire working area. The specifications of the two gearboxes are listed in table 3. In figure 10 the delta efficiency map is created by subtracting the worm gear efficiency map from the bevel gear efficiency map.

Table 3: specifications of a helical bevel and a helical worm gearbox

	Brand D	Brand D
Type	Right angled	Right angled
Technology	Helical bevel	Helical worm
Stages	3	2
Ratio	72,21	77
Torque (Nm)	190	180
Power (kW)	0,39	0,34
Catalog efficiency	95%	78%

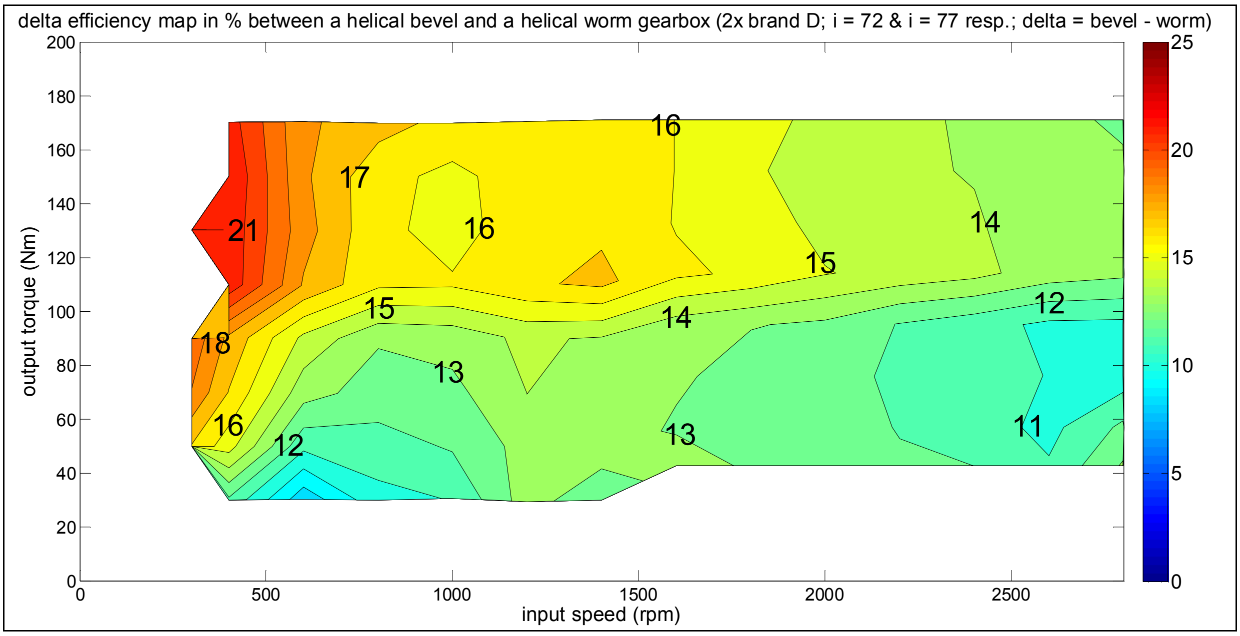

Figure 10: delta efficiency map in points efficiency of a helical bevel and a helical worm gearbox

The delta contour map shows that the efficiency of the helical bevel gear unit is higher in the entire working area. At nominal speed and load the difference is about 16%. This efficiency difference gets higher with increasing ratio.

On this topic, the common knowledge is still correct. Worm gearboxes have a lower efficiency than similar gearboxes. Although gearbox manufacturers optimize the right-angled worm gearbox efficiency the difference with a helical bevel gearbox is still considerably high.

Conclusions

This paper discusses a gearbox measurement campaign on industrial gearboxes. The current available information on gearbox efficiency is highlighted and the gearbox test bench and measurement flow chart are briefly explained. Thirteen commercial gearboxes were extensively tested. The results and the impact gearbox parameters on the efficiency are discussed.

The literature study reveals that availability of research results on gearbox efficiency is very limited. Moreover, the efficiency information in catalogs is limited. Typically only one efficiency value is stated for a large range of different gearboxes with varying ratio, power and technology. The literature study also made clear no standards exist on gearbox efficiency. This makes is hard to compare the efficiency of gearboxes of different brands.

The measurements reveal a significant difference between measured efficiencies and catalog values at nominal conditions. The difference between the catalog and measured efficiency is discussed and confirmed with information of a manufacturer. Manufacturers now determine the efficiency in different ways, with different ambient temperatures, based on theoretical calculations, etc. As a result, the catalogue values cannot be compared.

The efficiency in the entire working area is presented by means of efficiency contour maps. It is shown that the efficiency is mainly torque dependent. When the gearbox power range increases or the ratio decreases, this efficiency variation is smaller. Currently such information is not available for gearbox customers causing them to make a selection for a particular machine which is not optimal in terms of energy efficiency. In general the efficiency is higher for gearboxes with a higher power range. This is similar to electrical motors. When the ratio of a gearbox decreases the efficiency is higher. This was already stated in most worm gear catalogs but also helical and helical bevel gearboxes follow this trend. The latter is not yet stated in commercial catalogs. This indicates a clear lack of knowledge with respect to the use of the Extended Product Approach suggested in EN 50598.

Straight and right-angled bevel gears have similar efficiency but the price difference is high. Comparing a bevel and worm gear shows a higher efficiency for the bevel gear in the entire working range.

In this paper other external parameters, such as temperature, kind of lubricant and the oil level, were not discussed but surely also have an impact on the gearbox efficiency. Further research on the gearbox efficiency can certainly be interesting.

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Impact of IE3/IE4 Motors on Switchgear Standards, Manufacturers and Customers

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CAPIEL (European Association of Switchgear Manufacturers)

Summary

Higher-efficiency motors (IEC class IE3/IE4) have entered the market as a result of worldwide regulations on energy efficiency. The electrical behavior of these induction motors is different with typically higher inrush and locked-rotor currents. In some cases issues may occur with other components of the installation. In this paper we investigate potential issues regarding direct-on-line starting. We give an overview of the work being done in standardization technical committees to adjust switchgear and motor standards. Finally we provide guidelines to design an energy-efficient and robust motor system.

Introduction:

Electrical motors account for 70-80% of the electrical energy consumed in the industrial sector and therefore represent huge opportunities for energy savings. Regulations specifying minimum performance standards are in effect in most countries worldwide. In Europe, motors operated direct on line shall be of IE3 class, but even more efficient IE4 motors are occasionally available on the market.

The new, higher efficient asynchronous motors featuring IE3 or IE4 class have significantly different electrical characteristics. The nominal current is generally a bit less as a result of better efficiency, but the transient inrush and the quasi-static locked rotor current during start up may be significantly increased. In some cases, this altered electrical behavior is likely to cause issues with other parts of the installation, including motor starters. The different stakeholders are aware of this issue and are starting to react. Switchgear manufacturers are adjusting their products and standardization technical committees are revising the relevant standards.

In this paper, we focus on asynchronous motors, because they are used in the majority of industrial applications by far. These induction motors are even more important for fixed speed applications, which are controlled by switchgears, like contactors or soft-starters. The changes in the transient electrical behavior of asynchronous motors during start-up have a big impact to switchgear and the electrical installation as well. We then describe how some standards are being reworked to take these new characteristics into account. Finally, we give guidelines on how to design an energy-efficient motor system preserving the reliability and dependability of the electrical installation.

1. Electrical behavior of higher-efficiency induction motors

1.1. Typical motor start-up waveform

From the point of view of a motor starters (contactors, soft-starters, motor protection devices) connected to a motor, what matters is how the motor behaves electrically, especially during its transient phases like start-up. Typically, the electrical current waveform of a motor started at rated load has the characteristics shown in Figure 1, together with the motor speed.

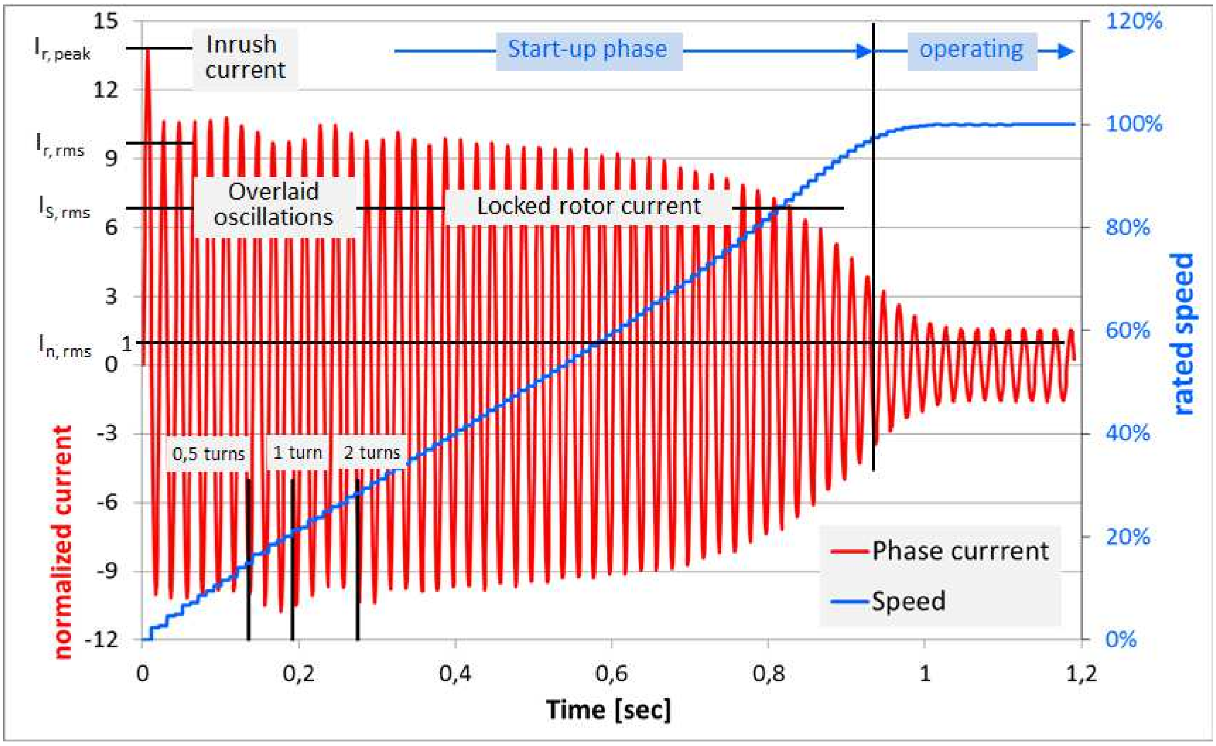

Figure 1 - Typical current waveform (normalized by nominal current) and speed pattern for a starting induction motor

The whole starting process can be separated into the following subsequent phases:

1. An inrush peak $I_{r,peak}$ appears with very high current during the first half cycle. Due to 120° shift between the phases, one phase is likely to exhibit this peak much more clearly than the others.
   This inrush peak is increased for higher efficient motors because of an additional saturation effect around the windings which is in turn caused by lower stator resistances.
2. Immediately after the inrush peak the current keeps a value several times greater than the rated current for a certain period of time. During this moment the rotor is not yet rotating, the magnetic field is establishing within the motor. Oscillations and differences between phases are typically present as the three phases are trying to find their magnetic balance. These oscillations typically amount to 10 to 20% of the locked rotor current.
3. After that the rotor accelerates, but its speed is less than about 80% of rated speed yet. During this time, the locked rotor current $I_{s,rms}$ can be observed.
4. Finally, the rotor rotates and the motor progressively reaches its nominal current value $I_{n,rms}$. If the load applied to the motor is the rated load, then the nominal current is the rated current $I_{e,rms}$.

1.2. Relevant motor start-up characteristics for switchgear operation

There are essentially four relevant features for describing the impact of a motor start-up on a motor starter. They are listed in Table 1.

Table 1- Main features describing the electrical behavior of an induction motor during start-up

Feature	Characterization	Influence parameters	Published data?
Nominal current	Nominal r.m.s. current value $I_{n,rms}$ in Amperes. This value can be lower or higher than the rated current $I_{e,rms}$.	Motor design Application Motor sizing	Yes
Locked rotor current	Locked rotor current ratio relative to the rated current: $\frac{I_{s,rms}}{I_{e,rms}}$	Motor design	Yes
Starting time	Duration of the starting phase in seconds	Motor design Load level and load type (e.g. linear or quadratic), Moment of inertia	No, but can be calculated
Inrush current	Ratio of the maximum possible inrush current to the locked rotor current: $\kappa = \frac{I_{r,rms}}{I_{s,rms}} = \frac{I_{r,peak}}{\sqrt{2} \cdot I_{s,rms}}$	Motor design Initial voltage angle Initial rotor position Electrical installation	No

1.3. Changes observed with premium-efficiency motors

In order to meet new and emerging Minimum Efficiency Performance Standards, motor manufacturers have optimized and partly redesigned their motors with the following trends:

- lower stator and rotor resistances,
- improved steel laminations for better magnetization and lower eddy currents,
- reduced air gap for lower magnetic resistance,
- various improvements in rotor design, bearings and cooling to reduce other losses.

As a consequence, significant evolutions have been observed on relevant features included those listed in Table 1. These data were derived by a catalogue comparison of several thousands of motors from different manufactures as well as by a huge measurement campaign. These observed or expected changes are listed in Table 2.

Table 2 - Evolution of main motor features with improved efficiency

Parameter	Typical value for IE1 motors	Typical evolution from IE1 motors to IE3/IE4 motors
Rated current $I_{e,rms}$	Depends on rated power	Generally a slight decrease
Locked rotor current ratio $I_{s,rms}/I_{e,rms}$	Motors < 15kW: 6 or less	+10 to +20%
	Motors 15–55kW: 6-7	+10%
	Motors >55kW: ~7	+ 4%
Starting time t_{start}	Depends on load	Expected to decrease, but marginal effect in practice.
Inrush current factor $\kappa=I_{r,rms}/I_{s,rms}$	1.2 to 1.4	+30 to +50%
Steady-state temperature	Depends on class	Core: -10 K to -15 K Windings: -10 K to -20 K

Note that this table provides typical values and trends, but in practice there are large discrepancies between one motor and the other, even for the same rated power, because of different design choices.

As an illustration Figure 2 shows the evolution of the probability distribution of the locked-rotor current ratio for a collection of small and medium motors of class IE1 to IE3, based on analyzing several hundreds of catalogue entries. Average values are indicated by the dashed vertical lines. The increase from IE1 motors to IE3 motors is about 19% in the 0.75 – 15kW range and 9% in the 15 – 55kW range. Considering the whole motor power range from 0.75 kW to 1000 kW, the locked-rotor currents increase from an average value of about 7.1 to 7.6 times rated current which is 7%. A good side effect is the decreasing scatter band of these locked-rotor current factors for higher efficient motors.

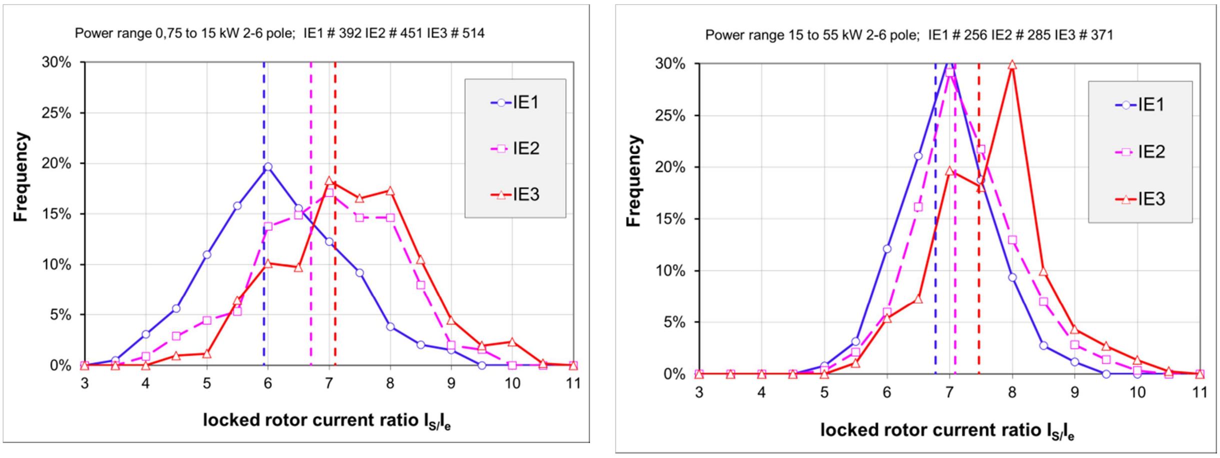

Figure 2- Probability distribution for the locked rotor current ratio for 0.75–15kW motors (left) and 15–55kW motors (right)

There are not yet enough IE4 motors on the market to allow good statistical analysis, but the trend to higher values will continue.

2. Impact on relevant motor and switchgear standards

There are a couple of relevant standards that address the problem of matching the start-up characteristics of induction motors and the withstand characteristics of switchgears. They are analyzed in more detail in the following sections.

2.1. IEC 60034-12 motor starting performance standard

[IEC60034-12] standardizes the start-up performance of induction motors by specifying maximum values for the relative locked-rotor apparent power, expressed as:

$$\frac{S_l}{P_n} = \frac{\sqrt{3} \cdot U_e \cdot I_{s,rms}}{P_n} = \frac{I_s/I_e}{\eta \cos\varphi}$$

Where $I_{s,rms}$ is the r.m.s. locked rotor current, U_e is the rated r.m.s. voltage and P_n is the rated mechanical motor power, I_s/I_e the locked rotor current ratio, η is the efficiency and cos φ the power factor. These locked rotor apparent power S_l reflects the quasi-static start-up behavior, neglecting the aforementioned dynamic phenomena (see Figure 1).

In general new motor designs are being considered for introduction (e.g. Design “NE” and “HE” in addition of Design “N” and “H”), which allow higher locked rotor apparent power S_l. The motor manufacturer can choose which design (e.g. N or NE) the motor fulfills, but it has to indicate this on the nameplate of the motor. There is no correlation to a certain efficiency classes, each motor/efficiency class can be stamped as Design N or NE.

These new designs will allow a higher ratio S_l/P_n for motors from 1.8 kW above. The increase amounts to 15% for smaller motors and climbs up to 22% for motors larger than 630 kW. Some analysis have shown, that this normative allowed increase is leading to higher locked rotor currents in the same order of magnitude, even if this ratio S_l/P_n is also depending on the efficiency and power factor of the motor.

2.2. IEC 60947-4-1 motor starter standard

[IEC60947-4-1] specifies minimum performance values for contactors, motor protection devices and other motor starters regarding their electrical switching capacity in case of standard operational mode, but also in case of overload and short-circuit conditions. For motor applications two different utilization categories exist:

- AC-3: Squirrel-cage motors: starting, switching off motors during running. This also covers a reversing after a complete stop implicitly.
- AC-4: Squirrel-cage motors: starting and switching off like AC-3, but also frequently operated in inching mode or occasional plugging.

Each category has different requirements for making capacity (closing the circuit) and for breaking capacity (opening the circuit).

In order to respond to the electrical behavior of high efficient motors, a new utilization category AC-3e is being planned for introduction. Basically this new category AC-3e is based on the existing category AC-3, but a 20% higher switching performance has to be fulfilled for making operation (12 times rated current instead of 10 times), considering increased inrush and locked rotor currents. Furthermore, the test conditions also generate a kind of inrush current, so that the real test currents climb up to about 15 times rated current (rms-value).

In case of breaking capacity, the increase of locked rotor current has to be taken into account only. A value of 8.5 times rated current will be requested, which is 7% higher and what corresponds to the average increase of the locked-rotor current factors of all motors as mentioned above. In this context it should be noted, although the percentage rise of locked rotor current factor is much higher for small motors, the new absolute value of 8.5 times rated current is much higher than the average of locked rotor current factor of those motors anyway.

An introduction of a further utilization category AC-4e is under consideration currently, because the requirements of existing category AC-4 are much higher than AC-3 in any case.

This new category AC-3e shall express the capability of the motor starter to handle IE3 motors in a proper way. This is the requirement of our customers and the aspiration of the switchgear manufacturers too.

However, speaking in terms of standards, this new category AC-3e is focused on motors of design NE or HE. This is to be in line to aforementioned motor standard IEC 60034-12 draft and is also a result of the established liaison between the relevant technical committees for motors and switchgear.

Unfortunately this motor standard IEC 60034-12 does not have a close link to certain efficiency categories, which are the customers are familiar with and which can also be taken from the motors nameplate easily. With respect to technical and economic issues in a worldwide market, we suggest using the “old” Designs N or H for IE1 and IE2 motors and the new introduced Designs NE and HE for IE3 and IE4 motors only. This is much easier for all stakeholders during the planning process of an installation.

3. Good practice for designing an energy efficient motor system

For a motor system, energy efficiency is obtained by matching the requirements of the application with the characteristics of the motor system. The following general guidelines are valid.

3.1. Do not oversize the motor and other components

There is a natural tendency to oversize motors, thinking that it’s good to “have a fair margin”. Actually, a motor operating below 30% of its rated power has a significantly reduced efficiency, as shown in Figure 3.

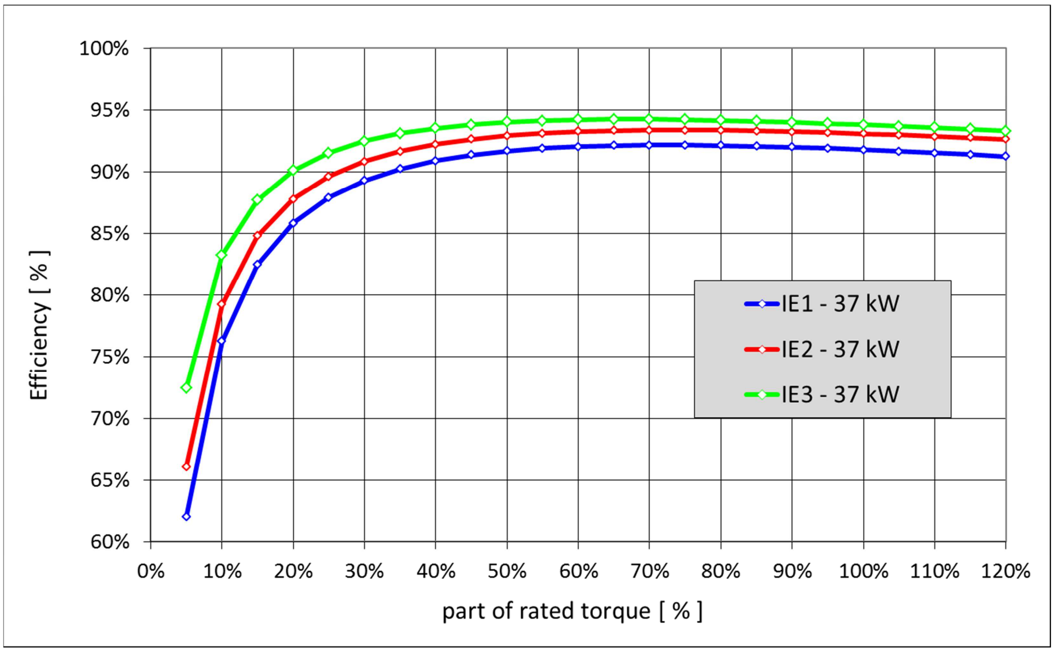

Figure 3 - Evolution of motor efficiency with respect to load (torque) level

Oversizing the motor also leads to oversizing other components like motor control devices, filters or mechanical transmissions, which is not in favor of overall energy efficiency (efficiencies of different equipment within the drive chain has to be multiplied, which often results in poor system efficiency). Unless there is a good reason to oversize, 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. This feature can be used in applications with big differences in power demand during start-up and normal operating conditions or in applications with short load peaks for instance.

3.2. Choose the right motor control system based on a system approach

A motor can be controlled by a Variable Speed Drive (VSD) or a motor starter (contactor, star-delta starter) or a Soft-Starter. All devices have advantages and drawbacks as shown in Table 3.

Table 3- Comparison of motor starters and variable speed drives

	Advantages	**Drawbacks**
Motor starter	Very high efficiency (lowest losses) Low CAPEX and OPEX costs Compact and easy to install/use No need for additional cooling Long lifetime, no EMC issues	No speed control Sensitive to higher inrush / start-up currents in some cases
(bypassed) Soft-starter	Very high efficiency Affordable CAPEX and OPEX costs Smooth motor start Insensitive to higher inrush/start-up currents, no EMC issues	Not applicable in some applications
Variable speed drive	Advanced speed/torque control Insensitive to higher inrush/start-up currents	Lower efficiency (higher losses) Higher CAPEX and OPEX costs May cause EMC issues Often require auxiliaries (cooling, harmonics mitigation…)

Fixed-speed, 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. The system efficiency (motor + switchgear device) for these load points is than very close to the motor efficiency as shown in Figure 3 for instance.

Variable speed drives allow more advanced speed and torque control but on the other hand they have higher internal losses. Many sources report about increasing losses with lower speeds and or lower torques [e.g. EuP Lot 30]. Furthermore additionally losses in the motor or other necessary equipment occur (e.g. filters, cooling). Therefore, from the point of view of energy efficiency, variable speed drives should be used only when the whole application process benefits from varying the speed of the motor. If it is not the case, a motor starter is always the most efficient solution.

A typical example where VSDs bring significant benefits in terms of energy efficiency is a pump system with a throttled valve, operating most of the time at much reduced flow. Replacing the valve by a VSD typically allows saving significant energy. On the other hand, if the valve is operated at nearly full flow most of the time, then a VSD would bring more losses than the throttle over a significant time period. Away from the kind of motor control, losses can often avoided by a proper piping system.

In any case, energy efficiency is not about assembling the most efficient devices together. It is about matching the requirements of the application with the proper equipment (motor system and mechanical systems) in an optimal way. The optimization should start with the processing machinery and then with the selection of the motor or the kind of motor control.
For a given application, optimal energy efficiency can only be achieved by minimizing the overall losses (or energy consumption) of the whole application considering its requirements and duty cycle. In order to do that, the system-oriented Extended Product Approach (EPA) described in EN 50598-1 (and in future IEC 61800-9-1) is the most relevant approach.

3.3. Consider reviewing your installation when changing to premium-efficiency motors

Most switchgear manufacturers are aware of the higher inrush and locked-rotor currents caused by IE3/IE4 motors. They have investigated the issue and have adapted their products accordingly. Therefore, for new installations, matching a premium efficiency motor with a motor starter is done according to the same criteria as before.
There remains the case of an existing installation in which old (IE0/IE1) motors are progressively replaced by IE3/IE4 motors. The installation contains components other than the motor (transformer, cables, protection devices, other loads) that may, in some cases, be negatively impacted when changing to more efficient motors. Table 4 describes some potential issues.

Table 4 - potential effects of replacing an old motor by a premium-efficiency motor

Component	Possible issue	Recommendation
Transformer	The higher transient current demand may cause a more severe voltage drop at motor start-up. Voltage drops may degrade the behavior of some electrical loads.	Check the stiffness of the power supply. If deeper voltage drops are an issue, consider replacing by a transformer with a higher short-circuit capacity, or implementing mitigation equipment.
Protection devices (fuses, breakers)	Protection thresholds may be set to values too small for IE3/IE4 motors, causing nuisance tripping.	Review the installation to make sure all protection devices are still coordinated.
Cables	If protection thresholds are increased, there will be higher transient currents in the cables, causing more heating especially with repeated start-ups (AC4 duty).	Depending on the duty characteristics, make sure the cables are able to withstand the increased heating.
Contactor	Existing contactors may have been designed for older motors and may not be able to withstand the increased inrush/locked-rotor current. Lifetime may be reduced. In extreme cases, welding may occur.	Check that the contactor is ready for premium efficiency motors (able to withstand increased DOL current). If necessary, consider replacing the contactor or using a soft starter.

If it is likely that the existing installation does not have enough margins considering the increased locked-rotor currents produced by new motors, review it. Installation specialists can provide support. It may be necessary to obtain relevant information from motor manufacturers regarding the electrical behavior of their motors.

Conclusion

For motor driven applications, energy efficiency is obtained by optimally matching the requirements of the application (type of work, duty cycle) with the equipment (supply, motor, control, transmission, mechanical load).

Fixed-speed applications implementing motor starters (contactors, star-delta starters, soft-starters) form by far the majority of applications because they are cost effective, reliable and robust. Motor starters are also important in terms of energy efficiency because they have very low losses. Therefore, it is important to continue using these motor starters whenever they bring energy savings.

The impact of the increased inrush/locked-rotor currents produced by new motors on motor starters and other components of the installation is an issue that is now easily dealt with. Switchgear manufacturers have adapted their products accordingly. In some cases installation specialists can provide efficient support in adapting the components of the installation that are impacted.

A difficulty that may arise in this adaptation process is that motor data such as inrush current factor and full-load starting time, which are important for sizing the different parts of the installation, are generally not provided as catalog data. More generally, the transient electrical characteristics of the motor are often not a strong requirement for motor manufacturers when they design a new motor.

Considering the impacts IE3/IE4 motors may have within an installation, we strongly encourage motor manufacturers to become more aware of the electrical behavior of their motors and publish relevant data. On the other hand, the motor manufacturers and also the related standards committees for motors should ensure that locked-rotor currents and inrush currents remain at a reasonable level in order to ensure compatibility with existing installations and to protect the electrical supply against considerable voltage dips.

References

[IEC60034-12] IEC 60034-12 standard – *Starting performance of single-speed three-phase cage induction motor*s – Edition 2, 2002. Revision pending.

[IEC60947-4-1] IEC 60947-4-1 standard – *Low-voltage switchgear and controlgear – Part 4-1: Contactors and motor-starters – Electromechanical contactors and motor-starters* – Edition 3, 2009, revision pending.

[EN50598-1] EN 50598-1 standard – *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)* – Edition 1, 2015.

[EuP Lot 30] De Almeida, Falkner, Fong – *EuP Lot 30 preparatory study "Electric Motors and Drives" Task 4: Technical analysis existing products*
Original source: CENELEC – *"Ecodesign for power drive systems, motor starters, power electronics & their driven applications - Part 2: Energy efficiency indicators for power drive systems and motor starters (Draft)*", 2013.

Loading means for the characterisation and measurement of converter loss and efficiency

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Abstract

Methods for the measurement of converter loss and efficiency form an important part of the new IEC 61800-9 standards which are currently in preparation. This paper addresses the problem of electrically loading ‘stand-alone’ converters in order to make such measurements, where the term ‘stand-alone’ is used here to describe a converter for which the motor finally to be driven is absent, and with the characteristics of the latter known therefore only in quite general terms.

Electrically loading converters for the purpose of making both loss and efficiency measurements presents a significant problem. Balanced three phase currents with a lagging power factor are required, which are both representative of rotating machine loads and with magnitudes variable over a relatively wide range.

The various means of loading a converter for test and measurements purposes are discussed, including back-to-back operation with another converter, passive electrical loads, and loading with real rotating machines. The paper discusses in detail the usefulness of readily available induction machines as (variable) loads for converter tests and measurements.

The experimental work described consisted of a series of loss and efficiency measurements made on an 11 kW converter which was loaded, in turn, with three 11 kW 4 pole motors from different manufacturers. Converter loss and efficiency measurements were made at a number of carefully chosen load points, providing information which will facilitate the fitting of loss and efficiency ‘surfaces’ to the results, thus aiding the comparison of converter performance and the determination of the overall characteristics of converter-driven motor systems (the ‘extended product approach’).

It is hoped that this work will aid the development of the new IEC 61800-9 standards, by describing a method for the determination of ‘stand-alone’ converter losses and efficiency using electrical loads which are readily available.

Introduction

The new IEC 61800-9 series of standards will complement IEC (TS) 60034-2-3; the former relating to power drive systems (PDS) and converters (CDM) without reference to the specific motors they supply, and the latter dealing with induction motors in the absence of a specific converter.

Previous work carried out by CENELEC on the characterising of converter losses and efficiency (see EN 50598) has concentrated on ‘semi-analytical models’ of converters in order to estimate, by calculation, the losses which they incur under different operating conditions. Such calculations will not generally be acceptable as a substitute for actual measurements, however.

Two crucial elements of such a measurement process will be the specification of means by which a converter under test is loaded, and the way in which its losses are then to be measured.

Total converter losses include two components. One which is independent of load, and another which is directly related to load (current magnitude and the number of power switching transitions per unit time). Calculations based on the semi-analytical model provided by CENELEC in EN 50598 suggest that the power factor of the load presented to a converter has little effect on losses (see

Appendix 1). Thus motors themselves will represent the best 'reference loads' for making such measurements. It must be ensured that those motors can draw load currents over a sufficiently wide range, namely from about 50% to 100% of a given converter's rated current. Differences in the power factors presented to the converter at a given current level are thus expected to have little influence on the measured converter losses.

Converter nameplates often carry two figures relating to their rating: a current or kVA rating and a motor rating, the latter expressed in kW. Since load-dependent converter losses are produced by the *current* which is drawn from its output terminals, the current or kVA rating takes precedence, as the motor *power* rating may refer to a rotating machine with a comparatively low power factor.

Because it is generally not possible to identify the individual power loss components in converters, there are only two basic techniques by which to measure losses, and therefore overall efficiency: input-output (output/input) methods, in which efficiency is the simple quotient of input and output electrical power, and calorimetric methods, in which the total losses are measured directly by the total amount of heat which they produce.

The question thus arises as to which method is best, and whether or not a 'preferred' method should be stipulated. At this stage, the answer is not clear:

The new standards will need to stipulate the load currents and output frequencies (and *not* speed or torque in a fictitious motor) at which converter loss measurements are made. It has been suggested that converter loss measurements be made at points carefully chosen to facilitate the generation of a mathematically fitted surface in the efficiency/load-current/output-frequency space. This will allow for estimation of performance of a given converter, by interpolation, at a large number of practical operating conditions, whilst minimising the time and effort required to make the necessary measurements.

Loading means

The majority of three-phase pulse-width modulated converters will, for the foreseeable future, supply induction motors. It is thus appropriate that machines of that type be closely examined in terms of their suitability to provide reproducible converter loss and efficiency measurements. The question arises, however, as to the way in which such a load should be specified, and whether or not motors of different makes and models will provide the necessary agreement between loss and efficiency measurements made on a given converter.

The aim of this work has been to suggest a broad specification for a suitable means by which converters may be loaded electrically. Various possibilities have been suggested, including the use of 'back-to-back' converters, passive (L-R) loads and the use of rotating machines. The use of a second converter, whilst possible in principle, would require very specialised equipment, and passive loads capable of providing a wide range of load currents would be very difficult to implement in practice. It is suggested, therefore, that induction machines provide a ready solution to this problem, as they are generally in plentiful supply in those laboratories in which converters are most likely to be evaluated.

For a given converter output current magnitude, load power factor influences the way in which output load current is shared between the output stage active and passive power semiconductors. Load current power factor also determines the amount of active power which must be handled by the mains input rectifier system. It might therefore be assumed that the power factor of an electrical load presented to a converter would have a significant effect on converter losses. Appendix 1 to this paper shows, however, that this is not the case. Even over an output power factor range between zero and unity, converter output stage losses are essentially constant.

This paper describes laboratory measurements on a converter using a number of different motors as loads, and compares the results.

It is suggested that a suitable motor-load for a given converter might be specified as a 4 pole, three-phase, cage-rotor induction motor with efficiency class IE2, which can draw current from a given converter in the range from 100% down to 50% of the output current rating of that converter.

Experimental converter loss and efficiency measurements

Experimental work has been undertaken, in which a single 11 kW 3-phase converter was subjected to loss and efficiency measurements when loaded with three randomly chosen 11 kW, 4 pole, IE2 efficiency class motors in an experimental system as shown in Figure 1, below:

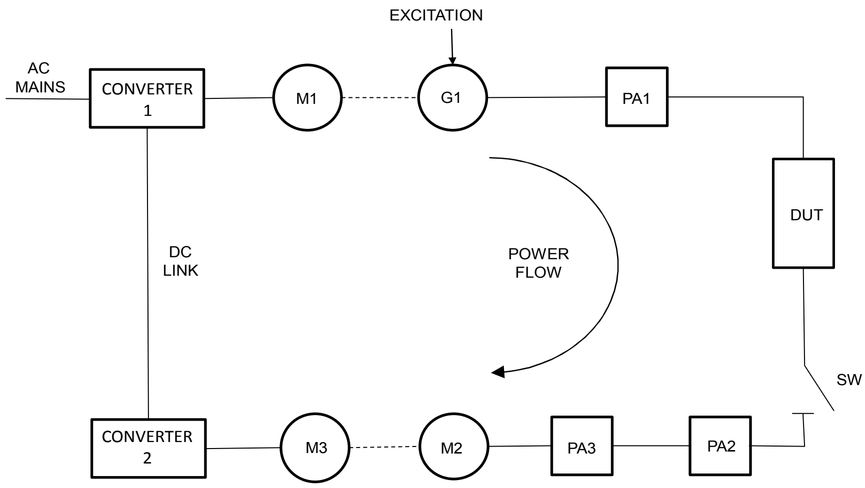

Figure 1: Converter loading system

In the above figure:

Mains-supplied converter 1 drove a large motor-alternator set which provided the power supply for the converter under test ('DUT') via power analyser PA1, a Yokogawa model WT230. Excitation to the alternator G1 was adjusted to provide rated supply voltage to the DUT (400 V, 50 Hz) for all measurements.

The converter under test was electrically loaded, via power analysers 2 and 3, by an induction machine (M2) with a similar power rating to that of the DUT. Power analysers PA2 and PA3 were, respectively, a Yokogawa model WT3000, and a Newtons4th model PPA 3350. Both power analysers were found to provide measured power values which agreed very closely, and the measurements recorded here in Table 3 are from the Newtons4th instrument. Both power analysers were connected in a '3P3W' configuration.

Induction machine M3, which was mechanically connected to M2 (but without torque transducer), loaded the latter and returned electrical energy back to the above loop via the DC link connection between Converter 2 and Converter 1. Power thus circulated in a clockwise direction around the loop.

The purpose of the isolator, SW, was to disconnect the motor from the converter in order to measure the converter's stand-by losses.

Not shown in the above diagram is a shielded cable (6 m of 3-core + earth flexible stranded copper, each core having a cross-sectional area of 4 mm^2 in this case) connected between the DUT and the power analysers. (For converters with comparatively low output power ratings, switching losses associated with shielded-cable charge-discharge currents at the PWM 'carrier' frequency can contribute significantly to converter losses).

The motors used as experimental loads were chosen at random from a group which had previously undergone MEPS check-testing in the laboratory. Table 1, below, shows the nameplate ratings, and confirms the IE2 classification for those machines:

Motor	Power rating (kW)	Pole number	Voltage rating (V)	Current rating (A)	Speed (rpm)	Power factor	Efficiency rating or value	Measured efficiency (IEC 60034-2-1 Method B)
ABB M3GP160MLC4	11	4	400	21.2	1470	0.82	91.2% IE2	91.4 ± 0.2%
SEW DRE160MC4/F1	11	4	380 – 420	22	1475	0.80	Not stated	90.0 ± 0.2%
CMG HLA160M-42-4	11	4	380 – 415	20.7	1470	0.84	91%	91.5 ± 0.2%

Table 1: Nameplate ratings and measured efficiencies of motors used to load the converter

The converter nameplate data was as shown in Table 2, below:

Make:	ABB	**f1:**	48-63 Hz
Model:	ACS 355	**U2:**	3 ph 0-U1
Power rating:	11 kW (15 HP)	**I2:**	23.1 A
U1:	3 ph 380-480 V	**f2:**	0-600 Hz
I1:	30.9 A	**Degree of protection:**	IP20/UL open type

Table 2: Converter nameplate data

The converter was set to 'factory default' settings, and the voltage rating of the driven motor entered into the converter software as 400 V (nominal) at 50 Hz.

The measurements were made under un-controlled ambient air temperature conditions, with the ambient air temperature in the range 24-30°C during the measurements.

Preliminary measurements of converter heat-sink temperature indicated a thermal time-constant of approximately 3 minutes, with thermal stability achieved after about 5 time-constants, namely 15 minutes. For the actual tests, the converter was loaded to 100% of its current rating at a fundamental output frequency of 50 Hz for 30 minutes before measurements were made. That period also allowed for 'run-in' and stability of lubrication conditions in the converter's cooling fan motor.

Measurements of electrical parameters as shown in Table 3, below, were made, starting at the 100% frequency (50 Hz) and 100% (full-load) current point, and then, as rapidly as possible, at the following points, and in the following order:

100%,75%; 100%,50%; 75%,100%; 75%,75%; 75%,50%; 50%,100%; 50%,75%; 50%,50%; 25%,100%; 25%,75%; and 25%,50%, a total of 12 frequency/load points.

Note that it had initially been the intention to include points at 25% load current, but it became clear that such currents are not generally available from induction motors, as a result of the relatively high no-load current drawn by such machines and thus such points are not, in any case, representative of the way in which a given converter is likely to be loaded in practice. Figure 2, below, shows typical minimum (i.e. no-load) induction motor currents for motors with ratings in the range 0.75 to 55 kW.

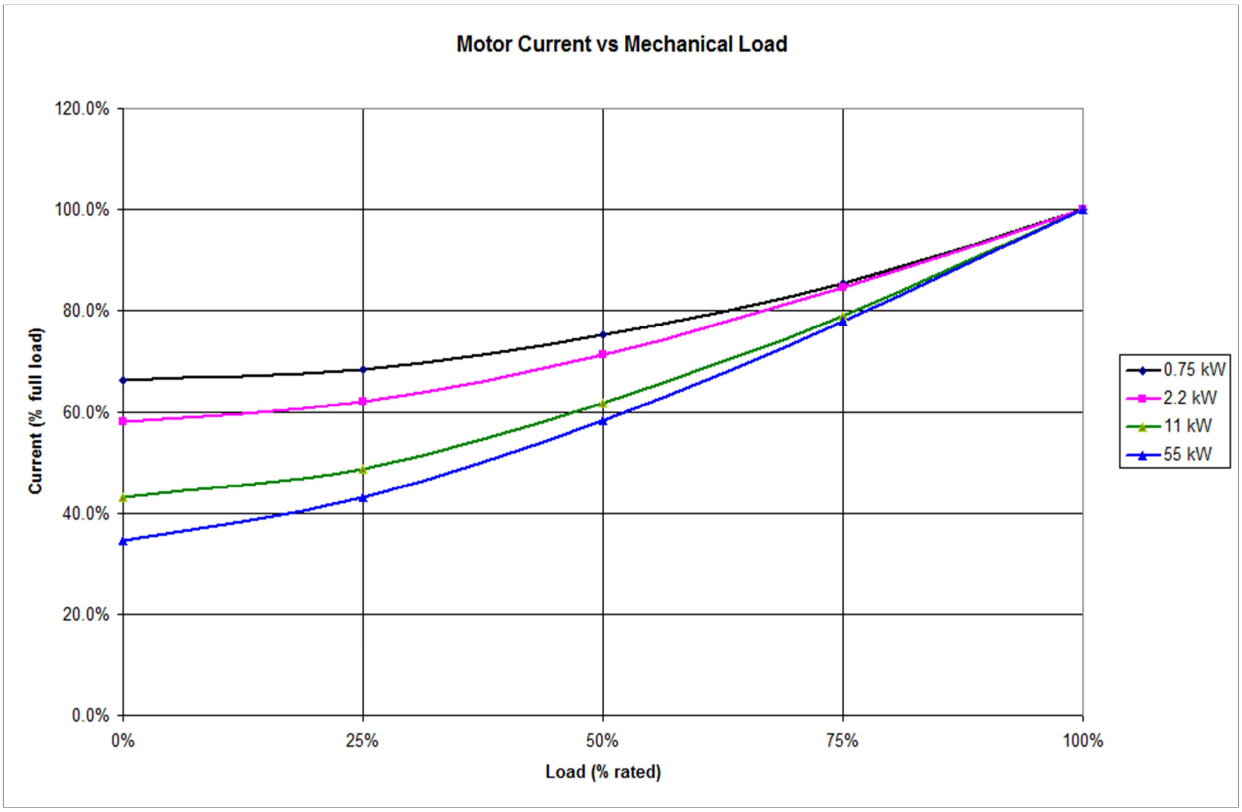

Figure 2: Typical currents drawn by 4-pole induction motors with ratings in the range 0.75 to 55 kW Significant current drawn by unloaded motors limits the range of converter load currents possible at the lower end of the range.

Experimental results

		Load motor:				
Load point		ABB	SEW	CMG		
Speed	Current	Converter Efficiency			Mean	Range
% 50Hz	% rated (nominal)	%	%	%	%	± %
100	100	97.4	97.3	97.5	97.4	0.1
100	75	97.2	97.1	97.3	97.2	0.1
100	50	96.8	96.8	97.3	96.9	0.2
75	100	96.1	96.1	96.3	96.2	0.1
75	75	96.3	96.3	96.5	96.4	0.1
75	50	95.5	95.1	96.2	95.6	0.6
50	100	94.8	94.7	94.9	94.8	0.1
50	75	95.0	94.9	95.2	95.0	0.2
50	50	94.0	93.9	94.8	94.2	0.4
25	100	90.6	90.6	90.8	90.7	0.1
25	75	91.2	91.4	91.6	91.4	0.2
25	50	90.1	90.3	91.5	90.7	0.7

Converter output ‘on’, frequency zero, with motor disconnected: Input power: 32 W

Converter output ‘off’, frequency zero, with motor disconnected Input power: 15 W

Converter output ‘on’, frequency zero, with motor connected Input power: 108 W

Table 3: Results for the 11 kW converter.

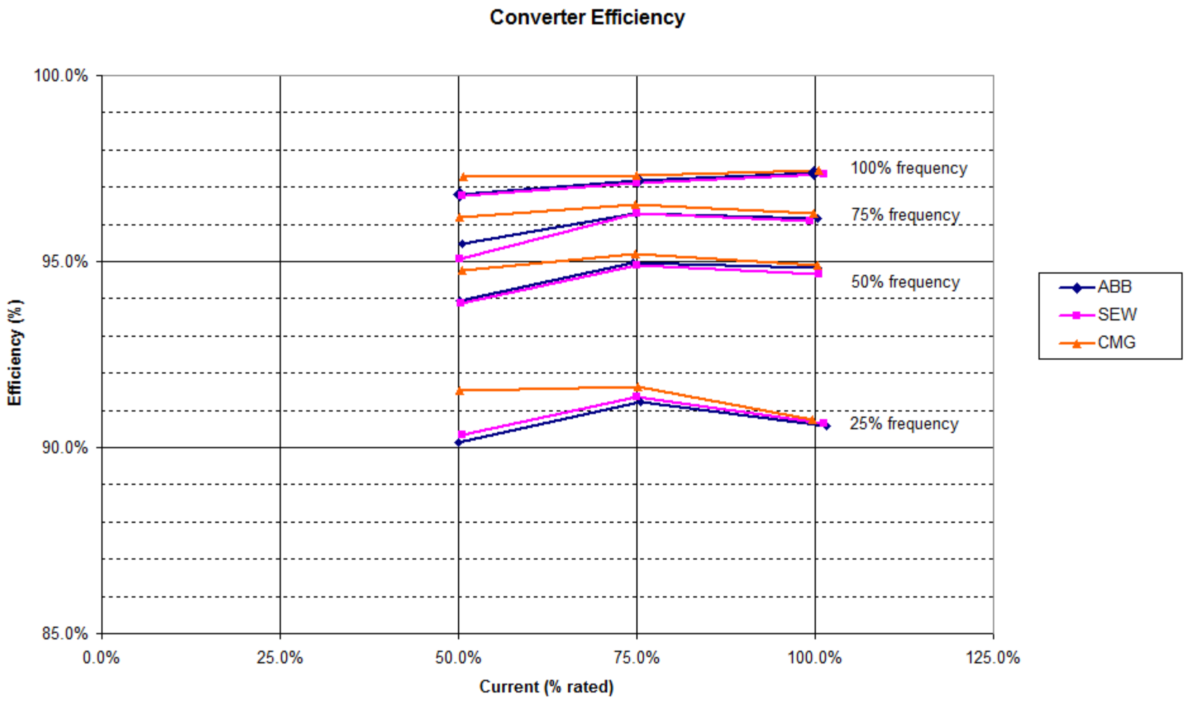

Figure 3: Converter efficiency as determined using all three loading motors

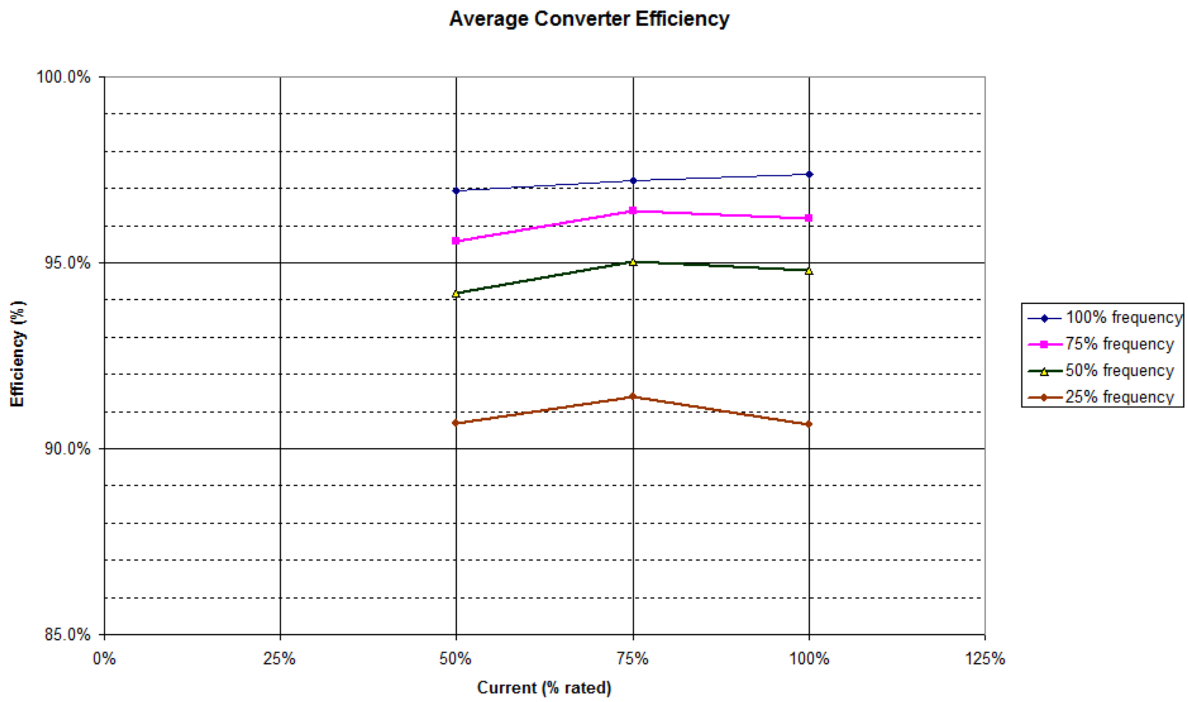

Figure 4: Average converter efficiency vs. load (current) with converter frequency as parameter

Figure 4 shows that the efficiency of the converter operating at a given fundamental output frequency varies remarkably little with current. Although not shown by the results presented above, efficiency falls rapidly below 50% (current) load, and is, in any case, zero, by definition, when the output current is zero.

The bar-charts in Figure 5, below, show the total converter losses, with one chart for each of the converter output frequencies.

There is little variation in the loss figures obtained using different motors as loads.

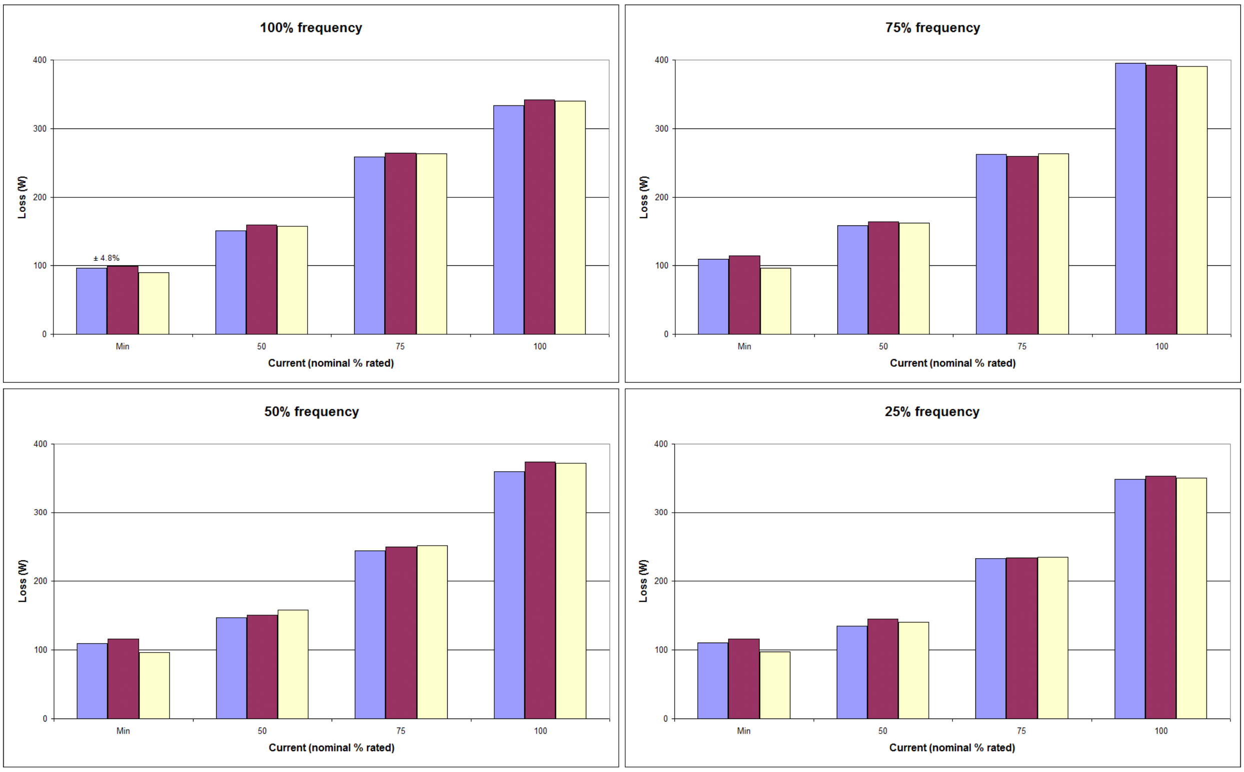

Figure 5: Converter loss (Watts) at motor no-load current, 50%, 75% and 100% of converter rated current for the three loading motors at 25%, 50%, 75% and 100% frequency.

Legend: Blue – ABB, Purple – SEW, Yellow – CMG

ABB SEW CMG

The charts above show that there is little variation between the loss figures obtained using different loading machines.

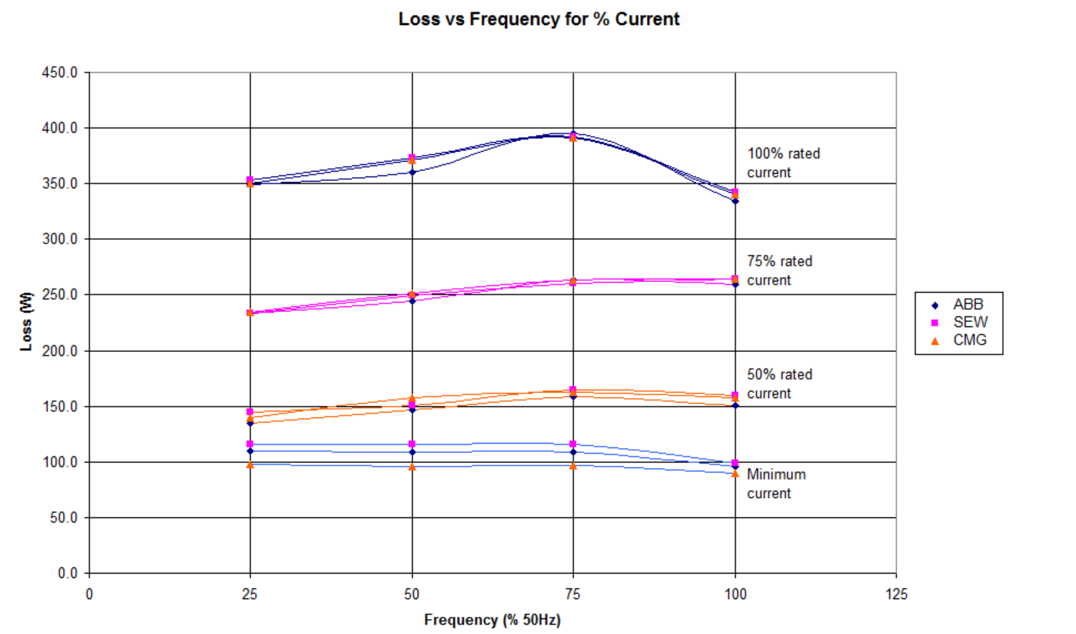

Figure 6: Converter loss versus output fundamental frequency for a range of output currents

Conclusion

Measurement of losses and efficiency of a converter using load currents drawn over the range 50-100% of converter rated current by three randomly chosen 4 pole, IE2 induction machines provided results which were in close agreement.

Load currents below about 50% of the converter's rating were generally not achievable, but, in any case, such loads do not represent realistic converter-motor operating conditions. Load currents less than about 50% of a converter's rated current will generally not be available from a motor having an output power rating which approximates that of the converter. This is due to the comparatively high no-load currents drawn by such machines. It is thus suggested that converters of the type used in this study be characterised by a matrix of 12 measurement points as shown in Table 3. Little useful information is provided by measurements at lower frequencies or output currents.

The work described in this paper suggests that close agreement will be possible between converter loss and efficiency measurements made by electrical machines and drives laboratories throughout the world if readily available motors are specified as electrical loads in the standards relating to such work.

References

[1] EN 50598-1: 2014 *Ecodesign for power drive systems, motor starters, power electronics & 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)*

[2] EN 50598-2: 2014 *Ecodesign for power drive systems, motor starters, power electronics & their driven applications. Energy efficiency indicators for power drive systems and motor starters*

[3] IEC 61800-9-2 (Draft) *61800-9-2 Adjustable speed electrical power drive systems - Part 9-2: Energy efficiency of adjustable speed electric power drive systems - Energy efficiency classification and relevant product determination methods*

Appendix 1: Effect of load power factor on converter output switching element losses

Three phase PWM converter output stages consist of three pairs of active switching elements (power MOSFETs or IGBTs), with a ‘bypass’ or ‘free-wheeling’ diode connected directly across each active switching element.

In the case of a resistive load, all load current is carried by the active switching elements, but if the driven load is an electrical machine, quadrature currents (with respect to the fundamental component of a converter’s output voltage) lower the power factor of the load presented to the converter. As the power factor decreases, more current passes through the by-pass diodes. EN 50598 provides the following formulae for the losses incurred by those power electronic components, as a function of both load current and power factor angle, Φ:

Transistor on-state losses (Equation (6) from EN 50598):

$$P_{L,on,T} = \sqrt{2}\cdot I_{out}\, U_{T,th}\cdot\left(\left(\frac{1}{2\pi}\right)+\frac{1{,}22\cdot m\cdot\cos\phi}{8}\right)+\frac{U_{T,r}-U_{T,th}}{I_{r,out}}\cdot 2\cdot I_{out}^{2}\cdot\left(\frac{1}{8}+\frac{1{,}22\cdot m\cdot\cos\phi}{3\pi}\right) \quad \textbf{(6)}$$

By-pass diode on-state losses (Equation (7) from EN 50598):

$$P_{L,on,D} = \sqrt{2}\cdot I_{out}\, U_{D,th}\cdot\left(\left(\frac{1}{2\pi}\right)-\frac{1{,}22\cdot m\cdot\cos\phi}{8}\right)+\frac{U_{D,r}-U_{D,th}}{I_{r,out}}\cdot 2\cdot I_{out}^{2}\cdot\left(\frac{1}{8}-\frac{1{,}22\cdot m\cdot\cos\phi}{3\pi}\right) \quad \textbf{(7)}$$

Substitution of typical values of switching element threshold voltages, again as provided in EN 50598 into the above equations results in the following graphs which show individual and total losses in typical converter switching elements as a function of load (fundamental frequency) power factor.

From Figure A1 it can clearly be seen that total switching losses are almost constant with load current power factor angle, suggesting that even though individual motors used as loads for making converter loss and efficiency measurements may have different power factor characteristics, the variation in measured converter loss is likely to be small, even taking into account the effective ‘unloading’ of the mains-end rectifier, which handles less current as the power factor drops at a given value of converter output current.

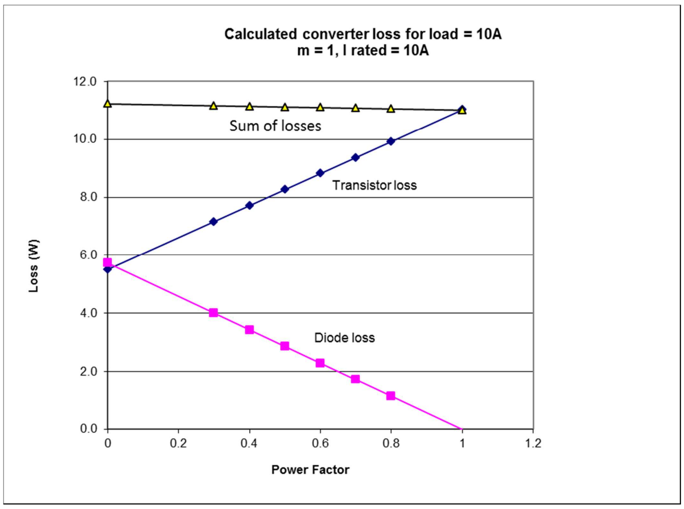

Figure A1: Variation of total motor-end converter on-state losses with load power factor

Appendix 2: Suggested outline converter loss and efficiency measurement procedure

1. Output/input or calorimetric methods may be used

2. Measurements should preferably be carried out in a controlled ambient temperature environment held at 25°C

3. Converter to be loaded by a 4 pole IE2 motor capable of drawing current form 50% to 100% of the converter's continuous output current rating

4. Converter PWM switching frequency to be set to 4 kHz (ratings up to 90 kW (equivalent)), or 2 kHz (ratings above 90 kW), except for converters in which a single PWM frequency cannot be identified

5. Converter setting to be 'factory default', and without field enhancement or weakening at low frequencies. All converter settings to be clearly documented.

6. Shielded cable of a specified length and conductor cross-sectional area shall be used to connect the converter to the motor load.

7. Converter output electrical measurements to be made at the motor terminals. (Note that care must be taken to avoid additional load, especially on converters with low power ratings, produced by shielded cables connecting voltage signals to the power measuring equipment).

8. Optional: Provide for the measurement of d.c. link parameters (voltage, current and power).

9. The converter to be supplied from an essentially sinusoidal voltage source at the nominal supply voltage in the relevant region (e.g. 400 V, 50 Hz in Europe)

10. Run the converter at 100% output frequency (50 Hz in Europe) and 100% of rated load current (the '100, 100' point) for 0.5 h, at the end of which time, internal temperatures may be deemed to have stabilised.

11. Read and record all relevant electrical parameters

12. Repeat (11) for at frequency/load points as follows: 100,75; 100,50; 75,100, 75,75; 75,50; 50,100; 50,75; 50,50; 25,100; 25,75; 25,50.

13. Disconnect the load and measure and record the converter no-load losses.

APPENDIX 3: Converter loss dependencies:

Origin of loss	Dependency
Control electronics, including d.c. link-derived power supply, d.c. link capacitor discharge resistor	Independent of load
Permanently energised, fixed speed cooling fans	Independent of load
Thermostatically controlled cooling fans	Load dependent
Converter-to-motor shielded cable charging	Independent of load
I^2R losses due to load current in all 'ohmic' conductors, including busbars, wiring, inductor windings etc.	Load dependent, and proportional to current squared
Losses due to semiconductor junctions exhibiting 'threshold' voltages	Load dependent, proportional to current (approximately)

Review of Energy Efficiency Measurement Standards for Power Drive System (PDS), Complete Drive Module (CDM) or electric motor driven by converter

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Abstract

Energy efficiency (and losses) of Power Drive System (PDS), Complete Drive Module (CDM) or electric motor driven by converter remains an important issue for the industrial community today but no common test protocol has yet been adopted. In Canada, the Canadian Standards Association (CSA) has developed Standard CSA 838: "Test Protocol for Determining the Efficiency of Variable Frequency Drives (VFDS)". In the USA, the Air-Conditioning, Heating and Refrigeration Institute (AHRI) published in 2011: "Performance Rating of Variable Frequency Drives". In Europe, European Committee for Electrotechnical Standardization (CENELEC) has drafted a 3 parts standard series EN 50598: "Ecodesign for power drive systems, motor starters, power electronics & their driven applications". On the International Electrotechnical Commission (IEC) level, working group (WG) 28 of technical commit-tee (TC) 2 published a Technical Specification (TS) IEC 60034-2-3: "Specific test methods for determining losses and efficiency of converter-fed AC induction motors".

This paper is aimed to review these documents and give to the reader a clear picture of what is inside each showing strengths and weaknesses and what could be used in the development of a new global IEC standard: IEC 61800-9 "Energy Efficiency of adjustable speed electric power drive systems" within the newly formed IEC WG18 under sub committee SC22G " Adjustable speed electric drive systems incorporating semiconductor power converters".

Publishes Standards

Canadian Standards Association (CSA): CSA C838-2013 [1]

This Canadian standard was published in 2013 to establish a test procedure to mainly evaluate the energy efficiency of Power Drive System (PDS) but also the Complete Drive module (CDM) and the motor if required by the user. The only test procedure developed in the standard is based on the input-output method and measurements of the electrical parameters at the CDM input, CDM output and motor output to compute the related efficiency figures.

Air Conditioning, Heating and Refrigeration Institute (AHRI): AHRI 1210-2011 [2]

The purpose of this standard published in 2011 is to establish for PDS: definitions; classifications; general test requirements; rating requirements; minimum data requirements for Published Ratings; marking and nameplate data; and conformance conditions within the heating, ventilating, air-conditioning and refrigeration (HVACR) context, to PDS used in the control of asynchronous induction motors. The range includes all those found within a building but not mechanically integrated into motors.

If this standard focuses on solely on the determination of the PDS efficiency (not CDM) by using the input-output method, it also provides test procedures for determination of motor insulation stress, and power line harmonics.

European Committee for Electrotechnical Standardization (CENELEC): EN50598-2 [3]

CENELEC European standard EN50598-2 is part of a series of 3 documents that aims to specify the methodology for determination of losses of the CDM, the PDS and the complete motor system (including motor starter, contactor, soft-starter, etc.) in the power range of 0,12 kW up to 1 000 kW.

Three methods are proposed: Input-output, mathematical models and calculations and calorimetric. It also defines IE and IES-classes, their limit values and provides test procedures for the classification of the overall losses of the motor system.

The other 2 parts of the series define the general requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA), and semi analytic model (SAM) (EN50598-1) and the quantitative eco design approach through life cycle assessment including product category rules and the content of environmental declarations (EN50598-3).

International Electrotechnical Commission (IEC): TS IEC 60034-2-3 [4]

The objective of this technical specification is to define test methods for determining the additional motor losses of three-phase induction motors when supplied by a CDM. These losses appear in addition to the losses when fed by a sinusoidal power supply and the results according to this specification are intended to allow for comparison of the harmonic losses of different AC induction motors when fed by a CDM. The emphasis is only made on the motor losses and not on CDM or PDS. This Standard specifies 3 test methods: summation of losses, input-output and calorimetric.

Definition of Type of Methods

To determine the energy efficiency (or losses) of motor, CDM or PDS, several methods are actually proposed in the reviewed standards but not all can be applied to each part of the drive system.

Input-Output Method

The input-output method involves the measurements of the power (electrical or mechanical) at the vicinity of the motor, CDM or PDS. Each part of the drive system could be considered as a black box with measurements at nominal or rated value and also at different load conditions. Figure 1 presents a block diagram of the method.

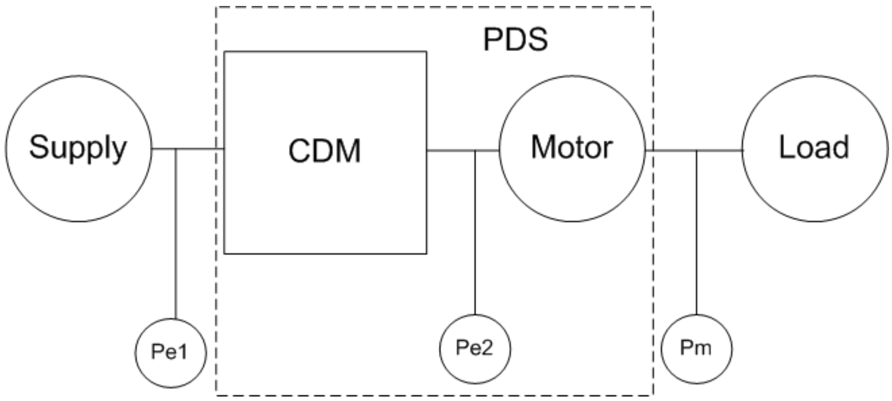

Figure 1: Direct input-output method

The computation of efficiency (or losses) or each system segment is performed by dividing the measurement of Pe2 by Pe1, Pm by Pe2 or Pm by Pe1. Each measurement has its own requirements that will be discussed later in this paper.

Mathematic Model and Calculations Method

With this method, a mathematical model is used to calculate the losses of CDM, motor and PDS. It consequently allows determining the losses of a product without measurements. The model consists of formulae, variables and parameters. The formulae describe the loss calculation procedure based on manufacturer's published literature. The variables depend on the operating point of the evaluated CDM, motor or PDS.

Calorimetric Method

The calorimetric determination method of the power losses is based on the calorimetric measurement of the dissipated power losses. Measurements shall be done at thermal equilibrium and the component to be measured has to be thermally isolated to guarantee conduction of the dissipated power losses by the cooling medium (air or water). Figure 2 presents an example of the setup required by this method.

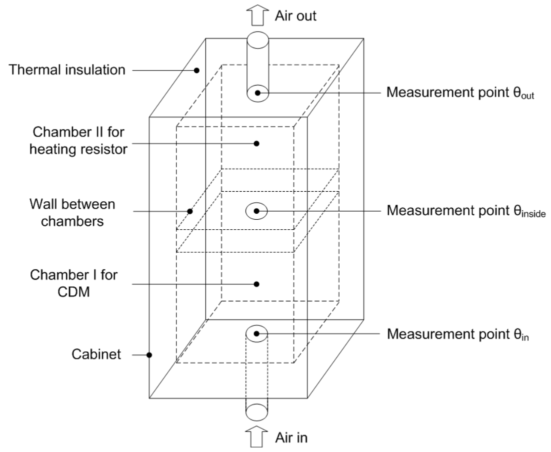

Figure 2: Example of Test Chamber for the Calorimetric Method [3]

Summation of losses

The summation of losses method is normally associated with the determination of the efficiency of three-phase induction motors by subtracting from the electrical input power, the mechanical power and all measured motor losses except the additional load loss determined by the method of residual loss. Though this method is recognized as having a low uncertainty requires the measurements of the motor torque and speed. This method could also be associated with the determination of CDM losses in the Mathematic Model and Calculations Method.

Specifications in Standards

Table 1 presents a summary of the specifications in each of the standards based on set-up conditions, instrumentation and test procedure. From this table, it can be seen that differences between standards exist. Here are the main points remarked.

- Specifications for Power Supply
- Determination of the Source Impedance
- Instrumentation Accuracy Specifications
- Error in Measurements
- Number of Points in Load Test
- Dynamometer Correction
- Motor Temperature Corrected
- Efficiency Classes
- Reference CDM, PDS, Motor

Table 1: Specifications in Reviewed Standards

	Standards and Methods							
	CSA 838	EN 50598-2			AHRI 1210	IEC 60034-2-3		
Technical Aspects	Input-Output	Input-Output	Mathematical Models and Calculations	Calori-metric	Input-Output	Summation of Losses	Input-Output	Calori-metric
Specifications for Power Supply	YES	NO	-	-	YES	NO	NO	-
Determination of the Source Impedance	YES	YES	-	-	YES	NO	NO	-
Instrumentation Accuracy Specifications	YES	YES	-	NO	YES	YES	YES	YES
Error in Measurements	YES	NO	-	NO	NO	NO	NO	NO
Rated Load Test	YES	YES	-	YES	YES	YES	YES	YES
Load Test	YES	YES	-	YES	YES	YES	YES	YES
Number of Points in Load Test	20	CDM (8) PDS (8)	-	CDM (8)	7	6	1	1
Dynamometer Correction	YES	NO	-	-	YES	NO	NO	
Cable Length Specification	YES	YES	-	-	YES	NO	NO	NO
CDM Efficiency	YES	YES	YES	YES	NO	-	-	-
Motor Efficiency	YES	NO	NO	NO	NO	YES	YES	YES
Motor Temp. Corrected	YES	NO	NO	-	NO	NO	NO	NO
PDS Efficiency	YES	YES	YES	-	YES	-	-	-
Power Line Current Harmonics	NO	NO	NO	-	YES	NO	NO	NO
Motor Insulation Stress	NO	NO	NO	-	YES	NO	NO	NO
Efficiency Classes	NO	YES	YES	YES (CDM)	NO	YES	YES	YES
Default Setup	YES	YES	YES	YES	NO	YES	YES	YES
Reference CDM, PDS, Motor	NO	NO	YES	NO	NO	NO	NO	NO
Auxiliaries Losses	NO	YES	YES	-	NO	-	-	-

Standards Comparison

The standards comparison demonstrates that all include the input-output method with CSA 838 and AHRI 1210 solely on this method. Moreover, EN50598 contain the calorimetric method for CDM and the mathematical models and calculations method. IEC 60034-2-3 also includes the calorimetric method but for the motor and the summation of losses method to determine the extra losses in motor only under CDM supply, similarly to well known and accepted IEC 60034-2-1 [5] low uncertainty method. However since the use of the summation of losses method in IEC 60034-2-3 is not fully accepted yet, the comparison is limited to three methods: input-output, calculations and calorimetric (CDM only).

Evaluation of the Input-Output Method

Since the input-output method for either CDM, PDS or motor losses (or efficiency) evaluation is proposed in all standards and directly impacted by the different power measurements (electrical and mechanical), it is of the premiere importance to have the best possible accuracy in each measurement. It is recognized that if the electrical power measurement at the input of the CDM is not a real issue, the electrical power measurement between the CDM and the motor and the mechanical power measurement at the motor output especially the torque require some precautions.

Electrical Power Measurement between the CDM and the Motor

Today's top quality power analyzers have basic power accuracy measurement in the range of ± 0.02 % of reading. But this specification is for specific "ideal" conditions that can rarely be achieved in conditions found in CDM and motor (fed from CDM) losses evaluation considering the type of voltage and current waveforms and related harmonics. Figure 3 presents typical waveforms at the output of a CDM.

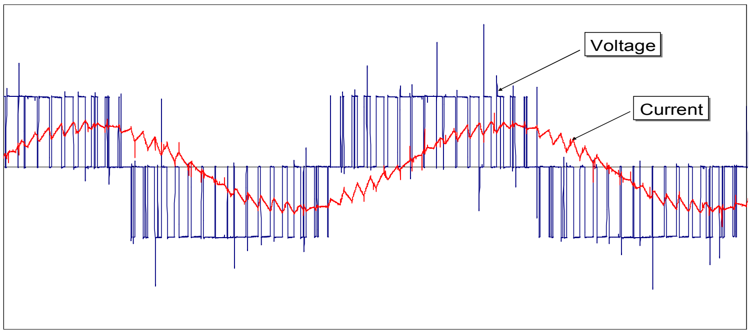

Figure 3: Typical waveforms at the output of CDM (One phase)

But what happens to the basic power accuracy in this case? By example, Yokogawa publishes for its WT3000 power analyzer [6] apart from its basic power accuracy ± 0.02 % of reading, other accuracy based on different frequencies of operation (Figure 4).

0.1 Hz ≤ f < 30 Hz	0.2% of reading + 0.3% of range
30 Hz ≤ f < 45 Hz	0.05% of reading + 0.05% of range
45 Hz ≤ f ≤ 66 Hz	
• Current sensor input • Current of a 30-A input element from direct input • Current of a 2-A input element from direct input at the 500 mA to 2 A range	0.02% of reading + 0.04% of range
• Current of a 2-A input element from direct input at the 5 mA to 200 mA range	0.05% of reading + 0.05% of range
66 Hz < f ≤ 1kHz	0.05% of reading + 0.05% of range
1 kHz < f ≤ 10 kHz	0.15% of reading + 0.1% of range
10 kHz < f ≤ 50 kHz	0.3% of reading + 0.2% of range
50 kHz < f ≤ 100 kHz	0.014 × f% of reading + 0.3% of range
100 kHz < f ≤ 500 kHz	0.012 × f% of reading + 1% of range
500 kHz < f ≤ 1 MHz	(0.048 × f – 19)% of reading + 2% of range

Figure 4: Yokogawa WT3000 accuracy at different frequency ranges

It can be seen from this figure that the total accuracy is influenced by the frequency of operation but also at the percentage of the range and the phase angle between the voltage and the current (power factor).

Figure 5 presents an example of the resulting accuracy based on these conditions of operation. In this example, the base frequency is 60 Hz and the resulting accuracy of the power measurement (no VT or CT) is ± 0.09 % of reading when using the three-wattmeter method (3P-4W).

Voltage:	**Reading**	266
	Range	300
Current:	**Reading**	25
	Range	30
		3P-4W
Watt:	**Reading**	17955
	Range	27000
Frequency:	**kHz**	0.06
Power Factor	**-**	0.9

Frequency	**% Uncertainty 3P-4W**
DC	N/A
0.1≤ f < 30 Hz	0.67
30 ≤ f < 45 Hz	0.14
45 ≤ f ≤ 66 Hz	0.09
66 Hz < f ≤ 1 kHz	0.14
1 kHz < f ≤ 10 kHz	0.31
10 kHz < f ≤ 50 kHz	0.62

Figure 5: Example of Total Accuracy Based on Frequency, Range and PF

But the frequency spectrum of the voltages and currents (hence power) between the CDM and the motor is larger than only the 60 Hz fundamental and one could have the tendency to compute the measurement accuracy with the above specifications.

However, the main contribution to real power is in the motor's fundamental frequency so a very large part of the energy from the CDM to the motor is at this frequency. The remainder is caused by the CDM switching frequency, normally between 1 and 10 kHz and its harmonics (of the switching frequency) produced by the pulse width modulation (PWM) control typical of industrial CDM.

Even in the presence of harmonics (of voltage or current) the real power can only be present if the harmonic voltage and current are at the same frequency. A high level of harmonic voltage content as in the case of PWM CDM output coupled to low level of harmonic current content (filtered by the motor) produce very negligible real power.

As an example, Figure 6 shows the power spectrum between the CDM and the motor for a 37 kW PDS set at 100 % of nominal speed and 50 % of nominal motor torque with a PWM switching frequency of 4 kHz.

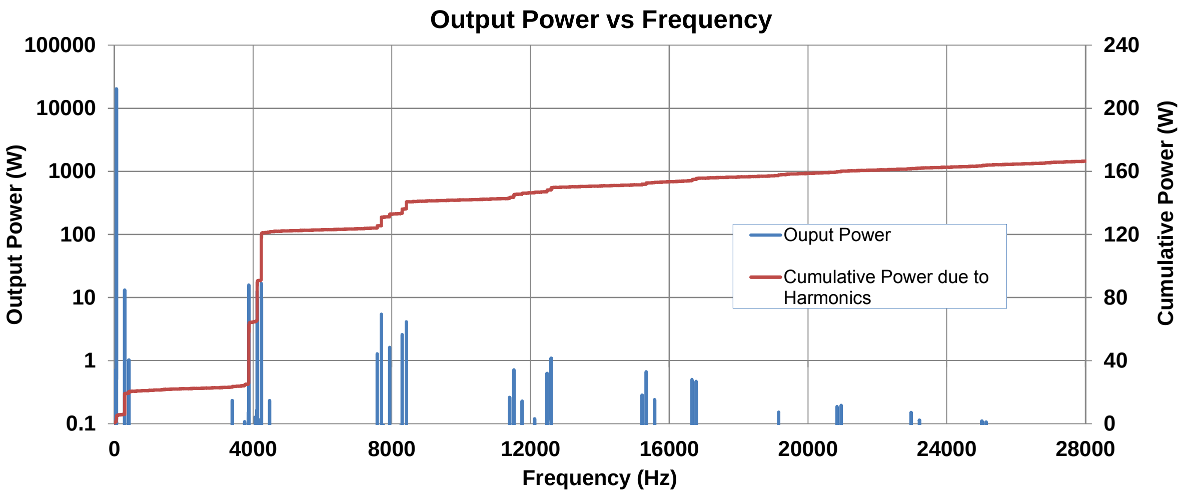

Figure 6: Power Spectrum between CDM and Motor

One can see that most of the real power is effectively in the fundamental and the contribution of the higher frequencies related to the PWM switching frequency is very limited. The cumulative real power due to harmonics represents 0.8 % of the total real power to the motor. For this case, a computation of the total accuracy in the measurement of the electrical power measurement between the CDM and the motor using the WT3000 power analyzer specifications has been evaluated as:

60 Hz Base accuracy = ± 0.09 %

66 Hz < f ≤ 1 kHz: ± 0.14 % * 0.1% = ± 0.00014 %

1 kHz < f ≤ 10 kHz: ± 0.31 % * 0.6% = ± 0.00185 %

10 kHz < f ≤ 50 kHz: ± 0.62 % * 0.2% = ± 0.00130 %

Total Accuracy = $\sqrt{}$ $(0.09^2 + 0.000142^2 + 0.00185^2 + 0.00130^2)$ = ± 0.09 %

So it is still possible to measure the electrical power between the CDM and the motor with a very good accuracy even if the frequency spectrum is large.

Electrical Power Measurement at the CDM input

Figure 7 presents the typical waveform at the CDM input and figure 8 shows the power frequency spectrum.

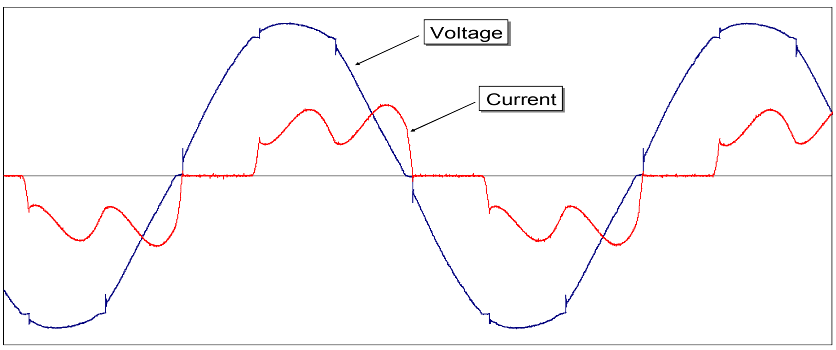

Figure 7: Typical Waveform at the CDM Input (One phase)

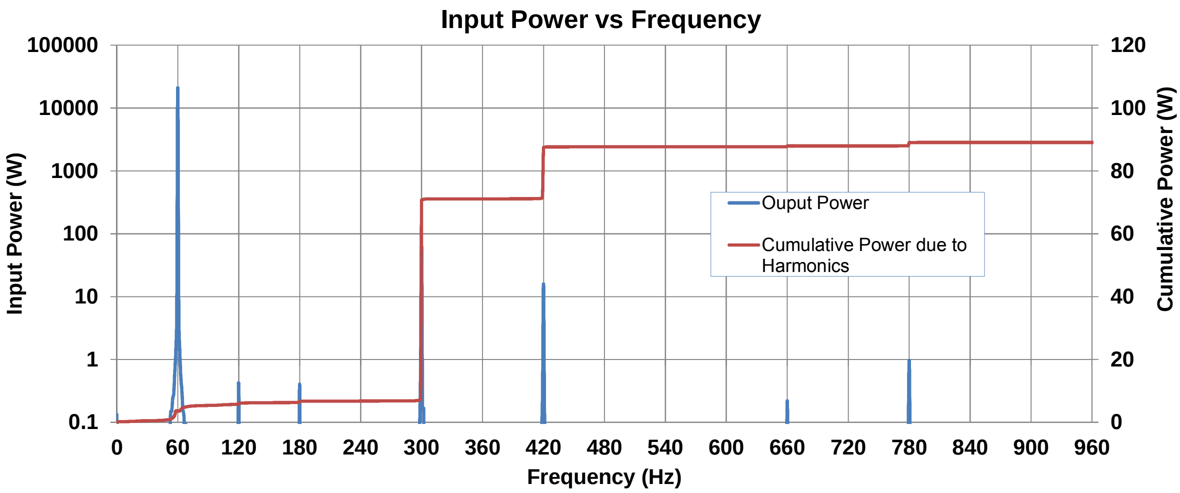

Figure 8: Power Spectrum at the CDM Input

The same approach can be taken with the electrical power measurement at the input of the CDM but with lower power frequency spectrum compared to CDM output. Here the cumulative power due to harmonics represents 0.4 % of the total real power from the source. The accuracy of the power measurement could be calculated when using again a Yokogawa WT3000:

60 Hz Base accuracy = ± 0.09 %

66 Hz < f ≤ 1 kHz: ± 0.14 % * 0.4% = ± 0.0006 %

Total Accuracy = $\sqrt{}$ $(0.09^2 + 0.0006^2)$ = ± 0.09 %

So it is again possible to measure the electrical power between the CDM input with a very good accuracy.

Mechanical Power Measurement at the Motor output

The computation of the mechanical power at the motor output implies the measurement of the torque and speed. If the measurement of the speed is made with relatively low uncertainty in the range of ± 0.01 %, the torque measurement represents a challenge.

Many years ago, the motor torque measurement was possible with scale and dynamometer and thereafter replaced with a load cell and torque arm to improve accuracy. In most today's manufacturers and independent laboratories, torque measurement is performed wit the use of in-line torquemeter (or torque transducer) placed between the motor and the bench's load. These torquemeters operates all on the same principle of using stain gages measuring the deformation of a shaft but are not all equal. Some have bearings, brushes or no-contact and may incorporate all the electronics inside the body. The transmission of the signal from the torquemeter rotor to the stator and to the data acquisition is also important to minimize the influence of the noise produced by the CDM. Another important parameter is the influence of the temperature of the torque transducer. The fact that in-line torquemeter have bearing producing heat, they have to incorporate temperature compensation that helps to minimize the effect of temperature variation during the test, especially considering that the calibration is performed when it is at ambient. Among the different technologies, the no-contact type is considered as the less sensitive to temperature since no bearing is used and have very low susceptibility to ambient temperature variation.

Actually, good in-line torque transducers have an accuracy ranging from ± 0.1 to ± 0.2 % of the range. Best of the class reach an accuracy of ± 0.03 of the range and the same type can be ordered with an improved accuracy down to ± 0.01 % of the range certified with a calibration report from the manufacturer. On this point, it is important to mention if these very high accuracy torquemeters are relatively expensive, it is possible to use the same torquemeter for a large range of torque meaning using in the low range of its nominal. By example, if one wants to limit the investment, he can use it at half range resulting in an uncertainty of ± 0.02 of the reading for the ± 0.01 class just mentioned.

Laboratory experience has showed good results down to 10 % of the range of the torquemeter and even at 1 %.

Here again, it is certainly possible to measure motor torque with low uncertainty.

Evaluation of the Mathematic Model and Calculations Method

The mathematic model and calculations method is unique for EN 50598 among standards reviewed and has been developed by CENELEC. This method defines the procedures and the operating points to be used for determining converters' and drive systems' losses as well as energy efficiency classes for voltages lower than 1 kV and rated power up to 1 MW. The efficiency classes are defined by comparing the converter and system losses with predefined reference converters and systems. This method represents the preferred method proposed in EN 50598 and contains more than 30 pages of data and calculations based on CDM's manufacturers and targeting this group. If this method is convenient for manufacturers, it has a limited application for independent labs and users since it requires extremely detailed data on all components inside a CDM which makes this method very difficult to use for others than manufacturers. The authors also mentioned that the uncertainty of this method is 10 % of CDM losses.

Evaluation of the Calorimetric Method

The calorimetric method is part of EN 50598 and IEC 60034-2-3 but not for the same test equipment, EN 50598 for CDM and IEC 60034-2-3 for motors. It is however worth to note that it is mentioned in EN 50598 that the calorimetric measurement method for PDS is excluded since it is very difficult to perform for motors and on the other hand that IEC 60034-2-3 mentions that test procedures for this method shall be in accordance with IEC 60034-2-2, a standard for evaluating motor losses of large machine.

According to EN50598, the calorimetric method for evaluating CDM losses achieves a constant accuracy in measurement whatever the CDM size and the amount of losses produced. EN 50598 publishes an uncertainty of ± 5 % on the measured losses. In the case of IEC 60034-2-3 that refers to IEC 60034-2-2 [7], the uncertainty of the calorimetric method is only labeled as "Low" and a note says that if the relative error in the power measurement is likely to be greater than 3 %, the calorimetric method is not recommended. Finally as a complement of information, a paper [8] mentioned that it is possible of measuring power loss in electrical machines rated up to 300 kW with an overall accuracy of 0.2%.

Impact on Losses from Uncertainty with Different Methods

Since different methods present different figures of uncertainty that are constant for some and vary for others, figure 9, 10 and 11 present an comparison of the impact of the evaluation of losses of the CDM, motor and PDS to their relative efficiency.

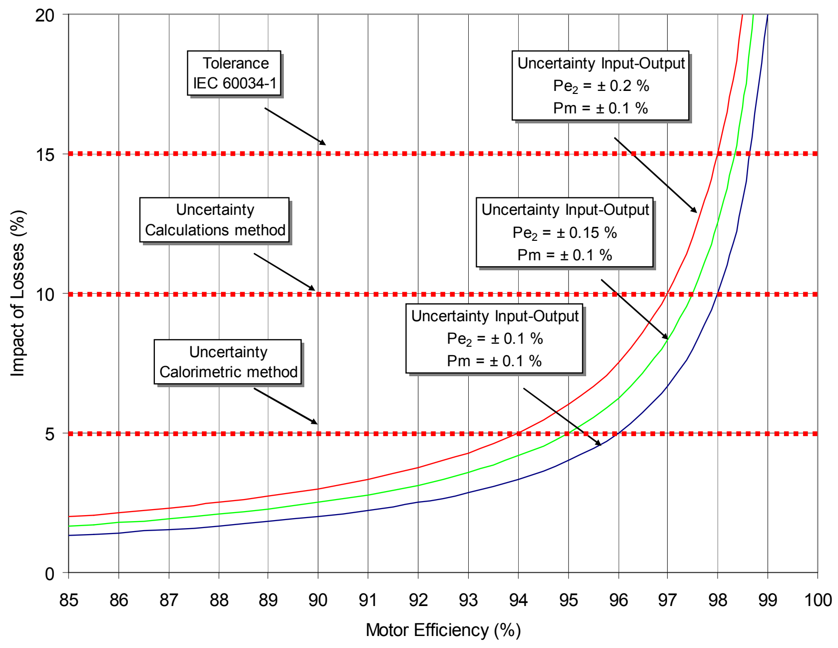

Figure 9: Impact on Losses from Uncertainty with Different Methods (Motor)

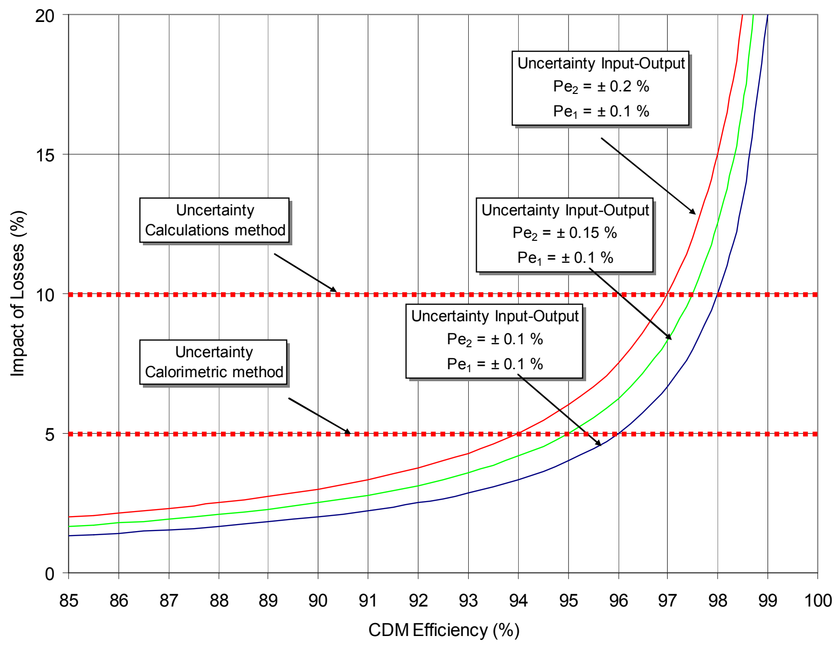

Figure 10: Impact on Losses from Uncertainty with Different Methods (CDM)

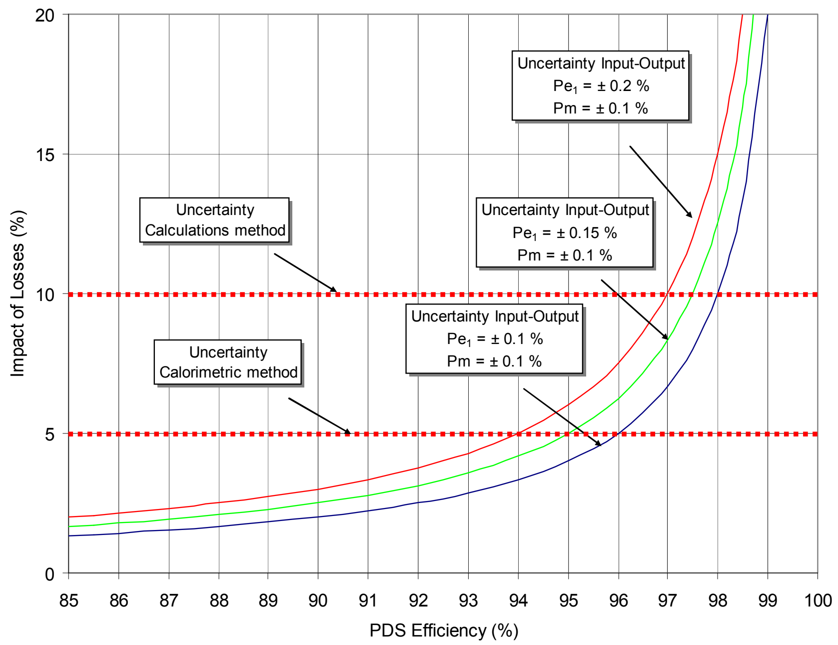

Figure 11: Impact on Losses from Uncertainty with Different Methods (PDS)

It can be seen from figure 9 that for motor efficiency up to 95 %, and with uncertainty of the electrical power measurement (Pe_2) of ± 0.15 % and 0.1 % for the mechanical power (Pm), the input-output method has the least impact on the determination of motor losses. The calculation method is the least accurate with a low margin from the tolerance attributed for motor efficiency classes (15 % of losses).

From figure 10, considering that the CDM efficiency is relatively high, in the range of 95 – 98 % efficiency, the calorimetric method is marginally better than the input-output method.

In figure 11, considering that the PDS efficiency results of the individual efficiency of the CDM and the motor, being at maximum 93 %, here again the input-output method is most favorable.

Conclusion

This review of the standards for the determination of losses (or efficiency) of CDM, motor and PDS demonstrated that different methods are proposed and one common method that is included in all standards seems to make consensus, the input-output method. The paper showed that if this method is used with instrumentation with low uncertainty and currently available on the market today, the determination of losses (or efficiency) can be also made with low uncertainty.

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Motors 3

A Comparative Efficiency Analysis of a 7.5 HP Copper Rotor Motor and Three Permanent Magnet Motors

Richard E. Defay
Copper Development Association, Inc.

Abstract

For some time, the efficiency of the Permanent Magnet Motor has been touted as far superior to that of the induction motor. Because the Permanent Magnet Motor relies on a drive to operate, the author sought to conduct a relevantly equal comparison using both the Permanent Magnet Motor and a Copper Rotor Motor using the drive specified by the PM manufacturer. The entire testing protocol, to be conducted over time, is to include three different horsepowers, namely 5, 7.5 and 10. The results presented here are for the first round of testing of a 7.5 HP Copper Rotor Motor and three different manufacturer's Permanent Magnet Motors. The drives suggested by the PMM manufacturer were used for both the PMM and the CRM, each configured to the Permanent Magnet Motor manufacturer's specifications. [1]

The testing of this first of three phases was conducted at the motor testing laboratory of Advanced Energy, Inc. of Raleigh, NC under the supervision of Emmanuel Agamloh, Ph.D., P.E. and his staff over a period of several months.

No manufacturer's name have be used, as the purpose is to conduct a fair comparison untainted by bias.

Objective

The purpose of this study is to determine the accuracy of marketing material of motor manufacturers (see figure 1) that make the claim of superior efficiency performance of the Permanent Magnet motor (hereafter referred to as PM) over an induction motor. For the study, the Copper Rotor Motor (hereafter referred to as CRM) was chosen. The 7.5 HP was the first of three such speeds to make comparisons. [2]

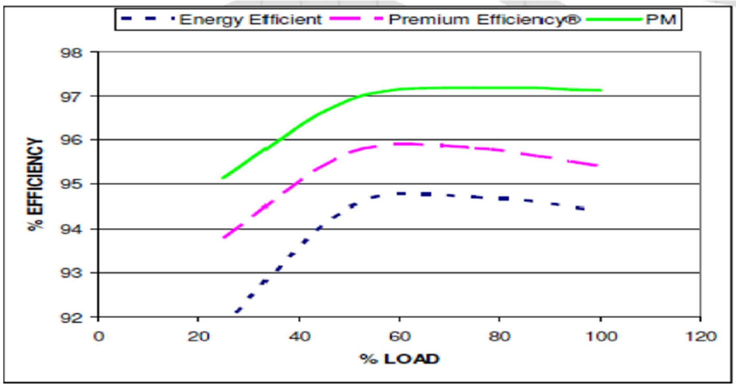

Figure 1

To that end, Advanced Energy, Inc. of Raleigh, NC, one of the most highly respected independent motor testing laboratories in the world, was asked to perform the testing under the supervision of Emmanuel Agamloh, Ph.D., P.E. and his staff.

Phase I -Test Procedure

Motors were operated off the same variable frequency drive recommended by the PM manufacturer and set precisely to that manufacturer's specifications. A 7.5 HP Siemens CRM was chosen and bought commercially through normal distribution channels. Siemens was not involved in the process in any way. An equivalently rated PM motor was provided on loan from a manufacturer from its catalogue. No mention of testing purposes were provided. In neither case was a motor handpicked due to above nameplate performance. [3]

Figure 2 shows a PM motor. The one actually tested is not shown for confidentiality reasons.

Figure 2

Figure 3 below demonstrates the data collection equipment. Each motor was mounted and aligned to Advanced Energy's AC dynamometer. Figure 4 illustrates the CRM set up with the VFD.

Figure 3

Figure 4

Figure 5 below demonstrates the schematic for the testing. Each of the three PM motors and the CRM were tested over the range of speeds and torques indicated in figure 6 below. The torque set points were calculated as a percentage of rated full load torque of the motor. Prior to taking data points, each motor was thermally stabilized. Advanced Energy's criterion for stabilization requires the temperature rise of the motor to change less than 1º C over a 30 minute period. Following the meeting of this criterion, the motor was operated at varying torque loads and speed points demonstrated in figure 6. For the PM motor, the motor was operated at 1800 RPM with a reduced torque of about 24Nm (Newton meters) until the motor was thermally stable. This prevented the motor from tripping. [4]

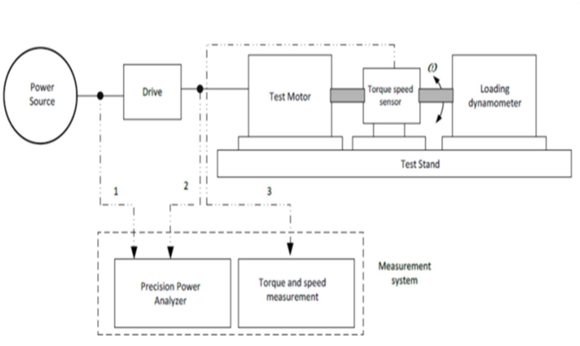

Figure 5

Torque, %	SPEED				
	1800	1600	1400	1200	1000
25	x	x	x	x	x
50	x	x	x	x	x
75	x	x	x	x	x
100	x	x	x	x	x
110	x	x	x	x	x

Figure 6

Performance comparison was carried out on the basis of system efficiency calculated as a ratio of shaft output to electrical input into the VFD and represented by figures 7, 8, 9. 10 and 11 below. [5]

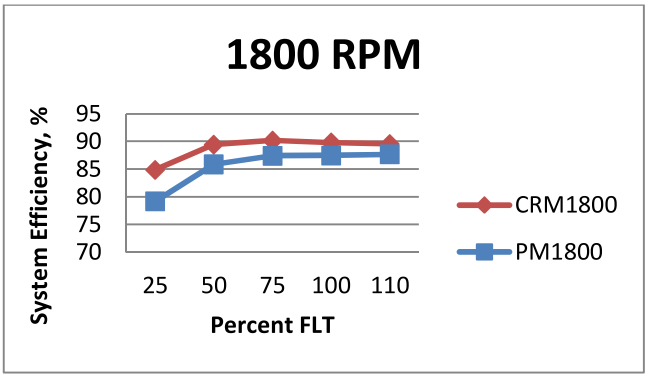

Figure 7

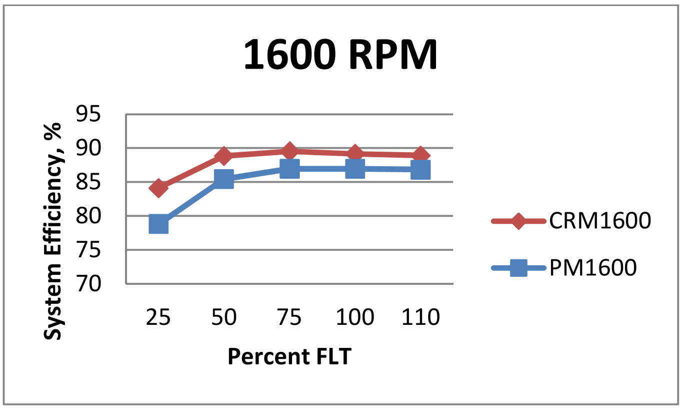

Figure 8

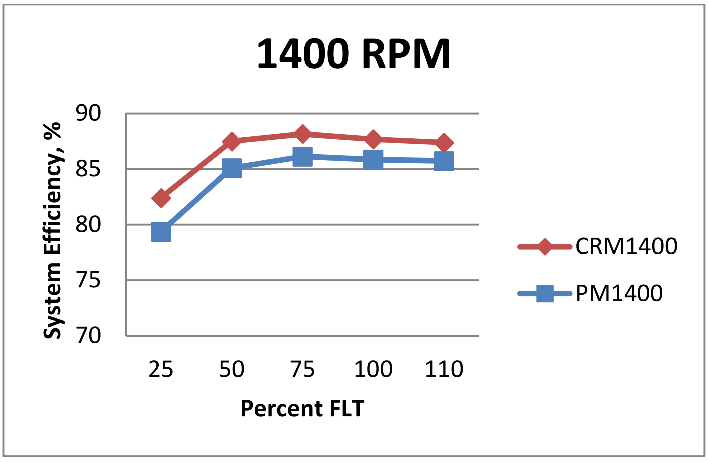

Figure 9

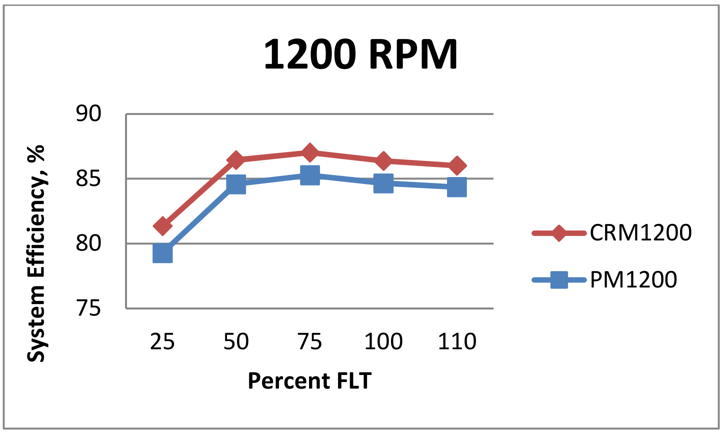

Figure 10

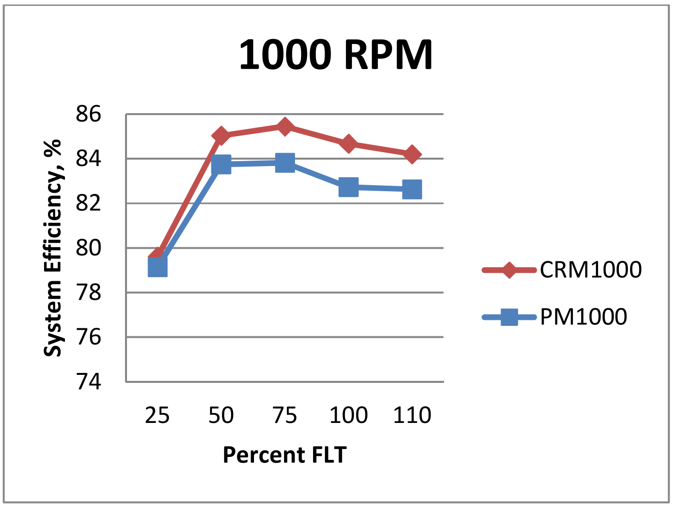

Figure 11

Phase I Conclusions

It is seen from the graphs that the CRM system efficiency is higher than that of the PM motor tested. The only criterion used in sourcing the PM motor is that it has the same rating (7.5 HP) and similar synchronous speed (1800 RPM) to the induction motor. While it was known and expected that the CRM was above NEMA premium efficiency, no attempt was made to identify the highest efficiency commercially available PM motor which is why we chose to test three different manufacturers. Therefor it is possible that there may be other 7.5 HP PM motors are more efficient than the one tested. While it is generally considered that PM motors are more efficient than induction motors, the foregoing results for two commercially available motors are quite interesting. This means that there is an opportunity to perform similar evaluations on a larger scale in order to properly evaluate the promise of the CRM technology. [6]

Phase II – Test Procedure

This is the second test of its kind performed by Advanced Energy, Inc. of Raleigh, NC, following the results of the first phase. Like Phase I, both motors were operated on the same variable frequency drive (VFD) with the objective of comparing efficiency. The same 7.5 HP Siemens CRM was used and a commercially available PM motor of equivalent rating was purchased for the testing. The VFD recommended by the PM manufacturer was purchased and used for both motors using settings prescribed by the PM manufacturer. Figure 12 illustrates the nameplate data for both motors. The same test data points as in the first phase were used. [7]

	PM	CRM
Rating (Hp)	7.5	7.5
Voltage (V)	460	230/460
Current (A)	9.4	19/9.5
Speed (RPM)	1800	1775
Frequency (Hz)	150	60
Weight (lbs)	150	131
Efficiency (%)	93.0	92.4

Figure 12

The following graphs are quite interesting in light of the results of the first phase of testing as seen below in figures 13, 14, 15, 16 and 17.

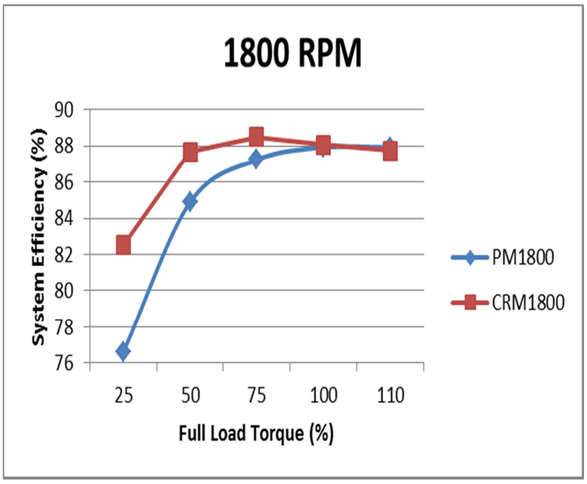

Figure 13

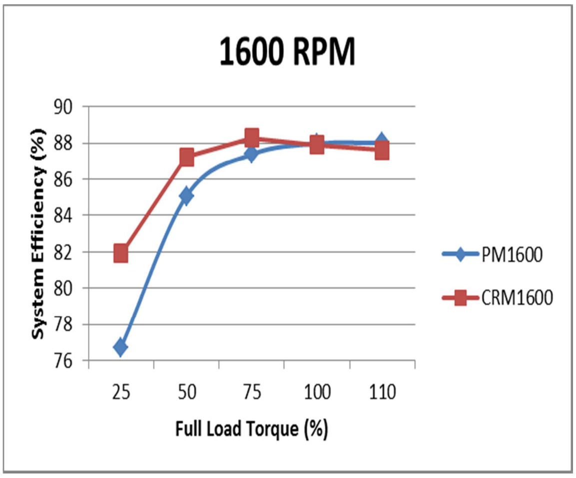

Figure 14

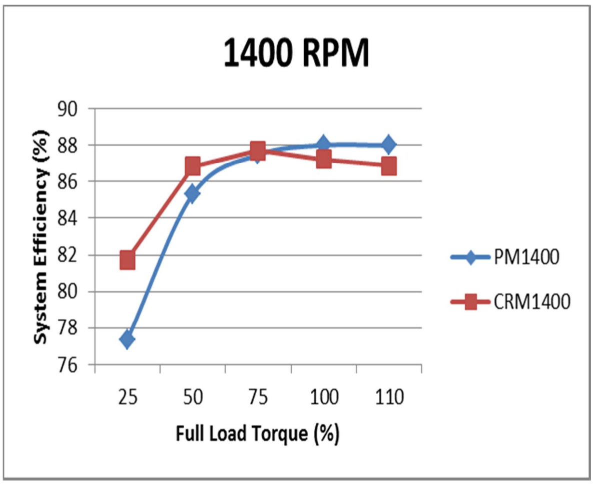

Figure 15

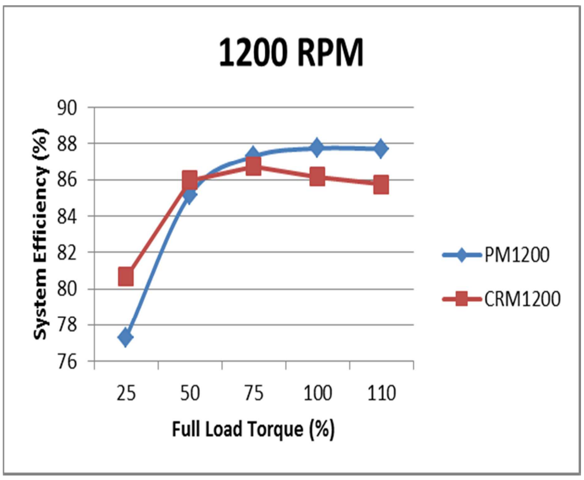

Figure 16

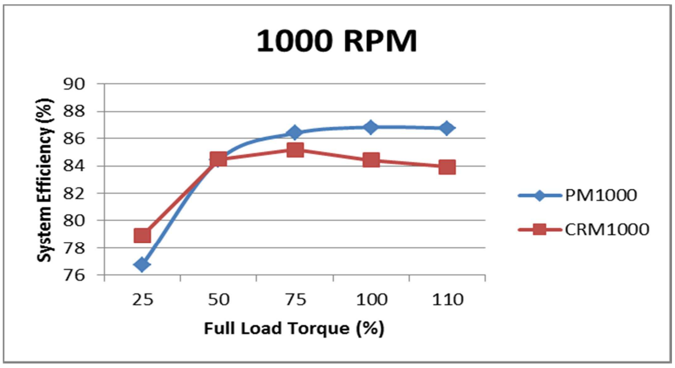

Figure 17

Phase II Conclusions

It is seen that neither motor's system efficiency is clearly higher than the other throughout the entire set of data points. Although both motors are rated above NEMA premium efficiency, neither performed as well as their rated efficiency values. At 1800 RPM the motors are very similar at loads of 100% and 110%. At loads below 100%, the CRM outperforms the PM. In general, the PM seems to outperform the CRM at higher loads (100% and 110%) as the speed decreases. In general, the CRM seems to outperform the PM at lower loads (25% and 50%). At 75%load, the CRM has a higher system efficiency at 1800 and 1600 RPM and the PM has higher system efficiency at 1200 and 1000 RPM. These results do not support that either motor is consistently more efficient than the other. Once again, the results seem to point to further testing. [8]

Phase III Test Procedures

This is the third test performed by Advanced Energy. Further testing was pursued based upon the data and conclusions from the first two phases. Once again, the same CRM is used as in the first two rounds and another PM motor was purchased from normal distribution channels. The VFD recommended by the PM manufacturer was purchased and used for both motors using settings appropriate for each motor type. [9]

Figure 18 below highlights the nameplate data for both motors being tested.

	PM	CRM
Rating (Hp)	7.5	7.5
Voltage (V)	460	230/460
Current (A)	7.53	19/9.5
Speed (RPM)	1800	1775
Frequency (Hz)	60	60
Weight (lbs)	150	131
Efficiency (%)	92.6	92.4

Figure 18

The following graphs in figures 19, 20, 21, 22 and 23 demonstrate the results of phase III testing.

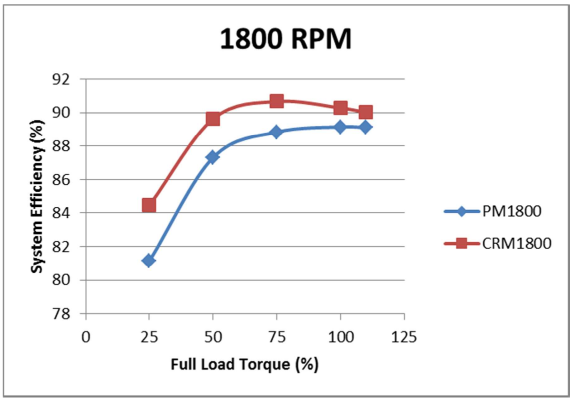

Figure 19

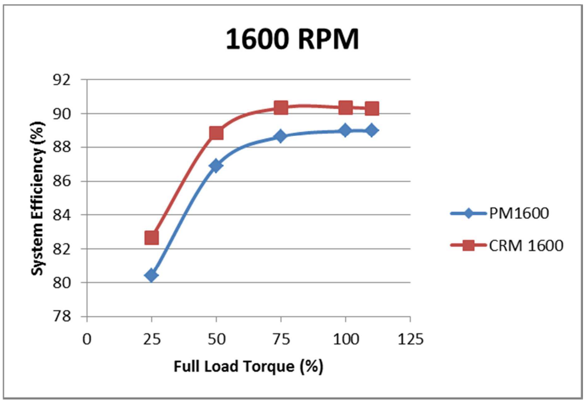

Figure 20

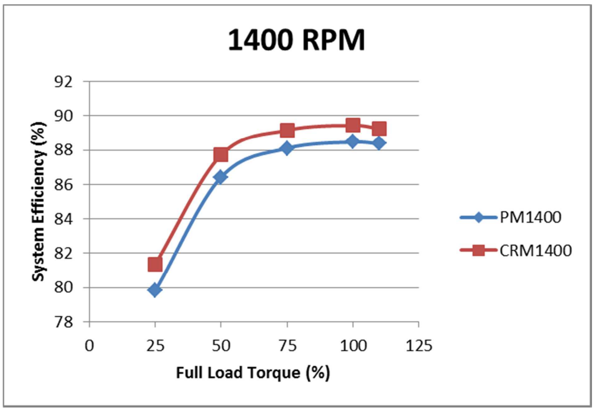

Figure 21

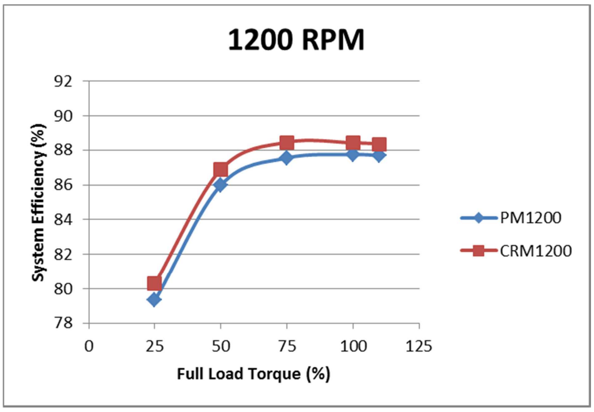

Figure 22

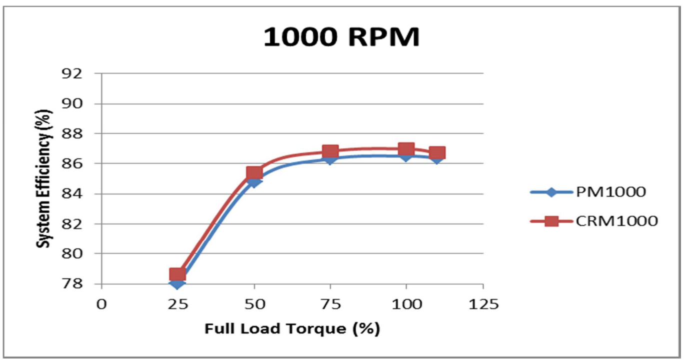

Figure 23

Phase III Conclusions

It is seen in this third round of testing that the CRM had the higher system efficiency throughout the entire set of data points. The gap between system efficiencies of the CRM and the PM motor seems to decrease with a decrease in speed. In other words, the system efficiency of the PM motor is closer to the system efficiency of the CRM at 1000 RPM (all loads) than it is at 1200 RPM. This trend continues as increasing speed points are compared. The largest discrepancy of system efficiency values for 75%, 50% and 25% loads is at 1800 RP, which is the rated speed of the PM motor as well as the synchronous speed of the CRM. For loads of 110% and 100% the largest discrepancy of system efficiency is at 1600 RPM. Although both motors are rated above NEMA premium efficiency, neither motor performed as well as their rated values. [10]

Conclusions

From the standpoint of the end-user, the motor consumer, the question thus becomes, based upon the costs detailed in Table 1 below, is the very high cost of the PM worth the small difference in efficiency potential?

7.5Hp Permanent Magnet Motors Cost Comparison				
	Motor	**Drive**	**Tax**	**Total**
PM Motor A	N/A	$ 899.30	$60.70	$960.00
PM Motor B	$1,097.95	$563.27	$112.13	$1,773.35
PM Motor C	$ 893.15	$1,000.11	$146.73	$2,039.99
7.5Hp Copper Rotor Motor				
Siemens	**Motor**	**Drive**	**Tax**	**Total**
	$565.85	N/A	$38.20	$604.05

Table 1

While it is considered that PM motors are more efficient than induction motors, the findings for these three commercially available PM motors are quite interesting. This indicates that further testing at other HP speeds are in order. [11]

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AT THE CUSP OF THE NEXT ELECTRIC MOTOR REVOLUTION: REPLACING COPPER WITH CARBON NANOMATERIALS

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Abstract

Despite the fact that electrical machines are considered a fairly mature technology, they hold the potential for further improvement. A true breakout innovation for accelerated improvement in electrical machines calls for the introduction of new elements. It is time to look at the newest advancements in carbon nanomaterials research to push development of rotating electrical machinery an important step further. The conductivity of CNT-fibre yarn materials is at the moment at 10 MS/m but future scenarios may bring it up to 100 MS/m and beyond.

Copper is responsible for a major share of the efficiency losses in electrical machines. Copper is also a valuable metal, produced and recycled in energy- and carbon-emission-intensive processes, which makes using copper in large-scale rotating machine industries resource expensive. By replacing copper used in the windings of an electrical machine with a lightweight carbon nanomaterial solution made of advanced carbon nanotube (CNT) fibres, it may be possible to improve the machine efficiencies as well as reducing the machine dimensions and masses in the future.

At Lappeenranta University of Technology, we have started to study the known and potential properties of the newest CNT-fibre yarn materials and have introduced these into electrical machine development. We have successfully developed a small prototype machine which operates at 15 000 rpm and delivers 40 W output. The test machine has windings made of CNT yarn, and it operates well, given the fact that the properties of present-day CNT materials are not yet fully exploited which generates a set of restricting boundary conditions. 100 MS/m conductivity should open up new application routes for CNT materials to be incorporated into the wide operational processes of rotating electrical machinery. Development of CNTs for conductor applications is, however, still in its infancy. We are, however, already at the cutting edge of development in electrical machinery design for special applications.

Introduction

Electrical machines have significant improvement potential. Since 2009, with the European Commission Regulation (EC) No 640/2009 [1], many technology and design improvements in electrical machines have contributed effectively to the low-carbon economy targets set by the European Union (EU) with regard to eco-design requirements for electric motors. Incremental improvements in electrical machines efficiency are indeed expected to continue, but the technology would need to come up with radical advances to substantially affect the cost, mass and performance of electrical machines in the future. In particular, *new advanced conducting materials are needed in developing better performing and sustainable electrical machines.*

In this article we look at how the newest results obtained from carbon nanotubes research could advance a disruptive breakthrough in the development of rotating electrical machinery. The article is organized in six sections. In sections I to IV, we introduce the topic, state the problem, provide a state of the art overview of development in electrical machine design, and make some recommendations for future research. Section V introduces the practical CNT yarn material and presents some results of the design and construction of a small prototype machine with CNT yarn conductors, and section VI gives conclusions.

Traditionally, electrical machine windings are made of copper or aluminium, for several reasons: Copper has the second best conductivity of metals at room temperature, it is less expensive than silver which has the highest metallic conductivity, it is relatively easy to manufacture because the mining industry is well-established, and the recycling value of copper is high. The use of copper to improve the energy efficiency of electrical machines is, however, not a cheap solution; not least because there are high costs associated with the mining and recycling of copper, and because the EU is dependent on imports to meet 50% of its copper demand and thus also dependent on globally set copper prices [2]. Moreover, the levels of cradle-to-gate energy consumption in the production of copper are very high. Copper has also a relatively high metal density (ρ_{Cu} = 8960 kg/m^3) which means that copper products are heavyweight. Increasing the amount of copper in a machine does not necessarily improve the energy efficiency of the machine. For reasons of comparison, the most important properties of conventional and prospective conductor materials are given in Table 1.

Table 1: Conductor properties

	Silver	Copper	Aluminium	CNT-yarn
Conductivity [MS/m]	63.0	59.6	35.0	3 … 10 …100 …
Resistivity temperature factor 1/K	0.0038	0.00386	0.0039	~ 0
Density [kg/m^3]	10900	8960	2700	~1500

Engineering scientists – following the overall ambition to improve the energy efficiency and lower the mass of electrical machines – are therefore seeking *to replace copper with other high-conductivity and lightweight solutions*. We envision that recent materials research advancements in nanotechnology can help enable radical technology advancement and industrial innovation by pushing both the resource efficiency and energy efficiency of electrical machines to new heights.

Despite the high conductivity of copper, most of machine losses occur in copper windings. Around 44 % of all electricity consumed globally is consumed by electrical motors. Motors can be considered to be responsible for ca. 12 % of the total greenhouse gas emissions in the EU [3]. A typical industrial motor – an 11 kW class-IE3 cage induction motor – has a minimum rated point efficiency of 91.4 %. At rated operating point it converts about 1040 W into heat losses. Of these losses, ca. 45 % are created in the stator winding, 27 % in the rotor windings, 21 % are iron losses and the rest are friction and additional losses [4]. Because copper is the most commonly used conductor material in electrical machines, the Joule losses in the windings are often referred to with the term P_{Cu} "copper losses". In an induction motor the "copper losses" are responsible for ca. 72 % of all the losses in the machine, which corresponds to 750 W of heat power. We may assume the 11 kW induction motor to be is a most representative case as it stands for the average type of motors used in the EU. If we then further calculate and take as an input a 45 % share of the total electricity generation in EU (which in the year 2013 was 3100 TWh) [3], we may conclude that every year around 86 TWh of the total electrical energy consumption is due to copper losses in rotating electrical machinery. 86 TWh corresponds to almost the total electricity consumption in Finland. In euros, the numbers associated with copper losses are impressive. With an average price of 110 €/MWh for electrical energy, the financial losses in the EU caused by copper losses in electrical motors is around 9500 M€, annually and alone for motors. Also high-power generators suffer from copper losses although their efficiencies are however significantly higher, and therefore their share of copper losses remains less impressive but not at all insignificant. We may estimate that the total amount of CO_2 caused by copper losses in the EU is 4.5×10^{10} kg annually.

Problem statement

The past decades of incremental development in rotating electrical machinery have shown that it will not be possible to significantly reduce the copper losses of electrical motors – and neither will it be possible to develop next generation lightweight motors – without the introduction of new materials into the field. Radical innovations, which are usually pioneered in niches, seem to have a hard time to break out. Similar as for others new technologies, also for the electrical machine technology a true break out of existing niches can only happen by riding along with growth in new markets [5]. Recent technological and economic development and commercialization of nanotechnology seem to open up totally new possibilities finally also for the electrical machine industry. *Nonetheless, the potential of carbon nanotechnology for the electrical machine industry is yet by far underexplored, and therefore, not yet understood*.

State of the art in development of electrical machine design

Conventional development in electrical machine design

Many of the significant efficiency improvements in electrical machines to date have been initiated by an emergence of enabling new material technology. Such emerging technologies have been the development of low loss magnetic circuit steel materials and high energy density permanent magnet materials. Nevertheless, considering material physics, traditional materials are reaching their limits; they do not offer clear perspectives for disruptive development of magnetic circuits. For engineering scientists, this means that the ferromagnetic materials which have robust temperature properties will continue to be a first material option for electrical machine design applications. Iron has a saturation flux density in the range of 2 T and the saturation flux density of 50/50 iron cobalt alloy is about 2.4 T. New materials that might replace iron as a magnetic circuit material in electrical machines do not exist.

Emerging alternatives from nanomaterials science

Where metals seem to have hit a ceiling, the new man-made nanomaterials offer one route towards development of electrical machines. Copper and aluminium based conductors are widely used in rotating electrical machinery. Superconductivity did not change that, because so far no such materials could be developed that remain superconductive in temperatures where rotating electrical machines operate.

Carbon has several forms. Nanotubes were invented decades ago and graphene is the latest finding. Graphene has a form of atomic-scale honeycomb lattice (a 2D sheet with thickness of one atom). In principle, a long graphene sheet could be rolled in the right direction to form optimal chirality nanotube to make the best possible conductors. Nanotubes have different properties depending on the chirality of the tube. The theoretical conductance of nanotube is $4e^2/h$ and the minimum conductance of graphene seems to be in the range of e^2/h resulting in practical conductivity of about 100 MS/m. The best measured nanotube conductivities are also in the same range and both have slightly negative temperature coefficients in the range of -0.0002/K. Such figures are naturally most tempting for electrical engineers opening future scenarios of less Joule losses in machinery.

Today, it seems finally within reach to increase the winding material conductivity in electrical machines by replacing metals with carbon nanomaterials. In particular, CNT fibre materials offer the potential to allow for higher conductivity levels. Recently, researchers have been successful in developing CNTs which have a specific conductivity level (ca. 3000 Sm^2/kg) close to that of copper (6650 Sm^2/kg). This has been possible due to the lightweight structure of CNTs (having a density of ca. $\rho_{CNT} \approx 1500$ kg/m^3).

CNT fibre and yarn development and application today

There is a worldwide commercial interest in carbon nanotubes (CNTs). The most promising present and future commercial applications of CNTs have been noticed in production lines and applications of, among others, CNT plastics solutions, lightweight composite and coating material solutions, loadbearing solutions and microelectronics solutions. CNTs have also increasingly been used as components in biosensors and medical devices and for energy storage devices [6]. Commercialization related challenges have much driven and will continue to drive research and development. Among the leading experts in the field are the research team of professor Matteo Pasquali at Rice University (US), the team of emeritus professor Jean-Paul Issi at Université Catholique de Louvain (Belgium), and the innovation team of Dr. Marcin Otto at Teijin Aramid (The Netherlands) [7] who have developed wet spinning technology to produce CNT-yarn of CNTs. We quote Prof. Issi who shared with us per email communication (dated 1.9.2014) his view that: "[…] Contrary to copper or graphite intercalation compounds, there is so far no established limit for higher conductivities in CNT fibres. In principle, the conductivity of an infinite, ideally pure, defect-free CNT could be much higher than that of copper, but the process involved to obtain fibres from these CNTs will finally determine the conductivity level. The CNT yarn process developed leads to very good results - probably the best - and any further improvement would probably result from the better quality of the CNTs used". In practice, however, presently realized mechanical, thermal, and electrical properties of CNT macrostructures such as yarns and sheets are still lower than those of individual CNTs [6].

Carbon nanotubes can be, by structure, highly conductive. Because of the one-dimensional structure of CNT fibre, the charge carriers can travel along nanotubes without "scattering", which is a phenomenon that is commonly referred to as "ballistic transportation". The absence of scattering helps carbon nanotubes to carry very high current densities, theoretically in the order of J = 100 MA/cm^2 [8] and achieve conductance levels of σ = 100 MS/m and beyond. Conductivity levels of 100 MS/m have been measured on individual CNTs.Today, 10 MS/m conductivity level in CNT yarns has been measured, but when the raw material problems have been solved CNT yarn will achieve at least similar conductivity levels as copper. The biggest challenge related to the wet spinning technology is to obtain and conserve high-conductivity raw material CNT purity. The spinning technology itself produces high-quality fibres that can be spun into multifibre yarns. There are no theoretical obstacles for why the conductivity of CNT multifibre yarn could not be increased to similar high levels as those of the best CNTs. If the best and purest high-conductivity CNT material will be used to spin multifibre materials, it should then theoretically also be possible to produce high-conductivity fibre. New high-conductivity CNT fibre and yarn is now within reach. However, continued CNT manufacturing research and development will be complementary to industrial upscaling of CNT yarn spinning technology, but also to the rapid rise of graphene [6]. Rapid innovations in graphene synthesis and characterization, as well as rapid development of the processes involved in manufacturing CNT multifibre yarn from CNT fibres will, therefore, determine how soon the conductivity of CNT multifibre yarn will achieve higher levels. The wet spinning process resembles producing common textile fibres and has therefore potential to produce cheap conductors. Insulating the CNT yarns should take place with similar methods as insulating copper wires and therefore the space factor should be in the same range as with copper yarns.

Present-day CNT fibre materials have also other important features. They are extremely strong and have simultaneously a high thermal conductivity. Both these features make CNT fibre materials very attractive for electrical machine applications. Theoretically, CNT-fibre yarn can reach thermal conductivities up to 6000 W/(Km) [9], [10], [11] while the thermal conductivity of copper is 401 W/(Km). CNT fibre materials also allow for lightweight and strong structures of electrical conductors. The density ($\rho_{CNT} \approx 1500$ kg/m^3) of CNT-fibre yarn is about one sixth of the density of copper. Already now, the specific conductivity of CNT-fibre yarn (σ/ρ [Sm^2/kg]) is almost equal to the level of the specific conductivity of copper. It is therefore realistic to expect that in the near term ongoing efforts to leverage the properties of CNTs will accelerate the development of CNT yarn that will be able to conduct electricity with the same mass as copper conductors do nowadays.

In this article, we exploit the (known and potential) properties of the newest CNT-fibre yarn materials and introduce these into electrical machine development. We thereby aim to significantly reduce the Joule losses. Such a significant introduction should open up totally new application routes for CNT materials to be incorporated into the wide operational processes of rotating electrical machinery. Development of carbon nanotubes for conductor applications is still in its infancy. However, there are promising results from recent research [7] which are driving indicators for us to believe that significant development in the conductivity of CNT-based conductors will take place in the coming years. For instance, the potential contribution of graphene to advancing the development of high conductivity CNT-fibre yarn for defect-free CNT conductors with optimal chirality has so far not been studied yet. The multidisciplinary approach presented in this research proposal might therefore push research and development in graphene in a way that has not yet been possible before.

A promising start calls for continuation

We are, however, already now at the cutting edge of development in electrical machinery design for special applications. Recently, Teijin Aramid BV (in Arnhem, the Netherlands) has developed the wet-spinning technology, in collaboration with Rice University (Houston, US). The new spinning technology has made it possible to turn microscopic CNT fibres into macroscopic CNT fibre based materials which show conductivity properties that are comparable to those of metals. The readiness level of the technology is yet still at laboratory scale but develops fast. The development of CNT technology seems to be very promising, especially when research and development for CNT-fibre yarn will meet industrial needs. This assumption is based on similarities between the technological development processes of CNT and Twaron Aramid yarn, the latter of which has been successful in scaling up the technology to industrial applications. The resistivity of CNT-fibre yarn is now finally low enough to allow for applying and testing the CNT-fibre yarn in different electrical apparatuses. The use of CNT-fibre yarn has been reported for supplying current to an incandescent lamp [7], and at least the testing of a 400 Hz small transformer with CNT-yarn windings is reported in [12].

Recommendations for future research

With our introduction of replacing copper with new carbon nanomaterials in electrical machine windings we may have the solution to overcome the challenge of agile development in electrical machines. The overall aim of the research that needs to be undertaken would be to study the feasibility of improving rotating electrical machine efficiencies and performance by replacing copper with highly conductive new CNT materials. The research must encompass three main, interrelated domains for investigation. We must study: 1) The use of new materials in rotating machinery which is equipped with CNT-yarns so as to be able to (a) optimize both the conductivity and insulation of the machine windings and (b) determine directions for further development of CNT-fibre yarn for electrical machine applications; 2) The design of a CNT-yarn electrical machine so as to achieve the best possible efficiency properties in terms of both energy and materials use taking the life cycle cost also into account. Replacing copper by CNT materials would involve fundamental technology change which may affect the whole supply chain and associated decision-making levels in the rotating electrical machinery environment. The proposed research project will therefore also study and make recommendations on 3) the impact on energy-environment-economy policies, as well as the safety requirements that must be taken into account in further development efforts.

If it will be possible to achieve higher conductivity values by substituting copper for new CNT fibre material in the windings of an electrical machine, most probably the efficiency of the machine will be improved or the dimensions and mass of the machine will be decreased, or both. Such development, consequently, will bring about the need for change in the machine properties determination and design. It will involve fundamental change in the overall design principles of electrical machines.

In present-day electrical machines the operating winding temperature is normally in the range of 120 °C. Under load the copper DC-conductivity decreases to the level of 42.9 MS/m. In CNT yarn conductors the resistivity should stay about constant when their temperature has risen to 120 °C. CNT yarn conductors consist of very thin sub-conductors which should considerably limit the possibility of skin effect at electrical machine frequencies. The yarn inherently resembles litz wires. Moreover, if we may assume that future commercial CNT yarn will be manufactured from multifibres which can be easily transposed, no circulating currents should appear either. Both skin effect and circulating currents can be very harmful in traditional high-current windings and lead into increased AC-resistance. In the copper conductors of a high-power electrical machine there is always the problem of possible skin effect and circulating currents which make the AC-resistance of copper conductors significantly higher than the DC-resistance value. It is not uncommon that the resistance factor ($k_R = R_{AC}/R_{DC}$) gets values of 150 % in higher-frequency applications [13]. In high-frequency, high-temperature applications we might, therefore, theoretically reach a situation where the practical AC-conductance of a carbon conductor is even three-times the conductance of a similar size copper conductor.

It should then also be possible to design carbon-winding electrical machines that can operate at higher operating temperatures than what we are used to apply in electrical machine design today. This is due to the fact that there will be no increase of Joule losses as the temperature increases. As far as we use steel in the magnetic circuit, its losses get smaller as the temperature increases because the eddy currents will be limited by the increased lamination resistivity. The eddy current losses are inversely proportional to the resistivity of the laminations [14]. The higher operating temperatures will naturally result in new challenges regarding the insulation and permanent magnet materials. Present-day insulation materials seldom can operate in temperatures higher than 220 °C [13] and NdFeB-based permanent magnets should normally be operated below 150 °C.

Let us assume that in the future researchers will succeed in manufacturing 100 MS/m CNT yarn conductors. Copper conductivity is 59.6 MS/m at room temperature with a resistivity temperature factor of $3.886 \cdot 10^{-3}$/K; at 150 °C it is only 39.6 MS/m. If eddy currents and circulating currents decrease the practical conductivity further by 20 % we stay at the level of about 32 MS/m while CNT yarn could maintain its 100 MS/m at 150 °C. This means that, in practice, we could reduce the Joule losses of a future CNT-yarn electrical machine by two thirds if the machine geometry is kept the same. Furthermore, CNT fibre materials also allow manufacturing of lightweight and strong electrical conductors. The density ($\rho_{CNT} \approx 1500$ kg/m^3) of CNT-fibre yarn is about one sixth the density of copper. Already now, the specific conductivity of CNT-fibre yarn (σ/ρ [Sm^2/kg]) is close to the level of the specific conductivity of copper. It is therefore realistic to expect that in the near term ongoing efforts to leverage the properties of CNTs will accelerate the development of CNT yarn such that will be able to conduct electricity with the same mass as copper conductors do nowadays. Though the significance of such development will be minor in electrical machines where the space reserved for conductors is limited, nevertheless, it might greatly benefit the development of other, special applications.

And last but not least, the availability of carbonic materials is of major importance for the further development of resource-efficient CNT winding machines. Carbon materials are among the most abundant materials on the Earth. As such, the presently high price of carbon-based conductors should decrease with the growth of industrial applications and commercial use. At present, the price of copper is in the range of 10 €/kg and its density is about six times the density of CNT yarn conductor material [15]. It is not expected that CNT yarn conductors will soon beat copper conductors. However, we may expect that in the short term CNT materials will enable the creation and development of new applications and new devices, there where CNT wires can, in niche applications, bring advantage over copper in light weight, flexibility, bending fatigue resistance, resistance to corrosion, high strength and high modulus of elasticity.

With this article, we suggest that it is now time to focus research efforts on the largely untapped potential for advance in electrical machine technology offered by already available and future CNT materials as these hold the promise of significantly improving the conductivity in electrical machines. In the following section we present the results of an experiment we have recently conducted. We have designed and constructed the first electrical machine in which we have used fairly (2.4 MS/m) conductive CNT yarn to replace the conventional copper wires in the windings. One of the main objectives of the experiment was to demonstrate that there is an urgent need for collaboration between the fields of CNT materials research and engineering research. Collaboration needs to reach a level where scientists and manufacturers will work together so as to increase better understanding of the benefits and challenges regarding the development and application of carbon nanomaterials to improve the energy and resource efficiency of rotating electrical machines.

The design and construction of a small prototype machine with CNT yarn conductors

As the conductivity level of the sample conductors is low, the yarn can be used only for demonstration purposes; that is to show the potential of CNT yarn for application in an electrical machine. A wider description is given in [16]. Figure 1 illustrates the conductor material on an Aramid paper tape. For transport purposes the wires are wound on a large paper cylinder. The conductors are spread on a 9 mm wide Aramid paper strip so that the surfaces of the flat conductor are insulated just on one side.

Figure 1: Ten parallel 26 AWG conductors (black ones) with aramid (Twaron) yellow yarns at the edges glued on aramid paper tape strips.

In Figure 1, the conductors are placed on a white paper cylinder for smooth transporting. The ends of the conductors have been treated by silver solution to allow for sleeve joints to external motor cables.

Practical CNT Yarn Conductors

The American 26 wire gauge conductor material that was used in the tests was composed of 300 filaments with 0.129 mm^2 cross sectional area (equivalent to ~0.4mm diameter wire). A single filament diameter is 22 µm. Single filament is made of carbon nanotubes which make an inconsistent structure but they all stick together. Such filaments can be connected in bundles and can theoretically be produced in infinite lengths. So far 500 m lengths have been manufactured by Teijin Aramid. As the 26 AWG yarns were non-insulated 10 yarns were bonded on an Aramid insulation. The axial thermal conductivity of the yarn is 450 W/(m·K). The specific heat is similar to carbon. The ignition temperature of the yarn is 500°C-600°C and at 500°C the yarn retains about 55% of its original strength. Ten parallel 26 AWG yarns were used for the test motor. This type of yarn has a cross-sectional surface of 10×0.1280 mm^2, each with an equivalent single wire diameter of 0.405 mm. The motor coil conductors are 1.2 m long, and their measured resistance is 0.4 Ω, yielding only 2.4 MS/m average conductivity. The yarn has also a small positive temperature coefficient (0.0008/K) whilst we expected the yarn to have zero or a small negative temperature coefficient. So far, the connection of CNT-yarn to other conductors can be made by crimping. The yarn can be treated by silver paste at the crimp.

The test machine

The complicated insulation system of the winding material suggests to use only a few winding turns. The machine should also have a high frequency to enable operating with such a low amount of turns. Permanent magnet excitation results in the best efficiency while using current in the excitation should cause problems with the high resistance winding. Therefore, a very low voltage permanent magnet tooth-coil (PM) synchronous machine (U_{ph} = 7 V) with 15000 min^{-1} rotational speed was selected as the design target. Table 2 gives the main design data of the machine.

Table 2: CNT-yarn permanent magnet synchronous machine design parameters in generating

Parameter	**Value**
STATOR MAGNETIC CIRCUIT	
Stator stack length l_{sFe} [mm]	42
Stator lamination space factor k_{Fe}	0.96
Stator core material	SURA NO10
Stator inner diameter D_s [mm]	25
Stator stack outer electromagnetic diameter D_{se} [mm]	75
Number of stator slots Q_s	3
Number of slots per pole and phase q	0.5
ROTOR	
Rotor outer diameter D_r [mm]	23
PM cylinder diameter, D_{PM} [mm]	20
Rotor PM length, l_{rPM} [mm]	50
PM material (N38UH) remanence B_r @ 120 °C [T]	1.15
PM relative permeability μ_r at temperature of 120 degrees Celsius	1.05
PM material coercive field strength H_c [kA/m]	871
Rotor construction: Cylindrical PM is located inside a stainless steel tube with 1.5 mm wall thickness.	
STATOR WINDING	
Winding type	Fractional slot, concentrated, non-overlapping, single layer q = 0.5
Winding connection: star connected	
Number of pole-pairs p	1
Stator coil-turns in series per phase N_s	7
In each coil turn there are 10 strands of 0.4 mm diameter.	
COOLING	
Cooling method	Air cooling

A graph of the stator design with smooth bending angels is shown in Figure 2, and Figure 3 illustrates a single stator lamination laser-cut from SURA NO10 and the rotor of the machine.

No load and load simulations

A finite element analysis (FEA) was performed with the CEDRAT Flux 2D software. A dynamic FEA with electric circuit was used to obtain the induced voltages at no-load. The generator load resistances were adjusted to get sufficient output power. Figure 4 shows the machine air-gap flux density distribution.

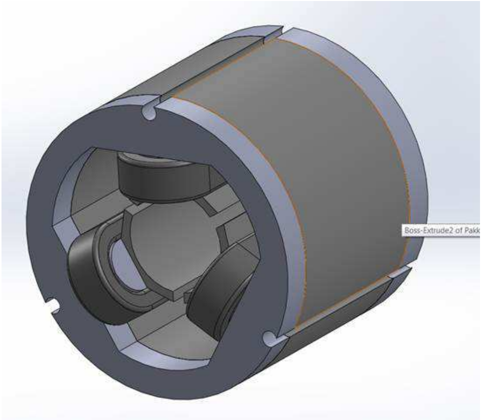

Figure 2: A graph of the stator design with softened bending angles at the kinks

Figure 3: Stator lamination sheet on the left and the assembled PM rotor on the right.

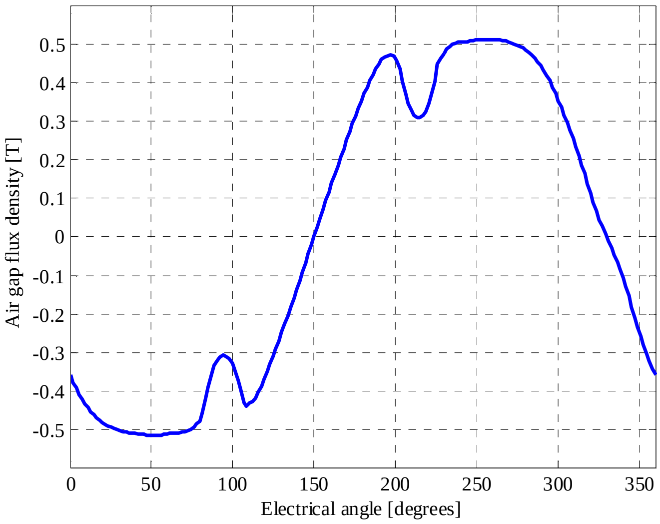

Figure 4: Air gap flux density peak value 0.51 T and RMS value 0.361 T.

Figure 5 shows the no-load induced at the rated speed. The peak value of the induced voltage per phase is 5.6 V. Induced no-load RMS phase voltage E_{PM} = 3.96 V. The iron loss of the machine at rated operating point is P_{Fe} = 6.34 W. The Joule losses in the stator are $P_C = 3 \times 0.4 \times 2.3^2$ = 6.35 W. The additional and mechanical losses will be in the range of P_{Mech} = 1 W. The total loss is 13.7 W at generator 30 W output power. This yields a generating efficiency of about η_{CNT} = 0.69.

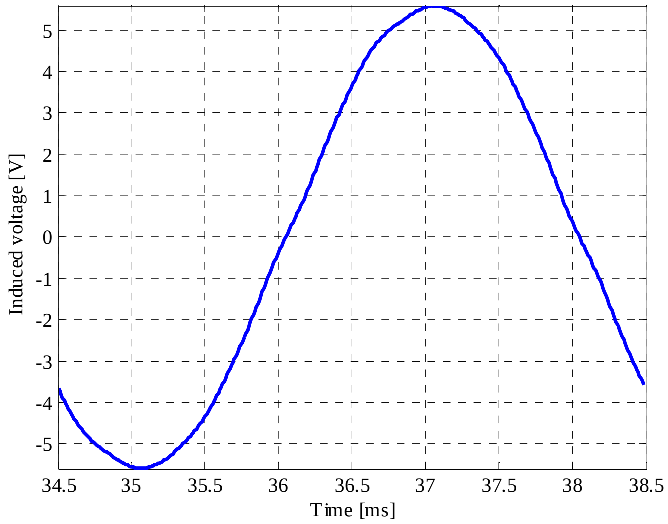

Figure 5: Induced voltage at no-load rated speed 15000 min^{-1}. The fundamental RMS no-load voltage is E_{PM} = 3.96 V.

Prototype Manufacturing

The stator laminations were laser-cut and the stack was glued to allow easy manufacturing. Figure 8 illustrates the wound stator

Figure 8: Machine stator wound with 10 parallel 0.4 mm CNTF-wires after the winding manufacturing, left. On the right, the same stator after impregnating. The length of each phase winding is 1.2 m and the measured DC-resistance is ca. 0.4 Ω at 20 °C.

The machine was back-to-back tested with a commercial grinding machine, Figure 9.

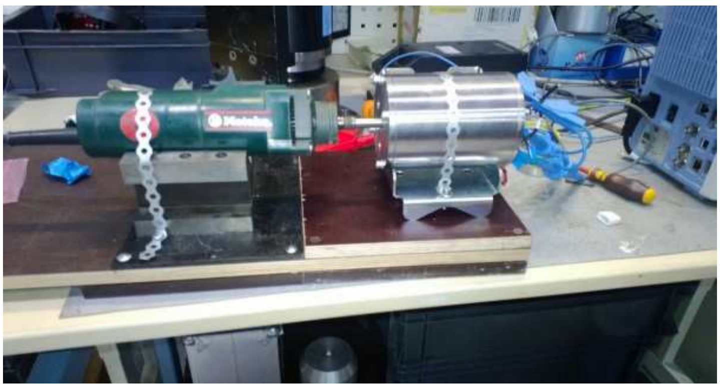

Figure 9: The machine on the right ready to be tested as a generator. The CNT-yarn-winding machine is on the right and a high-speed commutator motor grinder machine on the left connected back to back.

Measurements

Table 3 summarizes the four-wire DC-resistance measurement results at three different temperatures.

Table 3: The four-wire DC-resistance measurement results at three different temperatures

Phase, temperature	**20 °C**	**50 °C**	**90 °C**
U, resistance, Ω	0.400	0.416	0.455
V, resistance, Ω	0.393	0.396	0.437
W, resistance, Ω	0.388	0.390	0.430

The CNT wires have a slightly positive temperature coefficient for the resistivity. The temperature coefficient for the resistivity based on this measurement is in the range of +0.00155–0.00196/K which is about 40 % of the corresponding coefficient of copper.

No load Measurement

Generator no-load voltage measurement results are shown in Figure 10.

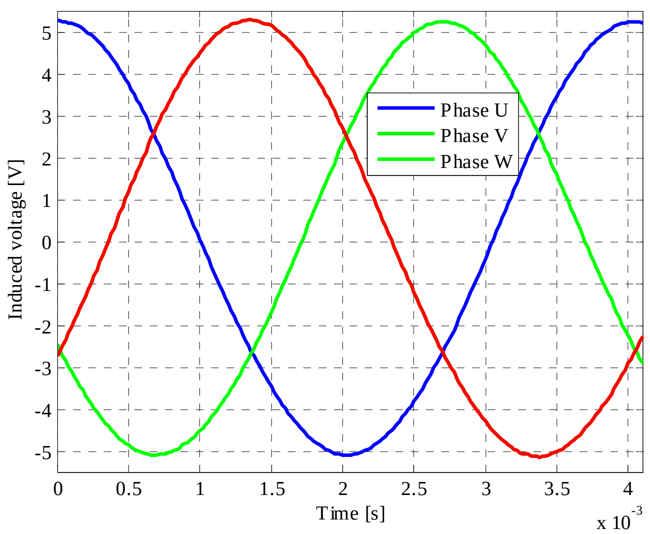

Figure 10: Induced voltages at no load at 15000 min^{-1}.

Load measurement as generator

The machine was rotated with external mechanical power supply and loaded as a generator supplying power to the 1 Ω load resistors, Figure 11

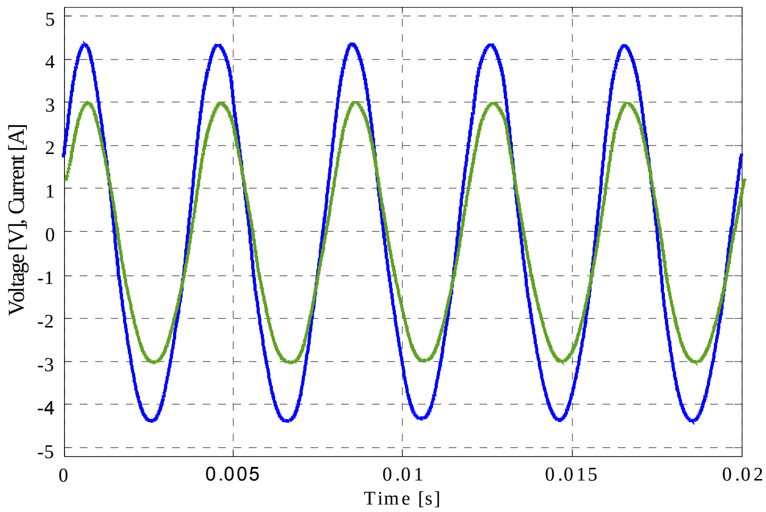

Figure 11: Measured voltage (peak value c. 4.2 V) and current (peak value c. 3 A) of the CNT-yarn generator operation with resistive load at the speed of 15000 min^{-1}.

Testing as motor

A small fan was attached at the machine shaft and it was tested also as a motor. The efficiency in this case was not measured but the test was used as an indicative test, only. Figure 12 illustrates the machine operating a fan.

Conclusions

This article is one of the first in its kind to introduce a break-through approach to the use of new carbon nanomaterials to enable the development of a new generation of rotating electrical machinery. The article scans the environment and indicates some future perspectives for potential applications of carbon nanotube yarn in electrical rotating machines where significant efficiency improvement can be achieved.

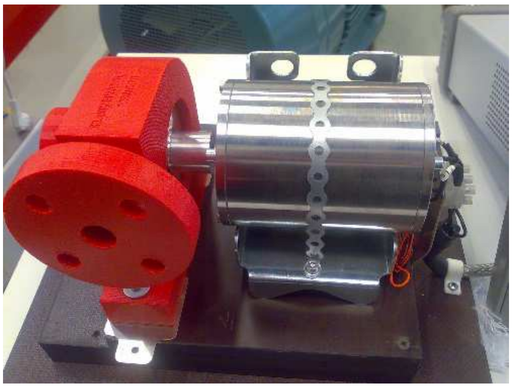

Figure 12: CNT-yarn motor in its first real application driving a blower at 15000 min^{-1}.

We explain the potential for integration of new and greener carbon nanomaterials into electrical machine development and innovation of industrial production lines within the context of the transition towards a more resource-efficient economy. In other words, it shows how it may now be within reach to considerably improve the energy efficiency of those millions of electrical rotating machines that keep industry and society on the move while coupling such development to the important and topical issues of natural resource savings, carbon savings as well as cost savings issues for more sustainable and economic growth.

The article uses the experimental results from prototype building and testing research the objective of which was to design and measure the world's first electrical motor applying a textile material; windings made of carbon nanotube yarn. A prototype of a rotating electrical machine using CNT fibre -based winding material was designed and tested. It demonstrates that CNT yarn has the potential to replace copper in the machine windings. Furthermore, based on the findings from the prototype construction and associated research investigations, the results presented in this article strongly indicate that by replacing copper with advanced conductive CNT materials in the machine windings it may be possible to improve the efficiency and performance properties of the future electrical machine.

Copper has continued to be used as an effective conductor in the electrical machine windings for over a century. However, in the search for higher energy efficiency we must look for a solution that will decrease the losses of electrical machines. Copper losses are the dominating losses in many types of electrical machines and, hence, even a slight improvement in the conductivity of the winding materials may revolutionize electrical machine development and call for redesign of complete production lines in the entire industry.

The experimental results presented here show well enough that further work is needed to pave to way for supreme CNT materials to be integrated into production lines that will change the electrical machine industry. Theoretically, the DC-resistivity of CNT yarn conductors in a future CNT-generation motor is, in practical operating temperatures, significantly lower than that of copper conductors. Very thin sub-conductors also remove all practical skin effect and circulating current related problems which further may increase the benefits achieved from using CNT yarn conductors. A significant reduction in the conductor resistivity should affect the design of machines most significantly. It is then only a question of optimization if we shall exploit the properties of CNT yarn material to design smaller and more lightweight or more energy efficient machines. The CNT-yarn spinning technology is ready for manufacturing of high-conductor materials. As soon as theoretical physicists, materials researchers, engineer researchers and experimentalists will closely together they may succeed in selecting the best of pure metallic CNTs. We believe that then a new era in electrical machine development will start. We may mention that, in the course of writing this article, the best laboratory results measured on Teijin Aramid CNT fibre yarn have been reported to be now in the range of 10 MS/m. Such an increase of conductivity value represents already a significant improvement compared to the CNT yarn material we used in the test motor.

With the introduction of replacing copper with new carbon nanomaterials in electrical machine windings we may have the solution to overcome the challenge of agile development in electrical machines. CNT materials may help realize the vision of building greener, better resource efficient, and better performing electrical machines. Notwithstanding the risk that further technology development in CNT materials will be less fast as may be expected today, the new carbon nanomaterials can be of considerable significance for important niche development in rotating electrical machinery, there where CNT materials have advantage over copper in light weight, flexibility, high bending fatigue resistance, resistance to corrosion, high strength and high modulus of elasticity.

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Advanced Materials for Motor Laminations: Past, Present and Future

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Abstract

Traditional iron-based, soft magnetic materials have been used for laminations in electric motors for over 100 years. Such materials provide excellent manufacturability and adequate magnetic performance, but exhibit more losses than are ideal when greater efficiency is also a design goal. The demand for higher motor efficiency is therefore a catalyst for research into better performing lamination materials. A number of material choices exist, such as Nickel-Irons and Cobalt-Irons, but these materials are generally expensive, compared with traditional silicon iron materials. However, there are other candidate materials with costs more in line with standard motor lamination materials. Two of these are amorphous iron and nano-crystalline iron formulations. These materials exhibit superior magnetic performance combined with reasonable cost. While cost-effective in their “as cast” form, these materials are challenging to manufacture into traditional motor structures because currently they are only readily available in a thin (25 micron) ribbon format and exhibit very high hardness. This creates an issue of how to design and construct a cost-effective motor utilizing these advanced materials. This paper will outline past and current efforts to build commercial motors with these materials and will also project potential future paths for developing cost-effective motor structures that utilize these high performance magnetic materials.

Introduction

This paper reviews the history of the use of amorphous and/or nano-crystalline metals in electric motor applications and examines possible new methods of utilizing these advanced magnetic materials to improve electric motor performance in the future.

The history of amorphous metals started in the 1960’s with a number of researchers formulating metal alloys and casting them with extremely fast cooling rates so that the formation of normal metal crystals was inhibited. The typical cooling rates utilized are in the range of one million degrees per second [1]. This is usually achieved by casting very thin strips of ribbon-like material on a refrigerated rotating drum.

While there are numerous amorphous metal combinations that exhibit unique magnetic properties, the commercial focus has been on iron-boron-silicon (FeBSi) formulations. The most pervasive formulations are 85 to 95 percent iron, 1 to 5 percent boron and 5 to 10 percent silicon. While many companies make some amorphous or nano-crystalline materials, most only sell very small volumes. Only two companies sell amorphous materials in high volume. The largest of these companies is Metglas [2], which is part of Hitachi Metals. The other is a Chinese company, Advanced Technology & Materials Co., Ltd (AM&T) [3].

Because the material does not contain any expensive elements and can be produced at high speeds via a continuous casting process, the base cost of the material is very reasonable for large volume applications. The main use of magnetic amorphous metal is in electrical distribution transformers, which can range from small residential pole-mounted transformers to megawatt substation transformers (Figure 1). While such amorphous transformers do cost somewhat more than traditional lamination transformers, the life cycle costs are significantly lower (Figure 2). This range of transformer applications validates the low loss performance of the amorphous materials used in them.

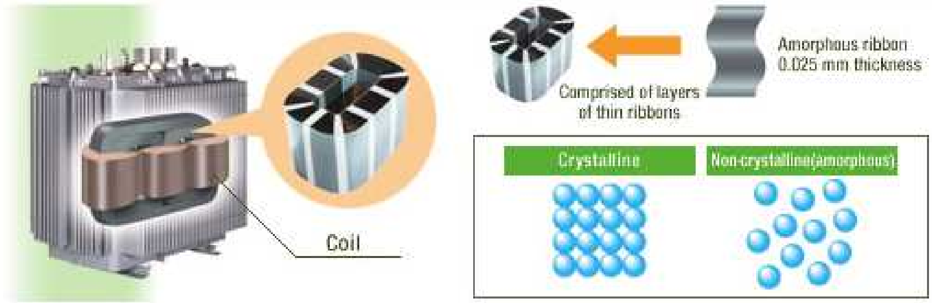

Figure 1: Amorphous metal in transformer applications (courtesy of Hitachi Metals [2])

Figure 2: Cost and benefits of amorphous metal transformers (courtesy of Hitachi Metals [2])

Material Properties

The three properties that make these materials highly attractive for magnetic applications are:

- Very high permeability,
- A square hysteresis loop, and
- An oxide layer on the surface of the material that provides electrical insulation.

The combination of an insulating layer with such thin material results in very low eddy current loss characteristics and enables higher frequency operation. The core loss for typical amorphous metals is about one-tenth the loss for normal non-oriented electrical steels (Figure 3) [2]. Such low iron loss makes this material especially attractive at this time because in recent years electric motors have become more efficient primarily by reducing losses in the rotor and secondarily by reducing copper losses with better winding techniques. Thus, the remaining stator iron losses have become a much larger percentage of the total loss remaining in modern efficient motors. This means that reducing the iron losses is now the greatest opportunity for further increasing motor electrical efficiency.

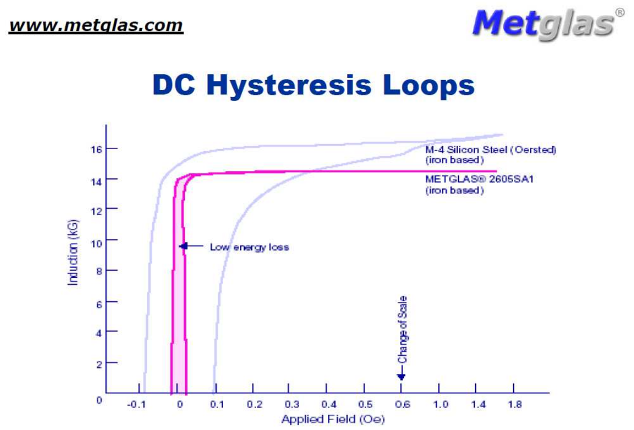

Figure 3: Hysteresis curves of amorphous metal and M-4 Silicon Steel (courtesy of Metglas [2])

While the basic magnetic properties of this amorphous material are attractive, there are several major disadvantages to this material. These include the fact that this material is very thin, very hard, and difficult to handle. In addition, the insulation layer is not very robust. A further disadvantage of the standard amorphous formulations is that their saturation flux density is typically about 1.5 to 1.6 Tesla. This limits the overall flux carrying capability, resulting in a need for more material to carry equivalent flux levels when compared to standard silicon iron lamination material.

The major manufacturing disadvantage of amorphous metals is that the production method for this material limits the thickness to a very thin (approximately 25 micron) ribbon. The extreme thinness of the material, combined with its high degree of hardness, makes processing amorphous metals into structures useful for electric motors extremely difficult. In fact, while there have been many attempts to make motors out of amorphous metals, no significant commercial success has ever been achieved.

The thin nature of this material also results in a lower packing factor, leading to less useful magnetic material for carrying flux. Given the large number of layers needed to make a useful motor structure, even small gaps between layers lead to lower packing factors.

The extremely thin oxide insulation layer is also easily damaged, and such damage can lead to shorting conditions between layers. Some of these shorts may be in the center sections of the ribbon material, but most will form at the edges of laminations where ribbon cutting methods often expose conducting edges. Shorts such as these lead to stray current paths around the material, creating their own magnetic flux paths. These sometimes can create flux paths that are orthogonal to the plane of the lamination, resulting in much higher eddy currents than would be anticipated in such a thin structure [4]. Again, due to the high number of thin layers, it is far easier for shorts to develop at the edges of a stack of this material during handling, stacking or wrapping. These edge shorts can lead to much higher losses than would be expected in a material that has such low intrinsic loss.

Methods of Motor Production

Four major approaches have been pursued to construct electric motors from amorphous ribbon coils. The first method is to cut the desired lamination shape from the material while it is a single ribbon and then assemble these laminations into the desired motor structure. The second approach is to wind the amorphous ribbon into the overall shape of the desired motor structure and then cut away the unwanted portions. The third method is to wind material into partial shapes of the desired motor and then assemble and magnetically connect these shapes into a final motor configuration. The fourth approach is to cut the desired shape into a strip of material and then wind it into the desired shape of the overall motor structure. This fourth method was one of the first tried [5] and is also described in one of the newest patents [6] on constructing motors from amorphous material.

The first approach, cutting shapes and stacking layers, has been attempted with a number of cutting methods. The cutting has been done with precision stamping, laser cutting, chemical etching and electric discharge machining (wire EDM). With all of these cutting methods, the major drawback is the large number of lamination layers that need to be cut and then assembled. From the pictures that are available, Hitachi has attempted to use this method in some prototypes to construct their 11 kilowatt high efficiency amorphous motor [7].

The second approach is to wind a coil of this material into a structure that resembles the final shape of the motor structure and then cut away the sections of this coil that need to be removed. The cutting methods for this approach are more limited, but include electric discharge machining (EDM) -- both wire EDM and plug EDM -- and water jet cutting. Lasers have been tried, but at this time can only cut relatively small structures. Work is currently being conducted in Adelaide, Australia [8] that uses a water jet cutting method to construct a motor.

The third method is being pursued by RADAM [9] and essentially is adapting the radial cut core or segmented core method to amorphous material. Here the amorphous material is wound into the desired sub-shapes and then connected into a final motor assembly [10].

The fourth method is both one of the oldest production methods tried and is the subject of some of the newest patents. Back in the early 1980's, General Electric (GE) attempted to directly cast concentric shaped ribbon with integral pole shapes to construct radial motors [5]. This very interesting and challenging approach was moderately successful, but was never carried to commercial production. As far as can be determined, no other attempts at direct casting have been made.

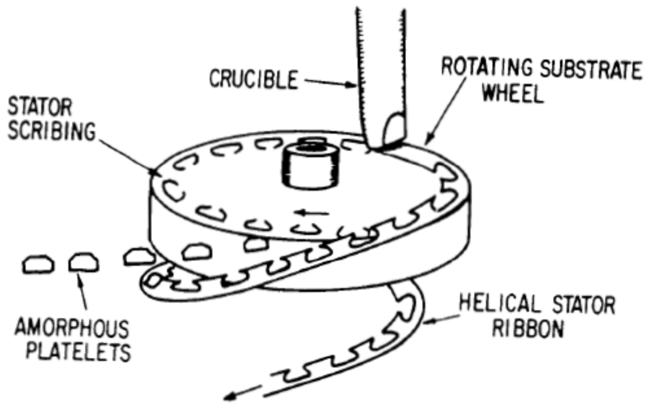

Figure 4: Early direct casting of helical ribbon for radial motor stator [5].

History of Use in Motors

There are a number of research examples of amorphous metals being used in electric motors, but very few commercially available motors. General Electric (GE) was issued a patent on amorphous motors in 1986, near 30 years ago [11]. The most prominent commercial amorphous motor is the Light Engineering [12] motor. Early designs of this motor were done in the mid 1980's. In the late 1980's, prototypes were produced. This motor used an axial motor design and was made available for sale in the early 1990's and stayed on the market for many years. It was made in a number of versions, from a few kilowatts to many tens of kilowatts. Light Engineering was moved from California to Indianapolis in 1998 and much later formed a partnership with XEMC Motors [13] from China. However, sales of this motor never reached high volumes, and now it is sold only to special purpose applications.

The performance of this motor was excellent, but it never established much market penetration. The primary market that valued the very high efficiency performance was small, fossil fuel-powered generators, where the higher generator efficiency was a significant benefit because of the high cost of fuel to operate the internal combustion drive engine. Over the years, these motors were sold mainly as components for high efficiency generators.

One of the early engineers working on the Light Engineering motor was Andrew Hirzel, who later worked on radial amorphous motor designs with his company RADAM, using the third construction approach described above. His designs are based on a radial motor concept and use wound sections of amorphous material that are linked together to form a complete motor flux path. This segmented core design has become popular for standard radial permanent magnet applications, and the use of amorphous materials enhances the overall motor efficiency. Prototypes have been tested and run for many thousands of hours to prove reliability.

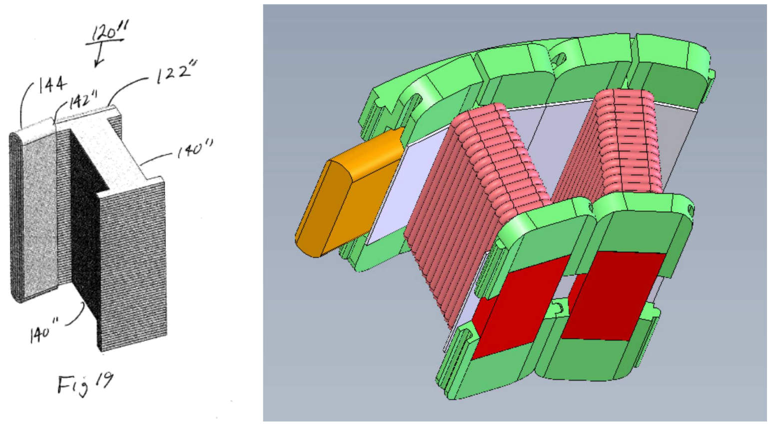

Figure 5: RADAM segmented core radial motor construction [10]

There has been substantial work at the University of Adelaide in forming axial motor stators by first forming a coil of amorphous metal into a wound conical form and then waterjet cutting slots into this coil [8] [14]. This forms an axial motor stator that, when combined with coils and a permanent magnet rotor, forms an electric machine that can be used as either a motor or a generator. This motor was designed as an axial motor with a single stator and single rotor. One unique feature is that this is a conical air gap motor, which creates a larger air gap surface area for a given motor diameter.

The waterjet technique has been perfected so that cuts of at least 5 cm deep can be accomplished. Of course, cuts that are shorter result in faster cutting times, and cutting time is an issue with respect to manufacturing cost. However, motor designs can be adapted to minimize the cutting depth by trading off other parameters such as overall motor diameter.

The waterjet cutting method has an advantage of being very flexible with respect to the shapes that it can produce. It allows the production of a single piece axial motor stator with pole shoes. This capability gives axial motor design the same flexibility enjoyed by radial motor designs This author, as well as others, have been looking for this type of design flexibility for axial motors for many years.

Waterjet cutting can result in some shorting of the individual laminations, but several techniques can be employed to reduce this shorting problem. This issue is being researched in more detail at the present time.

Figure 6: Water jet cutting of wrapped amorphous core [8]

Some results from this University of Adelaide motor development effort have recently been published and, while the motor's efficiency is not outstanding, it is still reasonably good. Examination of the motor design by this author indicates that there are a number of areas that could easily be improved to create a motor with much better efficiency performance.

Hitachi has been working on a commercial line of industrial motors based on the use of amorphous materials for a number of years. These motors are of an axial design with a single stator and dual rotors. The permanent magnet rotors use low-cost ferrite magnets to keep the total motor cost lower. Hitachi presented a paper on the first version of this motor, which is an 11 kilowatt motor at EEMODS in Rio de Janeiro, Brazil, in 2013 [7]. At that time the results were good, but not outstanding. Recently, a second version of the motor has been announced that has substantially improved over those initial results, making it one of the most efficient motors in that power range. My understanding is that they are currently sampling motors to potential customers and are working on expanding the product line to additional power levels.

Figure 7: Hitachi axial amorphous motor and individual stator pole [7]

Hitachi has attempted several manufacturing approaches. One approach was to wind individual cores as shown in a paper from 2010 [15]. The construction method of the final motor has not been disclosed but the pictures they have shared illustrate that the approach is one of cutting and stacking lamination layers together to form individual stator pole pieces. These stator pole pieces are then assembled into a complete stator structure and a molding compound is used to secure them in place within the stator housing. This author is very familiar with this approach to constructing an axial motor, given his experience in creating the NovaTorque axial motor, which also uses this construction method.

The Future

Superior Materials

There is substantial research work being conducted into improved formulations of amorphous metals, with the major focus on increasing the saturation flux density of these materials. One such material that has been announced by the Materials Solutions Center at Tohoku University in Japan is NANOMET [16]. This formulation adds copper and phosphorus to the iron-boron-silicon melt, which allows the iron percentage to be increased above 90 percent. However, phosphorus tends to oxidize rapidly, which creates problems with melting and casting that need to be solved before mass production of this material is available. However, the mere fact that this material exists, and uses inexpensive component elements, is a powerful incentive to continue work towards commercial formulations that have extremely attractive magnetic properties and can be produced in volume at competitive prices. There are many other efforts looking at other additives to achieve similar results of higher flux saturation values and high permeability.

Motor Production Methods

Clearly, none of the methods tried so far has achieved the goal of simple, low-cost production of motors with amorphous materials. However, that is not to say that these methods could not be improved upon in order to achieve that goal in the future. For instance, the ability to stamp thin, hard materials has greatly improved in the last 20 years. New die materials and the ability to hold higher precision between die and punch have greatly improved. Robotic stacking and other pick and place machines have also greatly increased in speed. Similarly, waterjet and laser cutting have increased in capabilities and precision. This has increased both the speed and the penetration distance that can be cut with these techniques. The cost of waterjet and laser cutting equipment has also dropped dramatically in recent years. Such improvements could lead to economical production in the future.

While laser cutting has been done for prototype laminations for many years, this type of cutting has been done by melting the material and using a gas assist to eject the melted material. This process is limited in speed by the need to physically move the laser head and gas nozzle. Much more recently, it has been shown that fiber lasers with an optical scan head can cut metal laminations and do so at much higher speeds. This then enables production processes to be envisioned using lasers as the lamination production method. A 100 watt fiber laser cost nearly $60,000 in 2006. A 100 watt laser with even better beam characteristics now can be purchased for under $20,000. This makes using multiple stations of this type of equipment feasible for production environments.

NovaTorque’s unique axial motor with a conical lamination geometry is, in fact, produced in this manner, with a single fully automated machine that cuts, stacks, and welds laminations into completed production pole pieces.

While direct shape helical casting and roll-to-roll shaping and processing have not been implemented yet as production processes, the concepts have interesting theoretical possibilities, even though they are difficult to implement. This is an area where additional research could yield significant progress.

Alternative Motor Designs

While radial induction motor design has dominated the motor industry for many years, recently a number of alternative technologies and motor geometric configurations have entered the market or have at least been proposed. These innovations open up the possibility of developing motor configurations that are particularly suited to using amorphous metals. One particularly interesting design area is in the use of axial motor configurations. An axial motor stator can be wound around a mandrel and built up in layers. One interesting patent in this area is U.S. 8,505,351, where an axial motor stator is constructed in a rolled-up assembly. While such manufacturing methods are not yet commercially available, work on such schemes is progressing.

Another motor design that is potentially suitable for construction with amorphous materials is the transverse flux type motor.

Conclusions

While amorphous and nano-crystalline materials do offer superior magnetic properties and these properties can result in superior motor performance, especially in terms of motor efficiency, it will be a number of years before I expect to see these materials in commercial motors in any sizeable quantities. The manufacturing problems are still the main road block, and, until the manufacturing can be done on a high volume scale and with cost structures that are competitive in the marketplace, the current domination of the market by radial motors using conventional electrical steels will continue.

The other main obstacle to market adoption is the axial motor format, which is currently the motor geometry that is best suited for producing motors with these materials. While there are many academic papers illustrating the advantages of axial motors over radial motor designs, commercial motor manufacturers have not agreed. Until these barriers can be surmounted, amorphous metal motors will be specialty and niche market items. However, if and when the above issues are finally solved, a dramatic change in the commercial motor industry will occur.

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Policy 2

EMSA- Policy Guidelines for Electric Motor Systems

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Abstract

An important insight into energy efficiency policy around the globe is that there is no single instrument that is able to bring along energy savings swiftly. Also, the most cost efficient solution will not automatically be adopted in the industrial context because other elements influence decision making like risks and value attributed to energy efficiency. Therefore a mix of policy instruments is needed to overcome the barriers for energy efficiency.

Within the IEA 4E Project the Electric Motor Systems Annex developed Policy Guidelines for Electric Motor Systems, a best practice guide for policy instruments in the area of electric motor systems. The Guidelines were developed under the task Motor Systems Policy led by an Austrian and Swiss team, in cooperation with international experts.

These Guidelines comprise a description of the Motor Policy Toolkit consisting of eight policy measures: Minimum Energy Performance Standards (MEPS), labelling, voluntary agreements with industry, energy management programs, energy audit programs, company motor policy, financial incentives and awareness raising and information provision.

For each policy definition, recommendations for implementation and selected examples are presented. This comprehensive approach should reach significant energy efficiency improvements in industrial electricity consumption. As an example, an analysis based on the Motor Policy Toolkit done for the situation is Austria is given.

Introduction

The IEA (International Energy Agency) Implementing Agreement "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.

EMSA has been engaged in motor policy since its outset in 2008. A first analysis was published in 2009 as "Motor MEPS Guide" [3] profiting mainly from the US experience in setting mandatory standards. In 2011, a second volume followed: "Motor Policy Guide, Part 1: Assessment of Existing Policies" [4] analyzing motor policy instruments in nine countries/regions.

The "Policy Guidelines for Electric Motor Systems" published in October 2014 [5] aim to provide assistance to policy makers who wish to design and to implement a strategy to encourage the greater energy efficiency of electric motors and motor systems in industry in their jurisdiction.

The guide offers a toolkit for policy makers, explaining the different policy instruments that can be applied to transform the market, depending on the individual national context, and provides guidance on the successful implementation of those. It builds on these previous publications and showcases best-practice policy examples that have been implemented in various countries around the globe. These span a wide range of types of policies: some focusing on technical issues concentrated mainly on one product, like Minimum Energy Performance Standards and labelling, others focusing on organizational issues within the industrial company, as energy management, awareness and financial support.

The publication has been led by an Austrian and a Swiss team, and has drawn on the experience of a number of international experts engaged with motor policy implementation within and outside EMSA.

This paper excerpts the most relevant information from the Guidelines summarized in a comprehensive form.

Savings and Barriers

Electric motor systems are estimated to be responsible for 46% of global electricity use [1] and are used mainly in industry, infrastructure systems, in building technologies and in the transportation of goods and people. In industry only, they are estimated to account for approximately 70% of electricity consumption [1]. Improvements to most old motor driven systems have the potential to save between 10% and 30% of energy consumption and running costs (in some cases up to 70%), typically offsetting the investment for high efficient components within three to five years (in some cases below one year). In addition, more efficient motor systems lead to process and quality improvements, lower cooling demand and reduced noise level. These advantages are due to the improved efficiency of the system components, better dimensioning, improved conditions of operation and easier maintenance, and particularly, due to energy efficient control and better adaptation to real demand.

A number of severe barriers between the manufacturer, the Original Equipment Manufacturer (OEM) and the end-user hinder the implementation of optimized electric motor driven systems.

Examples of these barriers include [1,2]:

- The cost of energy represents in general a relatively small share of the total costs of a company. Therefore, energy cost reductions are at risk of not getting too much attention.
- Purchasing decisions within a company are typically based on first cost (purchase price) rather than total cost of ownership or life cycle cost: the reasons for this are that higher energy costs arise later on and those costs are not seen as factor to be influenced by purchasing decisions.
- A significant share of motors are built into larger production machines by OEMs, who are keen to make their machines cheap and do not consider total cost of ownership or life cycle cost. Because OEMs do not profit from lower running costs and user do not calculate life cycle costs as mentioned above.
- The complexity of electric motor systems requires in-depth technical skills and knowledge to design efficient systems
- Motor/machine size is often not matched to the needs of production and tends to be oversized.
- Any changes to already installed motor systems are hindered by fears of production standstill.
- Considerable resources are needed to analyze existing motor systems on-site before retrofitting takes place in order to ascertain the actual demand from the production process.

Motor Policy Toolkit

The following major policy measures are currently used by countries to promote increased efficiency in motors and motor systems and were defined as part of a Motor Policy Toolkit, forming the core of a national motor policy:

MEPS (Minimum Energy Performance Standards), labeling, voluntary agreements, energy management programs, energy audit programs, financial incentives, company motor policy, awareness raising and information provision.

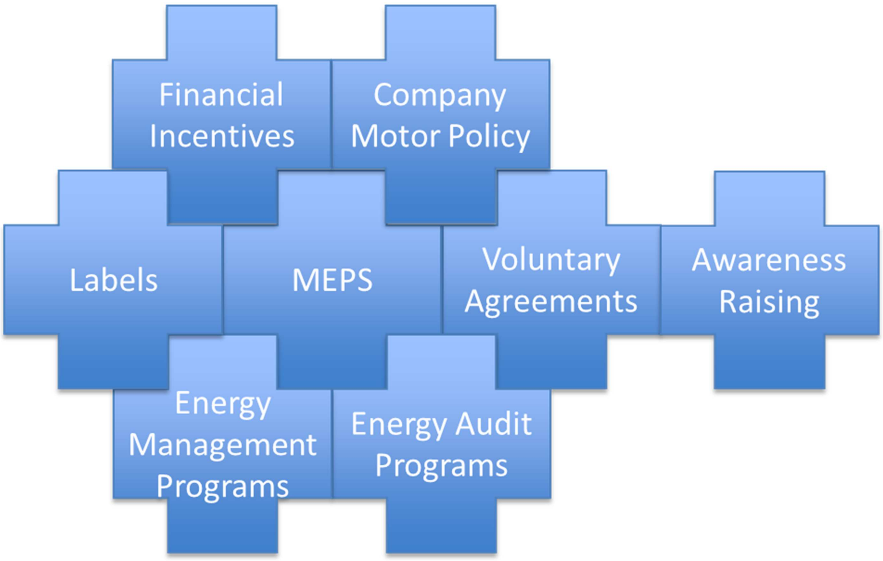


Figure 1: Overview of the Elements of the Motor Policy Toolkit

In the guide each measure is explained and a brief description is included. The main objective of each policy is outlined, together with other important attributes of the policy. For each policy measure, a number of examples are provided to illustrate how these are implemented by different countries. Finally, a set of recommendations are included, which represent the experience of EMSA members.

Minimum Energy Performance Standards

The first element or even the basis for motor policy is the development and implementation of Minimum Energy Performance Standards (MEPS). The objective of MEPS is to accelerate and focus market transformation towards higher efficiency motors. By specifying a minimum energy performance level, mandatory MEPS prevent inefficient products from entering the marketplace and help to increase the average product efficiency over time.

Mandatory MEPS are one of the strongest instruments that governments can use to achieve energy efficiency improvements. They are often implemented in conjunction with other instruments, such as energy labelling, to maximize their effectiveness. In addition the mere setting of MEPS has an effect on purchasing decision and awareness.

MEPS for electric motors are generally based on national, or preferably international, energy efficiency performance standards published by national or international standards organizations, involving competence from industry, academia and government to provide commonly agreed performance criteria. The standards are then quoted in national laws and regulations. This approach separates the detailed specifications from the enabling legislation.

But, the target of MEPS are always newly purchased motors and as motors have a very long life time, MEPS affect only a limited share of the motor stock annually. The average age of the motor install base was 17 years according to a Swiss analysis of 4,142 motors [2]. In addition, MEPS have no influence on for example correct sizing, installation and running time. Therefore MEPS have to be accompanied by several other measures, mentioned in this paper.

Recommendations when considering imposing MEPS in the field of electric motor systems include (depending on the status of the implementation in the specific country and region):

- Investigation on available international standards for testing and efficiency classification (for motors: international test standard IEC 60034-2-1 and the international efficiency classification standard IEC 60034-30-1).

- Applying the same MEPS levels within one geographic/economic region to reduce barriers to trade (e.g. EU; US, Mexico and Canada).

- Introduction of MEPS sequentially, first, for energy relevant components of a motor system, second, focus on integrated systems, including motor plus variable frequency drive (VFD) and an application.
- Assessment of the impact of the planned MEPS, including end-user, manufacturer, economic and environmental impacts.
- Involvement of all relevant stakeholders in the consultation process to facilitate market uptake and ensure technical feasibility of the planned regulation.
- Definition of the update cycles of the regulation.
- Setting up a Monitoring and Verification Scheme, including a scheme with accredited laboratories and a centrally controlled registration system (e.g. an online database) and definition of penalties for non-compliance.

Several countries all over the world followed the U.S. example and implemented MEPS at least for electric motors [13], others already implemented them for fans, pumps and compressors. An overview of current standards in this field is given in [15], an updated overview of MEPS for motors is given in [20].

Labelling

The overall objective of energy labelling programs is to move markets for energy-using products toward improved energy efficiency by providing consumers, e.g. industrial companies, with the information that allows them to include the energy consumption of the product in their purchasing decision. Therefore, energy labels can facilitate effective procurement and incentive programs providing a 'short hand' for utility companies, relevant government agencies when writing specifications for bulk purchase or allowing them to use products differentiated by labels when offering consumers financial incentives, such as rebates, to buy energy efficient products.

Comparative labels motivate manufacturers to build products that are more efficient than their competitors' products, while endorsement labels provide an incentive (market advantage) for manufacturers to build products that meet the specified criteria.

Energy labelling is often used in conjunction with Minimum Energy Performance Standards (MEPS), where they provide a readily identifiable demonstration of compliance with, and in the case of comparative labels, relative performance against the standards.

National legislation is necessary to set a precise scope for the label for a given product and to define whether the label has to be displayed at the place of sales or on the product itself.

As for MEPS, energy labelling programs should be complemented by a strong monitoring, verification and enforcement (MVE) regime. This ensures that only eligible products are using the label, verifies that the performance claims on the label are correct and provides for a system of penalties for non-compliance.

The key additional considerations for labelling in relation to MEPS are:

- The design must be easy to understand and accurately reflect the requirements of the labelling scheme.
- The decision for voluntary or mandatory labels: voluntary labels may provide a useful tool for engaging stakeholders as a precursor to the introduction of a mandatory program or MEPS, while a mandatory program will drive a more rapid market transformation.
- The decision making process for the performance scale for comparative labels or the absolute threshold for endorsement labels:
    - For comparative labels, the scale must be sufficiently broad to allow adequate differentiation between products and to avoid 'bunching' of products within one category at the top of the scale.

- o For endorsement labels, the threshold for eligibility must be sufficiently high to accurately differentiate the best in the market place from the majority.

- The thresholds for all types of labels should be periodically reviewed and adjusted to reflect advances in technology efficiency.

Examples are the globally well-known NEMA Premium Motor Label and the Chinese Energy Label for Electric Motors.

The China Energy Label scheme was implemented in March 2005 and mandatory labels for small and medium motors were included in June 2008. The program applies to 0.75 kW - 375 kW, 2-6 poles, up to 1000 V 50 Hz, motors (including motors for explosive atmospheres). To qualify for the China Energy Label, small and medium motors must meet the requirements specified in the Chinese National Standard GB 18613-2012 [6]. The specified testing method is GB/T1032 [7], which is identical to IEC 60034-2-1 [8], and the grades are in line with the classes in IEC 60034-30 [9] (IE2/IE3) and IEC 60034-31 [10] (IE4). Motor efficiency must meet the specified level both at 100% and 75% load. Further information on labels is given in [16].

Figure 2: Chinese Energy Label for Motors, Source: [5]

Currently, the US Extended Motor Product Label Initiative (EMPLI) led by the American Council for an Energy Efficient Economy started to develop new energy performance labels for pumps, fans and compressors as a basis for energy efficiency programs with prescribed savings values (utility incentive programs). http://aceee.org/blog/2014/01/voluntary-performance-label-industria

Voluntary Agreements

Voluntary Agreements for end-use industrial companies can be used to motivate companies to invest in high efficient motors and optimize their running system and therefore save energy and CO_2-emission. Combined with a strong motivation and penalty regime they can have a real impact on the energy consumption of participating companies.

Voluntary agreements are tailor-made negotiated covenants between public authorities and individual firms, or groups of firms, which include targets for actions aimed at improving energy efficiency, or reducing greenhouse gas emissions, and which may define rewards, tax rebates and penalties [11].

They are usually used as an alternative for legal requirements and are more flexible. One option is that companies voluntarily participating in the agreement have to fulfil the saving targets and/or other obligations but do not have to pay certain (e.g. CO_2) taxes. The main advantages of voluntary agreements are:

- They are extremely flexible and able to deliver tailor-made solutions for each sector or even company.
- With effective reporting and monitoring, they can provide a high degree of certainty that the specified targets will be met.
- They tend to be more acceptable to industry than regulatory approaches.

Voluntary agreements usually cover the following elements:

- A binding commitment once a party agrees to the voluntary agreement.
- Quantitative targets (such as, energy efficiency improvement, energy or carbon savings) and/or commitments by the signatories to implement energy saving actions with a specific payback period or within a certain timeframe.
- Commitment from the public authorities in supporting actions undertaken by the signatories, such as, the supply of fiscal incentives, practical support in developing energy efficiency plans and actions, and/or cooperative actions on the implementation of enforcement.
- An effective system for monitoring compliance: usually participants report on their implementation and on the energy savings (self-reported data).
- Voluntary agreements may also include:
    - Energy audits or special investigations.
    - Preparation of action plans and implementation of economically reasonable measures.
    - Introduction of energy management systems.
    - Procurement process (purchasing criteria).

The combination of binding commitment, quantitative targets and different instruments to support companies in reaching those targets is crucial for the effectiveness of voluntary agreements.

Motor energy consumption is just one component of the total energy requirement of companies in most sectors. Therefore, it is important to specifically identify motor system elements into sector voluntary agreements. This can be achieved through the following:

- When setting targets for an agreement, electricity consumption may be explicitly mentioned. Since motor systems are responsible for more than 70% of industrial electricity consumption [1], this supports the engagement of the participating companies in increasing the efficiency of motor driven systems.
- Motor specific issues, such as purchasing criteria for efficient motor systems, may be included within the specifications of the voluntary agreement.
- Motor systems could be explicitly identified as a target for energy audits and/or energy management systems.
- Voluntary agreements can offer training and capacity building on design, optimization and maintenance of motor systems.

Examples of successful voluntary agreements, which also successfully integrated motor system issues include:

- PFE - Programme for Improving Energy Efficiency in Energy Intensive Industries, Sweden
- LTA - Long Term Agreement program, Netherlands

- Energy Agreements Programme, Ireland

An example of a voluntary agreement that fully concentrates on motor systems is the Motor Challenge Programme (programs exist for Europe, U.S., China). An overview of these programmes is given in [4].

Energy Management Programs

Very often providers of energy efficient technology and motor systems providers (e.g. for control equipment for compressed air systems, for variable speed drive (VSD) for pumps, packages for leakage repair) are confronted with the decision of companies, not to invest in the high efficient equipment, even when a quick pay-back time can be proven. Energy auditors have the same experience when they suggest energy saving measures in this field. Also compressed air systems have in many cases a high leakage rate, or motors have no control opportunity as no clear responsibility was defined for such issues.

Energy Management, with the ISO 50001 defining the main elements internationally, is a strong tool to overcome these barriers. It comprises the systematic and structured approach for reviewing the energy needs of a company and for implementing measures to reduce consumption, including putting in place on-going monitoring and reporting systems. Furthermore, energy management systems concentrate on organizational issues, like purchasing rules for buying and installing high efficient equipment, maintenance procedures for equipment, training of personnel and the tracking, evaluation of suggested and implemented energy saving opportunities.

In implementing energy management programs, governments can play an important role in establishing a framework to promote the uptake of energy management systems, by developing methodologies and tools and promoting the creation of new business opportunities in the area of energy services

When considering the implementation of an energy management program for motors and motor systems, it is important to:

- Identify what materials and/or training are necessary to achieve the desired outcomes. E.g. guidance on how motor systems efficiency is to be considered within an energy management system, this would include:
    - The definition of purchasing criteria, motor inventory list, guideline for replacement, requirement for installation or acceptance tests, requirements for repair and maintenance.
    - The inclusion of purchasing recommendations (in cooperation with producers, suppliers and industry associations).
    - Design guidelines for the installation of new motor systems.
- To ensure active participation in the program, give careful consideration to how the program will be promoted and to any supporting mechanism for recognizing and communicating achievements. The program should consist of a balanced package of support, incentives and penalties for the target groups involved.
- Build mechanisms for monitoring the progress of participants and evaluating the success of the program into the program design. Decide what to measure and how and what level of reporting is required from participants to achieve this.

Examples of policy implementations include the US Implementation of the Global Superior Energy Performance Partnership, the Energy Agreement Programme in Ireland, the Danish Agreement on Industrial Energy Efficiency and the German Tax-Re-Imbursement Scheme (for implementation of ISO 50001). In the US, EPA's ENERGY STAR provides comprehensive resources on energy management, e.g. with the Industrial energy management information center. [14] Recommendations for energy management programmes are given in [17].

Energy Audit Programs

An energy audit is the systematic inspection and analysis of energy use and energy consumption of a system or organization with the objective of identifying energy flows and the potential for energy efficiency improvements, as defined in [12]. Therefore, energy audits are the only way to consider all efficiency aspects when motor systems are already in use. These include: efficiency of motor systems in place, proper sizing and control strategy, running time, user-behaviour. A pre-condition for this is an energy auditor with the appropriate skills, enough time and, sometimes necessary, metering devices.

The objective of audit programs is to encourage and support companies to undertake an energy audit and thereby take the first step towards proactively understanding and managing their energy requirements and therefore evaluate and optimize their electricity consumption for electric motor systems.

To encourage implementation of the recommended energy efficiency measures, energy audit programs are usually integrated with other policy instruments, such as an overarching legislative framework, financial incentive schemes and voluntary agreement schemes.

When considering the implementation of an energy audit program for motors and motor systems, it is important to:

- Clearly define the intended goals for an energy audit program, either in terms of the number of audits carried out or the energy savings achieved as a result of the measures identified. Develop a definition of motor systems as an area to be considered within energy audits.
- Appoint an administrator (very often a government level body) and operating agent (e.g. an energy agency) for the program and, if required, establish a mechanism to authorize auditors to conduct audits on behalf of the program.
- Identify what materials are necessary to inform the target groups and support the energy audits. For motor audits you may require energy audit reporting guidelines for different motor systems, energy consumption calculators for specific systems, and/or saving calculation methods for energy saving measures.
- Define how training and qualification (certification) of energy auditors will be organized for different types of motor systems (motors and frequency drives, chillers, compressed air, fans and pumps).
- Consider how the program will be promoted and integrated with other instruments (such as energy management programs and voluntary agreements) to ensure that the energy saving opportunities identified are implemented.
- Build mechanisms for monitoring the progress of participants and evaluating the success of the program into the program design – decide what to measure and how and what level of reporting is required from participants to achieve this.

Policy examples include the European Energy Efficiency Directive stipulating the execution of an energy audit at least every four years for large enterprises, and the standardization process for energy audits on ISO, EN and ASME level: e.g. ISO 11011 for compressed air energy efficiency assessments, ISO/ASME 14414 for pumping system energy assessment, the ISO 50002 for energy audits, the EN 16247-3 Energy Audits – Part 3: Processes.

Company Motor Policy

Considering the long life time of motors it is crucial, when a motor fails, that the most efficient motor is available or will be purchased and it is not replaced by another old motor on stock or repaired in a not appropriate manner. Also during the installation process several efficiency aspects should be considered. A motor policy provides a mid- and long-term strategy for the adoption of efficient motor systems throughout a company or plant, for integration within the company's business planning framework and should be integrated, therefore, in energy management system. The aim is to achieve the most cost-efficient motor systems justified under economic conditions. A motor policy typically covers the following aspects:

- A set of purchasing criteria.
- Establishing an inventory list.
- Requirement for installation or acceptance tests.
- Requirements for repair and maintenance.

Policy makers should seek to maximize opportunities to integrate initiatives to support the wider adoption of motor policies within other policy measures, e.g.:

- Purchasing criteria for efficient motor systems should be integrated in energy management programs.
- National energy audit programs should be required to include motor inventory lists.
- Procedures for replacement, installation, repair, maintenance and replacement should be integrated into energy management systems.
- Training on these issues should be provided to energy managers, installers, energy auditors and motor sales and distribution personnel.

Examples how this topic could be considered within national motor policy include the ANSI/EASA Standard AR 100-2010, Recommended Practice for the Repair of Rotating Electrical Machines or the definition of purchasing criteria for electric motors within the Swedish PFE program, a voluntary agreement mentioned above. Details on the technical aspects of company motor policy are given in [19].

Financial Incentives

The main barriers for high efficient motors in the stock and the modernization of old equipment and control equipment, the installation of new and/or additional equipment are very often financial ones. These include:

- High initial costs, including the cost of evaluating potential benefits.
- Access to internal funds for investing in energy efficiency: energy efficiency projects reduce energy costs over time and increase the net profit, but do not increase the gross revenue of enterprises, which is very often the focus of management.
- The very short (three years or less) pay-back periods usually required for investments in 'auxiliary' services, which may not be met by energy efficient equipment.
- Potential financial losses as a result of business interruption during implementation of energy efficiency measures.

Financial incentives overcome these barriers by the use of the provision of a monetary benefit to individuals or organizations to encourage actions that might not occur otherwise. They include a range of tools, such as tax incentives, rebates, grants, loans and alternative financing or procurement (via public-private partnerships, utilities and equipment producers).

In this context, public policy aims to use financial incentives to stimulate demand and catalyze private investment in energy efficiency, with the ultimate objective of increasing the market share of highly efficient motor systems. Financial incentives are particularly useful to promote the latest efficient technologies and activities above the level defined by regulations or 'business as usual'.

The Guidelines present a wide range of financial instruments: public-private financing partnerships, grants and rebates, loans, on-bill financing, tax incentives, contracting and energy service companies, leasing. White certificates (as implemented in Italy, France or Poland) were not included in the analysis because of their more general approach.

In this paper, grants and rebates, an often used financial instrument, are chosen for a more detailed description from the Guidelines. Further information on financing is given for example in [18].

Grants and Rebates

Grants and rebates are very useful to bring existing high efficiency products or new technologies into the market. They reduce the upfront cost of energy efficiency projects, increase the financial rate of return on investment and improve cash flow, thereby increasing investors' access to debt finance. They can also raise the general awareness and trust in energy efficient technologies, but often have limited duration for budgetary reasons.

The instrument relies on:

- Defining clear criteria for the efficiency of qualifying products. National MEPS, high efficiency products (HEPS) or international standards may be used as the foundation for this definition. These efficiency levels should increase with technical progress over the duration of the instrument. Grants are allowed to be given only above the defined MEPS level.

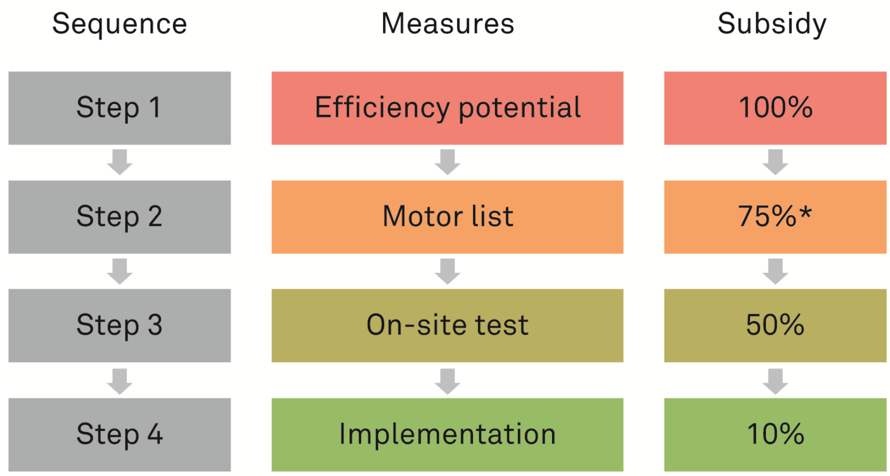
- A transparent definition of the grant or rebate amount, which clearly states any variation in the amount relating to product specification or use, e.g. motor size or level of protection against wet environments.

Care should be taken to ensure the program is not too complicated and that the timescale for its availability is appropriate. The duration should be long enough for market actors to become informed on the instrument and make a decision, but short enough that the availability of the grant or rebate does not distort the normal pricing of the product (making them more expensive than they would be without the instrument).

For motor systems, these programs should also ensure that the size (power) of the motor being purchased under the scheme is appropriate for the given application. This can be achieved by establishing installation rules and providing training and information workshops for approved or certified installer companies on aspects of appropriate selection and installation of electric motor systems.

One example standing for many other similar ones is the Xcel® Energy Colorado Equipment Efficiency, an electric and gas company that offers cash rebates for its business customers for specified higher efficient motors, drives, constant speed motor controllers, and electronically commutated motors for refrigeration applications. Rebates are available for new motors or for upgrading operating motors (between 1-500 horsepower (hp); motors above 500 hp have special conditions). The rebate varies by power, application, and efficiency level.

The Swiss EASY program uses the provision of grants to help companies overcome the barrier of undertaking the preliminary analyses required by the motor-check methodology for identification and retrofitting of existing motor systems with the highest potential savings within an industrial plant by giving a higher grant (in relation to the total cost of each step) for these stages than for the final implementation stage. This is shown graphically in figure 3. The funds for the program are secured through public funding (through a surcharge on the electricity tariff).



* min. 25 %, max. 75 %.

Figure 3: Grant Scheme of the Swiss EASY program, Source: S.A.F.E., 2014

Raising Awareness and Information Provision

In the context of the Guidelines, information provision refers to the development of materials for end-users to equip them with information and tools to help them understand the general benefits of installing more efficient motor systems and to assess the level of savings that they could achieve in their own situation. This includes:

- General awareness-raising materials and activities, such as best-practice case studies and energy efficiency awards.
- Technical assistance materials, such as guides and training.
- Self-assessment materials, such as energy saving/system optimization calculators, life-cycle costing methodologies and benchmarking tools.

The following instruments are used for raising awareness: best practice case studies, energy efficiency awards, guides, training, energy saving/system optimization calculators, life-cycle costing methodologies, and benchmarking. For this paper some of these are selected for more detailed description.

Best Practice Case Studies

The use of case studies to highlight examples of best practice is an extremely useful awareness-raising tool. By sharing actual examples with the target audience, it allows them to better understand and identify with the technology and its potential benefits for them. Once developed, case studies are very versatile and can be used in many ways as part of a communications campaign, for example, for publication on websites, in presentations, in articles in trade press or online, in fact sheets and brochures, or as the basis for interviews.

Successful best practice case study databases are for example:

The Australian Energy Efficiency Exchange website (http://eex.gov.au/) shares best-practice information on energy efficiency.

Industrial Assessment Centers Field Managers (IAC) Case Studies are detailed summaries of IAC assessment success stories involving both assessments and recommendations of significance: http://iac.rutgers.edu/case_studies

Energy Efficiency Awards

High profile awards programs offer a useful tool for raising the profile of energy efficient technology and their benefits and may form part of a wider communications campaign. They reward companies for their progressive approach (usually through recognition and endorsement, but sometimes through financial means) and also provide a very good instrument for collecting best-practice case studies.

Awards can be used for several purposes, e.g. highlighting very high efficient equipment, awareness raising for possible saving measures, demonstrating new technologies. But also motivating already well doing companies to further develop their saving strategies.

The Super-Efficient Equipment and Appliance Deployment (SEAD) initiative of the Clean Energy Ministerial launched a Global Efficiency Medal Competition for Electric Motors. The goal of the competition was to recognize the world's most energy efficient electric motors.

Figure 4: SEAD Global Efficiency Medal, Source: www.superefficient.org

More than 200 best practice examples (with a significant share in the field of motor system efficiency) were awarded and collected since 2008 within the Austrian klimaaktiv energy efficient companies program: www.klimaaktiv.at/energiesparen/betriebe_prozesse/vorzeigebetriebe.html

Training

Training of key personnel (energy managers, energy technicians and energy auditors, electricians) is crucial when installing new equipment, especially when adding a component to existing motor driven systems. Through the provision of training programs that include a focus on optimizing the energy efficiency aspects of new equipment, policy makers can increase the understanding of energy efficiency in motor driven systems, explain the importance of maintenance and increase the quality of energy audits or saving calculations. This will in the long run lead to more efficient motor systems. The operation of training programs will also help to build better engagement with the different target groups.

The training topics will vary depending on the target group, the planned duration of the training, the pre-qualification of the trained personnel and other aspects, but may cover:

- General introduction of the technological field.
- Use of the audit guidelines or software calculation programs.
- Monitoring and/or data collection and metering of the systems.
- Specific energy efficiency topics, such as leakages for compressed air systems, effects of the installation of frequency drives.

The Indian Institute of Social Welfare and Business Management offers a '*Short-Term Certificate Course on Energy Management and Audit*' to help prepare candidates for the Bureau of Energy Efficiency (BEE) examinations for certified energy managers and certified energy auditors, under the Energy Conservation Act 2001. The courses include an element on motor systems in industrial appliances. For more information see: www.energymanagertraining.com/new_energy_course.php

Within the klima**aktiv** energy efficient companies program more than 1,600 participants, mainly energy auditors, have been trained in the energy auditing of motor driven systems within 1-day special trainings for each motor technology (pumps, fans, compressed air, chillers). The material can be found on: http://www.klimaaktiv.at/energiesparen/schulungen/spezialschulungen.html

Energy Saving Optimization Calculators

The term energy saving/system optimization calculators is used here for applications that are intended to facilitate the estimation of energy saving possibilities or quantification of energy consumption in motor driven systems. These may be web-based or stand-alone and use Excel or other software application for their operation. The use of recommended calculation tools can help to standardize energy audit processes and enables energy efficiency program managers to promote a uniform product.

Motor system tools are usually designed for very specific purposes and are tailored to the group being targeted. Training should be provided for more complex calculators. Examples of specific functions are:

- Calculation of energy savings when replacing an AC-motor with a higher efficient one (these tools may sometimes have a database with new motors behind them).
- Estimating the benefits of installing a variable frequency drive on a pump or fan application.
- Estimating heat recovery by a heat recovery system for an air compressor.

Simple, Excel-based calculators are also used to estimate the energy demand of electric motor systems and to identify the most relevant motors.

Examples include the Motor Systems Tool, developed within the 4E Electric Motor Systems Annex to calculate the efficiency of a complete motor system (motor plus VFD, gear and transmission). It is intended to assist engineers, machine builders, machine component suppliers, energy consultants and others working on optimizing machine systems to benefit from reduced electricity consumption. Download: www.motorsystems.org/motor-systems-tool

Excel-based software tools developed by the Swiss Topmotors program of S.A.F.E. help industrial users to assess the savings potential of their existing motor systems: SOTEA, a software tool to estimate potential energy savings, ILI+ (intelligent motor list), and the STR (Standard Test Report). More information: www.topmotors.ch

Further examples of well-known tools are PSAT (Pump System Assessment Tool), MotorMaster International in the USA, CanMost in Canada and Eurodeem for the EU. These motor tools are based on catalogue data of electric motors combined with a motor saving analysis tool. In Europe the data was not updated for several years.

When considering the implementation of an information provision policy, it is important to:

- Undertake preliminary investigations to understand the information gaps that need to be addressed.
- Consider what action you wish the target audience to undertake and which tools, or combination of tools, offer the most effective mechanism for fulfilling these requirements.
- Consider how the materials used will be delivered to the target audience.
- Tailor the materials to the groups being targeted, ensuring that the style of presentation and level of technical detail is appropriate.
- Engage stakeholders, such as trade associations, equipment manufacturers and distributors, professional associations, in the development and delivery of the materials.
- Ensure that the materials developed are accurate, reliable, consistent and as easy to use as possible.

- Ensure that the cost of developing the material and implementing any associated program is commensurate with the savings achievable.

Example of Analysis - Austria

The "Policy Guidelines for Electric Motor Systems" can be used on a macro-level to identify gaps and possibilities to further promote industrial energy efficiency in motor systems. As an example the following table summarizes this kind of analysis done for Austria:

Table 1: Overview on policy analysis with the Motor Policy Toolkit for Austria

Instrument	Status in Austria	Recommendations for Austria
Minimum Standards	Austria is part of the European Union, with the same Ecodesign requirements for motors, pumps and fans. For cooling- and compressed air compressors standards are in draft status.	National or international coordinated market surveillance, support for European market surveillance structures: international test-labs, support of EU-wide registration system, incl. database
Labelling	For motors IE1-IE4 is used similar to labels; for pumps, fans, compressors no international label are available;	Support of international labelling initiatives;
Voluntary Agreements	Voluntary agreements are available, but not broadly used (one national, one local);	Inclusion of purchasing recommendations for high efficient motors; definition of motor systems as topic for energy audits and introduction of energy management systems; offer of trainings for planning, optimization and maintenance of motor systems (as already done in one regional agreement);
Energy Management	According to the energy efficiency law big companies have to implement energy management system or conduct energy audits;	Development of guidelines for the integration of motor energy efficiency aspects in energy management systems; trainings for members of the certifying organisations (for ISO 50001) on the possibilities of energy savings in motor systems; development of national monitoring of the success of energy management systems;
Energy Audits	According to the energy efficiency law big companies have to conduct energy audits (every 4 years); trainings in the field of energy audits for motor systems are accepted to proof the qualification of registered energy auditors; motor systems have to be considered according to annex III of the law.	For big companies it should be checked if enough energy saving measures for motors are implemented; for SMEs: further trainings for energy auditors in this field;
Company Motor Policy	Status very different depending on companies; there are no trainings in this field;	Development of purchasing criteria with industrial associations; specification for compiling a motor inventory during energy audits; integration of motor systems policy in energy management systems; trainings for stakeholders;
Financial	Energy efficiency measures are	Checking of tax reductions for efficiency

Instrument	Status in Austria	Recommendations for Austria
Instruments	subsidized in Austria (motors are not explicitly mentioned); there was a special subsidy for high efficient motors;	measures in the field of motor systems; involvement of stakeholders for development of specific financial instruments in this field; information of the banking sector;
Raising Awareness and Information	In Austria done by klimaaktiv programme: audit guidelines specific for motor systems, trainings, best practice cases, newsletter, award ceremony, benchmarking-tools;	Development of purchasing guidelines for high efficient motor systems together with industrial associations; public procurement in the field of high efficient motors; development of Life Cycle Calculator; further events in the field of energy efficient motor driven systems;

Conclusions

The most effective government policies are those that stimulate action amongst key stakeholders within the motor systems market to achieve long term market transformation. A comprehensive range of policies are therefore required to influence international/national standard makers, industry associations, industrial users and power utilities. In the policy guideline a process to develop a national policy framework is described: each policy option should be assessed according to its ability to achieve the identified objectives. Costs and benefits depend on the affected stakeholders, the detailed implementation strategy and the national context.

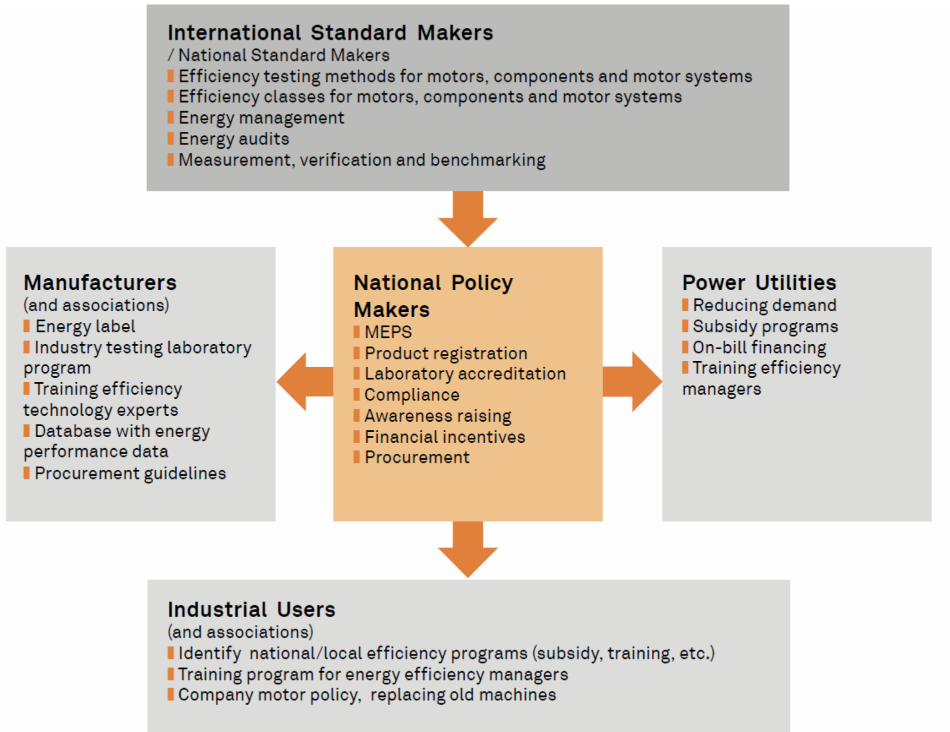


Figure 5: Policy Makers interacting with other Stakeholders for Market Transformation, [5]

At least five different stakeholders need to interact to transform the market for motor systems:

- Governments can set mandatory energy performance standards (MEPS). MEPS based on international standards are already applied in several countries, reducing barriers to trade. For setting MEPS, all relevant motor systems components and their combinations need to be considered, as well as a system for tracking which products enter the market (e.g. registration) and for enforcing compliance. Governments can choose to complement MEPS with other policy instruments: defining an energy label, setting energy efficiency targets, entering into voluntary agreements with industry, implementing energy management and energy audit programs, encouraging individual businesses to set up a company motor policy, launching awareness-raising campaigns and giving financial incentives.

- International standard makers should focus on developing international standards in all relevant areas from motor system components to certification and labeling programs, energy management and energy audits, measurement, verification and benchmarking.
- Manufacturers and industrial associations can develop and/or support energy label programs, establish accredited testing laboratories, initiate and support training programs and define procurement guidelines.
- Industrial users are encouraged to set energy saving targets, define responsibilities and train personnel for designing new motor systems and retrofitting old systems.
- Electric power utilities can design and run procurement programs and subsidy programs for end-users and use innovative financing instruments to benefit from energy savings.

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STRATEGY 2030 – how can motor systems deliver their expected share of energy savings?

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1. Abstract

A number of economies have discovered the untapped energy efficiency potential of electric motor systems in industrial applications. The IEA has quantified and a number of governments (EU in its “Energy Efficiency Plan 2011, for 2020” and in the “Energy Roadmap 2050”, the USA in “National Action Plan for Energy Efficiency, Vision for 2025” and China’s energy targets in its “12th 5-Year plan”) have emphasized the importance of enhancing the energy efficiency of industrial production (and society as a whole) in order to mitigate CO_2 emissions and to fulfill their ambitious targets by 2030 to 2050.

The problems of renewing industrial production and equipment on its path to energy efficiency are well known. Industry leaders think of their own in-house innovation as the key driver for market advantages. Sustainability and energy efficiency are no key indicators in their perspective. They dislike government interventions, mandatory requirements including a lot of bureaucracy and external experts auditing on their premises. They accept financial incentives only if not much paper work is involved. And, they distrust their power utilities to be a qualified efficiency council.

Sustainability and energy efficiency can climb the ladder of key drivers when customers, consumers and shareholders become more demanding on this issue. This applies mostly to the small visible group of very large companies who have sustainability programs in place. But even then the distance between the board room (Key Performance Indicators) and the daily practice in the boiler room on the work floor - in the separate divisions - is huge. Leaving much space for the actual improvement and renewing of industrial production.

Based on the IEA 4E Electric Motor Systems Annex (EMSA) Policy Guidelines for Electric Motor Systems ([2]) a number of avenues are open to speed up and focus an increased industrial (and broader) efficiency development: The harmonization of product’s efficiency standards at the International Electrotechnical Commission (IEC), the introduction of product’s performance data bases, the build-up of a network of accredited testing laboratories, the introduction of integrated systems’ based software tools (Motor Systems Tool) and audits, a global product certification system at IECEE to avoid multiple certificates, etc.

2. Background

Electric motors consume 45% of global electricity by driving pumps, fans, compressors and industrial handling and process machines (see [1]). If energy efficiency progress is high on the agenda in any economy around the globe, also industry has to deliver its share alongside the many efficiency programs for household appliances, consumer electronics, lighting, buildings, etc.

The industrial electricity consumption is heavily determined by electric motors. 87.8% of the total electricity consumption in 25 factories surveyed in Switzerland is used on average for electric motors. The rest is shared by lighting, information & communication technology, some high temperature processes and special uses like electrolysis. 56% of 4 142 motors assessed were older than their technical life expectancy. And, 60% of 104 motors tested were oversized [3].

Oversizing in this context means machines that work on an annual average with a load factor below 60% of their rated output power. This implies that such machines operate a big part of their time below 50% of the rated output where efficiencies decrease heavily. Between 100% and 75% most electric motors today have their best efficiency point and run smoothly without overheating and irregular wear.

This is where they should be operated most of the time, also taking into account the torque they need during the short time of the starting condition. This correct sizing already includes a safety margin for a short overload during the few seconds in the start condition. Not only the motor, also converters and all the applications suffer heavily from low load factors and operation away from their best operating point. This evidence points toward a large untapped reservoir of energy efficiency in industrial motor systems.

Industries are driven towards their competitive edge in ever changing markets. The environment and energy use is not high on the agenda as a value proposition and in their strategy for the future. Flexible adaptation to market demand, labor and material costs are usually much more urgent for reducing production cost and time. Only in times of price explosions and scarcity of supply, industry starts their own energy efficiency program to reduce dependency and risks. In all other cases governmental actions like tax incentives, procurement programs, standards & labels, minimum energy performance standards, etc. have to drive the market towards higher efficiency. Only then, manufacturers who promote highly efficient and cost-effective products profit from their preparatory investments. The same market rules and benchmarks are necessary for developing environmentally better products. Global standards can help. However, national governments need to enforce.

3. The harmonization of product's efficiency standards at IEC

Industrial products manufactured, shipped and traded globally need a framework of harmonized performance standards, including safety, protection, geometrical size, energy efficiency, etc. Only a harmonized framework of global standards allows for products to be comparable in terms of price and performance, making the competition more transparent. And, in a market economy, progress in quality and performance as well as cost effectiveness is depending on a level playing ground.

IEC has, since decades, tried to work toward harmonization of electric products. Rotating machines, namely motors and generators have been the first group of products addressed by IEC standards. The Technical Committee 2 dealing with rotating machines is the first product committee launched in 1911 in IEC. TC1 was launched already in 1910, but deals with terminology, terms and definitions only.

The IEC standards have to deal with the fact the hundreds of national standards exist, some before a respective IEC standard was published. Also, many national standards are based on IEC standards. In the field of IEC TC2 with its 46 member countries[1], five working groups and a total of 88 standards, today according to the official IEC data base 1672 national adoptions exist. In particular:

- the performance standard IEC 60034-1 is nationally adopted 65 times,
- the testing standard IEC 60034-2-1 (including the older version IEC 60034-2, and the special motors in IEC 60034-2-2) is nationally adopted 113 times,
- the efficiency classification standard IEC 60034-30, IEC 60034-30-1 is nationally adopted 7 times.

National adoptions of global standards do not always copy the international publication to a full extent, but add national context, exceptions and special elements.

That means, that even with solid internationally agreed standards, not every country adopts them fully, not necessarily in due course, plus they can add variations. Therefore, the harmonization goal is generally adopted, but its realization is a continuous process both within IEC (because of revisions of existing standards) and with its national members.

Two more elements (see Figure 1) are making the harmonization process slow and tiresome:

- Motor Systems – the combination of components into a complete motor system from the electric input from the grid to the eventually used flow for the finally processed product at the end of the chain.
- Motor Driven Units – combination and integration of electrical and mechanical standards/things.

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[1] Each country has a National Committee that is formally member of IEC. In IEC TC2 there are currently 46 members, with 31 participating countries and 15 observer countries.

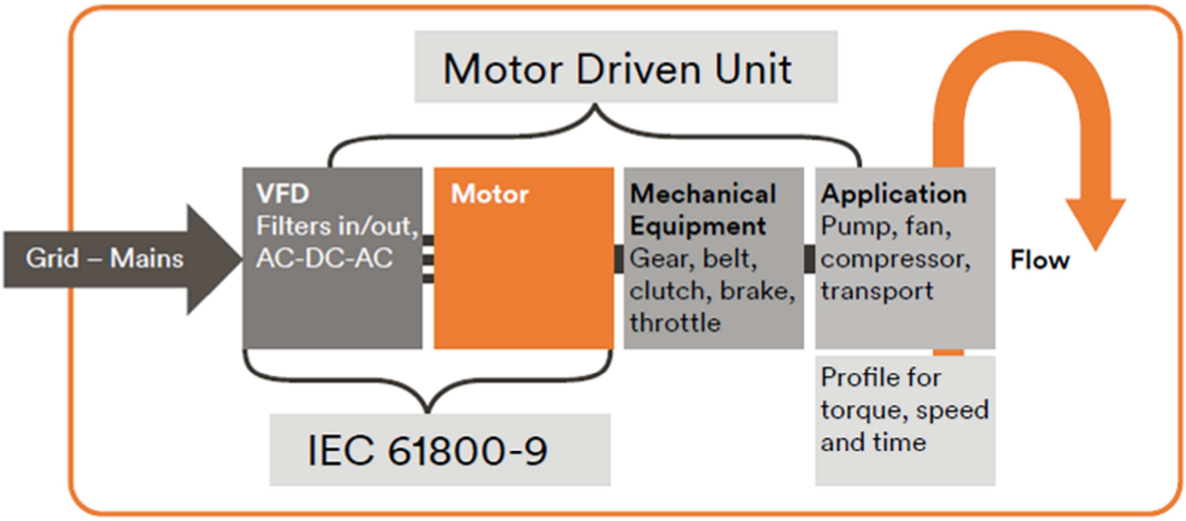

Figure 1 Motor system and its components (Source: EMSA, 2014)

In the case of motor systems (variable frequency drives, electric motors, applications like pumps, fans, compressors) the complexity increases. Traditionally, IEC published product standards. With variable frequency drives plus motors a first level of system interaction has started in IEC 61900-2, to be published in 2016/17. It requires the collaboration of two technical committees: IEC Technical Committee TC2 for motors and IEC Special Committee SC22G for converters. Two traditions, two philosophies and two terminologies have to be merged. Two working groups, namely TC2 WG28 and SC22G WG18 have to collaborate, informally with designated liaison persons or formally as a joint working group. The experience so far has shown that this is indeed a challenging procedure, quite a new experience within IEC standard making processes.

Dealing with **Motor Driven Units** (sometimes also called "Extended Products") adds a new level of complexity: traditionally IEC is responsible for electrical equipment and ISO for mechanical equipment. This means that the pumps (ISO TC 115: 24 standards), fans (ISO TC 117: 26 standards) and compressors standards (ISO TC 118: 72 standards) are dealt within ISO. Here the dimensions, technical specifications, performance, special applications and testing standards are published: usually both IEC and ISO work in close cooperation with the respective national and regional industry associations, see Table 1:

Table 1 Regional manufacturers' associations

Pumps	Europump (European Association of Pump Manufacturers), HI (Hydraulic Institute)
Fans	AMCA (Air Movement and Control Association International), Eurovent (European Committee of HVAC&R Manufacturers) EVIA (European Ventilation Industry Association)
Compressors	CAGI (Compressed Air and Gas Institute), Pneurop (European Association of Manufacturers of Compressors, Vacuum Pumps, Pneumatic Tools and Air & Condensate Treatment Equipment)

So, the harmonization goal for motor systems is a challenge. The World Trade Association in Geneva (WTO) with its 160 member countries is a solid partner on this way. It deals with lowering Non-Tariff Barriers called Technical Barriers to Trade (TBT) which non-aligned standards typically are. A new national and international product standard always has to go these days through a TBT notification procedure where WTO checks if the national (or international) standard hampers market access.

As mentioned earlier, national policy makers use the global standards by adopting them in their national regulation (note: not always as one-to-one, but adding national context, exceptions and special elements). This also can work vice versa, i.e. a need felt by national policy makers for extra regulation on efficiency by MEPS can bring about extra demand to the standard makers for developing new or updated international standards on these issues. They stimulate IEC and ISO members to work on new / adjusted standards in order to be able to impose new efficiency regulations. The interaction of standard makers, policy makers, manufacturers and utilities is shown in Figure 2.

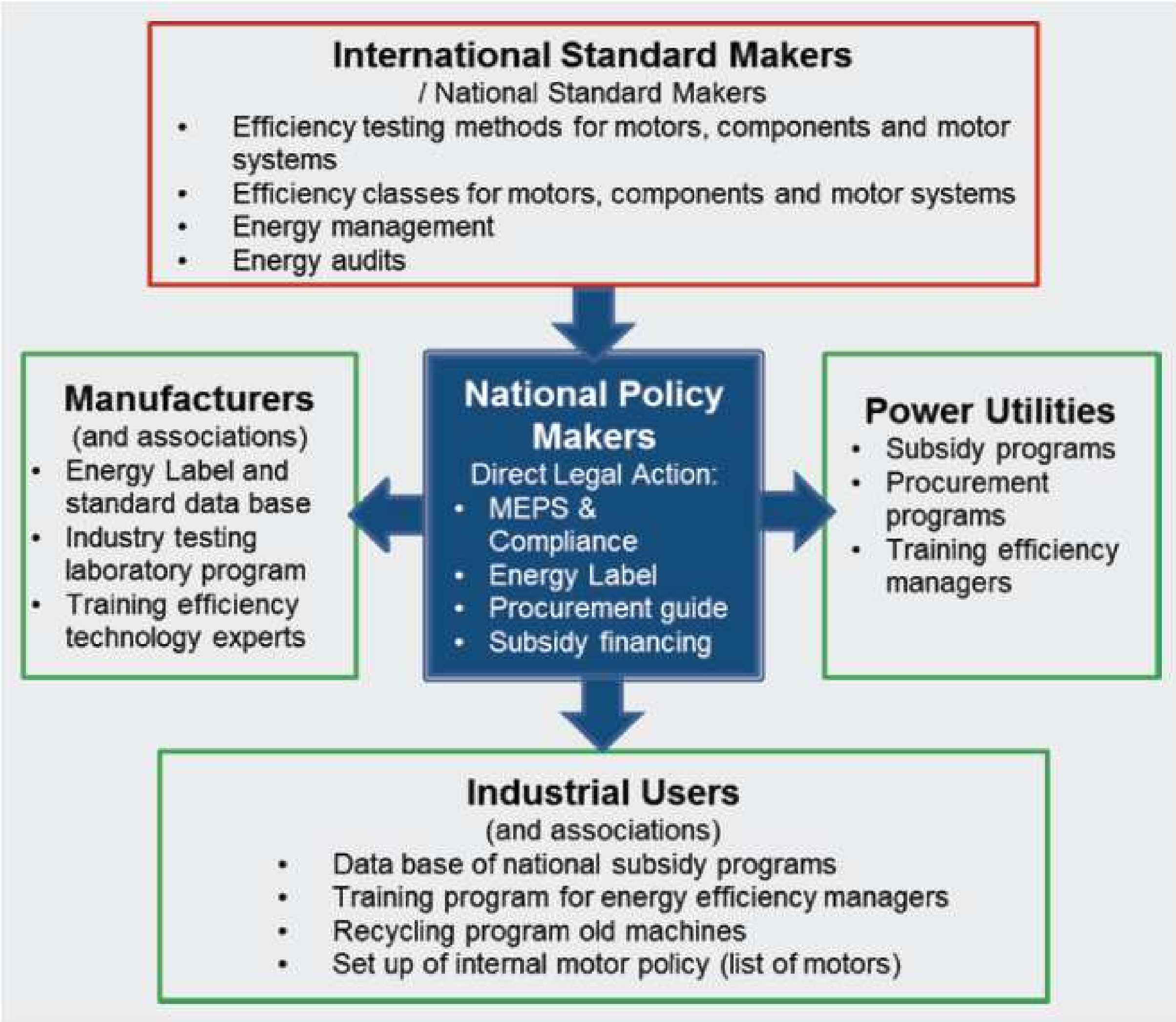

Figure 2 Interaction of National Policy Makers (Source: Impact Energy Inc., 2014)

4. The introduction of product's performance data bases

A technical product is usually displaying its performance characteristics in two elements:

- Rating plate, directly placed on the machine
- Technical documentation, delivered in paper or electronically with the product.

When traded products need to conform with international standards like IEC and ISO and national performance standards depending on legislation, the transparency of product performances in a wide array of topics (like health, toxic material, safety, energy, recycling, etc.) is necessary.

Electric motors have to carry a rating plate (see Figure 3) with information defined in IEC 60034-1 (see [4]) that includes the energy efficiency classification with the IE-code and the efficiency defined in IEC 60034-30-1 (see [5]). Products following the required European standards and laws can carry the CE mark (Figure 3). US manufactured electric motors that follow national minimum performance requirements need to go through an accreditation procedure of the manufacturer and the product group in order to receive a control number stamped on the rating plate (Figure 4).

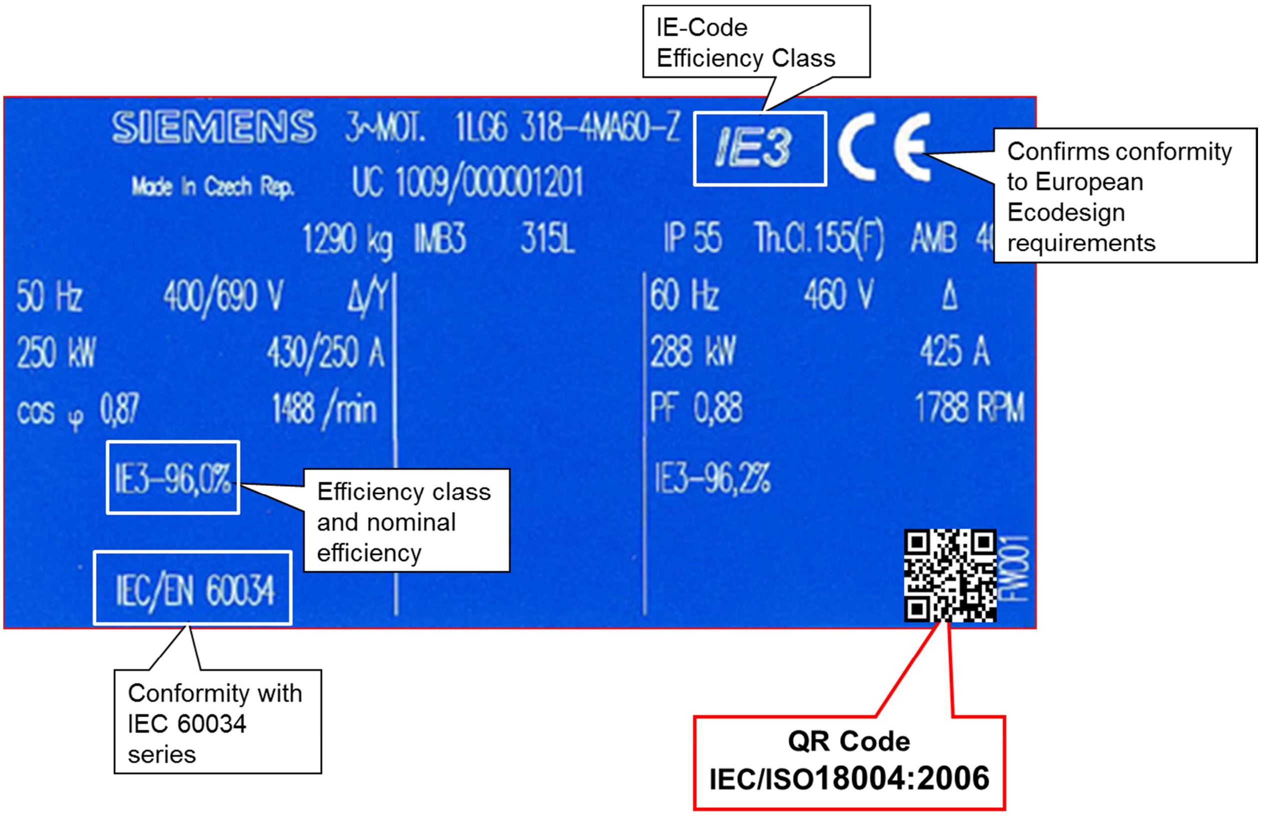

Figure 3 Rating plate for electric motor

The current situation is not satisfactory both for international trade, national compliance programs and check tests because many products carry incomplete (or false) information on their rating plates and their product documentation is in many cases not available anymore.

One possible solution for this problem could lay in the use of a modern product data base, which needs to include these steps:

- Standardized information package, both for the rating plate and the technical documentation.
- Additional national information requirement like energy labels, certification numbers, etc.
- Product registration and number.
- QR code on rating plate (see Figure 3) to easily access the full technical documentation both at the manufacturers' website as well as at the national product registration data base.

Currently, we are far from that. Neither are in electric motors the IEC requirements for the rating plate fully followed, nor is the information of the technical documentation including the registration standardized, nor is the data base established at manufacturer's or government's sites (with the exception of Australia). Some countries though, have made progress in parts of this procedure:

- US — Manufacturer' registration with Compliance Certification number on rating late (see Figure 4)
- Australia — National product registration data base (available online: http://reg.energyrating.gov.au/comparator/product_types/54/search/)
- China — QR code on energy labels with access to government database with technical documentation
- Europe — CE mark for compliance with Ecodesign regulation no 2009/640 (see Figure 3)

It is obvious that this is a herculean task to achieve, both because of the large number of products involved (and their variations) and also because of the ongoing change of product performance features and government Minimum Energy Performance Standards (MEPS) over time. Other possible solutions – or one step less comprehensive - for the missing transparency on product information (incomplete or false on their rating plates, and/or availability of product documentation) can be the use of regional (per continent) databases.

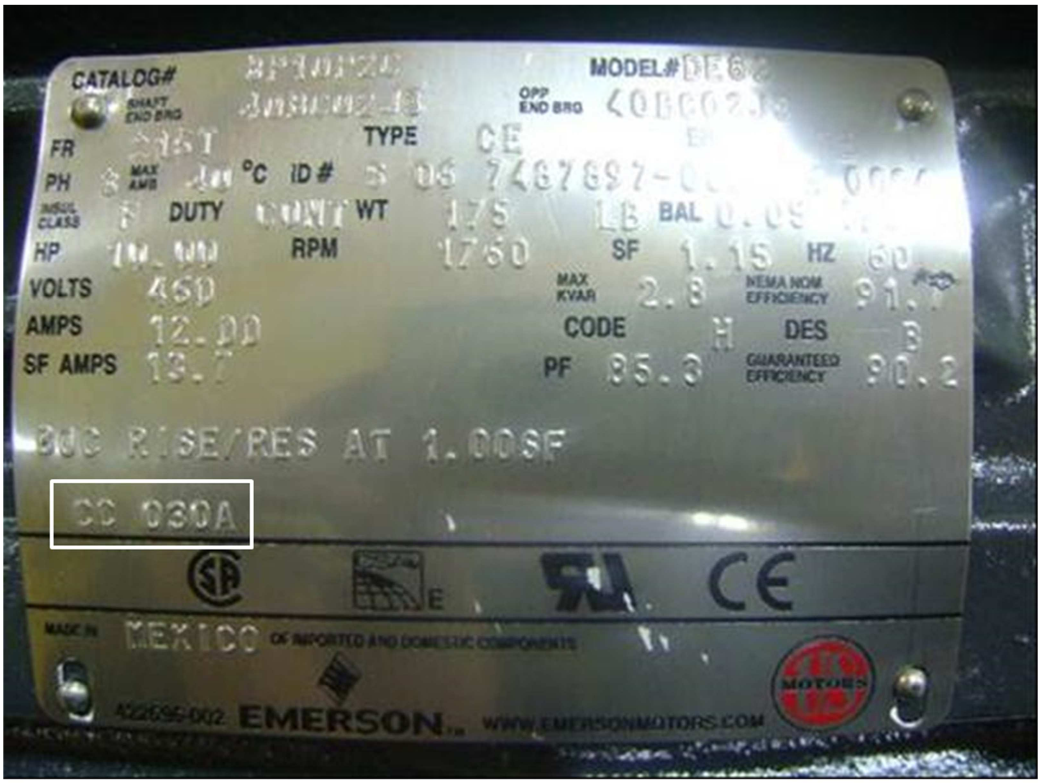

Figure 4 US registration number code for electric motors

5. The build-up of a network of accredited testing laboratories

Product performance needs to be checked preferably by independent laboratories. The measurement of energy losses in electric motors is by now well described and globally agreed in IEC 60034-2-1 (see [6]). The performance test needs to be both accurate and repeatable because motors today have efficiencies of between 90% and 96% which allows only for small measurement uncertainties. But, the national laboratories, both in industry, university and research and government, only slowly adopt the new measurement standards and buy the necessary modern equipment. Also, the laboratory staff has to be trained in using the standards in the proper environment and sequence, and to handle the delicate measuring instruments that are necessary today to measure small deviations of losses. The instruments like torque transducers and power analyzers have to be dealt with great care and regularly checked and calibrated.

The tolerances for motors vary between 15% (up to 150 kW) and 10% (over 150 kW) of the losses. This means we are dealing with a margin of 1.0 – 1.5 percentage points in smaller sizes and with 0.5 percentage points in bigger sizes. This means the measuring inaccuracy has to be much smaller than that to be able to assess the product performance quality.

The visits to many manufacturers' factories and other testing labs show that there is a long way to reach a satisfactory level of performance testing around the globe. The effort is driven by countries with a large number of manufacturers and a fair share of global product volumes like Germany, Finland, France, USA, Brazil, China and Japan. The build-up of a national network of reliable, trained and independent laboratories is especially difficult in developing countries where both the necessary resources lack and eventual MEPS are not enforced.

6. The introduction of integrated systems’ based software tools (Motor Systems Tool) and audits

“Think systems” does not yet automatically mean: being able to design a system consisting of an electric motor, a converter, a transmission, a gear and an application like a pump. Systems are more complex than their individual components. Complex interactions take place to align power from the grid to the converter, its output as current, voltage and frequency for the motor, and the motors output as torque and speed and finally the pumps output in volume and pressure at the required operating point.

In new installations, better designed systems need tools to optimize this integration. The Motor Systems Tool (see Figure 5) is a good example for that. This tool is an impartial calculation tool in which the efficiency of complete motor systems is calculated. It is an easily accessible tool which gives good technical support for choosing the optimal motor system and is available for a broad audience.

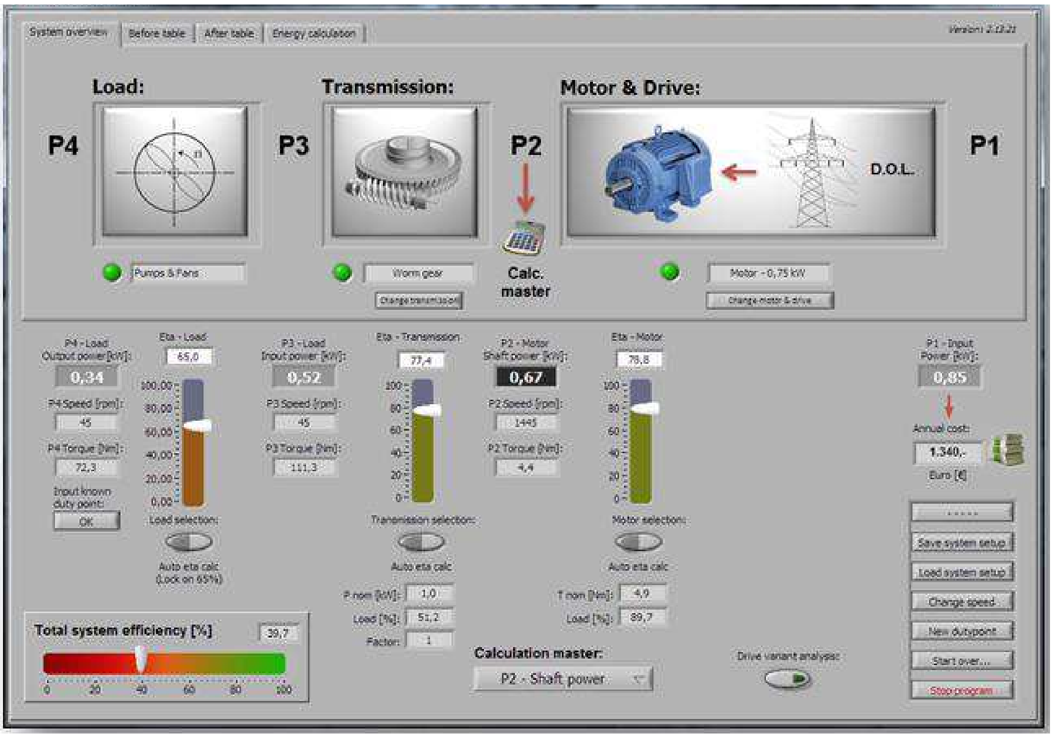

Figure 5 Motor System Tool (MST), (Source: Danish Institute of Technology, 2014) (download at www.motorsystems.org/motor-systems-tool)

Industry audits which identify quickly the machines with the highest savings potential and the most cost-effective improvement measures are needed with factories counting between 100 and 10’000 individual machines. The Motor-Systems-Check method is a good example for that. It consists of a standardized four-step audit process (Motor-Systems-Check) from the Topmotors program of the Swiss Agency for Efficient Energy Use (S.A.F.E.), with the first three steps being preliminary analyses and the last being the implementation of efficiency measures. For each step a supporting tool can be used, to help find the motor systems promising the highest savings in a systematic manner (see Figure 6). [3]

The execution of steps 1 – 3 bring mainly costs for analytic work, e.g. the necessary time and work for putting together the motor list and e.g. on-site tests. The work is usually a cooperation of internal personnel and consulting engineers. Step 4, the actual implementation process, concerns all types of measures for improving the complete motor system efficiency, e.g. improved operation and part load control, improved transmission and gears, advanced driven application, planning, installation and putting into operation.

Tools and audits need capable staff to perform the right analytical steps, with data digging, on sight visits, measurements, and systems analysis. With these tools and audit concepts specific actions and programs can be executed to upgrade the capacity of staff and companies involved. Examples of this capacity building and awareness raising are the Green Deal EEA, and the program ET&M, training program for energy technology and management in industry [7].

Finally the uptake of industry audits and tools for efficient motor systems can be supported by implementing energy management systems in industry, e.g. ISO 50001 [8] and an audit system like ISO 50002 [9]. Having an energy management system in place should lower the barrier for executing regular audits, for continuous improvement of efficiency and for monitoring the results of measures and of energy use. The European Union has already introduced a mandatory and regular audit system for medium and large industries in its Energy Efficiency Directive[2].

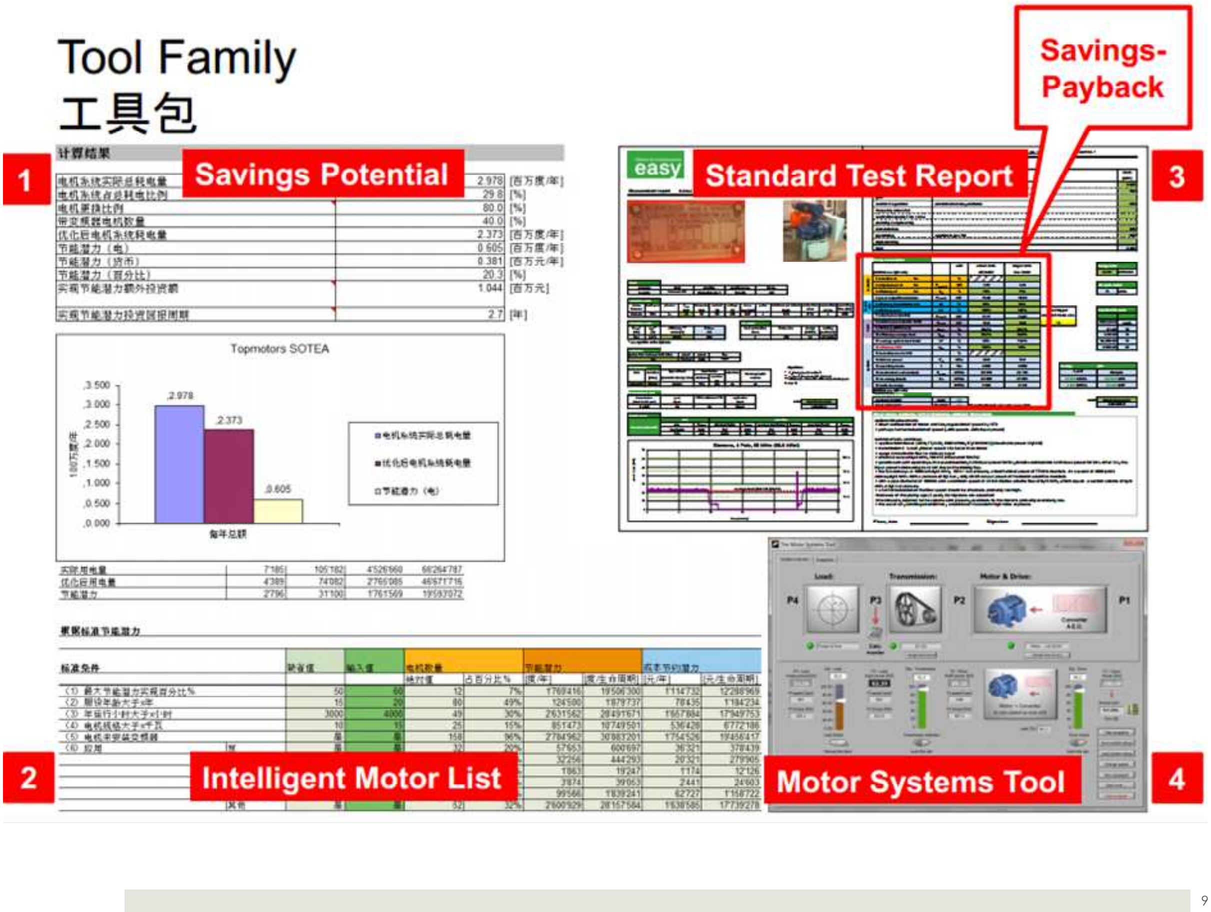

Figure 6 **Motor Systems Check: Tools for a 4-step audit (Source: Topmotors China, 2014)**

7. One globalized motor product certification system

Having a clear product scope in Figure 7 (1), a standardized method of determination of losses and efficiency (2), an agreed efficiency classification (3), and a guide (4) for a systems optimization process, the next logical step requested by industrial product users and government regulation agencies includes a certification system (5) that also issues a label for products that comply with all the necessary requirements. But, this element of product registration still has to be clarified. Several countries have introduced as part of their MEPS policy, a registration system that requires each manufacturer (like in the USA) or even each product group (like in Australia) to register its product and show the respective number on the rating plate.

In response to this need and current practice of national registration systems, IECEE (which is the IEC conformity assessment association) has launched its Global Motor Energy Efficiency Program (GMEE) to develop a common global MEPS registration process in order to expand the global market access for efficient motor products. There are a number of shortcomings of not having a globalized motor

[2] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Brussels Belgium, 2012

product certification system. First of all, the registrations of MEPS vary and can slow or block international trade. Secondly, there is a lack of effective MEPS enforcement and verification processes. Thirdly, developing nations are creating new requirements without having a proper guideline. A globalized motor product certification system can help the industries to overcome these challenges. Imagine a single MEPS certificate being accepted by industries and governments all around the world. GMEE can alleviate the issues regarding compliance & enforcement process and improve the certification process. (Source: Dan Delaney, [10]).

1	2	3	4	5
IEC	IEC	IEC	IEC	IECEE
SCOPE	TESTING	EFFICIENCY CLASSES	GUIDE	CERTIFICATION
IEC 60034-1	IEC 60034-2-1	IEC 60034-30	IEC/TS 60034-31	IECEE e3
standard use conditions, only selected technologies in the scope	one preferred testing method, procedure prescribed in detail (accuracy, repeatability); check-testing!	3 major efficiency classes: IE1 > IE2 > IE3, open to advanced technology (IE4)	background, application, context, system integration, tools?	conformity assessement, lab accreditation, expert training, round robin, global label

IECEE: System of Conformity Assessment Schemes for Electrotechnical Equipment and Components

Figure 7 The necessary five elements (Source: Brunner et al., 2013)

The objectives of GMEE are to expand global market access for efficient motor products and to develop common global MEPS registration process such as test laboratory qualification and registration & certification. The final goal of GMEE is to have one test certificate which can be accepted globally by national regulators.

Having a test report accepted around the globe is only the first step. The key points in GMEE are a “direct to Market “certificate approach, global test standards, ISO test laboratory quality requirements, no labelling requirements, no verification program and each motor manufacturer determines the appropriate IE level.

The second phase will be the Global Motor Labeling Program (GMLP). The main focuses of GMLP are developing effective process for Market/Factory Surveillance on top of GMEE, embedding GMLP into national regulations as an alternate certification program and creating a global recognized motor efficiency label.

There are many challenges ahead for the GMLP. First of all, global “labelling” can be challenging. A successful introduction and promotion of this label need to be presented and accepted by the industry and the governments. In addition, adaption by existing national certification bodies with recognized label is required. Finally, national border patrol education is required for effective enforcement. The second challenge is to develop a globally recognized certification process such as product line certification uncertainty and manufacturing test laboratory qualification process. Thirdly, a globally harmonized test standard and efficiency levels need to be further improved. Lastly, the industrial motor newcomers are concerned about the additional cost and performance/efficiency factor. It is crucial for GMLP to overcome these challenges in order to achieve the goal of having a single certificate which is accepted worldwide.

8. Where do we want the motor world to be in 2030?

Motor technology will continue to advance: Smaller size frames, lower weight, stronger performance with high torque over a wider range of rotational speed, better starting performance with lower starting currents and better power factor, etc. Permanent magnet and synchronous reluctance motors will join the induction technology to be the workhorses of rotating machines. Cooling will be easier for high efficient machines with lower losses that do not overheat. Improved longevity and lower maintenance are the co-benefit of this development. Linear motors will take over tasks that pneumatic and hydraulic systems had to do so far with much lower efficiencies. Direct drives will make belts and even gears dispensable and move the motor much closer into the process machine.

New production methods like 3-D printing will make complex copper windings become more densely packed helixes with proper spacing for new insulation materials. New automation and information technology applied to motor systems will offer opportunities for better designing, engineering, operating and monitoring production processes separately and combined in larger numbers.

But, more important, variable speed motors will merge with their driven application to close coupled integrated products (see Figure 8 and Figure 9). Pumps, fans and compressors that show this integration already now in sizes up to a few kW, will be available up to 100 kW and beyond. What a standard air conditioning or heat pump unit does already for a long time by assembling pumps, fan, air washers, heat exchanger, cooling compressor and the motor in a box together with the controls, should become standard practice for any motor driven unit. The integration will bring many advantages: the match of size and performance is there by design not by default. Today with three or more individual components from different manufacturers bought and assembled later on site, the possibility for mismatch and oversizing is much larger. The integration delivers complete service units that can more easily be merged into process lines and controlled by factory automation. The problem of parallel machines for varying loads and redundant machines for operating security can be solved more easily. This will enlarge the opportunities for advanced factory automation, for new and for existing motor systems (installed base).

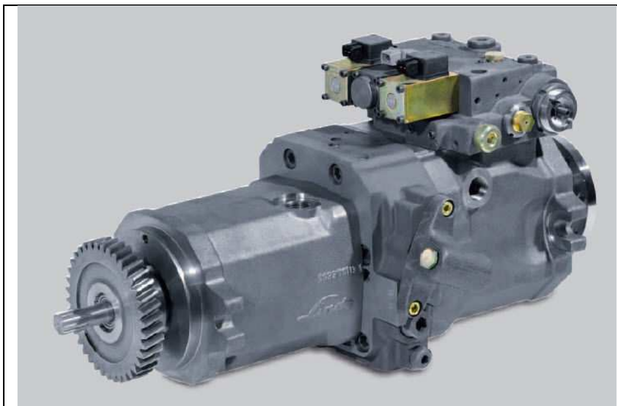

Figure 8
Integrated Hydrostat 165 kW
(Source: Linde)

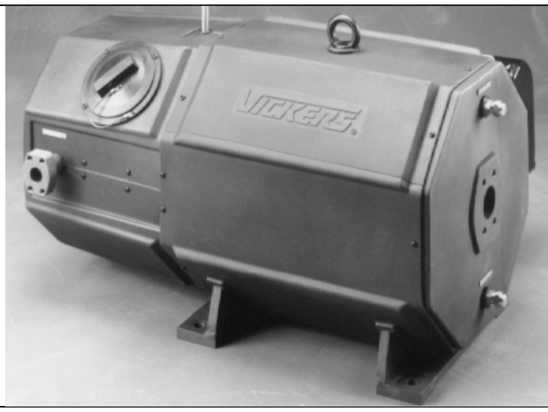

Figure 9
Integrated motor and pump with 92 kW
(Source: Eaton/Vickers)

This tendency for integration will of course heavily influence manufacturers: in the last decade we have seen a number of mergers of international players across continents: from Japan to USA, from Europe to China and back. The motivation for this first generation of mergers was to get complimentary competences, access to global markets and services as well as higher production volume. With the increased volume the effort for research & development per unit can be reduced. State of the art high tech production methods can be used both in the electronic factory for converters as well as in the electro-mechanic factory for rotors and stators. Expensive laboratory testing capabilities can be used. These first steps are all prerequisites of product integration.

A global manufacturer will need to be able to deliver a complete pump system, fan system or compressor system. The finished system is then shipped to its final destination and put to work by one switch. Users will love it because they have one manufacturer and service contractor. They can then concentrate more on their real issue: better products. After the initial phase of product integration, also manufacturers will come to like it: their own in-house designed pump is easier to be assembled with their own motor and converter. They will buy a pump manufacturer or start joint ventures for integrated design programs. Or the other way around: today a number of large fan, pump and compressor manufacturers started to build their own motors and converters that fit into their applications more smoothly.

An opportunity resulting directly from this tendency for integration lies in 'forward integrating into the supply chain'. Manufacturers and/or their national sales offices, and/or service companies, will be able to expand their services towards energy efficiency analyses and advising services, and to combine the actual sale of products (efficiency measures) with the proposition of financing the proposed measures (energy efficient motor systems solutions). The financing can be a loan system paid back by energy cost savings within 3 years. The manufacturers will be able to expand their market share and increase the speed of implementation of efficient motor systems.

Also, energy supply will change until 2030. Low energy cost for electricity, oil and gas are currently no driver for this innovation process that could reduce the over aged rolling stock all over the world. Even with a hopefully much lower carbon and nuclear content of electricity in 2030[3], the price will not necessarily go up. With global energy consumption still rising until 2035 mainly from developing countries' demand, efficiency starts to have an impact. Also, according to IEA "A ray of hope. Nearly half of the net increase in electricity generation comes from renewables". We have seen the rapid development of wind and solar capacity in parallel with hydro, biomass and geothermal in the last decade. But, the hope of rapidly climbing energy and electricity cost that would support energy efficiency did not happen, to the contrary: abundant new fossil fuel sources led - not respecting any CO_2 emission restraints - to a collapse of energy prices worldwide. The price of electricity as an economic driver for the development of efficient integrated products might fail in the next decade. Harmonized international standards and strict national market rules will be necessary to avoid cheap products with high operating cost to keep their market access in the developing world and so lead to high energy consumption, pollution and carbon emissions.

9. Conclusions

Efficient motor systems are the key electric energy savings potential still untapped worldwide. Better components and much better systems integration is the path towards renewal of the overaged and oversized industrial rolling stock. Specific programs to give incentives to renew old machines are a win-win situation for society, industry and also the environment.

Global standards and upcoming global performance certificates lead the way to an easy global market of superior systems and less red-tape on frontiers. National minimum energy performance requirements are beginning to push the so far slowly developing market more successfully now. But, without strict compliance and systematic check testing the results will be disappointing.

Technology is capturing new fields beyond IE3, IE4 and IE5 motors. Integrated machines that have a matched set of components (converter, motor, application, gear if necessary, higher level control of several machines) are a successful way to make smaller, better and cheaper machines available to the market place. This will lead over the short run to a new wave of mergers between motor and application manufacturers who are able to deliver a complete system to an industrial costumer anywhere around the globe.

Industrial manufacturers of machines and industrial users of equipment need to achieve a new accord both with standard makers, requirement-setting governments and power delivering and tariff-setting utilities. As well as involve their stakeholders in setting sustainability targets for their businesses. The solutions are to be defined on a global level and they also include capacity building for factory engineers, managers and government representatives. National programs (like Green Deal in the Netherlands, Energy Technology and Management ET&M[4] and VELANI[5] in Switzerland) can help to implement such programs and to transform the markets before the deadline of 2030.

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Assessing Energy Efficiency Opportunities in US Industrial and Commercial Building Motor Systems

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Abstract:

In 2002, the United States Department of Energy (USDOE) published an energy efficiency assessment of U.S. industrial sector motor systems titled *United States Industrial Electric Motor Systems Market Opportunities Assessment.* The assessment advanced motor system efficiency by providing a greater understanding of the energy consumption, use characteristics, and energy efficiency improvement potential of industrial sector motor systems in the U.S. Since 2002, regulations such as Minimum Energy Performance Standards, cost reductions for motor system components such as variable frequency drives, system-integrated motor-driven equipment, and awareness programs for motor system energy efficiency have changed the landscape of U.S. motor system energy consumption.

To capture the new landscape, the USDOE has initiated a three-year Motor System Market Assessment (MSMA), led by Lawrence Berkeley National Laboratory (LBNL). The MSMA will assess the energy consumption, operational and maintenance characteristics, and efficiency improvement opportunity of U.S. industrial sector and commercial building motor systems.

As part of the MSMA, a significant effort is currently underway to conduct field assessments of motor systems from a sample of facilities representative of U.S. commercial and industrial motor system energy consumption. The Field Assessment Plan used for these assessments builds on recent LBNL research presented at EEMODS 2011 and EEMODS 2013 using methods for characterizing and determining regional motor system energy efficiency opportunities.

This paper provides an update on the development and progress of the MSMA, focusing on the Field Assessment Plan and the framework for assessing the global supply chain for emerging motors and drive technologies.

Introduction

Research and development into advanced motor system technologies and the design of effective energy efficiency policy (e.g. awareness campaigns, technology deployment, regulations, incentives) require information on installed motor system performance. However, collecting and analyzing the information to assess installed motor system performance is a significant effort. As a result, there have been few comprehensive assessments of the energy performance of the installed motor system base at a national level using the results of current field assessments.

In the United States, the most notable assessment of industrial motor systems using current field information was initiated by the U.S. Department of Energy (USDOE) in 1995 as part of the then-USDOE

Motor Challenge Program [9]. The results were published in 2002 in *The United States Industrial Electric Motor Systems Market Opportunities Assessment*[1] (2002 Assessment) and:

- led to a greater understanding of motor system energy consumption and the opportunity for improvement within the U.S. industrial sector, and
- provided the information required for manufacturers, utility and energy efficiency programs, and government agencies to develop products and programs that increased the uptake of energy efficient technologies

Since its publication, the 2002 Assessment has guided the development of motor system program offerings both at the government and the utility level, been cited numerous times in research, and influenced the marketing and product design decisions of motor and motor system manufacturers. Similarly, the most notable comprehensive national assessment of commercial motor driven equipment using field information was conducted by the USDOE in 1999 [1]. Since these two reports are the only national-level assessments of the motor and motor related equipment stock in the U.S. industrial and commercial sectors, they remain influential despite outdated information.

Neither of these reports reflects the current industrial and commercial motor system energy consumption baseline and reduction opportunity. The results from the 2002 Assessment were based on the state of U.S. industrial motor systems in 1997 and the results of the USDOE commercial motor driven equipment assessment were reflective of the installed base in 1995. Additionally, the U.S. Bureau of the Census discontinued its collection of data on motor and generator importation, manufacture, shipment and sales more than a decade ago, thereby eliminating a valuable stream of publicly available and up-to-date motor market information. Since the publication of both motor system reports, the energy efficiency of these systems has improved due to:

- higher efficiency of motors being available for sale in response to standards and labeling initiatives,
- the use of variable speed drives greatly increasing due to greater awareness of their benefits, reduced capital costs and various incentive programs, and
- the use of DOE and electric utility initiatives that provided software tools, training and information.

In addition to improvements to the overall efficiency of motor systems, U.S. industry itself has experienced significant changes since the 2002 Assessment. Manufacturing facilities have moved offshore, expanded U.S. oil and natural gas extraction has led to new manufacturing facilities with intensive motor system use, global competition for materials and motor driven system components is greater, and the increased availability of, and reliance on, real time data and use of robotics has had profound effects on both end user and motor and motor-driven system manufacturing processes. Further, advanced motor technologies and materials for meeting specific demands have emerged.

Recent studies on motor system energy efficiency improvement potential have all noted the lack of current and comprehensive information on motor system energy use and consumption as a limiting factor to their findings [3-5]. At EEMODS 2011, LBNL presented results from constructing energy conservation supply curves developed for pumping, fan, and compressed air systems in the U.S., Canada, EU, Thailand, Vietnam, and Brazil. The precision of the curves was limited by the lack of available regional information [6].

This lack of information affects a broad range of stakeholder groups:

- Government agencies must rely on outdated information to direct their research opportunities, policy measures, and awareness campaigns;

[1]Originally published in 1998, and republished in 2002 with minor corrections

- Utility and energy efficiency programs cannot accurately target their programs or evaluate the impact of a potential incentive program or energy efficiency campaign;
- Motor, drive, and motor driven equipment manufacturers do not have reliable information on the energy efficiency characteristics of their markets to better evaluate and serve their customers' interests, and
- End users are unable to assess their own motor system performance and operating practices with respect to their peers to identify potential methods for reducing motor system energy consumption.

The collective result from this "information gap" is the inability to reliably assess the potential for new technologies and operating practices to improve regional motor system energy performance, thus creating a barrier to their adoption.

To address these concerns, the USDOE initiated a new Motor System Market Assessment (MSMA) in 2014, to be led by LBNL. This paper provides an overview of the MSMA, and provides details on methodologies to meet the study's objectives. The new motor systems market assessment will help motor system component manufacturers, policymakers, and researchers better assess the energy consumption of the motor and the system in which it operates, and identify the potential for energy efficiency improvement.

Overview of US Motor System Market Assessment Update

The MSMA includes two major tasks:

Task 1: Motor System Field Assessments - An assessment of the installed motor system base in the U.S. industrial and commercial sectors, including the energy consumption, operational and maintenance practices, and their potential for greater energy efficiency

Task 2: Supply Chain Assessment - A study of the global supply chain for advanced motor and drive technologies.

Objectives:

The objectives for each of 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.
   - Develop a profile of commercial and industrial motor and motor system purchase and maintenance practices
   - Analyze the opportunities (by market segment) for improved energy efficiency and cost savings available through implementation of efficient motors, control technologies, system optimization, and new and future advanced motor and motor system designs

2. Supply Chain Assessment:
   - Evaluate the state of the global supply chain that supports motor and drive technologies including: the accessibility and sustainability of key materials and components, the progress of R&D directed at decreasing the quantity of heavy rare earth materials required in high energy-density permanent magnets, and the factors impacting the manufacturing of motor and drive technologies.

To meets the objectives, the MSMA will combine a bottom-up and top-down approach. The bottom-up approach will include on-site motor system assessments of several hundred industrial and commercial facilities in the U.S. This will provide the primary assessments required to develop the analysis for the MSMA. The results of the bottom-up approach will be compared to top-down estimates based on the available literature to verify the findings from the bottom-up approach.

Scope:

The MSMA will cover the following sectors within the U.S.:

- Manufacturing sector as categorized within series 31-33 of the North American Industry Classification System (NAICS)[2] and the water/wastewater treatment sector
- Commercial building sector as categorized by the USDOE's Commercial Building Energy Consumption Survey 2003 (CBECS)

The sectors covered by the MSMA are an expansion of the sectors covered by the 2002 Assessment. The 2002 Assessment excluded both the commercial building and the water/wastewater sector.

Motor systems in the assessment will include those driven by polyphase motors 1 horsepower and greater regardless of end-use (e.g., compressed air, pumping, fan). Large (i.e., greater than 50 horsepower) DC motors observed will also be included. The "motor system" includes the drive and controller, the motor, power transmission, motor driven equipment, and distribution system.

USDOE Interest:

The USDOE Office of Energy Efficiency and Renewable Energy is interested in the update of the MSMA so as to increase manufacturing, municipal and commercial sector end users awareness of motor system energy efficiency and cost saving opportunities through improved operating practices and best-available and advanced technologies. The USDOE also wants to identify research needs that will drive greater increases in motor system energy efficiencies, as well as, to enable a more competitive US motor and motor system manufacturing equipment industry.

Timeline:

The MSMA was initiated in the summer of 2014 and the results are expected to be released by the end of 2017. LBNL is planning an interim report to be released in 2016. Site visits for the Motor System Field Assessment task will be conducted through 2016.

The balance of this paper will outline the methodology for completing each of the two tasks.

Methodology for completing Motor System Field Assessments

The Motor System Field Assessments will update and build upon the results from the 2002 Assessment by conducting field assessments and using the findings to determine the energy consumption baseline, operational and maintenance practices, and energy efficiency improvement potential for motor systems in the U.S. commercial and industrial sectors. Methodologies used in other countries and regions for evaluating motor and/or motor system energy efficiency potential, such as those used to evaluate EuP Lot 30 in the EU, will be reviewed and incorporated where beneficial [2].

Stakeholders and audience members:

Recognizing that the results from this task will serve the interests of several stakeholder groups and audience members, LBNL and USDOE organized meetings with various groups to determine the desired

[2] "The North American Industry Classification System (NAICS) is the standard used by [US] Federal statistical agencies in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy" [8].

outcomes for the task. To that end, the stakeholders and audience members for the MSMA were identified as being:

- End users and their trade associations;
- Motor and drive manufacturers, motor distributors, motor repair practitioners, and their trade organizations;
- Motor drive equipment manufacturers, their trade associations, and distributors;
- Electric utilities and their member organizations;
- Energy efficiency program administrators and their member organizations;
- Energy efficiency service providers, energy efficiency consultants, and end users' purchasing agents;
- Regional, state, and national government, including the USDOE, and
- Researchers studying motor system energy efficiency principles and design.

Desired outcomes for Motor System Field Assessment

The stakeholder meetings included representatives from the motor and motor system manufacturing community, energy efficiency advocacy groups, the USDOE, and electric utility and energy efficiency program administrators. From these meetings, the following were identified as the *desired outcomes* from the Motor System Field Assessment task of the MSMA:

1. Summary of the installed motor system base providing insight into installed motor systems identifying information and overall energy consumption;
2. Characterize energy management practices in industrial and commercial facilities, as related to the 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 their potential impacts on production;
4. Assessment of the investment required to implement existing and cost effective energy efficiency actions, and
5. Comparison of current installed motor system base to the results of the 2002 assessment, where applicable.

Additionally, the final report will include a description of the types of facilities and motor systems assessed and the assessment methodology in order to provide context for and confidence in the MSMA results.

Findings in support of desired outcomes

The MSMA team identified several findings from the MSMA that would support these *desired outcomes*. Divided into two categories, key and detailed, the findings represent the intended results from the analysis for the MSMA, once completed. *Key findings* are intended to be high level findings on energy consumption, operating practices, and savings potential of motor systems. *Detailed findings* are intended to provide information on energy consumption, operating practices, and savings potential specific to sectors. (e.g., by NAICS code or buildings type). Examples of each are provided below. Note that the examples are intended to illustrate the types of results sought from the MSMA. The final results will be dependent upon the outcomes from the field assessments, the desired level of statistical accuracy, and the relevance of the key/detailed finding upon reviewing the results. Also, where applicable, the findings will focus on the electricity and cost savings potential from cost effective (≤ 2 year payback) practices and technologies. This will allow motor system end users to identify practices and technologies that meet their business case requirements.

Examples of key findings:

- The total motor system electricity consumption and cost broken out by sector (e.g. industrial, commercial)
- Potential percent improvement and associated annual electricity consumption and cost savings through the adoption of cost effective (≤ 2 year payback) practices and technologies with a breakdown of electricity savings by category of measure (e.g., operational practice, capital expenditure, or advanced technologies) and sector (e.g. industrial, commercial)
- Distribution of typical load factors for motor systems in the industrial and commercial sectors and the potential for cost effective (≤ 2 year payback) installation of VFDs
- Annual energy consumption, energy costs, energy consumption savings, and energy cost savings by motor system type
- Sectors exhibiting the greatest potential for adoption of advanced and emerging motor system technologies as demonstrated by adoption rates of energy management practices

Examples of detailed findings:

- Breakout of the percent improvement in energy efficiency opportunity and electricity savings opportunity by system size
- For several industrial sectors at the 3 digit NAICS code level and commercial building types, the total motor system electricity consumption and cost broken out by motor system type
- For several industrial sectors at the 3 digit NAICS code level and commercial building types, potential percent improvement and associated annual electricity savings through the adoption of cost effective (≤ 2 year payback) practices and technologies with a breakdown of electricity savings by category of measure (e.g. operational practice, capital expenditure, or advanced technologies)
- Identification of the most common types of motor repairs and the commonly used decision making processes for deciding when to repair or replace a failed, failing, or aging motor system
- Use of third party assistance to identify, implement, or offset the implementation costs of motor system energy efficiency improvements

Achieving the desired outcomes

Results from field assessments will form the basis for the analysis conducted to meet the desired outcomes for the Motor System Field Assessment task. Where possible, available data sets can provide additional detail or highlight findings. However, since available data sets were collected for other purposes, they will most likely not include all of the information sought in support of the desired Motor System Field Assessment outcomes. For example, LBNL reviewed data compiled for the purposes of evaluating the impact of proposed USDOE motor efficiency standards [10]. The data compiled was not intended to assess the current energy consumption baseline for motor systems in the U.S. industrial and commercial sectors, but rather it was collected to determine the impact on energy consumption from proposed energy efficiency rules on future motor sales in the U.S. While the data compiled will be very useful to better understand the impact of motor regulations, motor system assessments conducted to meet the objectives and desired outcomes of the Motor System Field Assessment are still required. To this end, a robust and statistically accurate sampling plan coupled with a Field Assessment Plan outlining the requirements of the motor system assessments is under development at the time of this paper's publication.

Sampling plan

The U.S. industrial sector is comprised of over 200,000 facilities and the commercial sector is comprised of approximately 5,000,000 facilities. The primary objective of the Motor System Field Assessment sampling plan is to develop a statistically valid sample of motor system energy consumption, operating characteristics, and energy efficiency improvement potential for the U.S. industrial and commercial sectors. Since it is impossible to assess every U.S. industrial and commercial facility, a stratification scheme will be developed to determine the number of facilities to be sampled from each sector specific stratum. The stratification scheme will capture the statistical distribution of motor system energy consumption within the each sector.

For the industrial sector, subsectors characterized by three-digit NAICS code will be used as the sampling stratum. Information from the Manufacturing Energy Consumption Surveys (MECS) collected by USDOE Energy Information Administration (EIA) will be used to estimate motor system energy consumption for each subsector. MECS is a national-level survey conducted by the EIA every four years to gather energy-related data from several thousand U.S. industrial facilities for the purpose of estimating the energy consumption, energy use characteristics, and facility demographics of the U.S. industrial sector. The results are aggregated in several ways, including by end-use within each industrial subsector, and made public. Proxies for motor system energy consumption for each subsector can be developed by summing the estimated electricity consumption across all end-uses driven by motor systems within each subsector. The motor system driven end-uses, as categorized by MECS, include: process cooling and refrigeration, machine drive, and facility HVAC. Subsectors with greater motor system energy consumption will be more heavily sampled than others in order to capture the distribution of motor system energy consumption within U.S. industry. For example, Paper and Allied Products (NAICS code 322) will be more heavily sampled than an industry with a lower amount of energy for motor systems, such as Leather and Allied Products (NAICS code 316).

For the commercial sector, subsectors characterized by the classification scheme in the EIA's CBECS were used as the sampling stratum. CBECS is the analog to MECS for the commercial sector. Like MECS, CBECS aggregates and makes public the results by end use and commercial building type. Proxies for motor system electricity consumption for each commercial building type can be made by summing the electricity consumption across all motor system related end-uses within each commercial building type. End uses as categorized by CBECS that are driven by motor systems include: cooling, ventilation, refrigeration, and other. 'Other' includes miscellaneous motor system end uses. Here again, building types with greater motor system energy consumption, such as "offices", will be more heavily sampled than building types with less motor system energy consumption, such as "service".

The number of facilities assessed will depend on both the requirements for statistical accuracy and the available resources to conduct assessments. The 2002 Assessment included 270 assessments of industrial facilities. The current MSMA will include a similar number of assessments for the industrial sector and less for the commercial sector. Given the greater homogeneity in the commercial sector with regards to motor system energy use, the statistical distribution of motor system energy use can be captured with fewer samples the commercial sector than in the industrial sector.

In order to achieve a high level of confidence in the MSMA results, a statistical sample of motor system energy consumption should be random. This presents at least two challenges when executing the motor system assessments. The first challenge is to gain access to the facilities which requires the MSMA team to: 1) identify an appropriate contact person with knowledge of the facility's motor systems and 2) be granted access to the facility. The facilities must be willing to provide access to their motor systems, provide a representative to escort the assessors through the facility as required, and provide relevant details regarding their motor systems. As of the writing of this paper, LBNL and USDOE are considering providing the facilities that agree to participate in the field assessments a summary of the motor system assessment conducted at their facility along with recognition from USDOE for participation (i.e. a certificate). The second challenge is to develop a blind methodology for identifying facilities to assess. Several convenient techniques for selecting facilities to sample would lead to a biased sample. Examples of these techniques include: sampling multiple facilities owned by the same parent company, identifying facilities through their participation in energy efficiency programs (such as utility incentive programs), and identifying facilities through past experiences working with the MSMA team or stakeholders. While selecting facilities to assess using one of these approaches would help overcome the challenge of gaining access to facilities, the resulting sample, and by extension the results from the MSMA, would not be representative of the U.S. industrial and commercial sectors. This challenge can be overcome through the use of comprehensive directories of U.S. industrial and commercial facilities to identify assessment sites and providing incentives as described above to the facilities for granting access to the MSMA team.

Field assessment plan

The Field Assessment Plan outlines the objectives of the facility-level motor assessments and the requirements for the resulting report regarding the facility's motor system energy use and consumption. It will be executed at each facility ensuring consistency across all motor system assessments conducted for this effort. The goal for each field assessment is to develop a quantitative and qualitative understanding of typical motor system usage characteristics, including energy consumption, and to evaluate the potential for motor system energy savings at each facility assessed. The Field Assessment Plan employs a combination of staff interviews, visual observations, and spot measurements to determine the energy consumption and energy efficiency improvement potential of a given motor system.

At the 2013 EEMODS, LBNL outlined an assessment framework for conducting motor system assessment and a methodology for assessing the potential for energy efficiency improvement. The assessment framework outlined by LBNL approaches the assessment in stages─ collecting basic facility and motor system information first followed by information related to the energy efficiency of the system [7]. The methodology outlined for assessing energy efficiency improvement potential is based on the methodology employed by McKane and Hasanbeigi to develop motor system energy efficiency supply curves for several countries and regions [5, 6]. That methodology assigns an energy efficiency scenario (e.g. high, medium, low) to a given stock of motor systems based on the operational characteristics of the system as determined through system expert interviews and results from system assessments. Each scenario was assigned a band of energy efficiency. Energy efficiency improvement potential was then determined based on impact of a particular energy saving measure on each scenario. For example, ranges of system energy efficiency (expressed as a percent) were developed for each motor system scenario considered. The stock of motor systems in each country/region (e.g. all pumping systems in the US) was assigned a scenario based on its current operational characteristics as determined through interviews with system experts and the results of system assessments. To illustrate this concept, Table 1 shows the pump system energy efficiency ranges for each scenario used in the analysis by McKane and Hasanbeigi. Pump systems in the US were assigned to the medium scenario.

Table 1: Pump system energy efficiency ranges for each scenario used in McKane and Hasanbeigi [5]

	Low end (%)	High end (%)	Average (%)
Low scenario	20	40	30
Medium scenario	40	60	50
High scenario	60	75	67.5

Energy efficiency improvement potential associated with moving from a lower to higher scenario was based on energy efficiency improvement potential associated with a list of pre-selected measures. For example, a stock of pumping systems may have several leaks, damaged seals, or worn packing that would improve if they were fixed. The improvement potential is determined by the assigned system efficiency scenario with greater improvement potential for lower base case scenarios. To illustrate this concept, Table 2 provides the percent improvement in energy efficiency over the base case for pump system maintenance measures as determined and used by McKane and Hasanbeigi [5].

Table 2: Percent improvement in energy efficiency over base case for pump system maintenance upgrades as used in McKane and Hasanbeigi [5]

Pump System Energy Efficiency Measure	Typical % improvement in energy efficiency over current pumping system efficiency practice		
	% improvement over low efficiency base case	% improvement over medium efficiency base case	% improvement over high efficiency base case
Fix leaks, damaged seals, and packing	3.5	2.5	1
Remove scale from components such as heat exchangers	10	5	2
Remove sediment/scale buildup from piping	12	7	3

The Field Assessment Plan for the MSMA builds upon this past work and refines the approaches to fit the needs and resources available for the MSMA. The Field Assessment Plan calls for the motor systems to be assessed at three levels: facility characteristics impacting motor system energy consumption ('general information'), a description of each motor system ('system information'), and a more comprehensive estimate of the energy efficiency improvement potential for larger motor systems ('system energy efficiency'). Every facility will be assessed at the general information and system information levels. The system energy efficiency level assessment will be reserved for motor systems meeting certain criteria for minimum system size and operating hours

At the general level, the motor system assessment focuses on understanding the environment in which the motor system operates. Examples of information assessed at this level include: basic facility level information, facility annual electricity consumption, facility-level energy management practices, and facility-wide motor system practices such as repair/replace policies, maintenance schedules, or use of energy efficiency assessments.

At the system information level, the motor system assessment focuses on evaluating general information about a specific motor system. Much of assessment at this level will rely on quantitative information. Examples of information assessed at this level include: system nameplate information, motor nameplate information, use of VSDs or their potential applicability, load profiles and duty factors as determined through staff interviews.

At the system efficiency level, the motor system assessment focuses on gaining a better understanding of the energy efficiency of the largest energy consuming motor systems. Energy efficiency checklists will be developed for this purpose. They will combine observations, short interviews of facility staff, and simple spot measurements to quickly assess the energy efficiency level of a stock of motor systems relative to best available technology and maintenance/operational practices. As of the publication of this paper, LBNL is in the process of developing the energy efficiency checklists. Preliminary examples of information under consideration for inclusion are: description of system components (e.g. transmission type, type of pump or compressor), evaluation of distribution system (e.g. excessive bends, use of throttles or bypasses), system sizing considerations (e.g. the demand to which the system was sized), maintenance history (e.g. frequency and components of leak inspection program, motor repair history), and evaluation of sequence of operations (e.g. control strategy, sequencing scheme). The methodology for assessing energy efficiency improvement potential for these large motor systems will be based on the approach employed by McKane and Hasanbeigi with the scenarios further refined based on: 1) consultation with motor system experts 2) development of aforementioned energy efficiency checklists and 3) results from field execution of energy efficiency checklist. Estimates of the potential for energy efficiency improvement through the adoption of best available technologies, advanced/emerging technologies, and implementation of best practices for operations and maintenance will be based on the energy efficiency level of the facilities.

Methodology for completing Global Supply Chain Assessment

The Global Supply Chain Assessment (Task 2) will evaluate the market flows for motors and drives used, sold, and exported from the U.S., and also identify the factors impacting the supply chain for these products. This will include collection of readily available data to assess the current market and supply chains, as well as expected future trends. Another goal of this part of the study is to identify technology and research needs that could be met through joint industry and government partnership.

Data collection for this part of the project is anticipated to have three major areas of focus:

- Characterizing the export and import of motors and drives across U.S borders (e.g. country of origin, motor type, drive type, total shipped value);
- Characterizing the global supply chain for these motors and drives, - countries, industries, relationships – including the use, access, and sustainability of key materials and components, including rare earth materials,
- Identifying notable trends, such as the manufacturing characteristics of advanced motors and drives, emerging technologies, and the current state of research and development.

Beyond performing this market research, LBNL will convene experts to advise on advanced and emerging motors and drives that will impact the market, including expected future trends and preliminary estimates of their energy savings potential, and identify markets for these advanced and emerging motors and drives by application.

LBNL will also identify any factors impacting motor and drive manufacturing, including advanced technologies, materials, and components (e.g. wide band gap semiconductors for drives and soft magnetic materials for motors). Identification of any technology and research needs that could be met through joint industry and government partnership will also be included as part of this task. LBNL will also assess the impact of advanced motors and drives manufacturing on the U.S. economy.

Conclusion

This paper provides an overview of the USDOE initiated and LBNL led MSMA to: 1) develop 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 sector and 2) evaluate the global supply chain for advanced motor and drive technologies. The MSMA provides an update to the 2002 Assessment conducted by USDOE, which was similar in its objectives but smaller in scope. By basing the assessment on sampled field assessments, the MSMA will provide a much needed current and comprehensive assessment of motor system use in the U.S. The results will bridge a knowledge gap that has hampered policymakers, manufacturers, and researchers alike seeking to improve the energy efficiency of the installed motor system base in the U.S. industrial and commercial 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. Further, it is hoped that the MSMA will build upon the success of the 2002 Assessment by identifying several areas of potential improvement for U.S. motor systems and spurring the motor system community to research, develop, and deploy new technologies and practices to meet the challenges faced by motor system users today. It is hoped that the benefits derived from MSMA may serve as a motivating factor for other countries to initiate motor system assessments. Others seeking to conduct similar assessments may benefit from leveraging both the approach and the lessons learned from MSMA. The results from MSMA could be combined with the results of additional motor system assessments, allowing for greater knowledge sharing and benchmarking of motor systems energy efficiency and opportunities for improvement.

Acknowledgment

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Drives 3

An efficiency measurement campaign on belt drives

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Abstract

In this paper, the state of the art concerning belt drive energy efficiency is discussed. The paper also discusses the construction of a belt drive test rig. This test rig is used to define or confirm certain statements concerning belt drive efficiency. The test rig construction is briefly described together with the measurement procedure. Finally, the results of a measurement campaign with several comparative tests are presented. This is done by using iso-efficiency maps, which show the efficiency in the entire operation range. Both V-belts and synchronous belts are tested and compared. Furthermore, the test procedure is used to reveal the influence of the pulley diameter, use of a belt tensioner and maintenance parameters such as alignment, wear and belt tension. These tests were performed in a range of 3 – 15 kW nominal transmittable power.

Introduction

Due to forced regulations and social awareness over the last years, a lot of research has been done on energy efficiency. New concepts of electrical motors with high efficiency have entered the market. However, when the coupling between an electrical motor and driven load is considered, there is a lack of information on energy efficiency of these traditional transmission components such as belts and gearboxes. In comparison to electrical motors and drives, there is very few mandatory regulations on these components, especially when it comes to energy efficiency. Information on efficiency can be found in catalogues but the reliability of these numbers is often doubtful because there are no measurement standards for belts and gearboxes.

An industry related project, started in 2012, took a closer look at the efficiency of gearboxes and belt drives. This paper focusses on belt drives. A dedicated test bench was constructed to measure belt drive efficiency in nominal and partial load. A wide variety of belts were tested and the impact of mounting and maintenance on the efficiency was investigated. The results of this measurement campaign are discussed in the paper.

The first part of the paper describes the available knowledge and the blind spots regarding energy efficiency of belt drives. This clearly shows a need for more research and testing on this topic. In a following section, the belt drive test bench is briefly described together with the developed measurement procedure [1]. The aim is to spark the standardization of such tests.

In the second part of the paper, the results of the measurement campaign are discussed. Measurements were done in the entire working range of the belts and represented in iso efficiency maps. The tested belt length varies between 1500 and 2000 mm and the input power ranges from 3 to 15 kW depending on the number of belts. Different types of V-belts and synchronous belts are compared and discussed. The test results also show the impact of pulley size on energy efficiency for V-belts as well as the use of a belt tensioner on synchronous belts.

State of the art and blind spots

The energy efficiency of belt drives is typically assumed to be between 90 to 98%. These values are given by manufacturers in their catalogs and always stated as ‘up to’, indicating lower values can be expected. Since there is no regulation on how to measure the efficiency, it is unclear how and under which conditions the manufacturers are testing, nor is it known e.g. what belt length and pulley diameter is used or what effect partial load operation has on the efficiency of the belt drive.

The mechanism of power transmission and losses in a V-belt drive was studied in the past. The oldest theory is the creep theory, which is based on the idea of V-belts being elastic [2]. Due to new production techniques, V-belts are virtually inelastic. Firbank’s shear theory is based on this premise [3]. Recently, Gerbert postulated a new these, based again on the elasticity of V-belts [4].

Since there is no generally accepted theory on power transmission in a belt drives, it is hard to obtain reliable efficiency values from theoretical models. Furthermore, as no regulation exists on how to measure the energy efficiency, catalogue values cannot be compared nor trusted in all circumstances. The previous observations supported the decision to build a test bench and to define a measurement procedure.

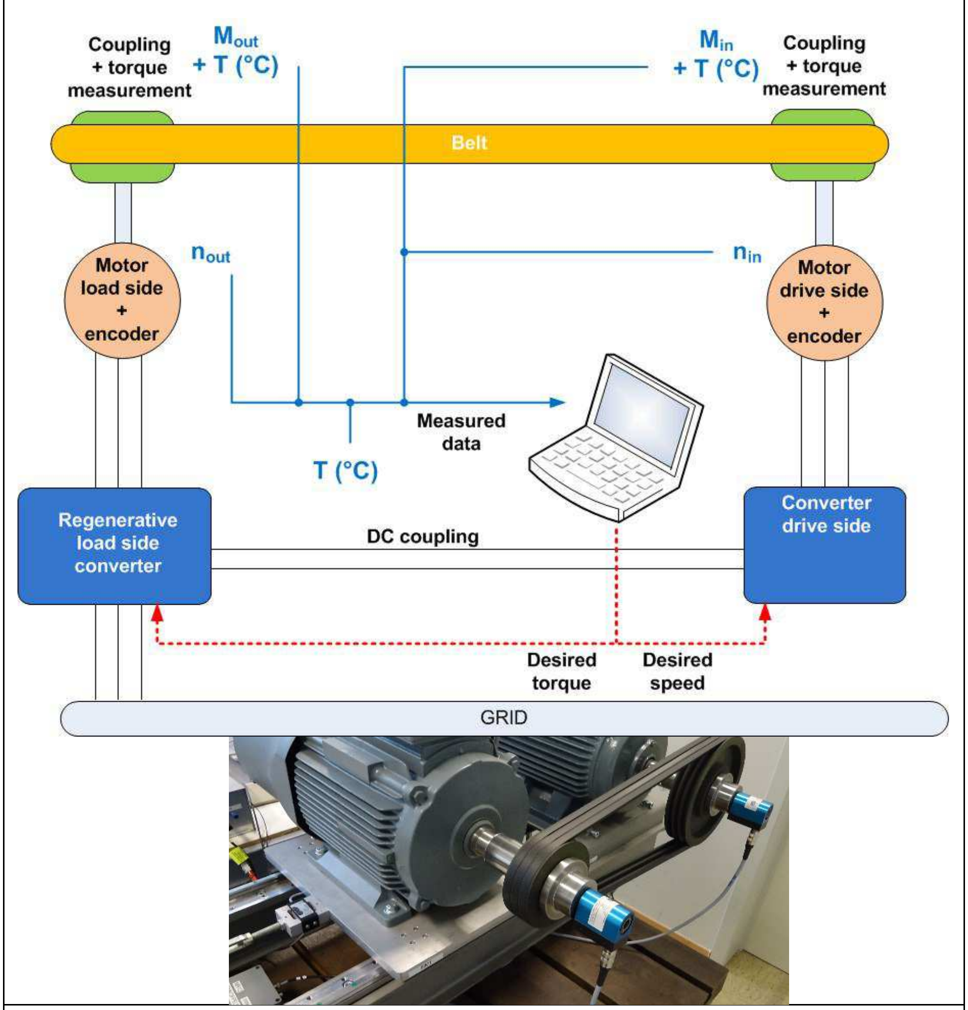


Figure 1: belt drive test rig (schematic view and actual test bench)

Belt drive test bench and measurement procedure

The test bench setup is based on comparing input and output mechanical power and speed and has been extensively discussed in [1]. The belt pulleys are mounted on dedicated 200 Nm torque sensors. The speed is captured by encoders on both 4p 15kW induction motors of which one is speed controlled (drive side) and the other is torque controlled (load side).

The measurement procedure is developed to guarantee reproducible and reliable results. First, two running in tests at constant speed and torque are performed to check for consistency between the results. When this is satisfactory, the efficiency is measured in 272 torque/speed measurement points for each belt test. This data grid makes it possible to create an accurate iso-efficiency map.

Measurement results

The set of belts tested and discussed in this paper was determined in close collaboration with the involved industrial partners and end-users in the related research project. V-belts (wedge SPA and moulded cogged XPA), poly V-belts and synchronous or timing belts (8M) with lengths varying between 1600 and 2000 mm were selected. Table 1 gives an overview of the tested products:

Table 1: range of tested belts during the project power

			State of the art on energy efficiency before the project	**Tested belts**
Design	Nominal efficiency		Partly known	SPA – XPA – poly V – 8M
	Partial efficiency		Unknown	SPA – XPA – poly V – 8M
	Number of belts		Unknown	SPA – XPA – 8M
	Pulley diameter		Partly known	SPA – XPA
	Belt tensioner		Partly known	8M
Lifetime	Mounting	Alignment	Unknown	XPA
	Maintenance	Belt tension	Unknown	SPA
		Wear	Unknown	XPA

Nominal efficiency

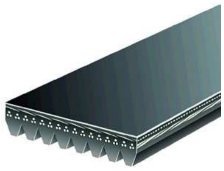
The first measurements focus on the nominal efficiency. This nominal efficiency can also be found in the manufacturers catalog. Comparing these values with the measured ones gives an idea of both the reliability of the manufacturers data and of our test setup (Table 2). It is clear that the given and measured efficiency values are very similar. The measured values are valid for belts with lengths between 1600 and 1800mm with a pulley size of 250mm.

Another conclusion is that the timing belt has the highest efficiency of all types. This is also confirmed by the measurement results shown in figure 3.

Part load efficiency with a single belt

A large number of belt drives is operated in variable speed systems. Knowledge of the efficiency of the belt in these part load conditions is crucial to determine the overall efficiency of the belt drive and of the system in which they are used. Iso efficiency maps provide this information for each steady state torque and speed combination in the operating range of the belt drive.

Table 2: nominal efficiency per type of belt (manufacturers data and measurements)

				
type	wedge belt (SP) or V-belt	cogged wedge belt (XP) or cogged V-belt	poly V- or ribbed belt	synchronous or timing belt
efficiency according to manufacturer	up to 97%	up to 97%	up to 96%	up to 98%
measured	up to 97%	up to 98%	up to 97%	up to 99%

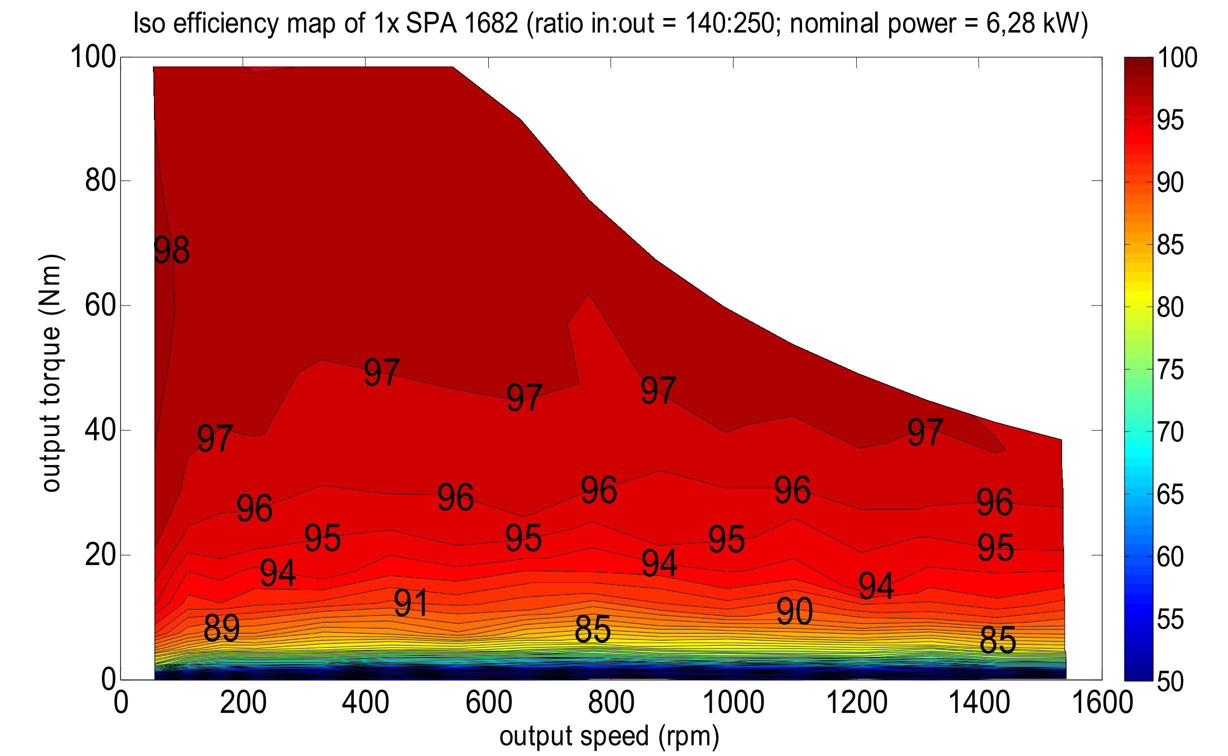


Figure 2: load profile plotted on an iso efficiency map

An example of a load profile plotted on an iso efficiency map is given in **Error! Reference source not found.**. The total belt drive efficiency can be calculated by multiplying the time and the respective efficiency.

$$\eta_{total\ load\ profile} = \frac{(1h * 97.5\% + 1.5h * 97\% * 0.5h * 95.5\% + 1h * 88\% + 0.2h * 95\%)}{(1h + 1.5h + 0.5h + 1h + 0.2h)} = 94.7\%$$

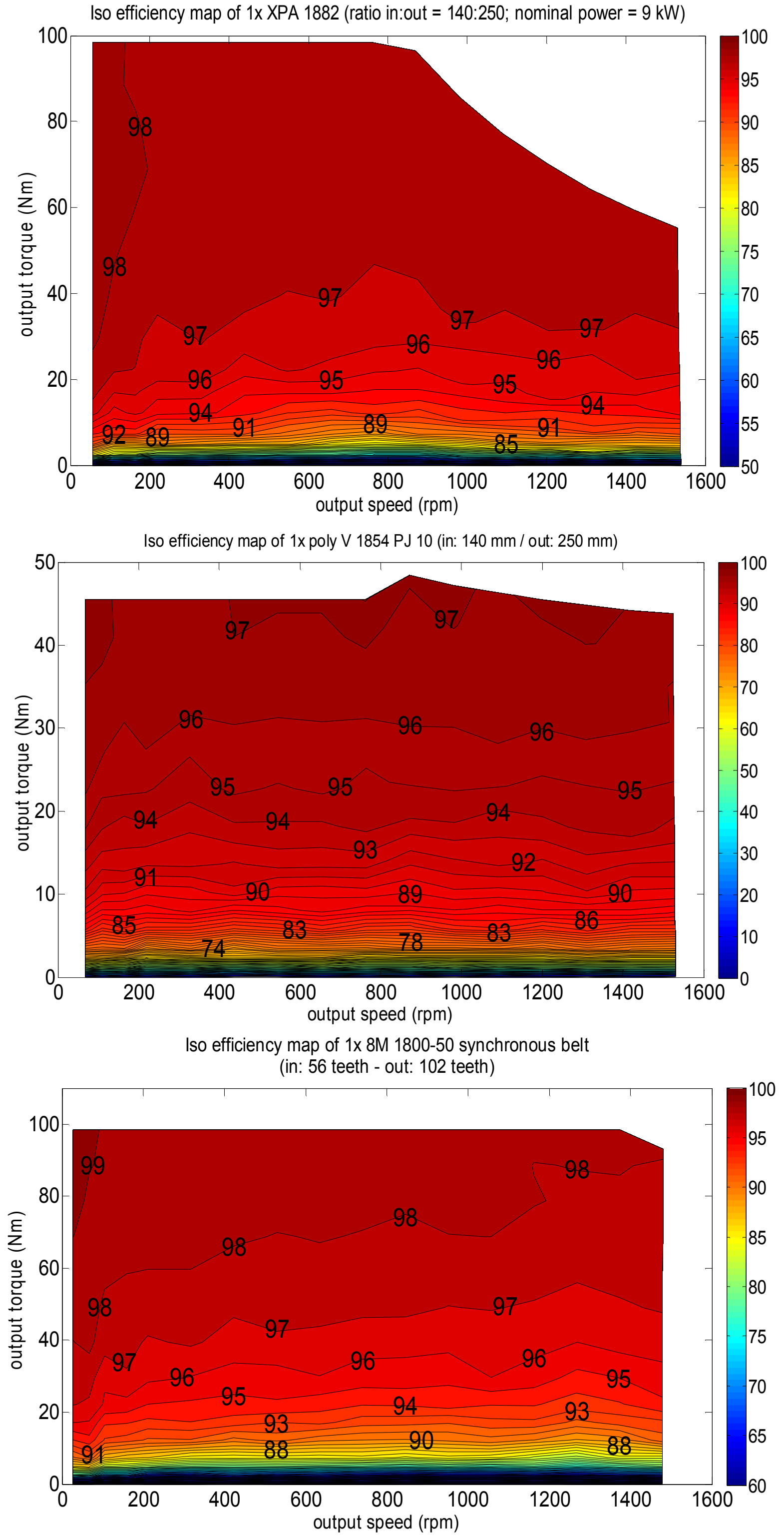


Figure 3: : iso efficiency map of XPA - poly V - timing belt (to show load dependency and highest efficiency)

Comparing the total load profile efficiency to the catalog value results in a difference of more than 2%. It is clear that the use of only the catalog value for belt efficiency is not sufficient for a good estimation of the total efficiency for a certain load profile.

From Figure 2 it follows that the efficiency is mostly torque (y-axis) dependent and the speed (x-axis) has little influence. Moreover, the efficiency for low speeds remains rather constant when the load torque varies. Measurements on other belt types lead to the conclusion that this observation is valid for all belt types (**Error! Reference source not found.**).

Number of belts

In industry, belt drives with a number of parallel belts are often used. They allow more power transmission and a more reliable and safe operation of the system, for example during a direct on line start of the system. Although for each belt, the efficiency remains relatively high at torques below half of the nominal value, one should take care to dimension the drivetrain correctly. A case study performed during the research project showed that an overdimensioned drive train with 3 paralleled belts could be ran without problems with only 1 belt. This resulted in an efficiency increase of 2%. In the original setup with 3 belts the belts were not fully loaded, from 97% to 95% (figure 4). Apart from the efficiency gain, the maintenance costs also reduce when reducing the number of belts. Only 1 belt needs to be replaced.

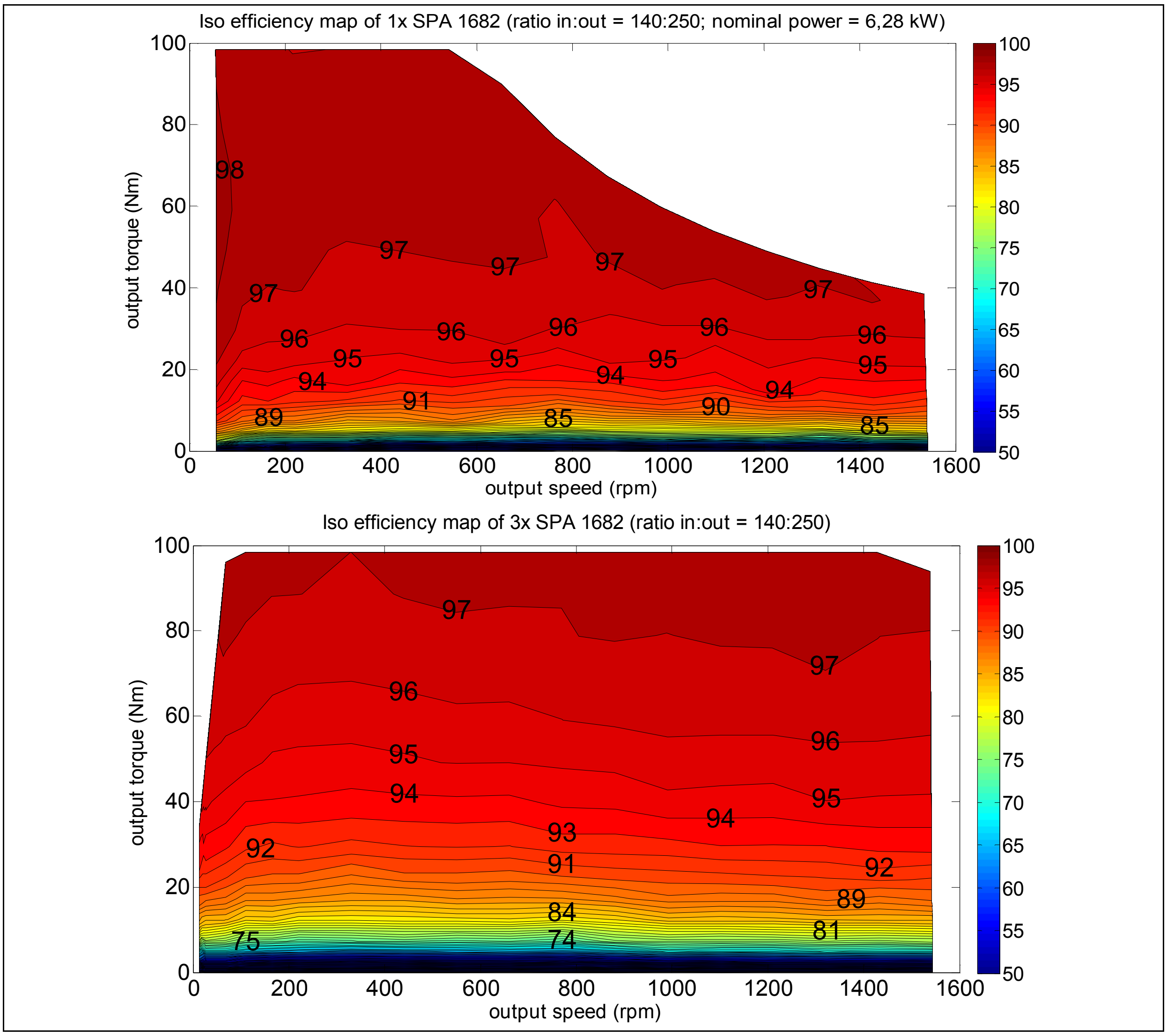


Figure 4: effect of too much belts on a drive train (from 97% to 95% efficiency), 4.A Single belt drive, 4.B Belt drive with 3 paralleled belts.

Pulley diameter

Another aspect important to designers is the pulley diameter. It is generally accepted that a larger diameter is better for efficiency as the belt bends less. On the other hand a trend towards smaller devices is visible in machine building.

A test setup with both SPA and XPA belts is created. A comparison is made between a drive train with two pulleys of 140 mm and another with two pulleys of 250 mm. The pulley ratio is 1:1 to exclude as many other influences as possible.

Table 3: effect of pulley diameter on efficiency

Pulley diameter (mm)	**140:140**	**250:250**
SPA	94%	96%
XPA	96%	98%

Error! Reference source not found. shows a significant 2% difference for both SPA and XPA belts. If space requirements are flexible, larger pulleys are to be preferred. The higher cost of the bigger pulley and the longer belt should be taken into account. When applied to a specific industrial case, the payback time to switch to larger pulleys was less than one year.

Belt tensioner

Belt tensioners are frequently used by manufacturers. It is obvious that an extra element will cause extra losses. From an economical point of view, it is good to have some actual numbers on this. Therefore a dedicated test setup was built for an 8M timing belt (**Error! Reference source not found.**).

The measurement was conducted at one specific speed and torque, as this was most relevant for the company involved. **Error! Reference source not found.** shows a reduction of the efficiency with 1% when the tensioner is used.

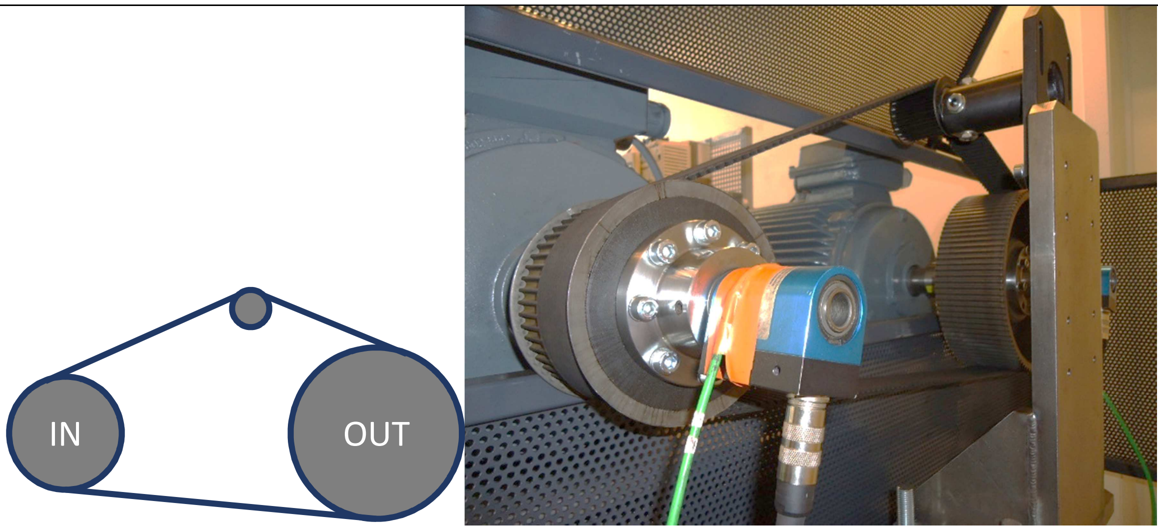


Figure 5: test setup with belt tensioner on a timing belt (8M)

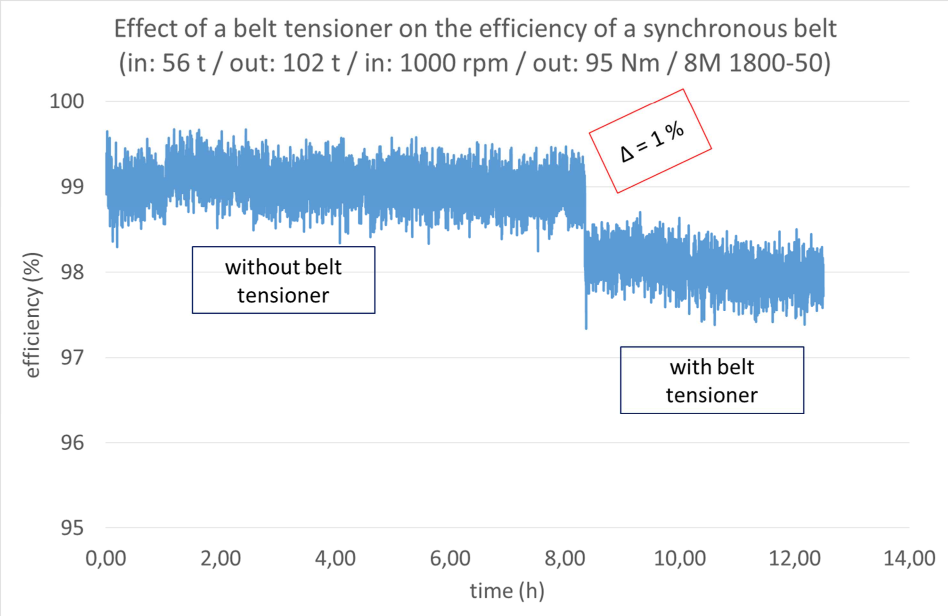


Figure 6: effect of a belt tensioner an a timing belt

Alignment

When the design of the belt drive is finished, it needs to be properly aligned and tensioned. Proper alignment and tensioning according to the manufacturers guidelines reduced the wear and tear. Here, the impact of misalignment on the efficiency is considered.

Misalignment may come in various forms, such as angular - or parallel error. Here the results are discussed for the latter error (**Error! Reference source not found.**) of 1 cm on a center distance of 60 cm.

It is expected that a XPA belt is harder to twist due to misalignment than a SPA belt. Therefore a test with a XPA belt is done. In **Error! Reference source not found.** there is no noticeable difference as depicted in the left and right part of Figure 8. Although misaligning does not have an impact on the efficiency, it should be avoided in order to limit the wear on the belt. Considering a timing belt, here a misalignment would lead to the belt running off the pulleys, comparable to a conveyor.

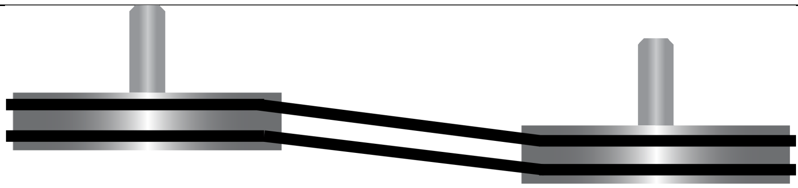


Figure 7: parallel error of belt drive pulleys

Belt tension

For good operation of a belt, it needs to be properly tensioned. Although tensioning testing tools are commercially available, many belts are tensioned based on experience without using this test equipment. The test bench used in this paper allows modifying the belt tensioning during operation.

The tension is measured before start-up and after shutdown with a frequency meter. A load cell allows to follow the evolution during the test. It is expected that a lower belt tension than prescribed causes slip and thus extra losses. Tensioning the belt too much will overload the bearings, but the effect on efficiency is less clear to estimate.

In **Error! Reference source not found.** a SPA belt was first tensioned correctly at 54 Hz. When reducing the tension to 38 Hz, speed went down by 5 rpm at the load side (the “machine side”). Raising the tension to 64 Hz did not notably change the speed or decrease slip.

The losses due to the increase of slip by 5 rpm are somewhere around 35 Watts on a 6 kW mechanical input power. For a fan application, the gain due to a lower speed will outnumber the loss due to slip. But from a production point of view, applying the correct tension makes the belt last longer and trouble-free. A higher tension has no advantages in terms of efficiency, as the speed does not increase.

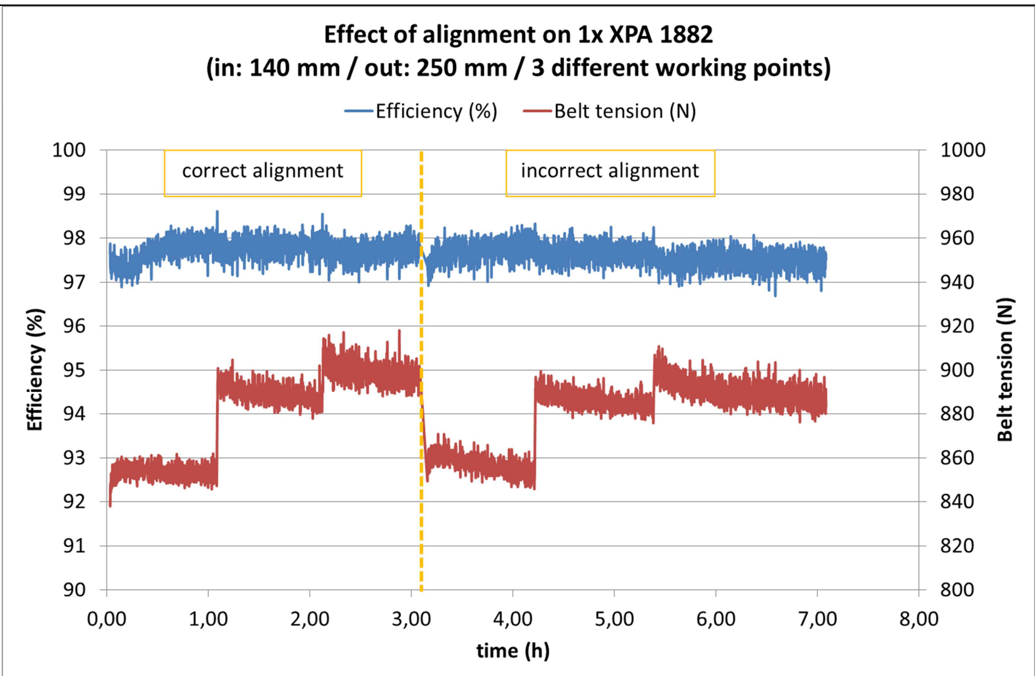


Figure 8: effect of alignment on the efficiency

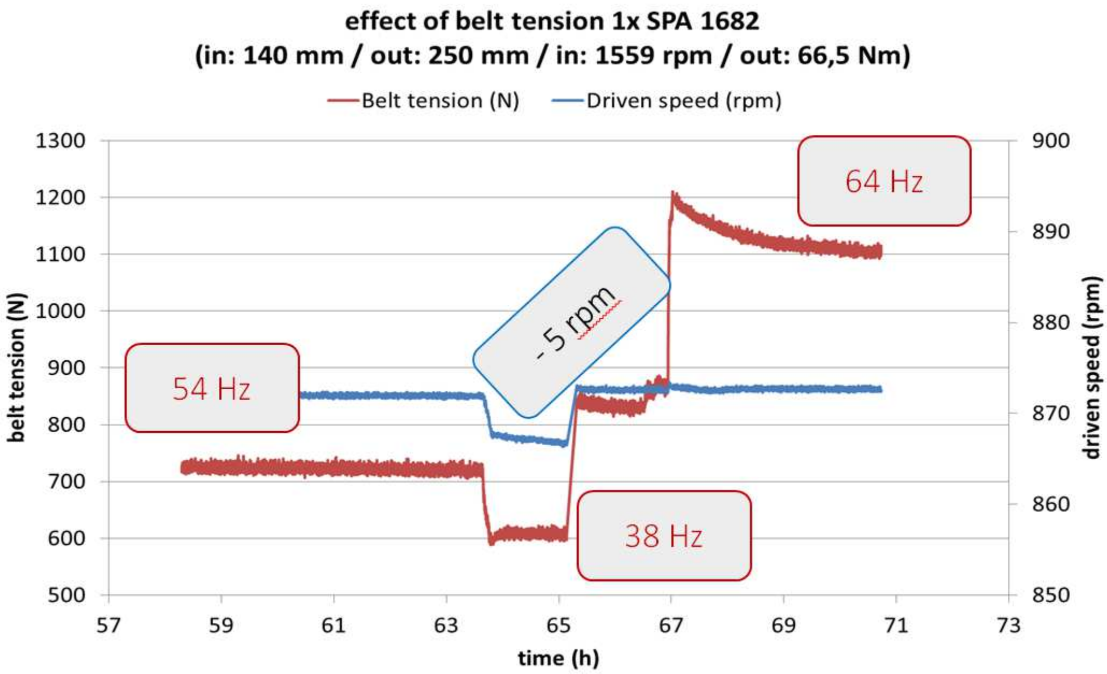
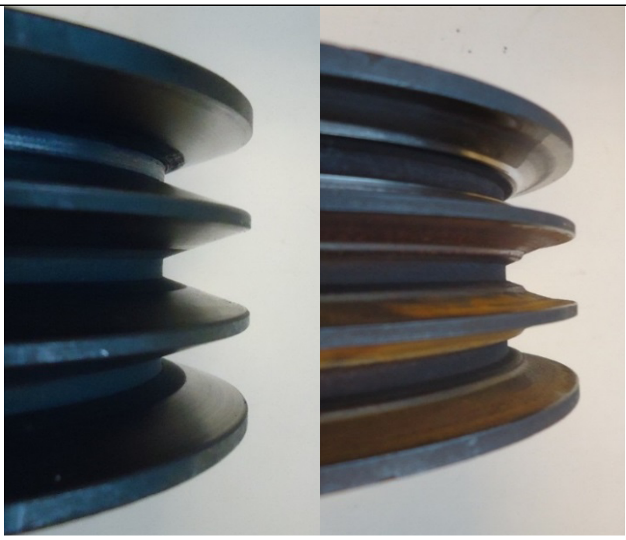


Figure 9: effect of belt tension on the efficiency

Wear

The belt drive suppliers involved in the project sometimes see worn pulleys (right in **Error! Reference source not found.**) on which new belts are mounted. A test was set up to analyze the effect on the efficiency. Within the first hour of the test with one XPA belt, the efficiency dropped 3%. Also, the belt showed already clear signs of wear (**Error! Reference source not found.**). This result shows that using worn pulleys with a set of new belts is not worth the savings of not buying new pulleys.



new pulley **worn pulley**

Figure 10: new vs. worn pulley

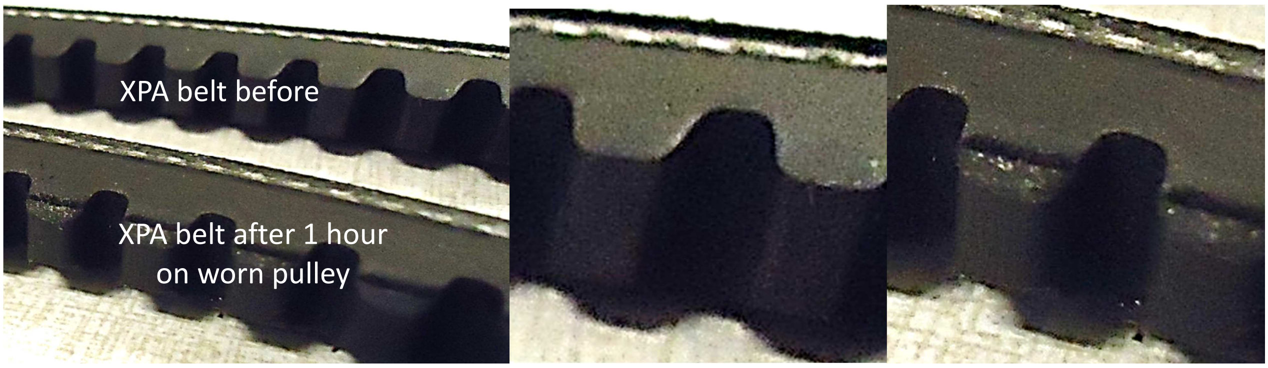


Figure 11: Effect of worn pulley on a new XPA belt (+ close-ups)

Conclusion

The paper discussed design, mounting and maintenance parameters and their relation to energy efficiency for belt drives.

When using asynchronous V-belts, the XP type is the most efficient. However, the timing belt is the most efficient of all belts. On the other hand, mounting a timing belt is notably more difficult as it does not allow misalignment. Furthermore, the theoretical lifetime of asynchronous belts is 25000 hours vs. 8000 hours for timing belts.

Iso efficiency maps give the possibility to plot a load profile and calculate the total efficiency of a VSD driven system. Adding extra belts for safety should only be done when necessary as efficiency drops when using an overdimensioned belt transmission. This also reduces maintenance costs. It is also shown that larger pulley diameters have a positive effect on the efficiency. Efficiency of a belt drive with a belt tensioner on the contrary dropped.

Aligning the belt is good for belt lifetime but the test campaign discussed in this paper shows no significant influences on the efficiency. However, the belt tension should be applied correctly to avoid slip or too high loads on the components. Belts should be retensioned from time to time, although there are maintenance-free belts on the market. Finally, worn pulleys should always be avoided.

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Integrated Sensor Bearing solutions for efficient eMotion Control

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Abstract

The permanent intention to gain higher power efficiency sheers the bearing to reduce weight and friction. On the other side, the ceaseless desire to achieve better motor performance drives the sensor to chase an improved performance. This article presents an optimized sensor bearing in terms of cost-to-performance for automotive hybrid and electric powertrains. A typical sensor bearing, as indicated by its name, consists of two parts, a bearing and a motor position and speed sensor. The former one, thanks to special designs, can achieve a considerable reduction on both weight and friction. The latter one, owing to accumulated expertise, is capable of offering compact and robustness sensing solution with an equivalent performance as its counterparts of the automotive market. This article will present a general description of the sensor bearing, including its utilization, lifetime and comparison with existing solution in the market. The specialty of the integrated bearing will be analyzed. The working principle of the sensor part and the ways to guarantee a good performance will be explained. The study on the relationship between the sensor and the motor efficiency will be illustrated. Finally, the incoming smart sensor bearing, which focuses on reducing automatically the motor speed and torque ripple, will be also presented in this article.

Introduction

Because of the increasing pollution, the intensifying energy crisis and the continuously developing electric motor and battery technique, electric and hybrid vehicles are attracting more attention and seizing more market these days. In EV (Electric Vehicle) and HEV (Hybrid Electric Vehicle) applications, the light weight and compactness are two critical requirements due to the bulky battery and the shortage of the cruise range. Besides, the complicated driving profile requires electric motor drive systems should have higher performance and more robustness. Both bearing and speed and position sensor are two essential parts in an electric drive system. The former one allows the relative movement between the motor rotor and stator (housing). The latter one feeds the rotor information back the controller, leading to high quality control. The latest developments on bearings and sensors (energy efficient bearing and integrated sensor bearings) bring a new product called sensor bearing, which mainly targets the automotive market. The most important character of this product is to unify the bearing and sensor as a final produce.

The structure of a sensor bearing is presented in Fig.1, which shows that a sensor bearing consists of five main parts, a bearing, an output cable, a magnetic ring attached to the inner ring of the bearing, a sensor body including the sensing components and a PCB and a cover. The latter four parts together contribute the sensor function of the sensor bearing. Thanks to this structure, the proposed sensor bearing shows an impressive compactness compared to other existing sensors, such as resolver, encoder and eddy current sensor. Meanwhile, this unique structure enables this product to offer friendly assembly procedures compared to others. More importantly, the performance of the developed sensor bearing is independent of the quality of assembly, which, inversely, is always a concern for other sensor technologies. In addition, with years of experience and knowledge on sensor development, the performance of the sensor bearing achieves the same level as its counterparts.

In order to provide a technical understanding of the sensor bearing, this paper is organized as followings. The second section reports the integrated bearing that is typically used for the electric motor drive system. This section highlights its attractive features such as low friction and lighting design. The third section first introduces the common working principle of a sensor bearing. Then, it explains the several technical efforts that guarantee a good performance. Besides, it shows an interesting study that reveals the relationship between the sensor performance and the motor efficiency, so then explains how harmonic content can be optimized to fit with permanent electric motor for automotive industry. Several simulation and experimental results are shown in this section as well. The third section shows one of advanced sensor bearing techniques, called smart sensor

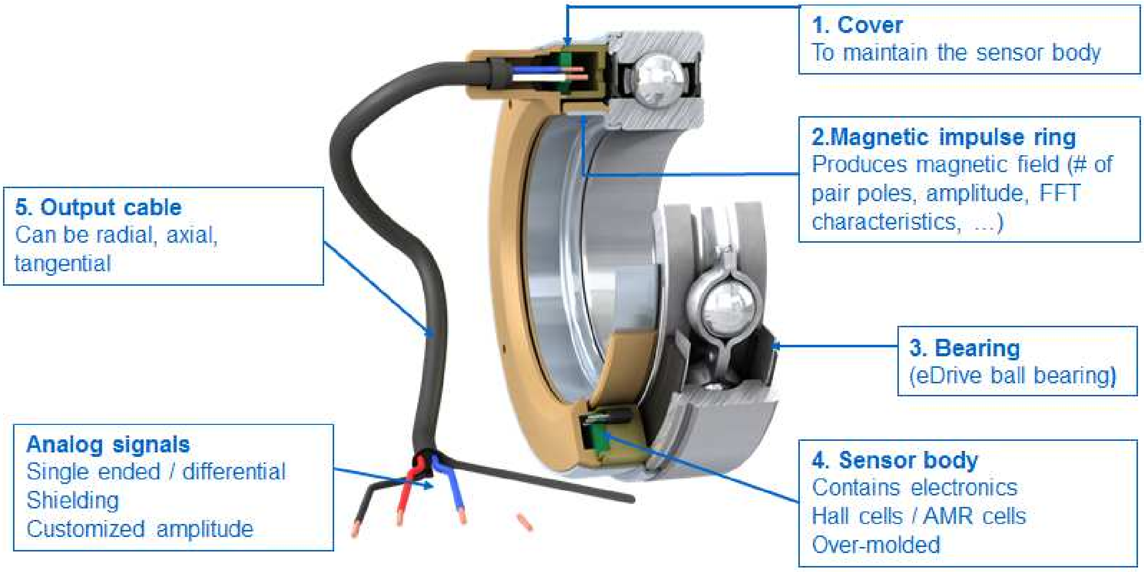


Figure.1 The structure of the proposed sensor bearing.

(1) cover, (2) magnetic impulse ring, (3) bearing (4) sensor body (5) output cable

bearing, targeting for an automatic reduction of the annoying electric torque ripples. A brief conclusion is given at the end of this paper.

The integrated bearing

Compared to the traditional applications, electric motors used in EV/HEV are designed to run at high speed ranges in order to guarantee efficiency. This means that bearing manufacturers must supply the designers of electric motors with bearings that can enable these higher rotational speeds while resisting the increased temperatures that these high speeds generate. Furthermore, they have to be robust in the entire life cycle of a vehicle without any significant loss of the performance.

Typically, the application requires a maximum operating rotational speed in the range of 10000-16000 rpm with sometimes higher speed peaks, for a rotor shaft diameter in the range of 35-60 mm. Usually, the speed ability of a bearing is expressed as the rotational speed (expressed as n in rpm) times the mean diameter of the bearing (expressed as Dm in mm), disregarding the influence of bearing size on the speed limit.

Catalogue open bearings have a typical speed limit about 600000 - 700000 nDm. With the above mentioned application conditions, the rotor bearings of an electric traction motor need to sustain a speed up to 1 million nDm. Besides, the bearing should meet both the low temperature requirement (down to -40°C) due to an utilisation of a vehicle in an extreme low ambient temperature and a high temperature requirement (up to 150°C) due to a high motor speed. In addition, minimum mechanical losses are allowed from the bearing, even at these high speeds, in order to optimize the overall energy consumption. This should however not degrade the bearing sealing efficiency.

Technical challenges for the integrated bearing

In order to achieve these targets, several of bearing parameters – listed below - needs to be optimized, and carefully selected with respect to each other:

- Cage design and cage material plays an important role in the bearing speed ability, as well as for the grease life and therefore bearing robustness. As an example, moving from standard steel cage to polymer led to an improvement of 12% of the grease life (test conditions: bearing inner dimension 60mm, shielded, C/P = 21, ~ 620000nDm, 150°C).

Figure.2 Design feature of the bearing

- The internal geometry, and more specifically the ball intimacy with the raceways, has a direct impact on the rolling resistance and therefore the power losses. Nearly 10% savings can be obtained by releasing slightly this intimacy.
- The choice of the grease is also the key and will impact the bearing life, the friction and the noise and vibration behaviour.
- The amount of grease has a proven impact on the bearing self-heating and on the bearing life. The best compromise needs to be found here.
- The sealing solution needs also to be carefully addressed: it has a strong impact on the power losses on one hand, on the grease retention (especially at high speed) and on dust exclusion on the other, but can also impact the bearing running accuracy and therefore noise and vibration behaviour.

Technical solution of the integrated bearing

The above technical challenges lead to an innovative bearing whose common structure is shown in Fig.2. The details of these using technical solutions are presented as followings:

- Polymer cage: distortions due to centrifugal forces at high speed are reduced. In addition, the special cage shape provides reservoirs for the grease and therefore improves bearing self-lubrication properties. Cage material is appropriate to high temperatures.
- Two wide temperature tolerating greases have been selected for this application, based on grease life calculations. Friction torque evaluations are enabling final recommendation.
- Optimum grease filling has been evaluated against grease life and bearing self-heating behaviour. Best compromise has been found.
- Bearing internal geometry is optimized to the best compromise between friction and load carrying capacity.
- Non-contacting seal, providing the best compromise between sealing efficiency and friction torque.

According to these new technical features, two eDrive bearings are developed and their difference with the regular bearing is presented in Tab.1.

Table 1: The components of a regular bearing and two eDrive bearings

Bearing type	Internal geometry	Cage	Sealing	Radial clearance	Grease type	Grease filling
6207 standard	Standard	Standard	same	same	Standard	Standard
Optimized V1	Polymer cage	Polymer cage			Grease 1	Optimized
Optimized V2					Grease 2	

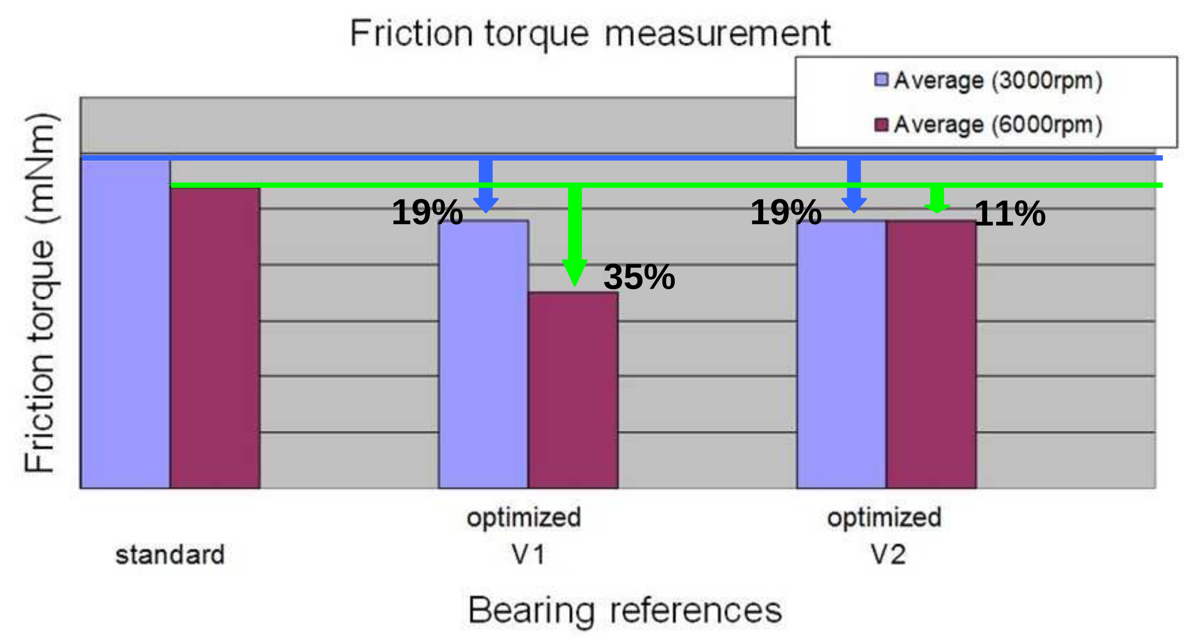


Figure.3 Torque friction test results

Performance of the integrated bearing

Several tests have been performed to verify the performance and the endurance of the special designed bearings.

The friction torque tests show that the eDrive bearing family brings the following benefits:

- Up to 35% friction torque reduction compared to standard design, along all application conditions. This statement is confirmed by the results presented in Fig.3.
- 30 to 40% speed ability improvement compared to standard design (from 600-700000 nDm to 1 million and above if using ceramic balls) thanks to the selected grease and the cage. This is an enabler for increased power density of electric motor.

The endurance tests with the conditions that the rotational speed up to 660000 nDm, the ambient temperature 120°C, the radial load 400N and the axial load 250N leads to a conclusion that the eDrive bearings have considerable longer life cycle than its regular counterpart. The tests results are shown in Fig.4, in which both optimized bearings obviously have longer life than the standard one.

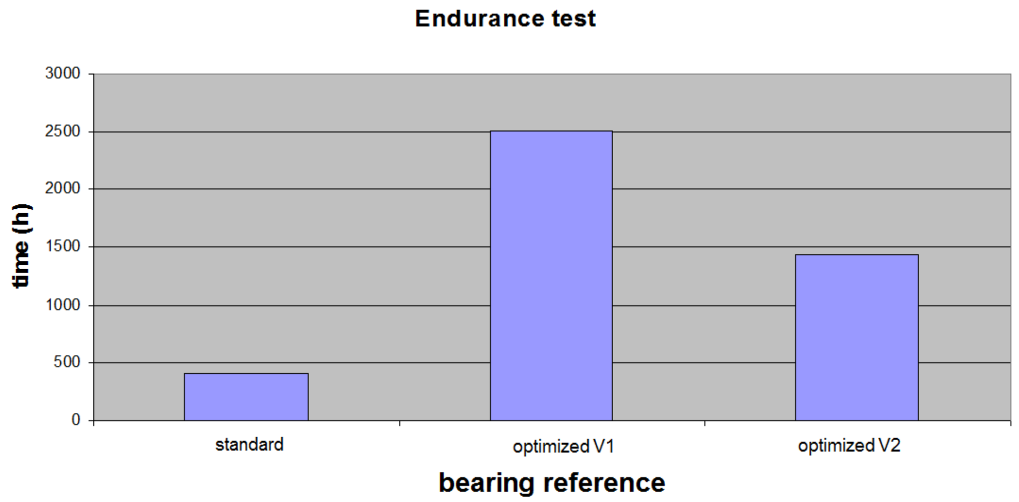


Figure.4 Endurance test results

The integrated sensor

General description of the integrated sensor

In order to get a clear overview of the integrated sensor, first of all, one needs to start from knowing its working principle as well as the functionality of each component. As shown in Fig.1, the position and speed sensor in a sensor bearing is composed of four main parts. The cover (1 in Fig.1) is used to provide the necessary protection as well as a physical connection between the sensor part and the bearing part. The magnetic rings (2 in Fig.1) used in a sensor bearing having one or more pairs of pole is strictly attached to the rotor (shaft) of the electric motor via a metal inner ring (the thin gray part along around the magnetic ring shown in Fig.1). The sensor body (4 in Fig.1) is mounted with the sensing components to transfer the captured magnetic field into a varying voltage and a few analogue electrical circuits that perform interpolation or other functions.

When the motor rotor (shaft) is rotating, the attached magnetic ring rotates with the rotor, generating a varying sinusoidal magnetic field. According to different ring configurations, one mechanical rotation could produce one or several periods of sinusoidal field. The sensing component (one or more, Hall effect ones or AMRs, GMRs) captures this varying magnetic field and outputs corresponding sinusoidal signals. Then the integrated electrical circuit treats these signals with reconstitution and interpolation. Finally, this position sensor outputs a sine and a cosine separately. The output cable could connect the customer using micro-controllers via two ADC connectors, which are naturally available in these controllers.

A brief comparison has been made to highlight the features of this sensor compared to the existing player in this market. In this table, Hall sensors due to their performance robustness and optical encoders due to their mechanical fragility are rarely chosen in the automotive industry. The MR sensor is limited by its mono output signal type: quadrature A/B incremental ones, which is not compatible with the popularly used permanent magnetic synchronous motors. Eddy current sensors and resolvers are two solutions that usually used in the EV/HEV application. However, thanks to the unification of the bearing and sensor together, the sensor bearing enjoys an unchallengeable advantage on the compactness. The signals generated by resolver and eddy current signal are two modulated ones. Hence, an integrated circuit responsible for the signal demodulation is obligated for them. For resolvers, this integrated circuit called resolver-to-digital converter is an extra digital chip and for eddy current sensors, this circuit is integrated into the PCB of the sensor. This converter and supplementary circuit will finally increase the cost and complexity of these solutions. Furthermore, as mentioned above, the frequent assembly faults deteriorate the performance of both resolvers and eddy current sensors, but not for integrated sensors. All above analysis contributes a conclusion that the sensor bearing, owing to utilization simplicity and mechanical compactness, is undoubtedly interesting solution for EV/HEV.

Table 2: Comparison amongst various sensors

	Sensor bearing	Resolver	MR sensor	Eddy current sensor	Hall effect sensor	Optical encoder
Accuracy	Middle	Middle	Middle	Middle	Low	High
Resolution	customized	12bit	12 bit	customize d	12 bit	14 bit
Assembly robustness	High	Low	Middle	Middle	Middle	Low
Output signal	Analogue sin&cos; Incremental A&B	Analogue modulated sin&cos; Increment al A&B	Increment al A&B	Analogue sin&cos	Incremen tal A&B	Incremental A&B
Performance robustness	High	Middle	Low	High	Low	Middle
Compactness	High	Middle	Middle	Middle	Middle	Low
Reliability	High	High	Middle	Middle	Low	Low

Design methodology of the sensor

Although the proposed sensor bearing holds inherited advantages compared to its analogues, still lots of studies have been accomplished and many cutting-edge technologies have been adopted so as to ameliorate its performance, robustness and endurance. Several used technologies and accomplished studies will be presented in this sub-section.

The harmonic of the sensor output is the principle factor that limits the sensor accuracy. According to a systematic investigation, these harmonic components come mainly from the imperfection of the sensing components and the magnetic ring, the tolerance of the mechanical parts and the exterior magnetic field disturbance. To reduce them, following solutions have been taken.

- Special combination of the sensing components (including the placement and the number). Since the variation of this sensor placement and number can largely change the landscape of the harmonics components and perform different behaviors to exterior magnetic disturbance, a special combination can deliberately reduce several harmonic components and diminish the influence of this disturbance.

- The tolerance of each mechanical part has different influences on the sensor configuration so as on the harmonic components. An optimum trade-off between different mechanical tolerances is commonly made to achieve an expected harmonic reduction without bringing extra manufacturing difficulties. Several internal design tools (simulation tools based on the expertise, the measurement and mathematic equations) are developed to simplify the design procedures and enhance the performance anticipation capability.

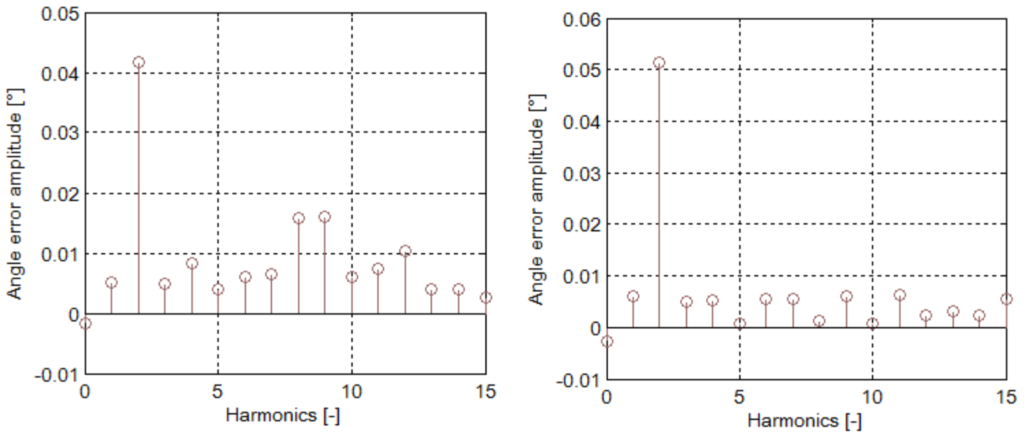


Figure.5 Frequency spectrum of the angle error

Left one is a regular configuration and right one is an optimized one

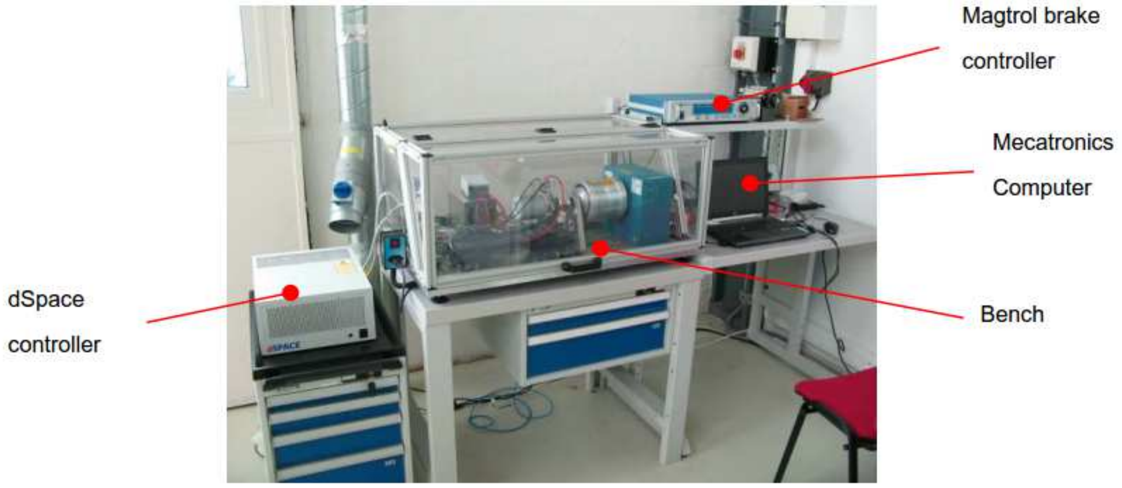


Figure.6 The overview of the 1kw multi-motor test bench

- The integrated electric circuit is also able to shape to the output signal. Clearly trimmed electric circuits are used in sensor bearing to compensate several harmonic components.

With all above design considerations, the integrated sensor can successfully reduce the harmonic components, then leading to a better accuracy. A comparison between the use of regular cell configuration and optimized one is shown in Fig.5. This figure shows that the optimized cell configuration is able to reduce the harmonic 8^{th} and 9^{th}, producing a more accurate output.

To obtain an insight of the utilization of the sensor, two electric motor test benches are established within our development center. The first one is a 1kW motor test bench that supports the PMSMs, BLDCs, Induction Motor (IMs) and Switch Reluctance Motors (SRMs). The overview of this test bench is shown in Fig.6. The other one shown in Fig.7 is a 30kW traction motor test bench. The installed motor is the same motor used for the Nissan Leaf (EV).

With the test bench, an interesting study aiming at revealing the relationship between the sensor performance and the motor efficiency has been accomplished. In this study, the common harmonic component and time-delay of an integrated sensor is intentionally added into the control loop in order to evaluate their influences on the motor power efficiency and the resultant torque ripple.

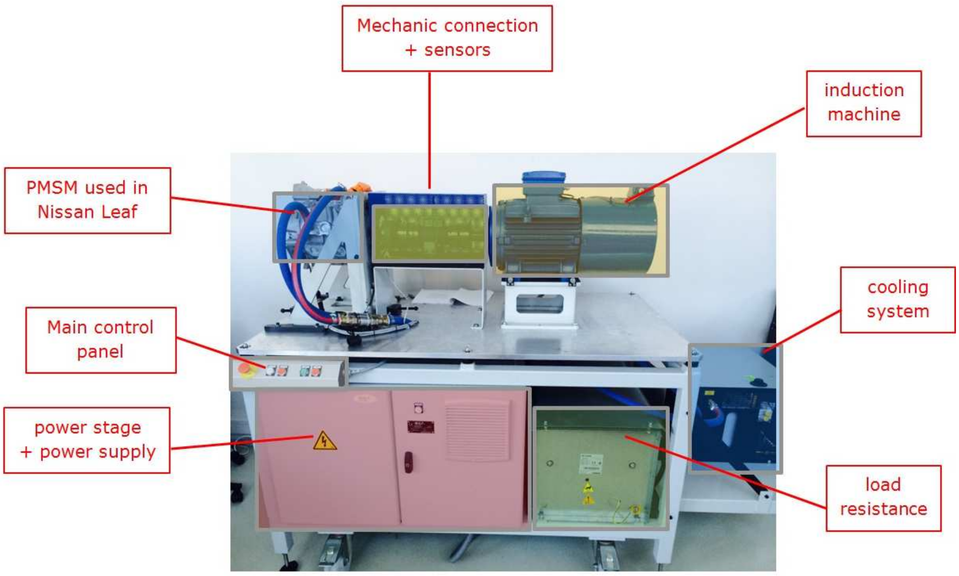


Figure.7 The overview of the 30kw traction motor test bench

One piece of knowledge obtained from this study is depicted in Fig. 8 as an example to briefly reflect the portrait of this study. This figure shows with intentionally added harmonic components and sensor delay, how motor efficiency changes due to the variation of the torque (y-axis) and the speed (x-axis). These harmonic and delays obtained from the profile of measured sensor bearings are added inside the controller so as to simulate the behavior of a real sensor bearing that usually outputs signals with certain harmonics and delays. In this figure, the red color represents higher efficiency and the green one represents lower efficiency. With considerable times of the mapping, we weaved the entire knowledge between the sensor performance (weight of harmonics and delay) and the motor efficiency. As a result, this study enables us to be capable of offering the customer a guideline about how to choose a suitable sensor directly according to their expected machine efficiency so to avoid over-engineering.

Two established electric motors test benches also allows the test of new idea about advanced sensor technologies. More details will be unfolded in the next section.

Smart sensor bearing

PMSMs are appealing candidates for many high performance applications in the automotive industry, because of their attractive characteristic, such as high torque density, high efficiency and high reliability. However, inherent torque ripples of PMSM are considered as a serious problem in many industrial applications, particularly in the low speed and high torque situation. These torque ripples usually lead to a degradation of PMSM drive system performance and may bring vibrations and noise, which strongly influence the vehicle comfortability. Hence, PMSM torque ripple reduction is a valuable and popular topic in both the automobile industry and the academic research.

Currently two kinds of methods are used to reduce the torque ripple [1]. The first one focuses on the machine itself, optimizing the machine structure. However, special designs increase the complexity of the machine, hence it is a kind of fixed and expensive method. The other one is based on the use of advanced control methods. Since the controller is a necessary part of the PMSM drive system, this kind of solution does not add any extra cost for torque ripple reduction. Moreover, active control algorithms can be easily matched to any kind of machine.

Since the torque ripple reduction can be considered as a kind of periodic disturbance rejection problem, the ILC (iterative learning control) technique, as an iterative control method, naturally fits this goal, as already reported in [2], [3], [4], [5]. As other advanced control methods, the ILC technique is usually implemented inside the controller also, which means that in the automobile industry, to reduce the torque ripple by the ILC technique, engineers have to redesign the system controller. Indeed,

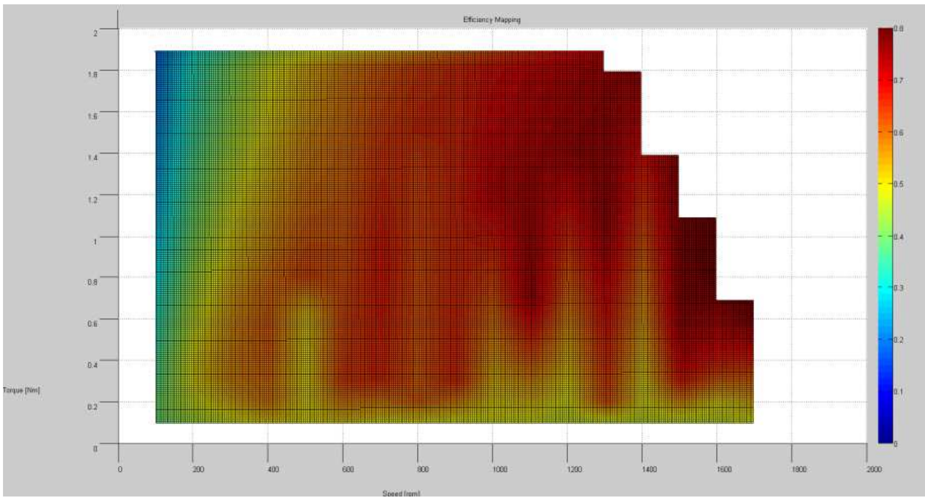


Figure.8 Motor efficiency mapping

sensor, as a fundamental part of the PMSM drive system, can take place of controller for embedding the ILC technique. The sensor bearing integrated the ILC technique to alleviate the motor torque ripple problem is called smart sensor bearing.

Torque ripples overview

Several kinds of parasitic torque ripples [4] such as cogging torque, harmonic torque, offset torque and mechanical bias torque exist in PMSM. In many commercially available machines, cogging torque has a nominal value of 5%-10% of the rated torque [6], therefore it is the main target of the torque ripple reduction. On the other hand, compared to other torque ripples, the harmonic torque is relatively more important. Their nature and model are briefly presented in this section.

Cogging Torque

Cogging torque [6] manifests itself by the tendency of the rotor to align in a number of stable positions, even when the machine is unexcited. It is caused by the interaction between the magnet flux and the stator slots [7]. An approximation expression of T_{cog} is

$$T_{cog}(\theta_m) = K_1 \sin(n_1 z \theta_m) + K_2 \sin(n_3 z \theta_m) + K_3 \sin(n_3 z \theta_m)\cdots \quad (1)$$

Where z is the stator slot number and n_i is the number which can make nz/n_p an integer, K_i is the coefficient which is determined by the machine structure. Eq. 1 indicates that cogging torque is a function of the mechanical angular position.

Harmonic Torque

Harmonic torque is caused by the interaction between the stator current and the rotor magnetic field and its mathematic equation is [8],

$$T_e = T_0 + (T_6 + T_{12} + \ldots) = \frac{3}{2} n_p i_q \Psi_0 + \frac{3}{2} n_p i_q (\Psi_6 \cos(\theta_e) + \Psi_{12} \cos(\theta_e)\ldots) \quad (2)$$

This equation shows that the electric torque can be separated into two parts: one is the product of the flux fundamental component and current, the other one is the product of the flux harmonic components and current, which is called harmonic torque and depends on the electrical angle. Since $\theta_e = n_p \theta_m$, the harmonic torque can also be considered as a function of the mechanical angle. According to this, the cogging torque, the harmonic torque and their sum are all functions of the mechanical angle.

ILC Technique introduction

Iterative Learning Control (ILC) is based on the notion that the performance of a system that executes the same task several times can be improved by learning from the previous executions (trials, iterations, passes). Compared to other kinds of active control methods, it has the following advantages: it changes the control signal, which means that it does not need to change the structure of the previous control system, and it is not sensitive to the parameter variation of the controlled object. In fact, a successful implementation of ILC can even be done without knowing the model of the controlled process.

A widely used ILC learning algorithm is

$$u_i[k+1] = Q(q)u_{i-1}[k] + L(q)e_{i-1}[k+1] \tag{3}$$

where the LTI dynamic Q(q) and L(q) are called the Q-filter and learning function respectively, u is the output signal of the ILC algorithm and the $e_i = y^{ref} - y^m$ is the control error y^{ref} is the reference input and y^m the measured output.

As an iterative method, ILC has a good performance when tracking a periodic reference or rejecting a repetitive disturbance. A PMSM with periodic torque ripple could be regarded as a process with a periodic disturbance. Therefore, it is reasonable to choose ILC for achieving torque ripple reduction.

Smart Sensor Bearing Working Principle

According to the basic PMSM control knowledge, we know that when the sensor is able to provide the true speed information to the controller, the controlling signal based on this correct information makes the PMSM generate a torque with unwanted ripples. Since the speed-loop controls current though a PI controller, the feedback speed information can affect the current signal which is the usual controlled object for torque ripple minimization. Therefore, in order to decrease the torque ripple, we can modify the speed information. Since the sensor is responsible for providing the speed and position information, the active control method which is used to control the speed information can be accomplished in the sensor. It means that the sensor will provide a modified speed signal which contains not only the true information but also the additional information which is calculated by the active control method and is used to minimize the torque ripple. In this paper, such torque ripple reduction strategy is called smart sensor technique. Consider the proposed sensor bearing, where sensor is integrated in the bearing of PMSM, therefore, the smart sensor can enable the bearing be capable of reducing torque ripples.

ILC technique, as analyzed above, is chosen to take the task of the torque ripple reduction. Fig.9 shows a scheme of a PMSM drive system using a smart sensor basing with the ILC technique. In this case, ILC algorithm is embedded inside the sensor, its input is speed error e which is provided by a high-pass filter and its output w^l is calculated by Eq.9. Finally, a new feedback speed information ω^c which can reduce the PMSM torque ripple is obtained by $\omega^m + \omega^l$. Note that there is no any modification of the conventional PMSM drive system. Therefore this technique may be used to improve a previously designed controller thanks to a replacement of the position sensor. The advantage of this technique is that it can decrease the complexity of the torque ripple reduction application for the PMSM drive system designer. Since the torque ripple reduction algorithm is integrated in the sensor bearing, the previously designed PMSM control system does not need to be modified.

Simulation and Experiment

Firstly, Matlab/Simulink as a simulation platform is used to verify the effectiveness of the proposed approach. To testify the method practical performance, the multi-motor test bench with a PMSM used for Megena EPS system will be used.

Both the simulation speed and torque results are shown in Fig. 10, which shows after using of the ILC at 1s, the amplitude of speed peak-to-peak decreases from 0.43 rpm to 0.05 rpm and the amplitude of torque peak-to-peak decreases from 7.52 N.m to 1.9 N.m. Therefore in the simulation, this smart sensor is capable of eliminating 89% speed ripples and 75% torque ripple.

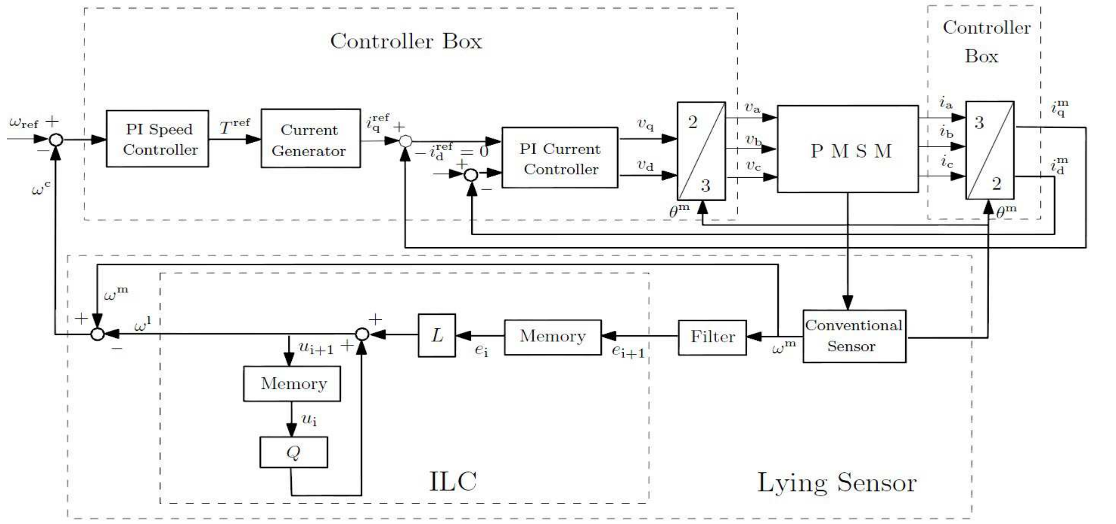
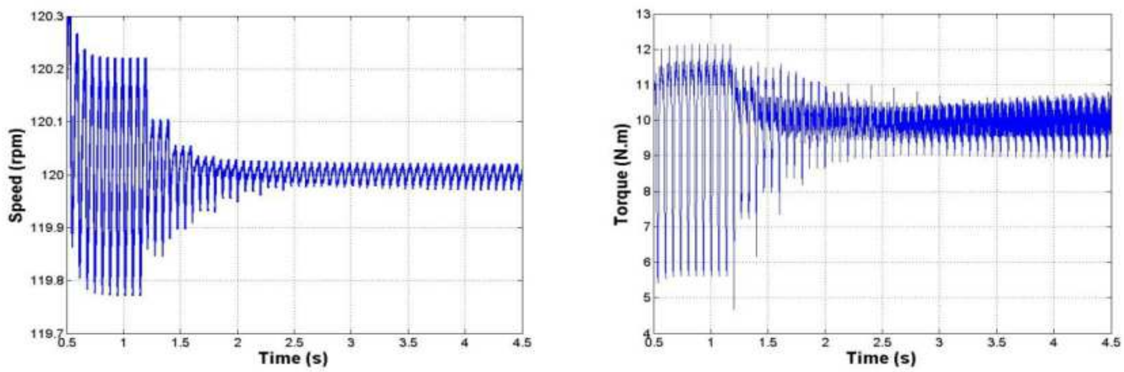


Figure.9 The PMSM drive system with the smart sensor scheme



(a) Speed result (b) Torque result

Figure.10 The simulation results

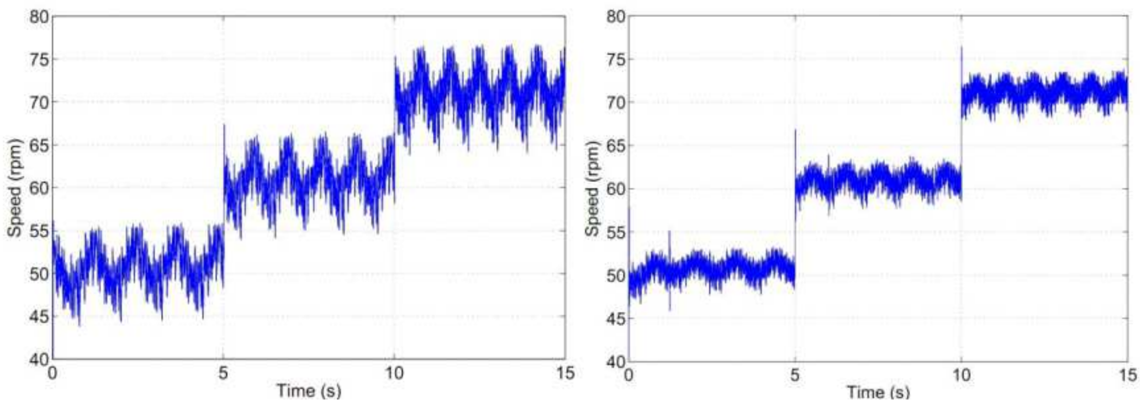


Figure.11 The experimental results

An experiment with three different speeds 50 rpm, 60 rpm and 70 rpm was realized in our experimental bench. Its results are shown in Fig. 11, where two figures show the speed ripple situations without and with the smart sensor respectively. The speed peak-to-peak without the ILC is around 12.2 rpm, and the speed peak-to-peak with the ILC is nearly 5.5 rpm, therefore 55% speed ripple was reduced by the smart sensor. Meanwhile, we notice that the smart sensor can keep its efficiency in various speeds.

Therefore, both the simulations and experimental measurements have shown an encouraging efficiency of this smart sensor bearing. There is no denying that the arrival of this new technology can alleviate the burden of the automobile engineer who needs to handle the PMSM torque ripple reduction problem and its realization can accelerate the project progress, winning time and profit.

Conclusion

This paper provides an overview of the new proposed sensor bearing that consists of an optimum bearing and a competitive sensor. The analysis shows that the special design bearing can effectively reduce its weight and friction, as well as prolong its life cycle. Meanwhile, the paper illustrates that the sensor enjoys inherent advantage on the compactness and simplicity with an equivalent performance as its competitors. In a word, the proposed sensor bearing is already a suitable solution for the EV/HEV applications. In addition, the presentation of the smart sensor bearing clearly shows how sensor bearing evolves with regard to customer needs. It should be admitted that though the sensor bearing technique enjoys numerous advantages compared with other solutions, there is still space for its improvement, for instance better high temperature (over 180 ºC) resistance and better robustness at high speed (over 30000 rpm).

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Improve the efficiency in AC-Drives: New semiconductor solutions and their challenges

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Abstract

New standards and requirements for energy efficiency and power loss measurements for variable speed drives are presented. The power losses of typical variable speed drives with rated power of 22 kW are analyzed and future alternatives to increase the drives efficiency are investigated. Solutions with Silicon (Si) in 3-Level or Silicon/Silicon Carbide (SiC) as well as full SiC systems in 2-Level topology are introduced in order to increase the achievable inverter efficiency. The impact and performance of motor drives systems using SiC are discussed based on the limits of the motors and installations. An innovative motor drive with SiC devices and integrated LC filter is discussed as a future possibility.

1. Introduction

Projects related to motor drive systems are generally focused on the cost/performance ratio. In the performance, not only aspects such as speed/torque control precision and dynamics are relevant; also the energy efficiency is considered and receives increasing importance.
In the majority of motor drive system applications, the biggest energy saving originates from the adjustment of the motor speed and torque to the optimal values for the process. This use of a variable speed drive (VSD) for saving energy according to system demands is considered an established concept.

Similar to the regulations for industrial motors based on the Eco-Design Directive [1] [2], efficiency classes for general purpose drives (GPD) are introduced in the EN 50598-2. The motor drive companies will have to focus on increasing the efficiency of their products accordingly. The study [22] concluded that the biggest contribution of the power losses comes from the semiconductor. To improve this part of the system, the use of modern and more efficient power switches, more efficient pulse width modulation (PWM) techniques and/or more complex power circuit topologies will be necessary.

Besides the cost constraints, the dominant challenge for the application of more efficient motor drives system is the system reliability. Issues such as motor insulation and motor ball bearing's lifetime become an increasing challenge for modern power electronic components. The new version of the IEC TS 60034-25 launched in 2014 classified the motor insulation system. This system is directly affected from the electrical behavior of the inverter semiconductor.

More details about the EN 50598-2 and the IEC TS 60034-25 are presented and the impact on drives systems is discussed. Based on that information, two types of VSD are analyzed, including general purpose drives (GPD) used in industrial designs and high-speed motor applications. These two motor drive applications present different requirements towards the power semiconductors. The power loss distribution of both is shown and possible scenarios are discussed based on todays and future power devices along with differences in topologies. The impact of new components and technologies is analyzed.

2. Applicable Standards and Requirements

In motor drive systems two technical aspects are in close relation and reinforced by standards: (1) The energy efficiency of the drives system within the EN 50598-2, and (2) the motor insulation and bearing described in the IEC 60034-25.

2.1 Energy efficiency and the EN 50598-2:

For a GPD the regulations of the Ecodesign Directive in Europe adopts the requirements of the EN 50598-2 standard [21]. This standard defines the efficiency classes for motor systems. The concepts introduced are:

The **Complete Drive Module (CDM) is** consisting of the VSD and the other components installed at the mains supply side, such as line inductors and EMC filters. At the motor side, output inductors, du/dt filters and motor cables are considered.

The definition of **Power Drive system (PDS) is** the combination of the CDM and the driven motor.
The EN 50598-2 defines the different efficiency classes to be used for a CDM. Regarding losses, a reference CDM (RCDM) is considered. These losses are taken at the operation point 90% of rated output frequency and 100% torque-producing current, the result classified as IE1. To achieve the higher efficiency class IE2, the CDM needs to have 25% lower losses compared to the RCDM IE1.

If the losses increase to more than 125% of the reference value, the CDM is said to have IE0. Figure 1 illustrates this explanation.

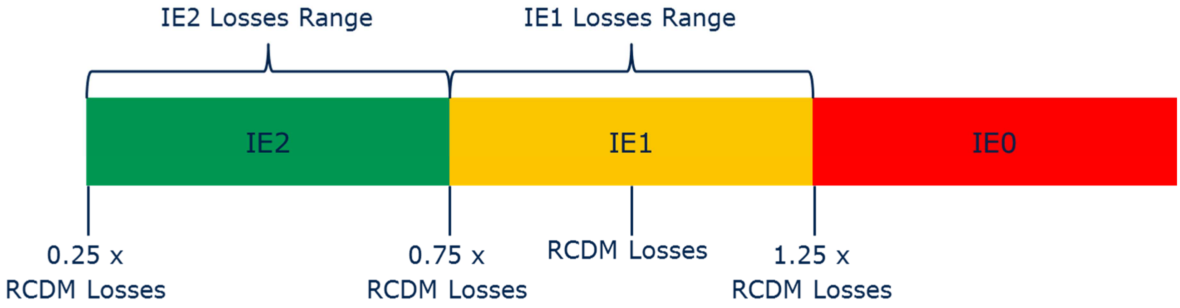


Figure 1: Efficiency classification for the CDM based on its energy losses according to the EN 50598-2

For a 22kW inverter, the RDCM-losses described in the EN 50598-2 at 90% of the rated motor frequency and rated torque sum up to 1500W. To achieve an IE2 classification, the inverter losses have to be below 0.75 times 1500W, resulting in 1125W. To meet a possible IE3 classification, the VSD has to generate losses below 375W. In this case is the IE2 window between inverter losses of 375W and 1125W.

It is important to know that the manufacturer of the VSD must specify the losses at eight different operating points. Every point has different combinations of motor frequency and torque. An overview about all working conditions is given in Table 1.

Table 1: Operation points where the CDM losses need to be specified by the manufacturer. f_{NOM} = nominal motor frequency. T_{NOM} = Nominal motor torque.

Motor Frequency (Hz)	Motor Torque (or the equivalent torque producing current)	Notes
$0.9 \times f_{NOM}$	T_{NOM}	Reference point for the IE classification of the CDM
$0.9 \times f_{NOM}$	$0.5 \times T_{NOM}$	
$0.5 \times f_{NOM}$	T_{NOM}	
$0.5 \times f_{NOM}$	$0.5 \times T_{NOM}$	
$0.5 \times f_{NOM}$	$0.25 \times T_{NOM}$	
0	T_{NOM}	When testing a deviation of up to 5% of the rated frequency shall be allowed: $f \leq 0.05 \times f_{NOM}$ accounting for the rated motor slip
0	$0.5 \times T_{NOM}$	
0	$0.25 \times T_{NOM}$	

The IE1 level is expected as a future requirement for AC-Drives in Europe.

The strategy in North America is to first establish the efficiency test methodology and conditions and later specify energy efficiency requirements for the VSDs.

The CSA C838-13 standard [3] published in 2013, defines a methodology for measuring the efficiency of VSDs and motors up to 750V AC. This methodology is based on the output/input power measurement at different speed and torque values. All the requirements from the AC power supply, the instrumentation and the dynamometer used to impose the load torque to the motor shaft are carefully defined in this standard. The aim is to minimize the variations between results from different test laboratories for a given system.

Common descriptions within the European requirements are the specifications for partial load losses. According to C838-13, the VSD manufactures have to specify the losses at 20 different operating points given by frequency and torque as seen in the overview in Table 2. This enables the user to calculate the expected efficiency of the complete PDS under real operating situations. The difference to the EN 50298, besides the number of measurement points, is the measurement at rated speed and torque. In contrast, the EN 50598 defines the speed at 90% of the rated speed to account for the voltage drop at the CDM and ensure operation on the V/f curve of the motor.

Table 2: C838-13 frequency and torque test points for loss measurements of the VSD.

Points	**1**	**2**	**3**	**4**	**5**
Frequency (%) Torque (%)	100 100	100 75	100 50	100 25	100 10
Points	**6**	**7**	**8**	**9**	**10**
Frequency (%) Torque (%)	75 100	75 75	75 50	75 25	75 10
Points	**11**	**12**	**13**	**14**	**15**
Frequency (%) Torque (%)	50 100	50 75	50 50	50 25	50 10
Points	**16**	**17**	**18**	**19**	**20**
Frequency (%) Torque (%)	25 100	25 75	25 50	25 25	25 10

2.2 Motor isolation and the IEC TS 60034-25

Motors supplied with typical PWM voltage signals from VSDs will experience higher stress in its isolation system as well as in its bearings. In real applications, the use of longer motor cables leads to higher peak voltages at the motor terminals [9]. Using short motor cables, the pulse rise time (t_r) or equivalently du/dt of PWM pulses will stress the insulation of the motor windings and also the bearings [6]. The increasing switching speed of the semiconductors to reduce the energy losses of the inverter system will intensify this situation if no proper countermeasures are taken.

The new version of the IEC TS 60034-25 [8], redefines the concept and requirements for the insulation system. For systems for general purpose and voltages up to 1000 V the IEC 60034-18-41 shall be used for the test and qualification of the motor isolation system. Additionally, they classify the isolation system according to the stress subjected during operation. The different stress categories are listed in Table 3.

Table 3: IEC 60034-18-41 - Classification of the motor isolation system according to its use: V_P and V_A are defined in Figure 2.

Stress category	Overshoot factor (OF) V_p/V_a	Impulse rise time t_r
A – Benign	OF ≤ 1.1	0.3 µs
B – Moderate	1.1 < OF ≤ 1.5	
C – Severe	1.5 < OF ≤ 2.0	
D – Extreme	2.0 < OF ≤ 2.5	

Stress categories for Type 1 insulation systems based on a 2-level converter

The *Stress Category C – Severe* is related to motors connected to the inverter via long cables and due to that suffering from higher overshoot voltage. The voltage impulse rise time t_r is limited at 3µs ±2µs. A t_r value limitation to more than 0.3µs is very conservative and poses a challenge for new faster switches.

In practice, the motor manufacturers allow lower t_r values. In Table 4 an example of the maximum peak voltages, maximum du/dt and minimum t_r is given for different induction motors from WEG company.

Table 4: Maximum du/dt and minimum voltage rise time allowed for different motor voltage classes [9].

Motor nominal voltage	Maximum overvoltage peak on the motor terminal	Maximum du/dt on the inverter terminal	Minimum VSD Rise Time (t_r)
460V	1600V	5.2 kV/µs	0.1 µs
460V – 575V	1800V	6.5 kV/µs	
575V – 690V	2200V	7.8 kV/µs	

A maximum du/dt of approximately 7kV/µs can be allowed for 460V motors with the use of the insulation system from 575-690V motors.

The voltage pulse rise time t_r, overshoot voltage Up and overall shape are introduced in Figure 2.

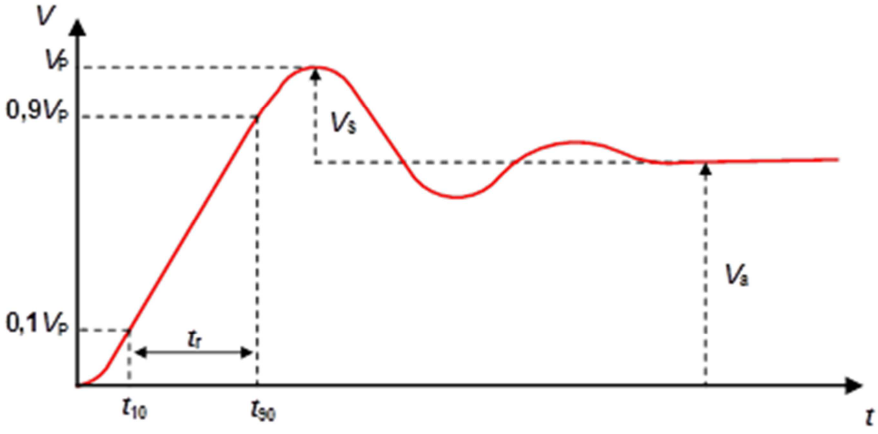


Figure 2: t_r evaluation according to the IEC 60034-18-41

In order to estimate the peak voltage and rise times expected in the motor terminals when driven by inverter the IEC TS 61800-8: "Specification of the voltage in the power interface" is recommended.

2.3 Motor bearings and the IEC TS 60034-25

The motor bearings lifetime can be affected by many factors and is difficult to predict exactly in advance.

The main causes of the motor bearing damages are:

a. mechanical forces
b. inadequate lubrication
c. Electric Discharge Machining (EDM) or Bearing Currents.

The causes a. and b. are not influenced by the inverter. The cause listed on c. is significantly influenced by the inverter's du/dt but depends on the installation conditions. The EDM is related to the erosion caused by discharge current pulses through the partially oil insulated film between bearing balls and race. This phenomenon occurs when there is a voltage difference between the rotor and the stator frame and this voltage is enough to create the above-mentioned discharge current pulses. Such voltage difference is commonly called *shaft voltage*. The root causes the shaft voltages are:

1. Circulating rotor currents related to the asymmetry in the magnetic circuit of the motor can typically generate significant shaft voltages and correspondent harmful bearing currents in higher power motors.

2. Electrostatic build-up can generate shaft voltage by friction from mechanical belt and pulley systems or when the motor drives specific loads like ionized filter fans.

3. Motor frame voltage or *shaft earthing currents* are caused by the voltage difference between the motor frame and the ground of the driven mechanical load, as the rotor is tied to the ground potential of the load.

4. Capacitive discharge currents due to the capacitive coupling between stator windings and the rotor can generate shaft voltage and the fast changing PWM pulses from the VSD intensify this phenomenon.

In practical applications, it is hard to predict the exact shaft voltage due to the fact that the stator and rotor stray capacitances are not known. It is safe to assume that compared to a pure sinusoidal supply, the motor will be subject to higher shaft voltages when driven by a VSD.

The measurement of the shaft voltage with some special probe adapters and a fast scope provides an insight into the stress of the bearings counting all causes.

The IEC/TS 60034-25 [8] standard lists many counter actions to avoid, or at list to minimize the risk of bearings being damaged. Each one can be effective for one or more root causes but the use of an inverter filter between the VSD and the motor will especially reduce the harmful effect of the capacitive coupling of the PWM pulses to the rotor, when reducing the voltage slopes at the motor terminals.

3. Typical Drives System

Two different VSD types driving 22 kW motors fed by 400V three-phase mains are analyzed and their typical loss distributions are presented. The main components of the VSD, operating conditions and main motor data used in the subsequent analysis are shown in Table 5. Typically a two level topology is used with Si IGBTs and free-wheeling diodes. The selected IGBT modules represent a state-of-the-art solution. All following calculations are performed at the operation point 90% of frequency and 100% torque-producing current.

Table 5: State-of-the-art reference VSD components and parameters for two different applications

Parameter	GPD	High Speed
Line supply	400 V / 50 Hz	400 V / 50 Hz
Rectifier	DDB6U144N16	DDB6U144N16
DC reactor	6 %	6 %
DC capacitor	1410µF/400V	1410µF/400V
IGBT inverter	FS75R12KT4	FS150R12KT4
f_{SW} [kHz]	5	16
U_{dc} [V]	621	621
U_{out} [V]	400	400
Modulation index (m)	0.91	0.91
Heatsink temperature [°C]	90	90
Motor type	AC-Induction	PM
Fundamental Frequency [Hz]	50	1500
cos(φ)	0.85	0.56
η_{motor}[%]	92.3	95.0
I_{out} [Arms]	40.5	60.0
Motor output power [kW]	22	22

In Figure 3, the typical power circuit for GPD and high-speed drives is depicted.

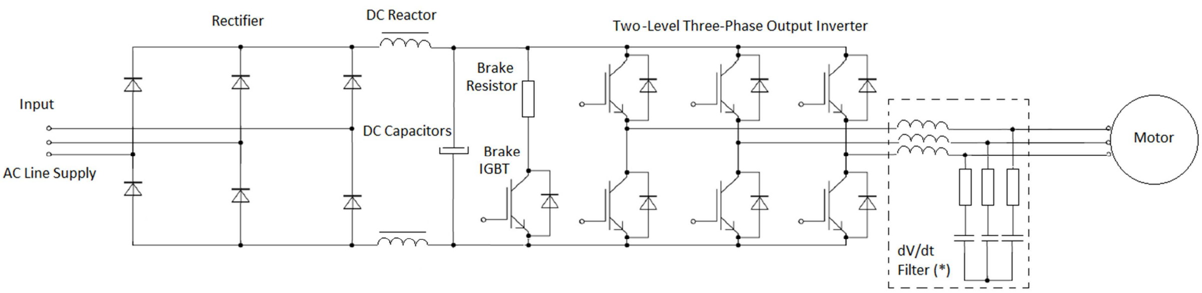


Figure 3: Today typical power circuit topology of a three-phase standard VSD. The du/dt Filter is typically required in high-speed drive applications.

VSDs have specific requirements depending on the target application. Here, the switching frequency of the power switches is an important parameter and at the same time it has a significant influence on the VSD efficiency.

The result of real efficiency measurement of a VSD with a motor mechanically coupled to a dynamometer is depicted in figure 4.

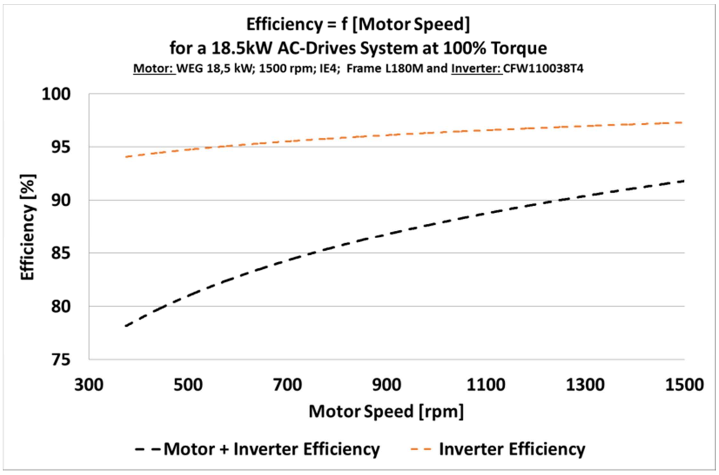


Figure 4: Real efficiency measurement of a GPD (WEG Model CFW110038T4) with an 18.5kW motor (WEG Frame L180M IE4) mechanically coupled to a dynamometer as a function of motor speed.

The achievable efficiency of the inverter at the operation point between 75% and 100% of the nominal motor speed and 100% torque is in the range of 97%.

4. Alternatives to increase the efficiency of the VSD and their impact on the motor drive system

Two ways for the loss reduction in the power electronic part of the standard converters are possible, namely the use of different topologies or the use of new semiconductor technologies. Both new approaches will bring benefits for the inverter manufacturers. The reduction of power losses will enable lower energy consumption during the operation and higher precision in classification of the VSD into the efficiency standard. The cooling efforts can be decreased, reducing the heat sink size and volume and thus increasing the inverter's power density.

4.1 3-Level Topology

The 3-Level topology has some advantages, like lower stress for the motor insulation and lower motor current ripple, compared to a 2-Level solution with the same switching frequency. Changing to this topology requires higher development effort from the drives manufacturers and a higher number of IGBTs and gate-drivers.

4.2 SiC-Switch

With the use of wide-band-gap materials like SiC, the dynamic and static losses of the semiconductor switches can be significantly reduced. The switching behavior of this type of semiconductor is characterized by faster turn-on and turn-off compared to silicon solutions. Figure 5 shows the turn-on and turn-off of a 1200V SiC-JFET device at maximum switching speed. The evaluation of the du/dt is marked as described in the IEC 60034-18-41 and IEC TS 61800-8.

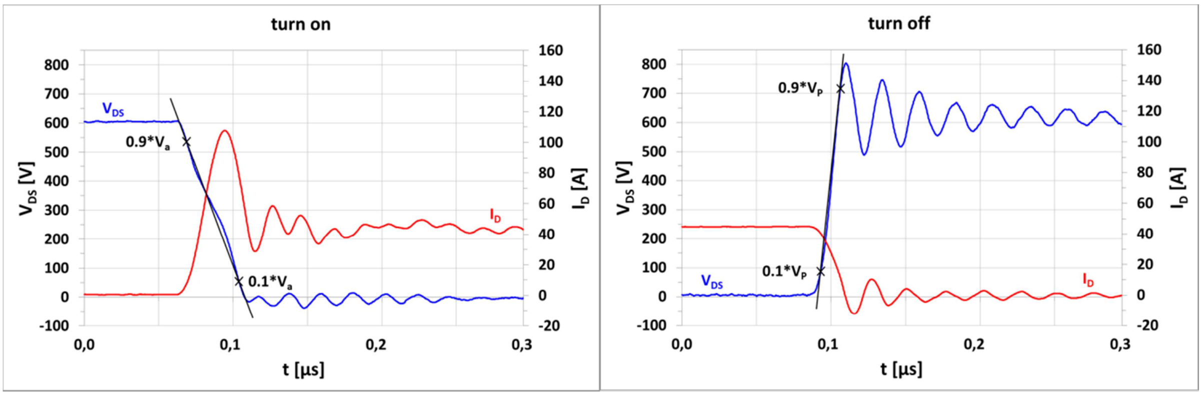


Figure 5: Turn-on and turn-off behavior of a 1200V SiC-JFET at maximum switching speed and evaluation of the du/dt as described in IEC 60034-18-41 and IEC TS 61800-8.

Figure 6 illustrates the maximum du/dt and the du/dt evaluated as described in IEC 60034-18-41 and IEC TS 61800-8 and the corresponding switching losses for a 1200V 45A SiC JFET [5]. The corresponding t_r values are depicted as well. The variation of the du/dt was achieved by changing the gate resistor value.

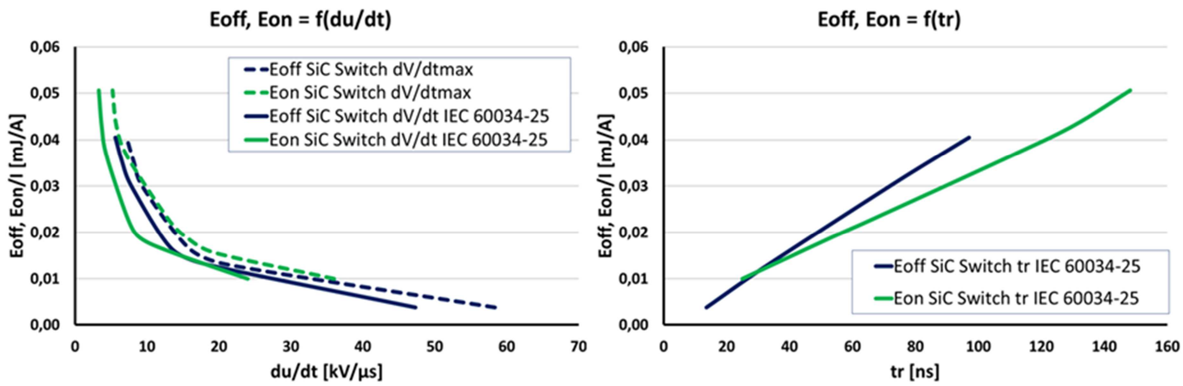


Figure 6 left: E_{off} respectively E_{on} as a function of du/dt. The switching energy is scaled with current. Figure 6 right: E_{off} respectively E_{on} as a function of t_r. The switching energy is scaled with current.

Depending on the evaluation method, different du/dt-values have been determined. Using the method described in the IEC 60034-18-41 and IEC TS 61800-8. The investigated 1200V SiC switch has achieved dV/dt values in the range of 48 kV/µs at turn-off and 24 kV/µs at turn-on under the boundary conditions of the measurement setup. This leads to 10% of turn-off and 33% of turn-on losses compared to a High-Speed 3 IGBT paired with a SiC freewheeling diode [22].

4.3 Motor windings, bearings and inverter's du/dt

The switching behavior of the SiC switch leads to lower switching losses. The high du/dt will be a challenge for the electrical motor. The issues related to the PWM signals with higher du/dt obtained with SiC switches applied to the motor cables and motor windings has to be considered. Also, the risk of damage within the motor bearings has to be taken into account [6].
As hinted out, a maximum du/dt of 7 kV/µs is allowed for 460V motors by the manufacturer with the use of the insulation system for 575-690V motors. This is far less than the 48 kV/µs possible with the 1200V SiC-switches. Slowing down the SiC switch is possible but will reduce performance due to the increased losses: The reduction to 7kV/µs for the full SiC inverter solution will result in increased dynamic losses.

4.4 du/dt Filter

A way to tap the full potential of loss reduction with the fast switch is the implementation of a du/dt filter at the inverter's output. The semiconductor can switch at maximum speed and the filter prevents the motor windings from being stressed with high du/dt and peak voltages. This is already implemented in high-speed drives. In various studies [10,11,12,13,14,15] such du/dt filters are presented and an improved filter solution can be achieved with a connection of the du/dt filter to the center tap of the DC-Link. Therefore, a du/dt filter implementation inside the inverter is a good way to unleash the full potential of SiC-switches. Of course, this modification needs to be planned and designed during inverter development. The negative aspects of this approach are the additional components and the losses within the filter.

New motors with improved insulation system in combination with an optimized du/dt filter will be one path to use the full potential of SiC switches.

4.5 EMC Behavior and du/dt

The higher du/dt tends to worsen the EMC behavior of the inverter, in particular the electromagnetic emissions. The study in [16] describes that for short motor cables, emissions are mainly related to the inverter output common mode voltage and the du/dt at turn-on. The EMC performance has to be considered during the development and tests of the inverter, as the SiC switch can achieve a du/dt of 24kV/µs during turn-on.

4.6 Low inductive system design

The geometry of the interconnection of DC-Link bus bars and power modules plays an important role when using very fast switches with high current density. The DC-link circuit needs to have a low stray inductance to avoid high overvoltage and oscillations during turn-off [17]. A careful selection of the DC capacitors, IGBT modules and bus bar design is required [18].

5. Evaluation of the losses in Current Designs and new Systems

Based on the facts described above, possible solutions were chosen to increase the inverter efficiency. A 2-Level Si-based topology is compared with 3-Level Si, 2-Level Si/SiC and 2-Level full SiC topology. The full SiC solution is evaluated in two ways. One operation point is at du/dt maximum of 7kV/µs to take the motor bearing and motor insulation system topic described in 2.2 into account. The other operating point is at maximum switching-speed to determine the power loss reduction potential of this technology. The selected devices for the comparison are summarized in Table 6.

Table 6: Chosen semiconductor solutions for a performance comparison.

Topology	GPD	High-Speed
2L Si	FS75R12KT4	FS150R12KT4
3L Si	F3L75R07W2E3_B11	F3L150R07W2E3_B11
2L Si/SiC	80A HS3 + SiC FWD	80A HS3 + SiC FWD
2L SiC at 7kV/µs	45A SiC Switch	60A SiC Switch
2L SiC at max speed	45A SiC Switch	60A SiC Switch

The selection criterion for the solutions in table 6 was to achieve similar semiconductor junction temperature at the operation point mentioned in chapter 2.1 and Table 5. All calculations are performed at the operation point 90% of rated output frequency and at nominal current. The losses for the inverter's semiconductors were calculated with IPOSIM [7] considering a sine-triangle PWM modulation. The losses of the other VSD components were calculated with computer simulations using a simplified equivalent circuit diagram, where the output inverter is modeled as a current source.

5.1 GPD

In Figure 7 the result of the calculations are displayed.

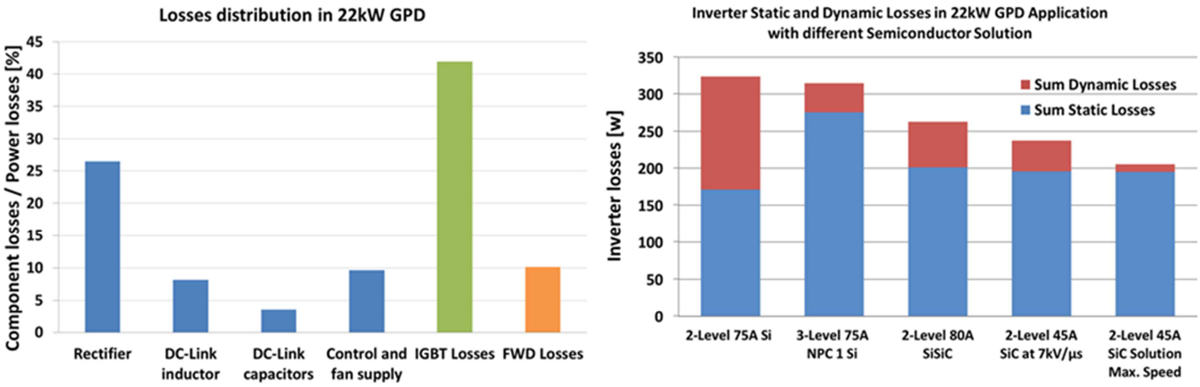


Figure 7 left: Losses distribution in a typical 22 kW GPD using 75A Silicon solution in 2-Level topology at I_{NOM} and 90% of the fundamental frequency. Figure 7 right: Corresponding Inverter dynamic and static losses with different semiconductor and topology solutions.

It can be seen, that in the GPD 52 % of the losses are related to the IGBT's and FWD's conduction and switching losses operating at 5 kHz switching frequency. The calculated efficiency $\eta_{VSD\text{-}GPD1}$ is 97.2 %; very similar to the measured values showed in figure 4. On the right side of Figure 7 it is visible, how much the power losses can be reduced using a 3-Level topology, 2-Level topologies with hybrid modules or full SiC solution. The GPD application operates at 5 kHz and benefits the least from a NPC 1 solution. The higher conduction losses of the NPC1 3-Level topology make the losses similar to the standard topology in the lower switching frequency region. The SiC-Solution working at maximum switching speed leads to lowest dynamic losses. The further reduction of the static losses achieved by spending larger SiC area remains an option.

How much the whole inverter efficiency can be improved with the new solutions is depicted in Figure 8. The potential to increase the thermal resistance of the heat sink at constant efficiency to save space and costs is demonstrated.

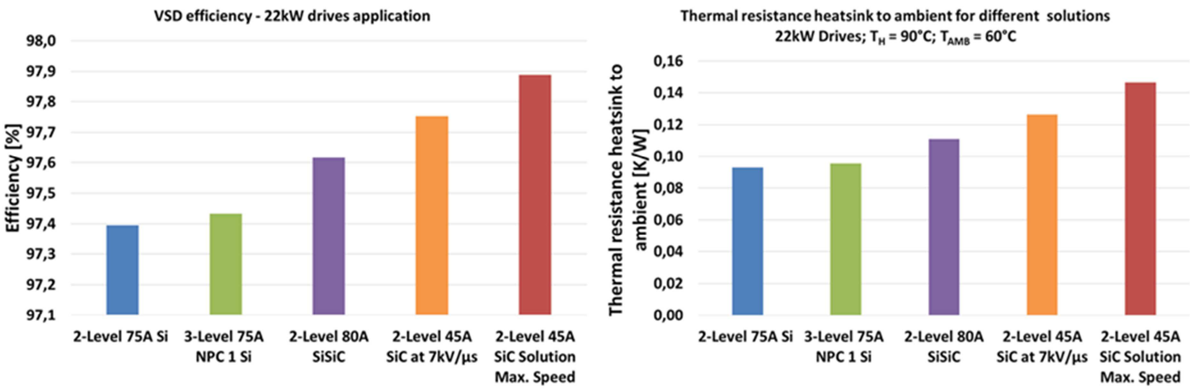


Figure 8 left: Efficiency level for 22kW GPD with different inverter solution at I_{NOM} and 90% of the fundamental frequency. Figure 8 right: Possible heatsink thermal resistance due to improved efficiency with new inverter solution

The application of new semiconductor significantly reduces the inverter losses increasing the drives overall efficiency. Using the best semiconductor solution, in this case the full SiC inverter at maximum switching speed, the losses is reduced by 118W leading to an efficiency improvement of 0.5%. The thermal resistance can be increased accordingly for the more efficient solutions, which leads to a reduction in inverter size and cost [4]. The reference system with 621 W losses already achieves the IE2 classification. All other solutions cannot fall below 375 W and cannot reach a possible IE3 classification.

5.2 High-Speed Drives

The high-speed drives require higher switching frequencies. An AC induction motor or a permanent magnet motor with 2 poles, specially designed for high speed operation, can achieve up to 90,000 rpm. This requires a fundamental frequency (f_O) of 1.5 kHz. Typically, the PWM switching frequency (f_{SW}) requirement is $f_{SW} \geq 10 \times f_0$. In order to achieve 1.5 kHz fundamental frequency at the VSD output, a switching frequency higher than 15 kHz is needed. The value of 16 kHz was chosen for the losses analysis. The standard topology can be used but, in order to deal with the switching losses, the IGBTs have to switch faster in comparison to the GPD, leading to higher du/dt values. An LC filter is usually used between the VSD output and the motor to protect the motor winding insulation as seen in Figure 3. The left part of Figure 9 depicts a typical loss distribution of a 22 kW VSD operated at 16 kHz switching frequency. The power module chosen was the EconoPACK™ 3 FS150R12KT4. Due to the higher current and switching frequency compared to the GPD example of the same power, a higher current rating for the semiconductor is mandatory. The IGBT junction temperature is kept below the maximum value allowed according to the IGBT datasheet. The output filter losses are additionally considered in this case. The VSD efficiency $\eta_{VSD-HS1}$ is 93.5 %. In the right part of Figure 9, the resulting losses on the inverter part with different solutions are summarized.

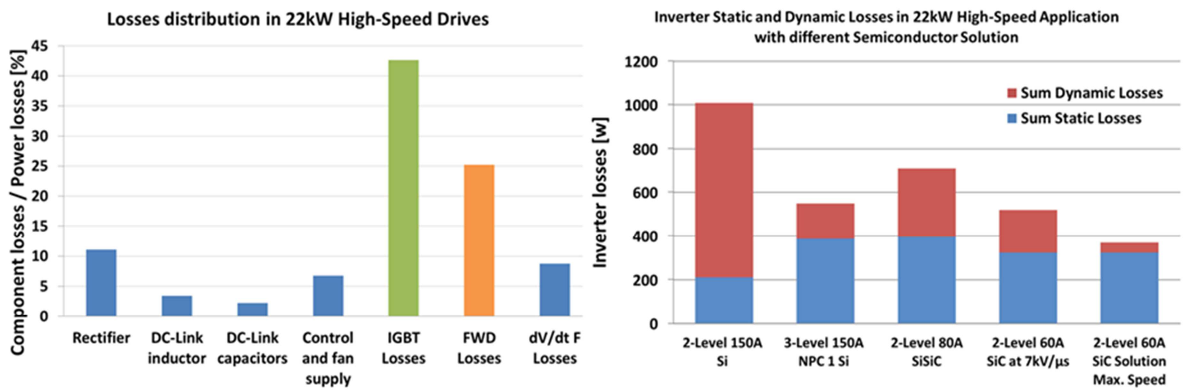


Figure 9 left: Losses distribution in a typical 22kW high speed drive using a 150A Silicon solution in 2-Level topology at I_{NOM} and 90% of the fundamental frequency.. Figure 9 right: Corresponding Inverter dynamic and static losses with different semiconductors and topologies.

At higher switching frequency, the benefits of the new systems are more pronounced. The calculation for the high-speed motors results in the highest loss reduction compared to the other example. A 3-Level Si solution achieves 45% loss reduction compared to a today's 2-Level Si system. The 2-Level full SiC solution at maximum switching speed achieves 59% loss reduction. The hybrid-solution, Si IGBT and SiC freewheeling diode (FWD), decreases the losses by 29%. It becomes obvious, that the higher the switching frequency in the application the higher the energy savings from the use of a NPC

1 3-Level or of a full SiC 2-Level solution become. The SiC-Solution working at maximum switching speed leads to lowest dynamic losses. The SiC-Solution working at maximum 7kV/µs has reduced switching losses as well. Similar to the GPD example, the reduction of the static losses spending a larger SiC area is an option to further reduction of the losses.

How much the whole inverter efficiency can be improved with the new solutions is depicted in Figure 10. The potential to increase the thermal resistance of the heat sink to save space and costs is calculated as well.

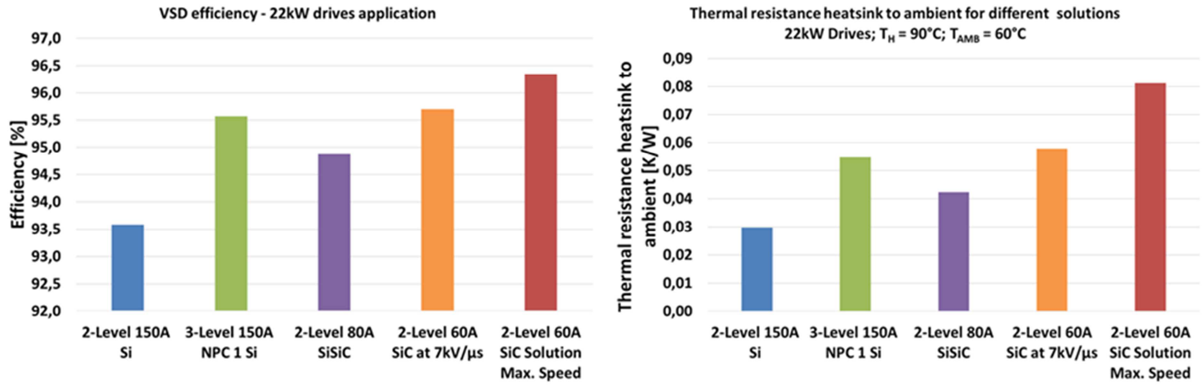


Figure 10 left: Efficiency level for 22kW high-speed drives with different inverter solution at I_{NOM} and 90% of the fundamental frequency.. Figure 10 right: Possible heat sink thermal resistance due to improved efficiency with new inverter solution

In the high-speed drives example, the improvement on the efficiency is more pronounced compared to the GPD example. Coming from 93.5% with today's solution, it is possible to achieve 2% higher efficiency using 3-Level topology or Full-SiC at maximum 7kV/µs switching speed. Here too, the Full-SiC solution at maximum switching speed allows the highest efficiency, achieving a value in the range of 96.5%. Due to the fact that this type of application is already using a du/dt filter, the implementation of the Full-SiC Solution at maximum switching speed can more likely to be adopted..

The increased efficiency brings the advantage of reducing the cooling effort within the system. On the right side of Figure 10, a diagram is depicted that denotes the required heat sink performance. This leads to a reduction in inverter size and cost [4].

6. GPD with SiC

The application of SiC-Switches in GPD systems is interesting in two ways. One possibility is to use the switch at moderate du/dt and increase the SiC area to reduce the static losses. The resistive forward characteristic of this type of semiconductor helps to reduce the forward losses to a minimum. Another possible solution is to use the SiC-Switch at maximum speed and to integrate a sinusoidal filter on the inverter output.

6.1 GPD with larger SiC area

To evaluate the benefit of larger SiC area the calculations described in chapter 5.1 were performed with a 75 SiC device at a maximum du/dt of 7kV/µs. Figure 11 illustrates the results, the new solution is highlighted with the red frame.

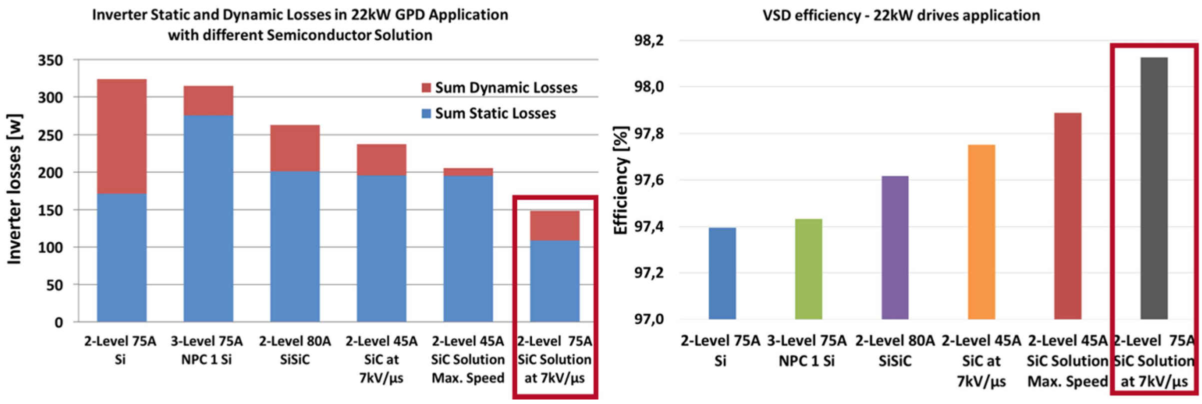


Figure 11 left: Inverter dynamic and static losses in a typical 22kW GPD using different semiconductors and topologies at I_{NOM} and 90% of the fundamental frequency. Figure 11 right: Efficiency level for 22kW GPD with different inverter solutions.

The increase of the SiC chip current by 66% leads to a static losses reduction of 45%. This solution achieves the best performance compared to all devices used in this comparison. Due to that, the inverter efficiency exceeds the 98% value and permits a further decrease of the cooling effort. From technical point of view is this solution the easiest way to install an SiC-Switch and profit from the performance at existing inverter systems. The whole inverter will generate 446 W losses and also cannot achieve a better classification than IE2.

6.2 GPD at higher switching frequency and small LC-Filter

Using SiC switches, a significant increase of the switching frequency is possible while maintaining the same efficiency level like today's GPD systems. Figure 12 shows the semiconductor efficiency level in a B6-Bridge at different switching frequencies for the 22kW GPD. The operation conditions are the same as given in Table 5 and a 60A full SiC solution at full switching speed is compared with a 75A Si solution. Using a 60A full SiC solution is possible to maintain the junction temperature below 130°C at 80 kHz under the conditions described in 2.1 and Table 5.

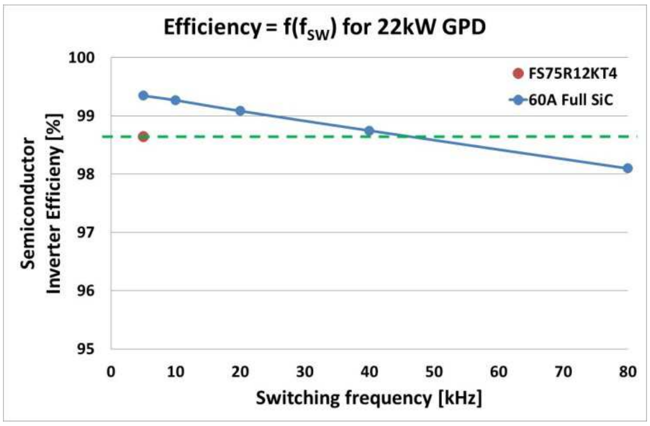


Figure 12: Semiconductor inverter part efficiency as a function of switching frequency in a 22kW GPD inverter using 60A SiC switch. The red dot represents today's semiconductor efficiency using a 75A Si solution at 5 kHz. All points are at I_{NOM} and 90% of the fundamental frequency.

In this example, a switching frequency of 46 kHz can be achieved, keeping the efficiency level of the B6 Inverter bridge equal to today's 5 kHz Si solution. Furthermore, 80 kHz is possible at 98 % *inverter efficiency*.

A significantly increased switching frequency will make the installation of a small LC-filter inside the inverter housing more attractive, as the dimension and the cost of such a filter is reduced with higher switching frequency [19]. This type of system then provides a sinusoidal voltage at the inverter output instead of PWM pulses. The filter can be also designed to reduce the inverter output common mode voltage leading to remarkable system benefits:

1. No high du/dt at the motor windings, allowing for motors without extra insulation and longer lifetime.
2. No issues using long motor cables
3. Utilization of motor cables without special shielding, saving investment and installation cost and, at same time, fulfilling the European EMC requirements.

4. Increasing the motor bearings' lifetime without the need of additional measures like grounding brushes or shaft isolation.
5. Reduction of motor losses

Figure 13 exemplary sketches a common Si-Based GPD and a virtual SiC-Based GPD.

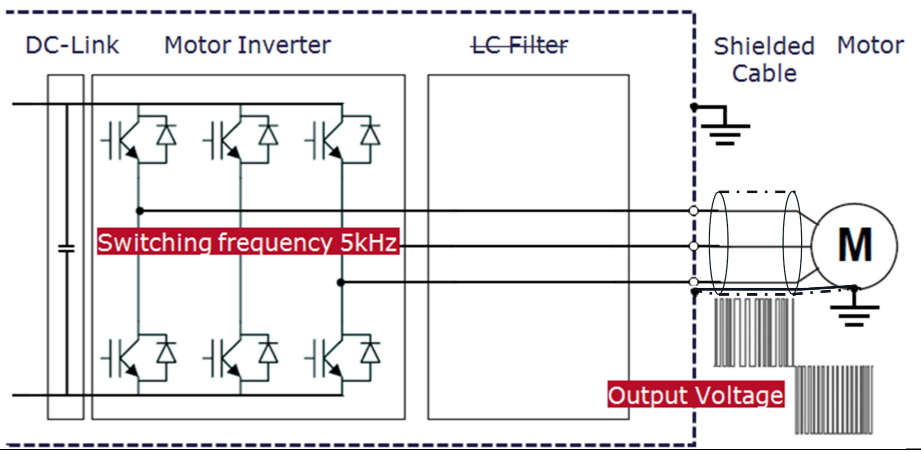
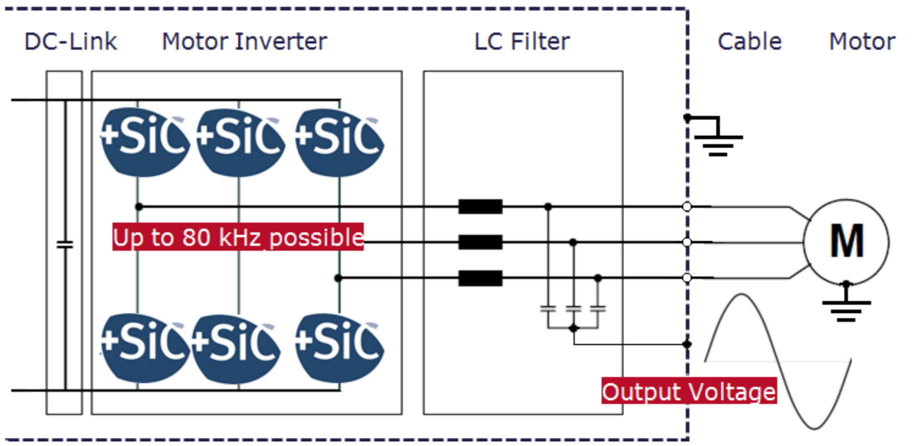
Today's Si-Based GPD: f_{S_MAX} = 5kHz No output Filter PWM output voltage Cable shielding High motor winding stress	
Future SiC-Based GPD: f_{S_MAX} = 80kHz Integrated, LC filter Sinusoidal output voltage No special cable shielding Motor winding friendly Noise reduction	

Figure 13: New approach for GPDs using SiC based B6-Bridge and LC output filter leading to system benefits

The technical advantages of a full SiC based inverter operating at high switching frequency with integrated LC filter are clear. The success of this type of solution depends on the system cost of filter, motor, cable and semiconductor and has to be evaluated in future studies.

8. Summary

The new standard for energy classification of drives and the new standard for the classification of the motor insulation have been presented. Motivated by that, different ways of efficiency improvement for two different VSD applications have been evaluated. The standard 2-Level Si was compared with a 3-Level topology, a 2-Level Si/SiC and a 2-Level SiC solution. All will allow for a significant reduction of the semiconductor losses. Depending on the explicit application and the operation point of the connected motor, the losses of the inverter can be reduced by up to 59% compared to today`s standard solutions using Si switches. Although this significantly improvement no solution can achieve a better classification than IE2.

Nevertheless, the requirement for a better efficiency classification level according to the future standards in conjunction with the benefits of lower losses, like smaller heat sink, lower energy consumption and smaller housing, will dominate over the technical challenges pointed out in this study.

The dependence of the switching losses from the du/dt plays an important role in the drives application in the future. This, in combination with improved motor insulation and du/dt filter can provide more advanced solutions for the safety of motor winding insulations.

16 times higher switching frequency at 98% inverter efficiency level is possible using SiC-switches. This solution is a key for inverter drives with small integrated LC filters, offering technical benefits for the system constituted of inverter, cable and motor. The economic aspects will decide about the success of this type of solution.

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Motors 4

Evaluation and comparison of advanced motor technologies

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Abstract

Induction motors have long dominated the market for general-purpose industrial motors. In today's world, however, ever-increasing expectations in terms of energy efficiency – combined with continuously evolving design, materials, power electronics and control technologies – have fostered the development of several additional motor types that are increasingly popular in both OEM and end-user applications.

This paper will review the qualitative benefits, drawbacks and relative energy efficiency performance of four principal motor technologies, with the aim of assisting the less experienced user in making an informed motor technology choice. The information presented here is unashamedly straightforward and is not new; rather, it has been gathered together (although we believe for the first time) as a tutorial, in response to requests from many customers who are seeking guidance in an increasingly complex landscape of different motor types. It explains the basic principles of operation together with the application benefits and drawbacks of each machine type. Total motor and drive performance is the foundation of change and market transformation that will be discussed.

1. Introduction

Manufacturers of products – and, for that matter, end-users – requiring an electric motor have an increasing range of options when it comes to choosing the most appropriate technology for their application needs. A number of different motor types are available today, each with its own particular set of advantages and disadvantages in terms of technical performance, purchase price and operating costs.

This paper seeks to document and compare the features and operating characteristics of the four most popular brushless motor types (which can be broadly characterized by their rotor construction – see Figure 1), and to assist the reader in deciding which is best suited to a particular application.

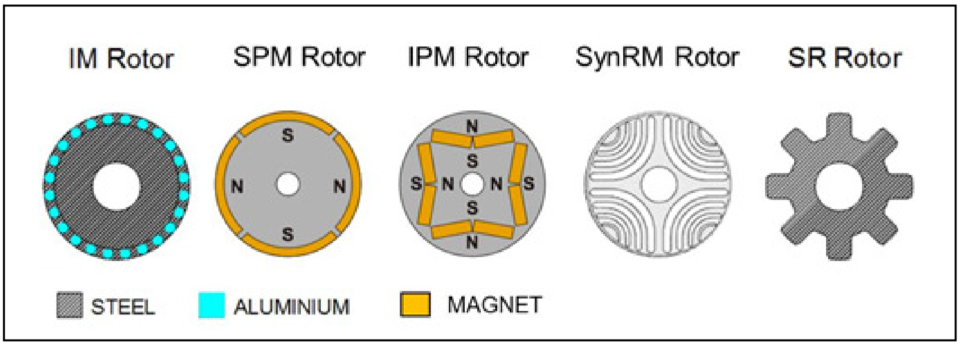


Figure 1: Principal brushless motor technologies – rotor construction

Traditional brushed commutator DC motors will not be considered here, because despite many positive performance attributes, they are largely obsolete. This is partly due to a combination of high motor manufacturing costs, limited maximum speed, comparatively poor energy efficiency and the need for brush and commutator maintenance. Their decline is also, however, attributable to the now-excellent performance of modern AC and other brushless motor controls, which in most applications offer a better balance of cost, reliability and performance.

2. Induction motor

The alternating current induction motor (Figure 2) is, without doubt, the most popular and important industrial motor today. It has long been the workhorse of many industries, and with good reason: it combines simplicity of manufacture with ease of application and generally good performance (e.g. low acoustic no`ise, and respectable energy efficiency at least in larger sizes – that is, outputs of a few kilowatts and upwards). Furthermore – of tremendous importance in the past – it can be operated directly from the AC supply, albeit at a more-or-less fixed and pre-determined speed.

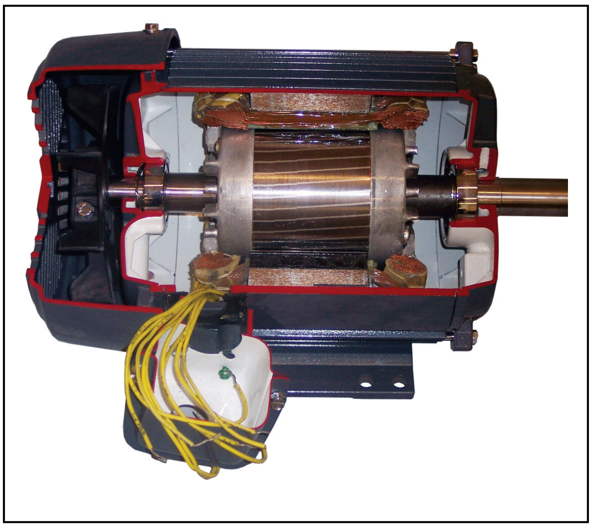


Figure 2: Induction motor cross-section

Historically, the main drawback of the induction motor was the difficulty and cost of varying its speed whilst maintaining an otherwise acceptable level of performance. This problem has been progressively solved over the past three decades thanks to advances in power electronics and digital signal processing. The energy savings made possible by speed variation are now increasingly important for both financial and environmental reasons, whilst improved control algorithms allow the induction motor to be used in applications where brushed DC or costly permanent-magnet servo motors were previously needed. Controlled (i.e. inverter-fed) induction motors are now found in diverse and cost-critical applications such as automotive auxiliaries, washing machines and hybrid electric vehicles, as well as their more traditional industrial territory of pumps, fans, blowers and materials handling.

Some drawbacks remain, however. Quiet and efficient operation requires that the stator windings are distributed throughout many slots in the steel stator core. Manufacturing considerations then require long stator end-turns which not only waste space, but – because of their electrical resistance – also waste energy.

Referring to Figure 3, the induction motor produces torque through the interaction of its rotating stator field Ψ_S with the current i_R that is induced in (traditionally aluminium) rotor conductors. These currents cause heating in the rotor resistance R_R, a nuisance not only because of the resulting reduction in efficiency, but also because heat on the rotor is difficult to remove and reduces the life of the bearings. The lower-resistance copper rotor bars found in some "super-premium efficiency" induction motors help to reduce rotor heating, albeit with the penalty of higher material and manufacturing costs.

Perversely, however, a lower rotor bar resistance also increases the detrimental impact of the unavoidable parasitic rotor inductance L_R. Because of the increased ratio of L_R to R_R, the rotor current tends to lag further behind the rotating field, necessitating an increase in rotor current for a given torque – so that the overall efficiency gain is less than might initially be supposed. For the same reason, starting the motor "direct-on-line" becomes more difficult, and inverter operation is usually required for copper-bar motors, and certainly so if high starting torque is a requirement. Some induction motor designs (especially larger machines) seek to improve the unhappy compromise between efficiency and starting torque by deliberately exploiting the so-called “skin effect” in the rotor bars. This has the effect of increasing at R_R as the slip frequency (determined by the difference between rotor and stator speeds) increases.

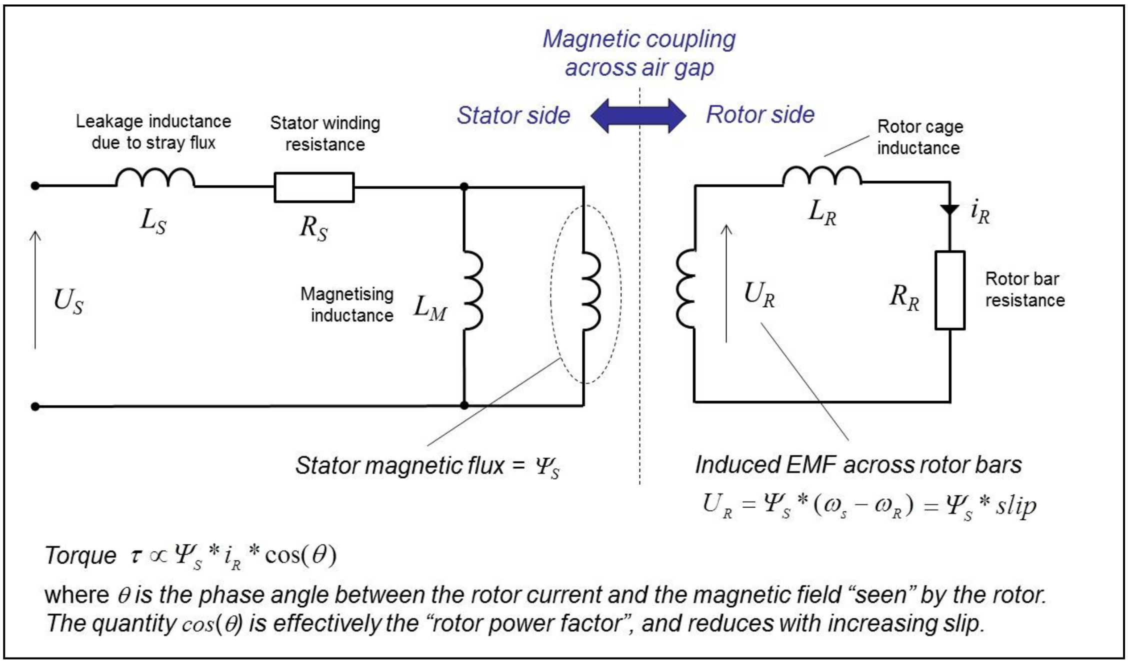


Figure 3: An equivalent circuit view of the induction motor (one phase only shown)

As an aside, it is perhaps worth noting that, in contrast to the standard text book form, Figure 3 deliberately avoids showing R_R as being a function of slip. This convention is, in the authors’ opinion, unhelpful and misleading; the current in the rotor bars rises with increasing slip because the induced voltage in the rotor U_R rises, and <u>not</u> because the rotor resistance reduces! In fact, if anything, skin effect (as noted earlier) is likely to make the rotor bar resistance *increase* with greater slip.

Returning to the stator, the electrical time constant associated with the stator (given by the ratio of L_M to R_S) is relatively large, typically tens or hundreds of milliseconds. To ensure an acceptably quick response to changes in load or commanded speed, it is usual to operate the motor at roughly constant magnetic flux at least up to the motor’s “base” speed. Unfortunately, the associated magnetising losses (in the stator windings and steel core) are then present regardless of whether the motor is working hard or spinning free-shaft, resulting in poor efficiency at light loads. This can be avoided if the stator flux is automatically reduced at low torques, a technique which is tolerable only if a rapid control response is not essential, and where the expected load is well-defined as a function of speed (e.g. fans and centrifugal blowers).

Above base speed (where, by definition, the stator field Ψ_S weakens because of limited supply voltage U_S) the controlled induction motor is typically used to deliver constant mechanical power. Unfortunately, motor efficiency falls progressively as the speed rises further in the field-weakening region. This occurs because inductance in the rotor circuit (L_R) causes the rotor current to lag behind the rotating field, so that as slip increases, ever more rotor current is needed for a given torque. (This same mechanism is the cause of “pull-out” as the motor load, and hence slip, increases – so restricting the maximum available overload torque.)

For these reasons, the controlled induction motor is typically used over only a 2:1 or (at most) 3:1 constant power speed range (CPSR). Applications requiring a wider CPSR – e.g. machine tools and vehicle traction – can be met by reducing the induction motor’s winding turns count. Effectively the motor is designed for a higher-than-needed base speed; a sharp decline in motor efficiency at high speeds is then avoided, but the resulting increase in stator current (for a given torque) makes for a more expensive and less efficient inverter.

A final note of caution: name-plate induction motor efficiency is almost always quoted for pure sine-wave operation. However, inverters or ("variable frequency drives") deliver a stream of rectangular voltage pulses ("pulse width modulation" or PWM) that result in only an approximation to sinusoidal current (Figure 4).

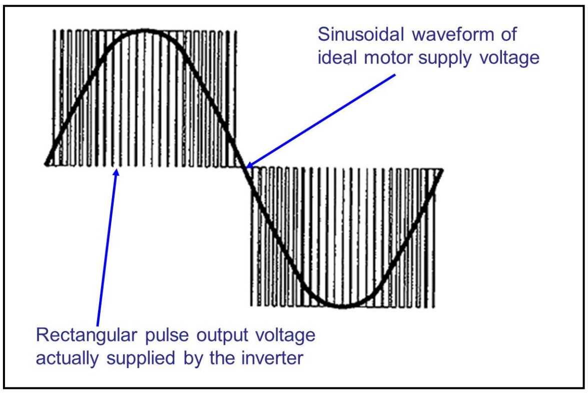


Figure 4: Ideal motor supply voltage, contrasted with PWM output voltage of inverter

Higher switching (i.e. PWM "carrier") frequencies improve the sine wave approximation so far as motor current is concerned, but the resulting gains in motor performance are unfortunately traded against increased power losses in the inverter. Passive filters can alternatively be inserted between the inverter and motor to reduce high frequency current ripple in the motor, but such filters are large, expensive and introduce power losses of their own.

Specifiers of motors and inverters should therefore be cautious in respect of efficiency expectations; the overall system efficiency achieved in practice may be significantly less than the product of individual data sheet figures for the motor and inverter. This may also be the case for some examples of other motor types (notably permanent magnet and synchronous reluctance), even though an inverter may be essential to their operation. Users should check the manufacturer's "small print" carefully to clarify under precisely what operating conditions the specified motor efficiency is quoted. Where the motor and inverter are supplied together as a package, customers should insist on seeing data for their combined efficiency (that is, from the AC supply input to the mechanical power output).

3. Permanent magnet motors

The permanent-magnet (PM) motor produces torque through the interaction of stator currents with permanent magnets that are mounted on, or embedded within, its rotor. In modern brushless motors, there is no mechanical commutator and hence an inverter is essential to control the winding currents.

The surface permanent magnet (SPM) rotor (shown second-from-left in Figure 1, also in Figure 5) is common in small, low-power PM motors such as those found in information technology (IT) equipment, business machines, automotive auxiliaries etc. These may use low-cost ferrite magnets or higher-strength "rare earth" magnets.

The interior permanent magnet (IPM) rotor – see third from left in Figure 1 – is more commonplace in higher power machines, e.g. for hybrid and electric vehicles, and in high efficiency industrial motors. If torque ripple is not a concern the stator may use a relatively small number of teeth with individual coils spanning only one tooth. Distributed windings (as used in the induction motor, and with the same disadvantages) are however the norm in larger interior permanent-magnet machines.

Torque ripple – that is, variation of torque with rotor angle, above and below the mean value – is a feature of these motor types to some degree, but is strongly design-dependent. Torque ripple is, in fact, seldom a major application issue in terms of motion control, except perhaps at very low speeds where (because the torque ripple frequency is, in an inverter-fed motor, proportional to speed) the integrating effects of mechanical inertia are insufficient to smooth out the resulting variations in speed and/or rotor position. Low-speed torque ripple can be reduced fairly easily by modulating the motor current as a function of mechanical angle, as the rotor turns. Torque ripple at higher speeds may however be a concern in terms of increased noise and vibration, and for this reason distributed windings (fed with sinusoidal phase current) are generally preferred for PM machines if low torque ripple and quiet operation is essential.

The total torque ripple of a PM machine actually comprises two distinct components of alternating torque. One is associated with the electrical excitation, and fades to zero as the motor output is reduced. The other is termed “cogging torque”, and is caused by interaction of the magnets with the stator teeth. Cogging torque occurs more or less regardless of excitation – and therefore becomes the dominant component of torque ripple at low average torque output.

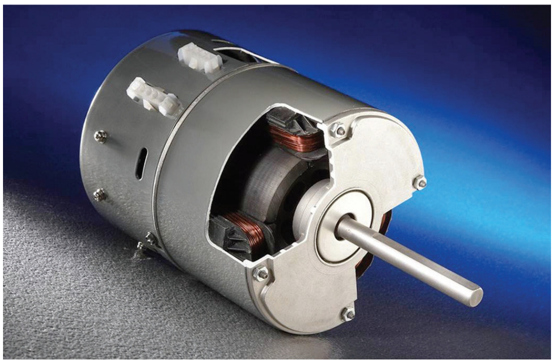


Figure 5: Permanent-magnet motor with surface rotor magnets and short-pitched windings

Unlike the other motors discussed here, the PM machine does not require any stator current to support its magnetic field; one might say the magnetic flux has already been “paid for” through the use of (potentially costly) permanent magnets. Consequently the PM motor is capable of delivering the highest continuous torque per unit volume, and is often the best choice if small size or weight is important. An absence of magnetising losses allows the PM motor to offer high efficiency at the so-called “sweet-spot” (the load and speed where the motor performs best), and this has led to a number of manufacturers to offer PM versions of general-purpose industrial motors as a means of meeting “next generation” efficiency requirements.

The most immediate disadvantage of the PM machine is in its manufacturing and material costs. High performance PM motors use “rare earth” magnets, made from transition metals such as neodymium, dysprosium, cobalt and samarium. These are expensive to mine, difficult to extract from their ores and mainly come from geopolitically “difficult” parts of the world including Africa, Congo and China. The market dominance of such countries presently allows them to substantially control the trade – and hence the price – of rare earth materials.

Furthermore, whilst permanent magnets bring undoubted performance benefits at low and medium speeds, they are also something of a technical “Achilles heel” in several important respects. Firstly, as speed increases, the peak voltage induced in the stator by the rotating magnets (the so-called “back EMF” – see Figure 6) eventually approaches the inverter’s DC supply voltage. At this point it is no longer possible to control the stator winding currents; this defines the so-called “base speed” of the generic PM machine (and in surface-rotor designs, usually represents the maximum possible speed for a given supply voltage). As was the case for the induction motor, reducing the winding turns allows for higher speed operation (at least from an electrical perspective), but again increases the motor phase currents, with consequent detrimental impact on both the cost and energy efficiency of the associated inverter.

Interior PM machines are operated above base speed using active field weakening, in which the phase angle of the stator current is shifted with respect to the rotor angle in order to deliberately depress the magnet flux, and so keep the back-EMF within safe limits. This phase shift of the current also introduces, beneficially, an element of so-called reluctance torque; this is due to the steel parts of the IPM rotor seeking to align themselves with the rotating field of the stator – see also section 5 of this paper. (Electrically, referring to Figure 6, the reluctance torque is caused by dependence of the motor’s phase inductance L upon the mechanical rotor angle θ.)

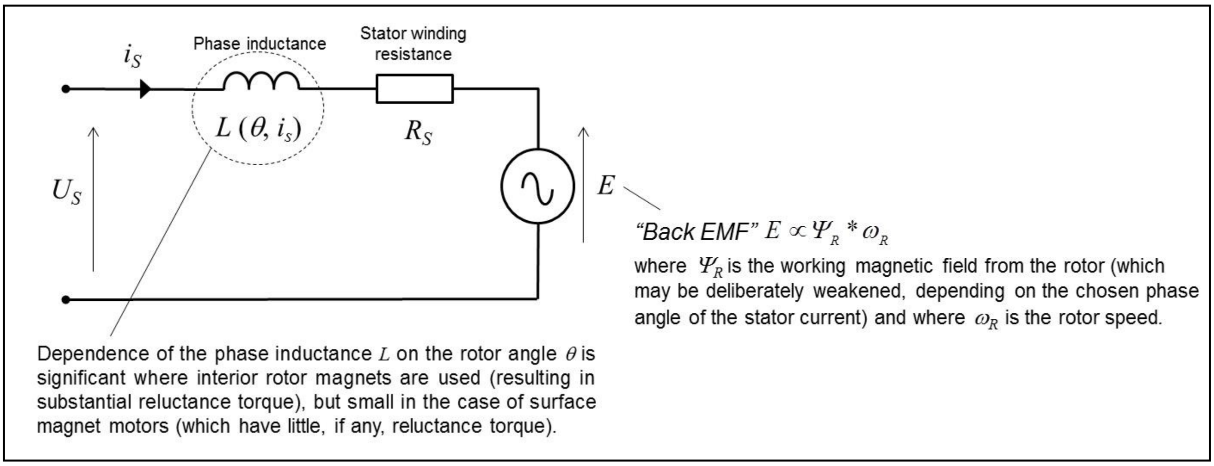


Figure 6: Equivalent circuit view of permanent-magnet motor (one phase only shown)

For any given speed and total torque, there is an optimum ratio between the reluctance and magnet-related torque components, at which the required output is delivered for the lowest stator current (the "maximum torque per ampere" condition).

Thanks to its reluctance torque component, the interior PM machine can operate well beyond its base speed, and will generally deliver approximately constant power output as speed rises. However, any loss of field weakening at high motor speeds – for example due to inverter shut-down – results in uncontrolled generating into the inverter, and the inverter DC bus voltage may rise to a dangerous or even destructive degree. This is problematic not only from a fault-tolerance perspective, but also because in highly dynamic applications it is difficult to ensure adequate control of the back-EMF during a transient from one load condition to another. One solution is to restrict the maximum allowed rate-of-change of torque reference; this may be undesirable where a rapid torque response is required. For these reasons, the speed range over which active field weakening can be safely and reliably implemented in practice is limited to about 3:1, perhaps 5:1 at the very most. Like the induction motor, this can be side-stepped by artificially increasing the base speed (via reduced winding turns) and accepting the consequent increase in inverter current and costs.

It is important to note that the need for field weakening is speed-related; full field weakening is needed even when the motor is coasting (without mechanical load) at high speeds. The consequent "demagnetising losses" – notably due to currents flowing in the stator winding resistance, and eddy current and hysteresis losses in the steel and magnets – are therefore present regardless of the desired output torque. This fixed burden of speed-related losses causes a sharp fall in the machine's light-load efficiency wherever field weakening is used. In EV applications – where cruising at higher speeds will inevitably involve field weakening – this represents a potentially serious efficiency penalty, especially as much of the time the motor will be working at only a fraction of maximum output. PM motors are often cited as the best choice for hybrid vehicles because of their low mass and high peak efficiency, but the latter benefit is, at best, less obvious when computed over a real-world driving cycle. It is interesting to note that at least one prominent EV manufacturer has switched from PM to induction motors, perhaps for this very reason [1].

The induced stator EMF makes the PM motor notoriously difficult to manage under fault conditions. Currents continue to flow in winding faults for as long as the motor rotates, even if the inverter is shut down or disconnected. This not only risks overheating and fire, but also the resultant large cogging torque may also be hazardous in the application (consider e.g. power-assisted steering or vehicle propulsion).

Permanent magnets are also problematic in mechanical and environmental respects. High operating temperatures (beyond, say, 130-140°C) are problematic for all but (costly) samarium-cobalt magnets. Gradual demagnetisation over time is a serious concern for ferrite and neodymium magnets even at normal motor working temperatures. High stator currents – for example due to overload or inverter faults – can also cause partial demagnetisation. Neodymium is a highly reactive metal, and magnets made from it must usually be plated or coated to avoid corrosion; care is then needed to prevent chips and cracking both during manufacture and in service. Maximum speed is limited by the strength of magnet retention (adhesive or wrap in surface PM machines, steel bridges in interior PM rotors), and even at low speeds, care must be taken to avoid fretting of interior magnets within their slots. Repair is more difficult than other motor types, and usually mandates a return to the factory because of the difficulty of extracting and safely handling the rotor. Finally, recycling at end-of-life is also troublesome, although the present high value of rare earth materials may still make this economically viable.

Despite the many disadvantages associated with permanent magnets, PM motors remain unsurpassed in terms of their low-speed and peak efficiencies, and where size and weight are of critical importance.

5. Synchronous reluctance motor

Although it has recently seen resurgence as an alternative to the controlled induction motor, the basic synchronous reluctance motor is actually quite an old technology, and was historically popular in e.g. glass and textile machinery, where multiple separately-driven shafts needed to turn in angular synchronism.

The synchronous reluctance machine can actually be considered an extreme case of the interior PM machine, in which all the torque is produced by variation of reluctance, and no magnets are used or needed. The surface magnet PM machine and the synchronous reluctance motor therefore sit at opposite extremes of an otherwise continuous range of possible motors, with the typical interior PM motor sitting somewhere in the middle (Figure 7).

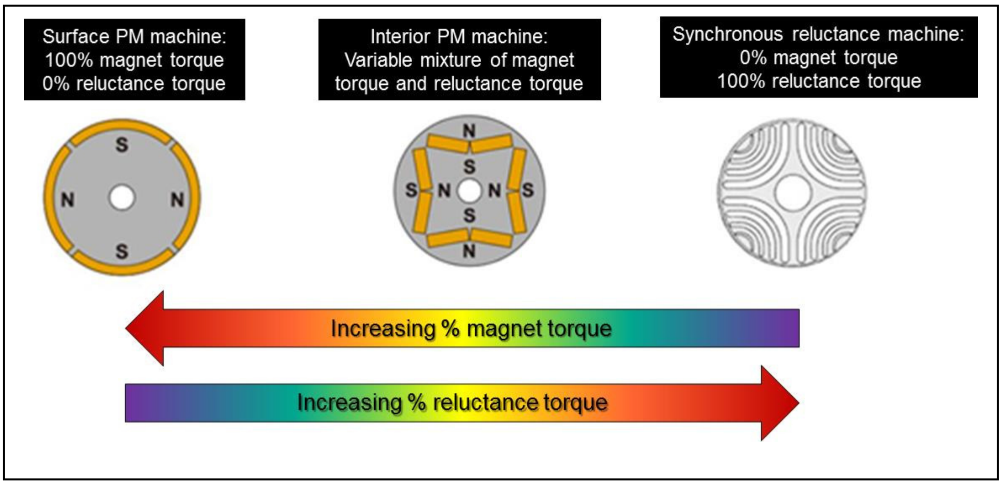


Figure 7: SPM to synchronous reluctance – a continuum, rather than three discrete choices

The modern synchronous reluctance motor is always inverter-fed, and uses essentially the same distributed-wound stator as the induction motor. The rotor is made only of laminated steel (no bars or magnets), but has circumferential "magnetic saliency" – that is, magnetic flux barriers are incorporated in the rotor steel so that it can easily be magnetized in one axis (that of low reluctance) but less easily in the other (high reluctance). Torque is produced by the tendency of this rotor to align itself with the rotating magnetic field of the stator, which itself is locked to the rotor angle. Like the inverter-fed PM motor, this is therefore a self-synchronous machine, in which the excitation frequency is synchronized (by the inverter) to the rotor speed, and not the other way around. Varying the motor excitation level adjusts torque; note that a separate servo mechanism is needed to regulate speed (e.g. a PID controller, usually implemented within the inverter software, which computes the necessary torque command in response to speed error). Low torque ripple and sinusoidal excitation make for generally quiet operation.

The principal benefit of the synchronous reluctance motor, relative to the induction motor, is that the rotor losses are very small. The rotor has no current-carrying conductors, and thanks to the synchronous nature of the machine, the magnetic field "seen" by the rotor is essentially stationary.

With careful design and control, the resulting motor (as distinct from system) efficiency can therefore meet forthcoming European “IE4” and NEMA “super-premium” standards, whilst avoiding the need for permanent magnets. Reduced heat losses also allow for improved torque and power densities relative to the induction motor, so that the synchronous reluctance motor can typically be one frame size smaller for a given rating. A very readable paper by Lipo [2] provides a mathematical basis for some of the fundamental efficiency differences we have described here.

A little-discussed feature, however, is that the synchronous reluctance motor operates at a low power factor compared with the induction motor, so that significantly more inverter current is needed for a given mechanical torque [2]. This not only raises system costs, it also significantly increases the inverter power losses. As a consequence, whilst the motor efficiency may be good in its own right, the benefit at system level (that is, the efficiency of the motor and inverter operating together) may be less convincing. Since the present EU standards (e.g. the IE3 and IE4 definitions of EN60034-30) presently consider motor-only efficiency, system designers should probe carefully into the likely overall system performance – especially where (for example) “IE4 efficiency levels” are claimed for variable-speed motors. It is important to remember that because of the way the standards are presently worded, such claims usually (and conveniently – at least for the Marketing Department!) ignore the impact of inverter-related losses.

In order to maximize the variation of phase inductance with angle (the so-called “saliency ratio”) the synchronous reluctance motor usually employs complex rotor laminations with punched flux barriers, which tend to make the rotor difficult to manufacture, somewhat fragile, and unsuitable for high speed operation. A recent publication by Kamper [3] also indicates that the motor does not perform well in applications requiring a wide constant power speed range – suggesting is not a good candidate for vehicle propulsion. Synchronous reluctance motors are however well suited to a wide range of industrial applications where large overload and high speeds are not required, and are particularly being targeted for efficiency savings in variable-speed pumps.

6. Switched reluctance motor

Like the synchronous reluctance motor, the switched reluctance motor (SRM) produces torque through the attraction of a magnetically-salient rotor with the stator field. The SRM stator, however, has comparatively few poles, each usually carrying one complete coil in a short-pitched winding configuration. The rotor is also much simpler, sufficient magnetic saliency being achieved through a coarse, open-toothed profile, rather than the internal flux barriers used in the synchronous reluctance motor (Figure 8).

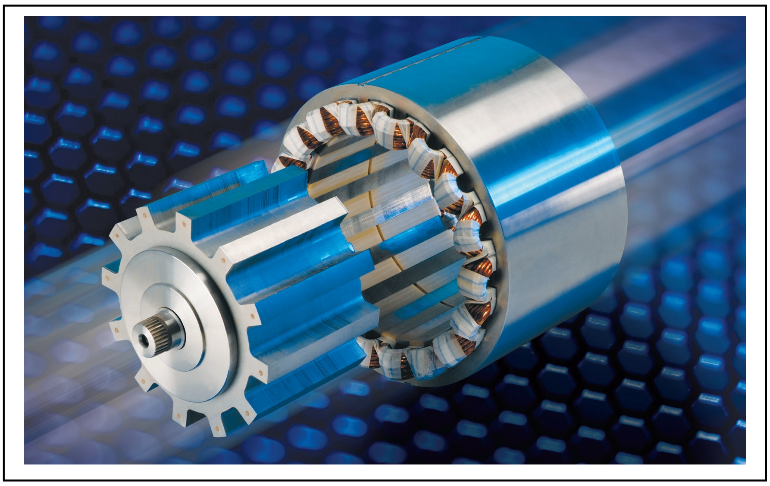


Figure 8: Stator and rotor of switched reluctance motor (SRM)

The difference in stator and rotor pole count causes a Vernier effect, and (with the stator pole count exceeding that of the rotor, as is usual) the SRM rotor rotates in the opposite direction to the stator field. Unlike the synchronous reluctance motor (which is an AC machine) the SRM usually uses pulsed DC excitation. This has important consequences for high speed operation in the "field weakening" range, as will be described shortly.

Because it uses no permanent magnets, some stator current is needed (as is also the case for the induction and synchronous reluctance motors) in order to support the SRM's magnetic field. The consequent magnetising losses result in somewhat lower torque density and reduced "sweet-spot" efficiency in comparison with the PM machine, but performance in these respects is nevertheless generally superior to the induction motor. Like the synchronous reluctance motor, a typical industrial SR motor (e.g. in the range 1-100kW) is one frame size smaller than the comparable induction motor.

A feature of the SRM is that field weakening occurs naturally as motor excitation is reduced, but (unlike the induction motor) without efficiency impairment. The stator time constant is relatively short, and rapid dynamic response of torque is possible without efficiency penalty. Furthermore, with unipolar excitation, there is no requirement for the flux linkage to fall to zero at the end of each electrical cycle, and a considerable increase in the high-speed output is possible through use of the resulting "continuous conduction mode". Very wide constant-power speed ranges (>10:1) are possible without difficulty or serious cost penalty. Efficiency remains high at elevated speeds and light loads, and the SR motor and inverter together can deliver high and remarkably constant efficiency across a wide range of operating conditions. Depending on the application duty cycle, the SRM may actually deliver lower overall energy (as opposed to power) consumption than a PM machine.

The SRM is also notably fault tolerant. With no permanent magnets, there is – as is also the case for synchronous reluctance and induction motors – no risk of uncontrolled torque or current under winding fault conditions, nor any possibility of uncontrolled generating at high speeds. Furthermore, because the SR motor phases are usually electrically independent of each other, the machine can, if desired, continue to operate at reduced output (and admittedly with increased torque ripple) when one or more phases are inoperative. This "limp-home" capability is attractive in applications such as aerospace, where an increased degree of fault tolerance and redundancy are desirable.

Simplicity of construction makes the SRM both inherently robust and inexpensive to manufacture. The plain steel rotor is well-suited to high speeds and harsh environments (e.g. high temperatures, strong vibration). The short-pitched stator coils reduce overlaps and crossovers between phases and so also reduce the risk of winding short circuits. Furthermore, the end-turns can be very short, so making good use of available space and avoiding unnecessary stator losses – a feature which is especially important in short-stack (so-called "pancake") motors. Rotor heating is confined to magnetically-induced losses which are small (at least up to moderate speeds), so the bearings generally run cool and prolonged stalling is not a problem.

The power factor of the SR motor is lower than the PM or induction machine, but the increased semiconductor conduction losses in the inverter are compensated by the fact that the inverter does not have to synthesize a sine wave for efficient motor operation. The inverter switching frequencies can consequently be very low indeed, and – in stark contrast to present inverters for the other motor technologies – the associated semiconductor switching losses are usually negligible at medium and high motor speeds.

The principal and well-known disadvantage of the SR motor is its acoustical noise and vibration, principally due to a combination of torque ripple and large radial forces. The resulting acoustical noise can however be managed through a combination of targeted mechanical design, electronic control (which can be very effective at low speeds) and – especially important – through careful mechanical integration in the application. By these means SR motors have been successfully used even in noise-critical applications such as domestic horizontal axis washing machines and passenger-car generators.

Torque ripple – often cited as a major obstacle to use of the SRM – is, as already noted, seldom a problem in terms of motion control; it is mainly of concern as a potential source of noise, and – by way of example – has not prevented the SRM being used with great success in as a servo motor in the textile industry. This application benefits from the SRM's excellent short-term overload capability and low rotor inertia (thanks to its toothed structure), which combine with a short electrical time-constant to allow for very rapid control response.

The SRM is presently finding increasing use in materials handling, e.g. conveyors, crushers and slurry pumps, where large amounts of breakaway and/or overload torque are needed, and where its inherently low rotor inertia is again a substantial benefit. Its high overload capability and good performance across a wide constant-power speed range make it an excellent choice for vehicle traction, both in heavy-duty off-road equipment and also in passenger cars, where it has yet to make its mark. This is perhaps due to concerns over acoustical noise or torque ripple – but it is worth pondering that the internal combustion engine is successful despite being a prodigious source of both.

7. Motor technology comparisons - summary

Recommended further tutorial reading, across the range of motor types and technologies, includes an excellent book on the subject by Hughes & Drury [4].

At the end of the day, no one motor type suits all applications. Each technology has its own strengths and weaknesses, and which one is most appropriate for a given application should be decided by firstly truly understanding that application and its requirements.

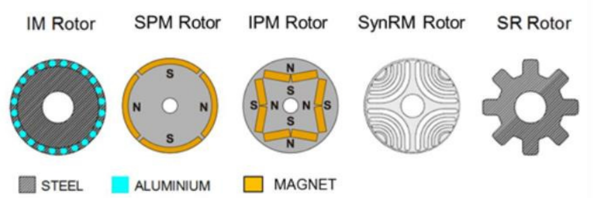
If an electric motor of some kind is already being used in the application, the designer should explore how and why it was selected – and equally, what constraints it brings. The answers are sometimes quite different to perceived wisdom; surprisingly often, an incumbent motor type has been used for many years simply because "it does the job", without anyone asking or fully understanding how it might be improved upon. Creative thinking is important, and system designers should not allow themselves to be constrained by the paradigms and properties of existing or conventional solutions.

The various strengths and weaknesses of each motor technology, as outlined in this paper, should always be considered and explored *in context of the particular application*. Figure 9 is presented in good faith as a guide and starting point, but with the caveats that it is necessarily somewhat subjective, is always highly application-dependent, and even with dispassionate scoring its perceived accuracy will inevitably vary from one opinion to the next!

Torque, speed, efficiency & control	AC	SPM	IPM	Syn RM	SR
Peak efficiency	3	5	5	4	4
Efficiency flatness *	2	3	2	4	5
Constant power range	2	1	3	2	5
Overload capability	3	4	4	3	5
Torque density *	3	5	5	4	4
Power density *	2	3	4	4	4
Stall withstand ‡	1	5	5	5	5
Torque ripple	5	2	4	5	1
Inverter VA requirement	3	3	4	1	5
Bus capacitor ripple	5	3	4	5	1
Sensorless operation	2	3	4	4	4

Mechanical and environmental features	AC	SPM	IPM	Syn RM	SR
Fault tolerance	3	1	2	3	5
High temperature use	2	1	1	4	5
High speed operation	3	1	4	2	5
Harsh environment use	3	1	1	4	5
Size & weight	3	5	5	4	4
Rare earth materials	5	2	1	5	5
Rotor inertia	2	4	4	3	4
Ease of recycling	4	2	1	5	5
Acoustic noise	5	3	4	5	1
Ease of motor repair	2	1	1	2	5
System cost	4	3	2	3	4

5	4	3	2	1
Strong	Good	Average	Weak	Poor



** IM, PM & IPM machines are poor in the field weakening (high speed) range*

‡ Stall capability of IM is poor unless motor is inverter fed

Figure 9: Subjective scoring matrix for brushless motor technologies - example

The technology selection process can usefully be informed in a structured manner by scoring the relevance of each quality to the specific application (rather like the ubiquitous "risk assessment" process). For instance, wide constant-power speed range is often valuable in vehicle traction applications, but is more or less irrelevant to centrifugal pumps. By rating the relevance of each quality to the application in question (e.g. 0 = irrelevant, 1 = somewhat relevant, 2 = very important), and then multiplying this "relevance index" by the performance score (from Figure 9) for that property. Finally, by summing the result, an overall numerical ranking can be obtained for each motor technology when used in the given application.

As a final point, the present edition of European standard EN60034-30 – which defines efficiency levels IE2, IE3 and IE4 – specifically excludes from scope any motors requiring electronic control. Manufacturers of inverter-fed solutions should therefore advertise their motors as having efficiency levels commensurate with IE(x), rather than simply claiming "IE(x) compliance". System designers and users should be aware that "IE4" and similar labels therefore usually refer to motor-only efficiency, and that the efficiency of the complete motor-inverter package may be substantially lower.

8 A plea to manage overall energy usage – and not just motor efficiency

In recent years, with energy costs generally rising and increased environmental concerns about the impact of global carbon emissions, there has been growing emphasis on the energy consumption and energy-efficiency of all types of plant and equipment, with the EU now starting to roll out legislation concerned with "eco-design requirements for energy-related products" [5].

It is a simple matter to verify that a typical electric motor consumes the equivalent of its own purchase price in energy within just a few weeks of operation, so that energy dominates the overall "cost of ownership" – and not the initial capital purchase price of the motor/inverter. This simple truth, together with the large fraction of electrical power that is consumed by motors, has encouraged higher and higher motor efficiency standards to be adopted globally, exemplified in Europe by the IE2, IE3 and IE4 standards of EN60034-30, and in the Americas by NEMA "premium" and "super-premium" efficiency ratings. This is of course welcome from an environmental perspective (assuming that the high-efficiency motors can be manufactured without serious environmental impact), and most cases will also make good economic sense.

However, there is also a risk – especially for less-expert customers, who may be relatively unfamiliar with the business of specifying electric motors – that the quest for ever-higher motor efficiencies diverts attention away from the area where most impact can be made, that is, in the energy consumed by the mechanical load itself.

Adopting, for example, a rare earth permanent magnet motor instead of an ordinary induction machine may raise the combined motor-inverter efficiency in a typical situation from (say) 90% to 93%, and we have reduced the energy-conversion losses by a very marketable 33%. However, the overall power consumption has only been reduced by about 3.3% – see Figure 10:

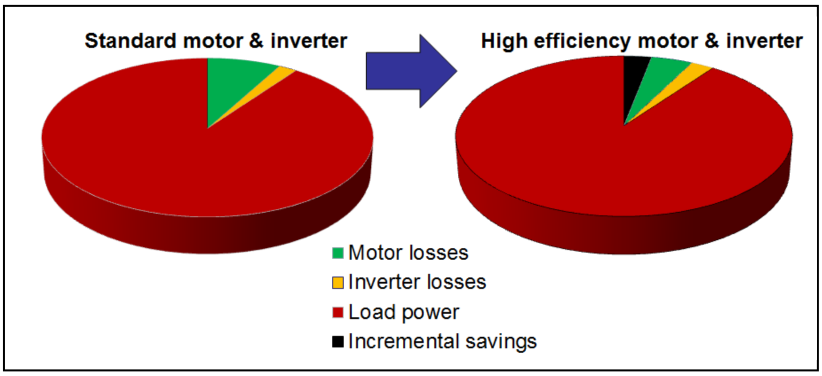


Figure 10: The majority of power is almost always consumed by the load!

The reduction in energy consumption described in the hypothetical scenario above is worthwhile, and in reality might well yield commercially-viable payback times (after taking into account the extra cost of the premium-efficiency solution).

However, we must not lose sight of the fact that the majority of power is, in both cases, consumed by the motor's mechanical load. If this can be reduced – for example by process or plant improvements, eliminating wasteful bypass or throttle valves, and by electronic control of motor speed to precisely meet process requirements and no more – then much greater energy savings may be possible. There is even perhaps a danger that the high capital cost and increased size of "super-premium" solutions might discourage some users from adopting variable speed at all, when in reality the majority of potential savings could be realised by changing from fixed-speed operation and/or mechanically managed variable flow (speed and load), to an electronic variable-speed solution of even modest efficiency ranking.

The situation is further complicated by the fact that many motors spend a great deal of time working at well below their full rated load. Under such partial load circumstances the efficiency of any motor is likely to be sub-optimal, and the benefits of high-efficiency motors are likely to be substantially reduced. In a 1998 motor market study [6], the U.S. Department of Energy estimated that more than 40% of polyphase motors operate below 40% load. Under these partial load conditions the efficiency delta between IE3 and IE4 motors – which are tested and rated at full load, under laboratory conditions – is very small. NEMA has estimated that the use of any of the motor/control technologies discussed in this paper, when compared to fixed speed induction motors with mechanical flow controls, could yield six times the energy savings (kWh) when used to manage partial load applications.

The Motor Section members of the NEMA (National Electrical Manufacturers Association) have joined forces with several other groups, including the American Council for an Energy Efficient Economy, the trade associations representing fans, pumps and compressors, and with power utilities and utility program managers to better quantify and identify the energy savings available from motor/control technologies as reviewed in this paper. The NEMA Motor and Controls Sections have initiated legislation in the USA to recognize the benefits that are gained through the application of any of these motor and power converter technologies promoting a "technology neutral" stance. Whilst the focus has long been limited to the motor efficiency as a component of the system, the US is now making great strides to move to a new stage of energy savings that far out performs these older methods, delivering exponentially greater results for Americans.

Of course, once all such savings in the mechanical load power really have been made, then the only scope for improvement may be in selecting a motor/inverter package that (when operating as a system) can deliver increased overall efficiency. But in our enthusiasm to develop ever-higher efficiency motors and inverters, we must not allow ourselves – nor, especially, our customers – to forget that "the lion's share is in the load".

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Copper Rotor Technology for High Efficiency Motors

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Abstract

The paper will introduce the recent progress in Copper Rotor Motor in China. The development of IE4 and IE4+ copper rotor motors are introduced, and the detailed performance analysis is given. A compacted motor design which use copper rotor for compressors and pumps is also introduced. A method which used rotor replacement technology to improve the installed motor efficiency will be presented. The total energy saving potential and the possibility to develop a new efficiency standard for the motor rebuilt will be discussed.

1. Introduction:

Small & Medium size squirrel-cage motors are most widely used in the world. The production volume is about 138,340 MW in China, 2013[1]. As is widely known, the conductivity of copper is about 40% higher than aluminum. By using copper motor rotors (CMR) to replace the traditional aluminum motor rotors (AMR), an improvement in motor efficiency can be expected. Based on copper rotors, super-efficiency or ultra-efficiency motors can be produced, especially in the area of small size motors. Motors can reach a higher level of efficiency in the same size by using copper rotors. It is one of the easiest and economical ways for motor manufacturers to meet IE4 and even IE5 efficiency.

Meanwhile, less motor losses means less electrical energy being converted to heat energy, and allowing the motor to operate at a lower temperature. This means that motors can use smaller fans or might not even need to use fans. It also serves to reduce the wind and friction losses, this all plays a role in improving motor efficiency. Higher operating temperatures will shorten motor life. For every 10°C rise in operating temperature, the insulation life will be reduced by one-half. So motors based on copper rotors can be expected have a longer life and higher stability.

Because of the good conductivity of copper, the current in copper rotors is smaller than aluminum rotors under the same inductive voltage. By using copper rotor, it is possible for motor manufactures to reduce motor physical size by 1 to 2 frame grades with the same power and efficiency. Together with the size reduction, the motor weight could be reduced by 20%-25%. An example for compressor driven motor will be given to illustrate the benefits in detail in this paper.

The copper rotor technology can be used to improve the installed motor efficiency. Beginning from 2010, the International copper association, Nanyang Motor and Yunnan Copper Die Casting Technology Co. Ltd have carried out research and development work of using copper rotor for in-use motor energy-efficiency improvement. The research results proved that the motor energy efficiency can achieve 1 to 3 percentage improvement after the aluminum rotor is replaced by the specially designed copper rotors, improving the motor energy efficiency levels by 1 to 2 grades, namely from energy efficiency grade IE1 to IE2 and even to IE3 [2].

Because of the advantages that CMR motors have, they also can provide flexibility to motor designers for developing new motors - we can focus on high efficiency, or low cost, small size, lower weight, or find the best solution to balance among these aspects.

Besides being used in industrial motor arena, the excellent characters of CMR makes it also very competitive in other areas, such as driven motor for electrical vehicles, submersible pump motors, crane & lift motors (brass rotor), high-speed spindle motors, etc.

2. The high efficiency motor market in China:

The motor production volume was declined in China due to the slowing down of global and Chinese economy. The total motor production volume is 198,310 MW in 2013, which is 91.2% of that in 2012. Table 1 gives the production volume from 2009 to 2013[1].

Table 1, Motor production volume in China

Year	Total Motor China Motor Market, New Built（MW）		
	Production Volume	AC Motor	DC Motor
2009	185,710	177,500	8,210
2010	206,230	196,910	9,320
2011	244,510	232,650	11,860
2012	217,550	207,680	9,870
2013	198,310	188,720	9,590

At present, IE2 and IE1 efficiency motor is still the major production in China. The high efficiency motor (IE3 & IE4) production volume is only 8% of the total motor market in 2013. The Chinese government has put a lot of efforts to improve the motor efficiency. The market share of high efficiency motor will be increased in the coming years. The copper rotor technology is one of the easiest and economical solutions to serve the growing demand for high energy performance in motors.

3. High efficiency motor (IE4 & IE5) development:

In order to improve motor efficiency, the usual way is to use more materials such as copper and electrical steel. But that will increase motor size. Due to standards there are limitations on motor center height or/and diameter. The materials that are needed to achieve these efficiency gains sometimes push the motors beyond the limits of the standards, especially in small motors. For small induction motors, in order to improve motor efficiency and reach the IE4 and even IE5 standards new methods and materials must be introduced.

Copper motor rotors are probably the best alternative to achieve this efficiency. When compared to using high quality electrical steel, copper rotor motors make it easier to control the whole production process and lower material cost. When compared to super-conduct material, copper motor rotors have a great cost advantage. It is possible for motor manufacturers to produce high or super efficiency motor without change their stator design too much based on copper rotor technology.

With the technology development, it is possible to produce copper rotors through the casting process. In addition it can be produced efficiently in both large and small scales. This allows copper rotor motors to be more competitive than other high efficiency motor solutions.

The conclusion is that copper motor rotors are one of the best ways to produce high efficiency motors, as well as gain small size, lower operation temperature additionally.

3.1 IE4 copper rotor induction motor

Nanyang motor Co. Ltd. has used copper rotor technology to develop IE4 induction motor successfully (YZTE4 Series). The frame size is from 80 to 250, the output power is from 0.75KW to 55KW.

The VZTE4- series super premium efficiency three phase induction motors (Frame HB0-250) are developed by copper rotor technology in line with IEC60034-30-1 Standards. which ratings, mounting dimensions and electrical performances meet the requirements of latest IEC Standards .These motors possess many remarkable features such as IE4 super premium efficiency, low noise, little vibration, large margin of safety in temperature rise, popular shape, safe and reliable operation. The detailed information of the YZTE4 series motor is as below:

Rated power: 0.75kW to 55kW

Frame Size: H80 – 250

Speed: 3000,1500 or 1000rpm @ 50Hz,

Insulation: Class F insulation with B rise @1.0 SF

Service factor: Service factor is 1.0

Phase: 3

Voltage: 380V ,415V,380/660V,440V @ 50Hz

Efficiency: IE4 (IEC60034-30-1,Super-Premium efficiency)

Protection: IP55 Protection

In the design procedure Nanyang motor optimized the entire design of the Copper rotor taking into account copper special characteristics. The electromagnetic density of copper rotor motors was designed larger than that of aluminum considering the higher efficiency and thermal conductivity of copper rotor motors. It improves the material use efficiency and reduces the motor size and cost.

The results shows copper rotor is one of the best ways to reach the IE4 efficiency . It makes it easy to improve the motor efficiency to reach higher level. For motor manufacturers, the copper rotors allow them to produce high efficiency motors without changing their current design too much with the cost advantage.

3.2 IE4+ copper rotor induction motor

Nanyang Motor Co. ltd. by cooperated with Yunnan Copper Die Casting Co. Ltd and International Copper Association to develop IE5 efficiency motor series based on copper rotor technology. In 2014, 4 types of IE4+ copper rotor motors were sent to attend the SEAD competition.

The Super-efficient Equipment and Appliance Deployment (SEAD) Initiative is a voluntary collaboration among governments working to promote the manufacture, purchase, and use of energy-efficient appliances, lighting, and equipment worldwide. SEAD is an initiative under the Clean Energy Ministerial (CEM) and a task of the International Partnership for Energy Efficiency Cooperation (IPEEC).

Table 2 shows the basic information about the IE4+ copper rotor motor to attend the SEAD motor efficiency competition.

Table 2, Basic information about the IE4+ copper rotor motors

Type	Frame	Pole	Power		Voltage (V)	Frequency (Hz)	Region
			KW	HP			
YZTE4	112M	4	4	--	415	50	Australia
YZTE4	160M	4	11	--	415	50	Australia
NSPE	184T	4	--	5	460	60	North America
NSPE	254T	4	--	15	460	60	North America

The competition requires a weighed efficiency which conclude the efficiency under different working load (25%、50%、75% and 100%). The efficiency was calculated based on the following formula:

$$\eta AVG=(0.05*\eta 25\%)+(0.20*\eta 50\%)+(0.40*\eta 75\%)+(0.35*\eta 100\%)$$

The efficiency calculation for the competition is different with the IEC standard. Please note that the efficiency listed here is based on the SEAD formula.

The following table gives the test result of the efficiency.

Table 3, Test results of IE4+ copper rotor motors[3]

Type	Tested Efficiency	Weighted Efficiency	Region
YZTE4-112M-4P 4kW 415V 50Hz	91.37%	91.16%	Australia
YZTE4-160M-4P 11kW 415V 50Hz	93.99%	93.3%	Australia
NSPE184T-4P 5HP 460V 60Hz	91.9%	91.22%	North America
NSPE254T-4P 15HP 460V 60Hz	93.62%	93.95%	North America

The tested efficiency listed in the table is measured according to IEEE112B. The other performance compliance with the N design (IEC motor) and NEMA B design (NEMA motor).

Copper rotor technology was selected in order to meet the IE4+ efficiency. As introduced, Nanyang motor has a lot of experience to develop high efficiency motor based on copper rotor technology. Nanyang has developed YZTE-4 series IE4 induction motor based on copper rotor technology.

Considering the copper rotor characteristic, the design for IE4+ series motor enlarged the magnetic density as well as electrical density of the motors. Meanwhile, the thermal duty was increased when compared with aluminum design.

The IE5 series motor has lower stray load loss. The stray load loss was only 0.6% of the input power by average based on the real testing results.

This is a good example to prove the induction motor efficiency can be improved to IE4+ or IE5 level by adopting copper rotor technology.

3.3 Special purpose motor development

As mentioned, copper rotor could reduce the motor physical size by 1 to 2 frame grade with the same power and efficiency. The table below shows the comparison between traditional aluminum rotor motor and copper rotor motor for the 75KW-2 compressor driven motors.

Table 3, Comparison between Cu rotor Vs. Al rotor for a 75KW-2 Motor

	Efficiency（%）	Frame Size	Steel in Stator (kg)
Copper Rotor	94.91%	225	300
Aluminum Rotor	93.8%	280	375

From the table we can see that motor frame size could be decreased by 2 grades by using copper rotor. Meanwhile, the efficiency could be improved from original 93.8% to 94.91%, which means the efficiency grade could be improved from IE2 to IE3.

4. Motor rebuilt with copper rotor technology

As one of the most important power equipments in the production and daily life, motors play the role of converting electric energy into mechanical one so as to drive mechanical equipment. The total electric power consumption of motor & motor system in China in 2010 was accounting for 75% of total electric power consumption in the industrial sectors.

It is just because of the high ratio of motor electric power consumption in the industrial field that the motor energy-efficiency improvement possesses such important significance in promoting the energy saving, environmental protection and sustainable development. If the motor efficiency can increase by 1 percent in China, the electric power saving can achieve 26.5 TWh valuing 26.5 billion yuan (US$4.27 billion), equivalent to carbon dioxide emission reduction of 26.5 million tons (1 ton CO_2/MWh).

To date, all the major countries in the world have formulated and implemented the minimum energy efficiency standards for motors (MEPS). These standards require that the energy efficiency levels of all the newly-made motors should reach the compulsory minimum energy efficiency standards. The standards' formulation and implementation greatly pushed forward the motor energy-saving promotion work. But the current standards only focus on the newly-made motors, and they have no impact on the motors already installed and in use. Because of the superiority in number, the motors already installed and in use consume much more electric power than the newly-made motors do. If the efficiency of the motors already installed and in use can be improved, the motor energy-saving work will be effectively promoted.

The mechanisms of encouragement and compulsory eliminations are the dominant measures adopted in China to accelerate the substitution of installed low-efficiency old motors so as to increase the motor efficiency level and reduce motor energy consumption. But these mechanisms mainly depend on the administration order. It is relatively difficult to promote these mechanisms in large scale without the financial subsidy support. In addition, the difficulties to recycle the large quantities of eliminated old motors increase. As a result, the impact on the environment increases.

The International Copper Association (ICA) in cooperation with the Yunnan Copper Die Casting Technology Co., Ltd. (YCD) and Nanyang Motor Co. Ltd put forward the scheme of using cast copper rotor to renovate low-efficiency motors for motor efficiency improvement for the first time. Beginning from 2010, the three sides jointly carried out research and development work of using copper rotor for in-use motor energy-efficiency improvement. The research results proved that the motor energy efficiency can achieve 1 to 3 percentage improvement after the aluminum rotor is replaced by the specially designed copper rotors, improving the motor energy efficiency levels by 1 to 2 grades, namely from energy efficiency grade IE1 to IE2 and even to IE3, so as to achieve the renovation process from low-efficiency to high-efficiency motors.

The research results also proved that this method is simple and feasible. Compared with compulsory replacement of original old motors, this method can effectively reduce resource and energy consumption as well as discharge of the wastes for environmental protection, not only achieving energy saving and emission reduction, but also turning the waste materials into useful ones to prevent energy consumption for the recycling, smelting and processing of the waste materials which complies with the national industrial policies of resources saving and comprehensive application. The cost of using copper rotor is greatly lower than that of using the newly-made motor in replace of the old one, greatly shortening the period of return on investment which no doubt can arouse the end users' enthusiasm and greatly reduce the promotion difficulties in the in-use motor efficiency improvement.

In 2014, copper rotor technology was listed into the “The National Key Promotional Catalogue of Advanced Motor Technology “by MIIT(Ministry of Industry & Information Technology) in China, the catalogue includes 25 selected advanced motor technology. The copper rotor technology (rotor replacement) was the only one for motor re-built.

Supported by the government, 2 pilot projects were ongoing to rebuilt the installed motor by using copper rotor technology, the total rebuilt motor number is around 1500 units for the 2 projects.

5. Conclusion

Through the above introduction, it is clear that motors and motor system have a great energy saving potential, and cast copper rotor is the simplest and most effective way of improving motor efficiency. In China, the process of producing cast copper rotors based on horizon casting machine has been mature and proven, producing massively cast copper motors with economics. By adopting copper rotor technology, motor manufacturers can produce IE4 and IE4+ induction motor. It is also possible to reduce the motor physical size and weight with the same output power by adopting copper rotor technology. The method of replacing the in-use motor's aluminum rotor with the copper one can effectively improve the efficiency of the in-use motor. This method possesses the superiorities of sample operation, high reliability, low cost and short period of the return on investment.

It is inevitable that copper rotor technology will greatly adopted to promote motor's efficiency level reduce the energy consumption, protect the environment and promote the sustainable development.

Reference:

[1] The report of Chinese motor market research, ACMR, 2014.

[2] Daniel Liang, Yang Xu, Yu Jiabin, Victor Zhou, A New Method to improve Installed Motor Efficiency, EEMODS 2013.

[3] Yu Jianbin, The development of the super high efficiency motor based on copper rotor technology, Motor & motor control system, 2014.

Facing the challenges of efficiency and sustainability with the low energy density permanent magnet assisted synchronous reluctance motor and its associated electronic inverter.

Régis Giraud, Cédric Plasse - Leroy-Somer

Introduction

Electrical machines have been invented in the 19th century. Different types of machines have been proposed. Technology evolutions have led to significant evolutions in magnetic and insulation materials, as well as winding techniques, leading to improved performance.

More recently, the discovery of the transistor and the deployment of power electronic converters have enabled the development of permanent magnet machines which need a position sensor and an "electronic commutator".

Today, permanent magnet machines are mostly used in manufacturing automation applications for their high torque to inertia ratio and in battery powered vehicles where low weight, high power and high efficiency are valued.

Their high efficiency compared to the mass produced induction machine allows energy savings in many process applications. Nevertheless, the rare earth magnet price volatility and environmentally unfriendly production process do limit the large-scale introduction of this technology.

In this paper, we will present the development which is being done by Leroy-Somer to propose a full range of Ferrite magnet assisted synchronous reluctance motors with position sensor less electronic inverter drives. The 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. Design optimization with NdFeB magnet is also considered for application where very high power density is required.

After a brief introduction, we will overview the technology and design tools improvements which have happened from the invention of the electrical machine till today. Then we will have a quick look at the market evolution and the user needs. In the third paragraph, we will share our design approach. Thanks to a multi-physic model, the design of the machine and its associated electronic inverter are optimized, taking into account supply chain and manufacturing constraints.

The design optimization methodology presented in the third paragraph has been developed by Leroy-Somer in co-operation with French Universities "Supelec" and "Art et Métiers" through Leroy-Somer sponsored PhDs.

1. Technology and design tools improvements

Electrical machines have been invented in the 19th century. Both synchronous and induction machines have been used in generator mode for electricity production as well as motor mode to provide mechanical power.

The Direct Current (DC) machine was invented to be able to work with direct voltage electricity sources such as batteries of accumulators. A mechanical commutator and at least two fixed brushes transform the direct current supply into rotating current vectors in the rotor reference frame which produce torque in motor mode or electrical energy in generator mode. The torque and the speed of the machine can then easily be controlled by adjusting the continuous voltage connected to the two brushes. Electronically controlled DC choppers which use power transistors and diodes to commutate the motor from a DC power source have been widely used in traction and automation applications such as train, elevators, conveyors and cranes to enable torque and speed control.

The main advantage of the DC machine is that it is very easy to control with this simple and cost effective electronic converter. Consequently, it has been the main solution to date for applications where speed or torque control is needed. However, its torque is limited by the maximum current density allowed by the brushes and its maximum speed is given by the ability of the mechanical commutator to carry current at high speeds.

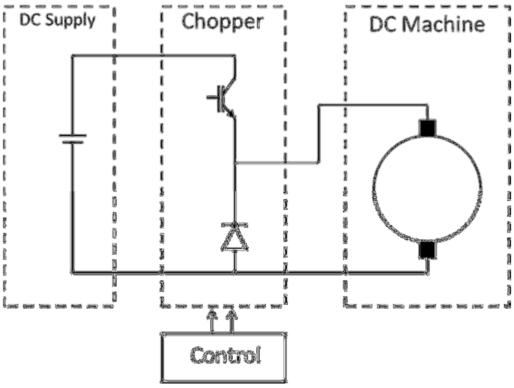

Figure 1: Chopper to control the DC Machine.

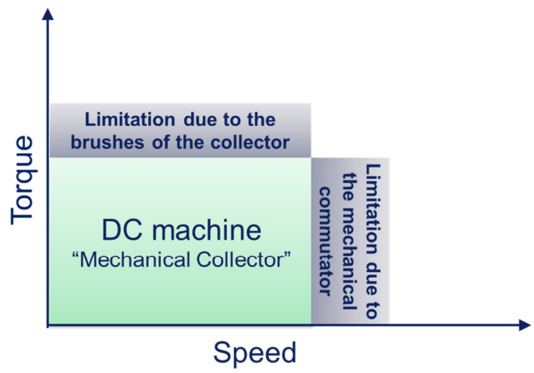

Figure 2: Limitations of the DC Machine.

Engineers have developed analytical models of the DC machine which are well adapted to optimize the geometry and the number of phases and poles of the magnetic circuit, taking into account the limitations imposed by the mechanical commutator.

The reduced cost of power electronic components and the increase of computation power of micro-controllers have enabled the invention of the "electronic commutator" which converts the DC voltage into a rotor position dependent Alternating Current (AC) voltage applied to the stator windings in order to produce torque. This type of power converter is known as an electronic frequency inverter, which allows the use of AC machines such as Induction, Permanent Magnet and Synchronous reluctance.

With the removal of the mechanical commutator, the maximum current is now limited by the electronic switches. Technologies such as MOSFET (Metal Oxide Semiconductor Field-Effect Transistor) or IGBT (Insulated Gate Bipolar Transistor) have such low conduction and switching losses that very high current in a very compact package is now possible. Consequently, the torque is only limited by the saturation effect in the iron of the magnetic circuit. Finite element models have been of great help to take into account the saturation effect in the optimization process of both synchronous and induction machines.

The switching speed of the MOSFET & IGBT switches is much smaller than that of the mechanical commutator. Consequently the maximum speed of the machine is then limited by the mechanical strength of the rotor and by the maximum losses due to the pulsating flux that occurs in the magnetic circuit which leads to “Iron losses”.

Mechanical finite element models have enabled engineers to design high speed rotors which withstand the high mechanical stresses caused by the centrifugal force.

The flux density level and the iron losses have also been calculated thanks to electromagnetic finite element models with the aim of optimizing the number of poles and the magnetic circuit geometry.

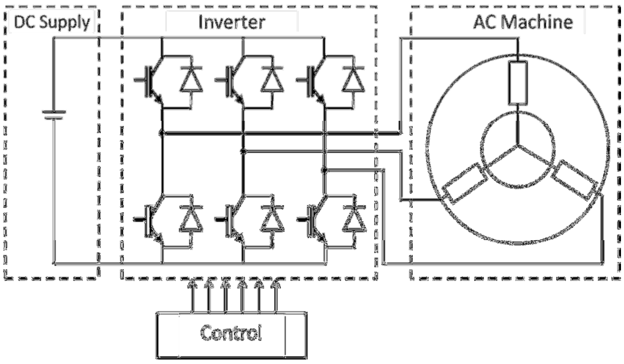

Figure 3: Inverter to control the AC Machine.

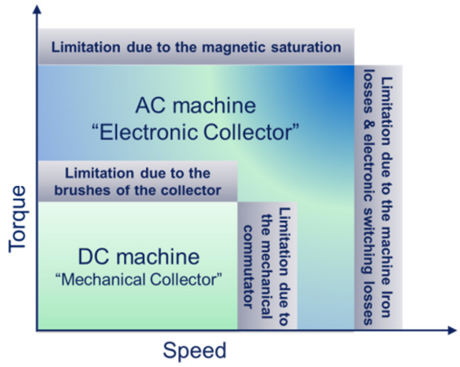

Figure 4: Limitations of the AC Machine.

The induction motor associated with an electronic inverter is since when the most popular solution for variable speed drive applications. The magnetic circuit can be the same as that of the fixed speed induction motor or can be specifically designed for inverter duty to reduce the cost of materials and increase the performances. In both cases, the user appreciates its robustness, ease of use and ease of control using a standard electronic inverter. In particular, a position sensor is not needed to reach the maximum torque because the torque, developed by rotor ‘slip’ with respect to the stator rotating field, naturally increases when the rotor speed decreases, resulting in a stable situation even when the load is not predictable.

Permanent magnet machines were initially used in manufacturing automation applications for their high torque to inertia ratio and in electric battery powered vehicles where low weight, high power and high efficiency are valued. However, they are more difficult to control, particularly when the position sensor is removed because, unlike the induction machine, the torque naturally decreases with the rotor speed.

Leroy-Somer has a long experience in permanent magnet machines such as servo-motors and torque motors for Manufacturing and Automation applications. Permanent magnets provide a high torque and low rotor inertia enabling high dynamic performance for robots. In elevator applications, a very high torque down to zero speed is possible thanks to permanent magnets, with very compact motors leading to easy installation in the machinery.

Figure 5: Servo-motor & Unidrive offer.

Figure 6: Elevator motor & drive package.

More recently, Leroy-Somer has introduced on the market a complete range of industrial permanent magnet motors and electronic drives “Dyneo” from 5 to 500 kW with high efficiency and position sensor-less control. Their high efficiency compared to the mass produced induction machine allows for energy savings in many process applications (such as fans, pumps and compressors) working 24h a day, 365 days a year.

The Dyneo range consists of the “LSRPM” permanent magnet motor associated with the “Powerdrive” inverter. The rare earth magnet 8 pole rotor with flux concentration which provides a high torque with very low rotor losses can be offered in highly compact motors and in standard size motors off-the-shelf (delivery in 5 to 10 days depending on the part number).

Thanks to a rotor position observer able to calculate the position of the rotor in real time, rotor position sensor-less operation is possible with full rated torque for fan, pumps and compressor applications. The set-up is as easy and as fast as for an induction motor thanks to an optimized control firmware.

Figure 7: Dyneo motor & Powerdrive offer.

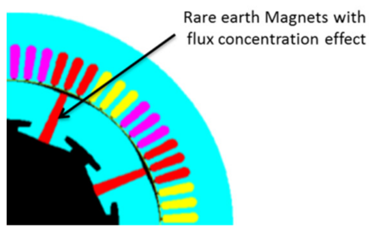

Figure 8: Flux concentration of PM motor.

Nevertheless, the rare earth magnet price volatility due to the Chinese monopoly as shown on figures 11 and 12, and their environmentally unfriendly extraction process have limited the introduction of this permanent magnet machine technology on a large scale for industrial applications.

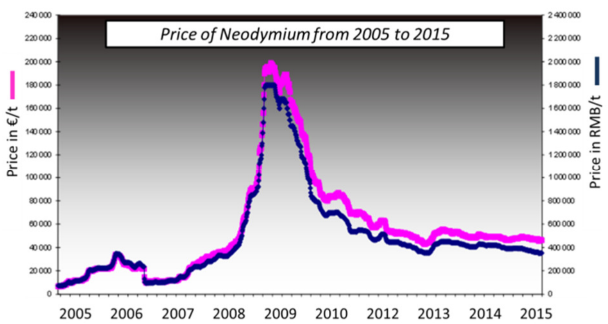

Figure 11: Price evolution of Neodymium.

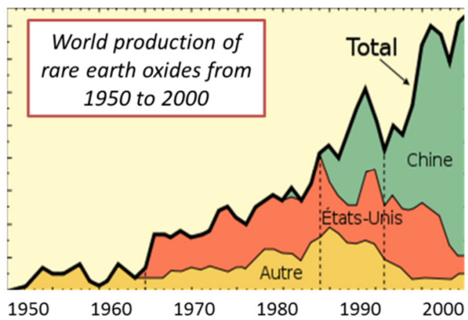

Figure 12: Production of rare earth oxide.

Leroy-Somer has confronted this situation by developing a range of permanent magnet assisted synchronous reluctance motors with position sensor less electronic inverter drive. The proposed optimized package provides the same high torque and high efficiency as today’s rare earth permanent magnet motor and is just as robust, as reliable, as easy to use and as environmentally friendly as the induction machine.

Electric Vehicles

Electric vehicles have always valued high efficiency motors due to the limited energy stored in the very expensive battery of accumulators. Thus, the technology and design tool improvements which have occurred in this field have always been in advance compared to those for industrial motors.

In 1899, Monsieur PATAY is authorized by a special law to drive his "electrical engine vehicle" (PATAY is now part of Leroy-Somer). Its DC motor supplied by a Lead-acid battery powered the vehicle to 105 km/h in 1899.

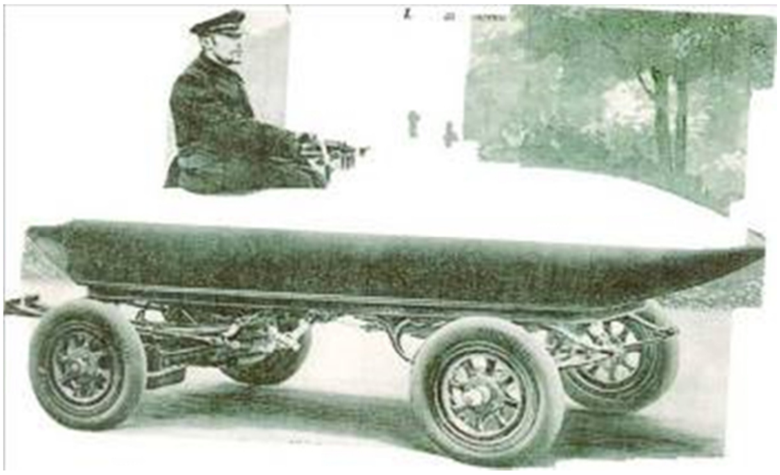

Figure 13: The "Jamais Contente", of Camille JENATZY.

From 1995 to 2000, Leroy-Somer has produced more than 10 000 DC Motors with transaxle transmission to power the Peugeot 106, Saxo, Berlingo and Partner vehicles. The power density was less than 1 kW/kg due to torque and speed limitation of the mechanical commutator as discussed earlier. Engineers designed the motors using analytical design tools and achieved a 75% maximum efficiency.

In 2000-2002, 1000 AC synchronous motors with a rotor excitation coil were produced to power the Renault Kangoo Express. The "electronic commutator" made by the inverter and a position sensor allows a higher maximum speed, only limited by the mechanical fatigue of the rotor which has been designed using finite element analysis. The maximum torque is determined by the inverter current capability and magnetic saturation in both the rotor and the stator. Magnetic finite element optimization led to a design with a specific torque of 4 Nm/kg. The maximum efficiency is 92% and 90% is achieved over a wide torque speed range.

More recently, despite lower torque and efficiency, induction motors have been proposed to reduce the cost. Performance is quite good with 3 N.m/kg and maximum efficiency up to 90% thanks to multi-physic models and optimization of the motor and electronic inverter system.

High-efficiency over a wide operating region compared to the induction motor has led to the widespread adoption of permanent motor technology for battery electric vehicles. Consequently, Dyneo technology has been adapted to power the electric Bolloré Blue Car used for Autolib car-sharing service in Paris as shown on figures 14 and 15.

Figure 14: Motor & Gear of the Blue Car.

Figure 15: Bolloré Blue Car.

The active motor components have been housed in a water cooled jacket and optimized together with the electronic inverter control laws for reduced losses over the vehicle drive cycle operating area. The maximum efficiency is 95%. A rare earth magnet rotor with flux concentration leads to a power density which exceeds 1,2 kW/kg and a specific torque of 4.5 Nm/kg. This leads to a competitive 40kg motor able to deliver 50 kW from 4000 to 13 000 rpm.

Figure 16 is a summary of both motor technology improvements and their associated design tools. The most recent is the permanent magnet assisted synchronous reluctance design where both motor and inverter are optimized using stochastic algorithms.

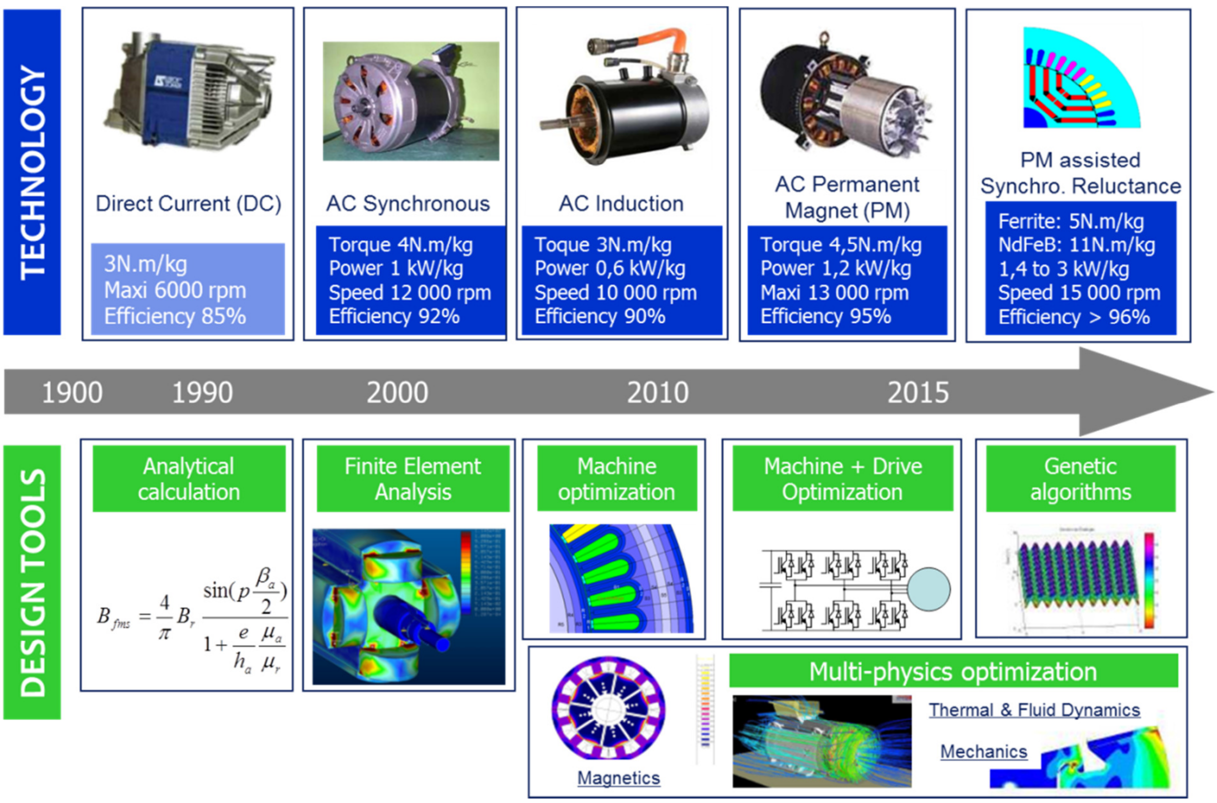

Figure 16: Motor technology and design tools evolution for battery powered electric vehicles.

2. Market analysis and user needs

Historically, the induction motors' ability to start on a 50/60Hz supply using an adapted squirrel cage rotor has made this solution the most cost effective and most popular for process applications where variable-speed operation is not required.

For manufacturing applications where torque or speed control is required, the induction motor associated with an electronic inverter is a robust and easy to use solution. However, permanent magnet motors are often preferred because they provide a higher throughput time and better productivity thanks to their high torque to inertia ratio.
Synchronous permanent magnet motors have also gained popularity in battery powered vehicles where low weight and high efficiency are important vehicle system level benefits.

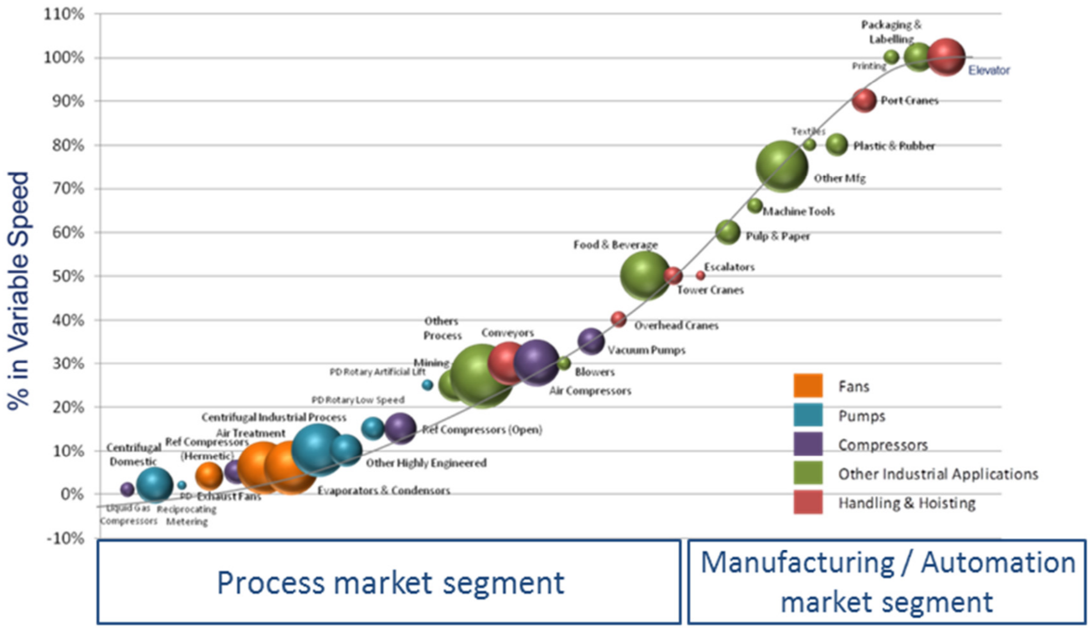

Figure 17: Variable speed penetration in different market segments and applications.

The trend to reduce energy consumption combined with lower power electronic costs leads to a shorter payback for variable-speed motor and inverter solutions in the process market segment.

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. 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.

3. The permanent magnet assisted synchronous reluctance machine

The permanent magnet assisted synchronous reluctance machine is an interesting alternative to the pure permanent magnet machine because its electromagnetic torque is mainly produced by rotor saliency. Therefore it is possible to use low energy permanent magnets such as Ferrite, with a stable low cost since they do not contain rare earth materials and are produced by several competing suppliers located in different geographical areas. The use of magnets provides a better power factor and a higher power density compared to similar structures which do not use magnets such as the synchronous reluctance motor.

Figure 18 shows how the permanent magnet assisted synchronous reluctance motor combines the torque produced by the magnets $E\ I\cos(\alpha)$ and the one produced by the rotor saliency $(Xq - Xd)\ I^2 \sin(\alpha)\cos(\alpha)$, where α is the load angle between the current I and the back electromagnetic force E.

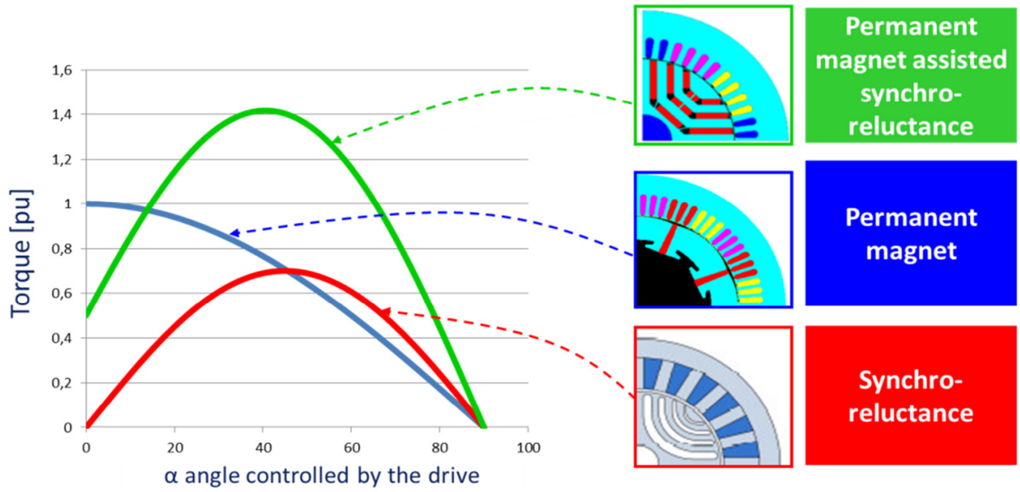

Figure 18: Torque of 3 different synchronous machines types

The optimization of a complete motor range requires a lot of calculations. Consequently, a multi-physics 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.

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 [2].

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.

a. Multi-physic analytical model

For most industrial applications the permanent magnet assisted synchronous reluctance machine is controlled by a PWM voltage source inverter as shown in figure 19.

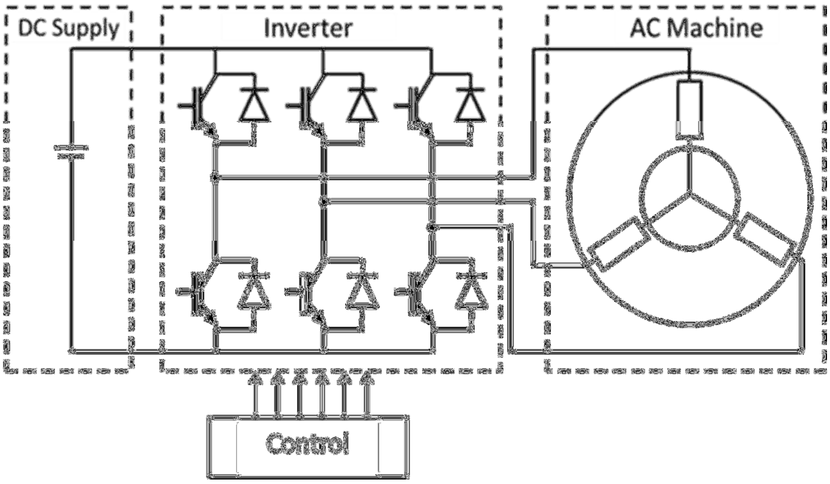

Figure 19: Model of the system Machine + Inverter + DC Supply

In order to optimize the system machine + electronic inverter cost, the power density and the total losses, two models are developed: one for the inverter and one for the machine. The parameters of each model which influence the performance of the other model are identified.

i. Inverter Model

The model consists of a 3-phase PWM inverter bridge.

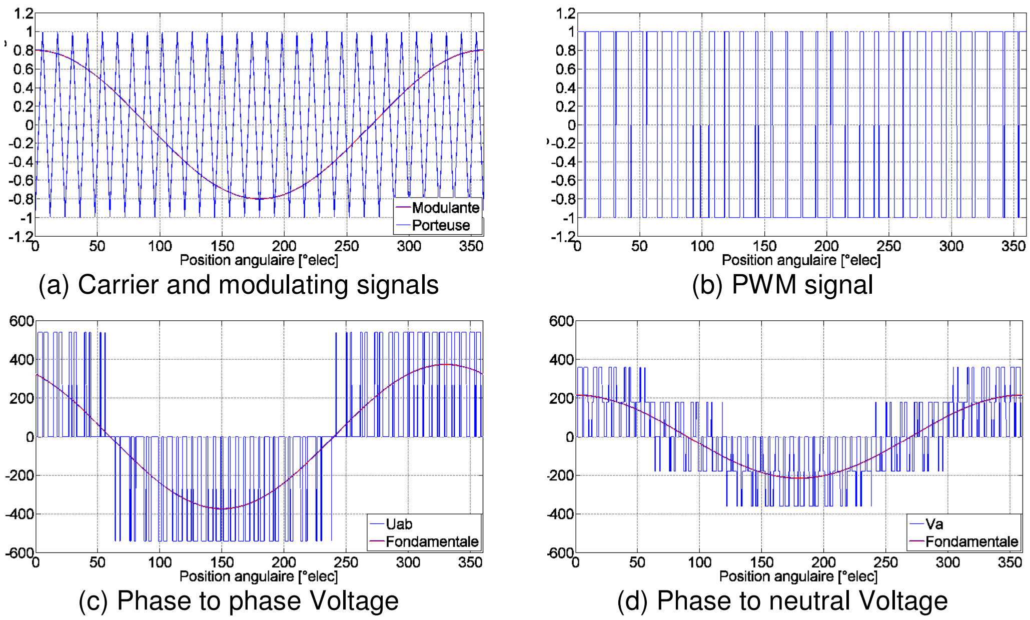

Figure 20: PWM generation for the voltage source inverter.

Each switch is composed of one IGBT and one anti-parallel diode. For simplification purpose, the control is a conventional sine-triangle PWM as shown of figure 20. The losses are also calculated and take into account the connection losses, the conduction losses and the switching losses in both the IGBT and the diode.

A thermal model gives the junction temperatures of the IGBT and diodes as a function of the case temperature. This model is valid for steady state operation as the time constant of the IGBT and diode are much shorter than that of the machine.

A cost model includes the maximum current ratings of the active components (IGBT and diodes) and of the passive (Capacitors) components as well as the cost of the control board. The inverter maximum current rating is treated as a discrete parameter during the optimization process.

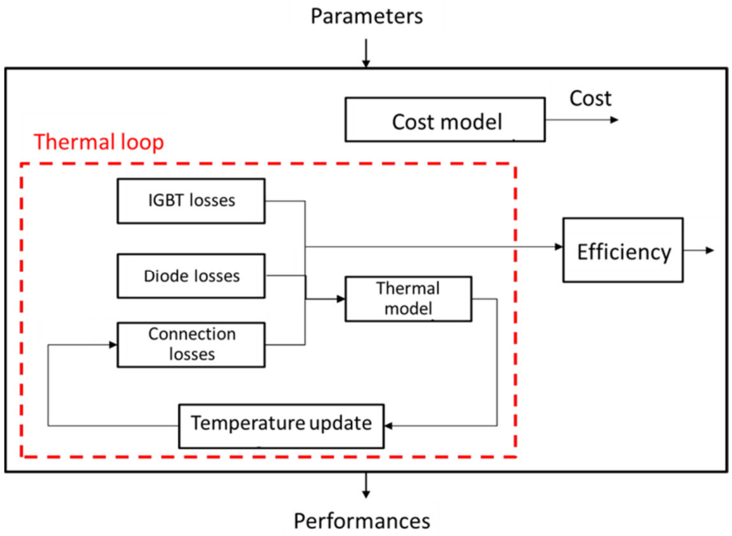

Figure 21: Coupling of the different models of the inverter.

The initial choice of the IGBT current rating is the one which just exceeds the maximum current of the inverter. If the junction temperature of the IGBT is below the maximum allowed temperature (to ensure reliable operation of the device over the required lifetime), the rating is reduced until the junction temperature of the IGBT is just below the limit. If the junction temperature of the IGBT is over the limit, the rating of the inverter is increased until the junction temperature is just below the maximum allowed temperature.

ii. Machine Model

The multi-physics model of the motor is a combination of the following models:

- Electromagnetic model: calculation of the electromagnetic torque, internal power factor and internal voltage,
- Electrical model: calculation of the power factor and phase voltage,
- Loss model: calculation of the Resistive losses, Iron losses and mechanical losses,
- Thermal model: calculation of the winding and magnet temperatures,
- Mechanical model: calculation of the stress in the rotor poles
- Cost model: calculation of the winding, magnets and Iron material costs.

1. Electromagnetic model

The motor under study consists of a standard distributed stator, identical to that of the induction motor. The rotor has four poles and three flux barriers per pole. The machine is supplied by a set of three phase sinusoidal voltages from the inverter. The magneto motive force produced by the resulting current which flows in the distributed winding is proportional to the current amplitude, the winding coefficients and the number of turns in series per phase. This leads to a rotating, sinusoidally varying magneto-motive wave in the air gap.

Figure 22 shows a simplified picture with the fundamental of the current and the magneto motive force represented as a function of the angular position θ.

The permanent magnets are inserted into the flux barriers. Parts of the barriers are empty (air). The use of flux barriers requires several magnetic bridges in order to ensure the mechanical strength of the structure, particularly for high operating speed variations. These air gaps around the magnets and magnetic bridges must be taken into account in the model since they affect the air gap flux density and the motor performance

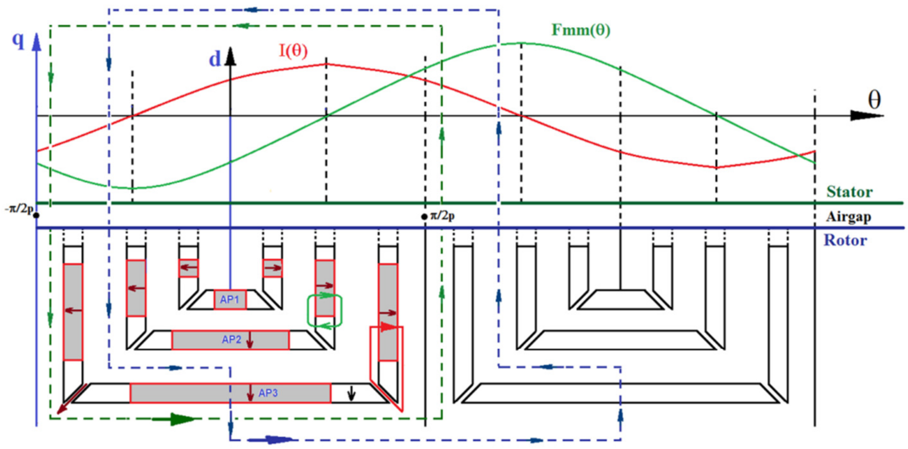

Figure 22: One pole pair of the permanent magnet assisted reluctance motor.

The flux density waveform in the air gap of the motor is determined using Maxwell equations: Ampere's theorem and the flux conservation law. This allows the electromagnetic torque and the internal voltage to be calculated as a function of the pole pair number and the flux barrier number.

Magneto motive force drops in the different regions of the magnetic circuit are calculated as a function of the air gap flux density, using Ampere's theorem, the flux conservation law and the magnetic material characteristics.

Ampère's theorem is applied to the main flux path through the rotor, the air gap and the stator as well as to the leakage flux paths going through the barrier air gaps and across the magnetic bridges. Saturation in the lamination steel is taken into account.

The flux conservation law is also applied along with the relationship between the flux density and the magnetizing force in the magnetic material characteristics.

2. Electric model

The internal voltage V*int* and the internal power factor cosϕ' have been calculated using the electromagnetic model. The aim of the electrical model is to calculate the machine phase voltage V and power factor cosϕ.

Figure 23 shows how the winding resistance R and the leakage impedance Xf can be taken into account.

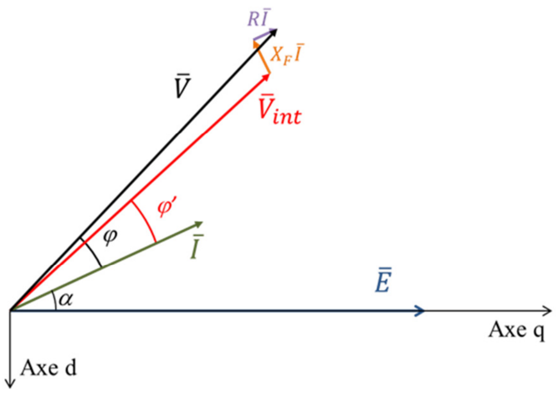

Figure 23: Vector diagram of the permanent magnet assisted reluctance motor.

The winding resistance can be calculated by well-known formulas involving the Copper resistivity, the average length of a turn of one coil, the wire diameter, the number of wires in parallel in a coil and the number of coil in series. The motor winding resistance is divided into two regions: the region which is located into the stator slots and the region in the winding end turns because their temperatures are very different as will be explained in the paragraph on thermal model below. The influence of the PWM on the resistance is taken into account in the loss model. The impedance Xf is due to the flux leakage in the winding end turns and is calculated as a separate parameter.

3. Loss model

The winding resistance increases due to high frequency harmonics generated by the PWM inverter. There are several conductors in series in each slot. Each conductor is made of several wires connected in parallel. The same total current flows through the conductor, but the currents in each wire are different. Maxwell's equations can be applied to each wire to calculate the current density to obtain the resistive losses in each wire. This allows the total resistance in AC condition of the winding of the motor to be determined.

The stator iron losses are the sum of the hysteresis loss, the eddy current loss and the excess loss components. A methodology has been developed to determine the coefficients of this so called Bertotti equation from the parameters given by the supplier of the lamination steel. The model takes into account the fact that the flux density in the stator is not sinusoidal as well as the effect of the PWM inverter supply. Then, the losses are calculated in the stator teeth and yoke as a function of the flux densities calculated using the electromagnetic model.

The rotor iron losses are caused by space harmonics on the surface of the rotor, due to the slot opening of the stator. A simple formula has been developed to determine the iron losses generated in each tooth of the rotor.

The mechanical losses include both the bearing losses and the windage losses which are mainly due to the fan. The windage losses are measured for different fan designs and vary with the rotating speed of the machine.

4. Thermal model

The losses calculated using the loss model produce heat, leading to a temperature rise of the machine.

A three dimension thermal model has been developed based on a nodal approach. This model takes into account the axial heat flow, to calculate the temperature gradient along the length of the machine winding. The thermal conduction in the radial direction of the machine is much higher than in the axial direction due to the laminations. The machine is assumed to be in steady state, so only the thermal resistances need to be considered.

All materials are characterized by conduction and convection heat transfer coefficients.

The thermal resistances of all components have been calculated by considering them as cylindrical or cuboid shapes of a unique known material with the exception of the stator slot area which is more difficult to determine since it is composed of copper wire, enamel, insulation paper, resin and air bubbles. Nevertheless, empirical formulae depending upon copper fill factor have been validated using experimental results.

Thermal convection in the air gap and between the frame and the external air include turbulent flow effects. The temperature estimation of the different components of the machine enables the coupling between the electrical model (impact on Copper resistivity), the magnetic model (impact on permanent magnets performances) and the thermal model (intensity of the loss sources).

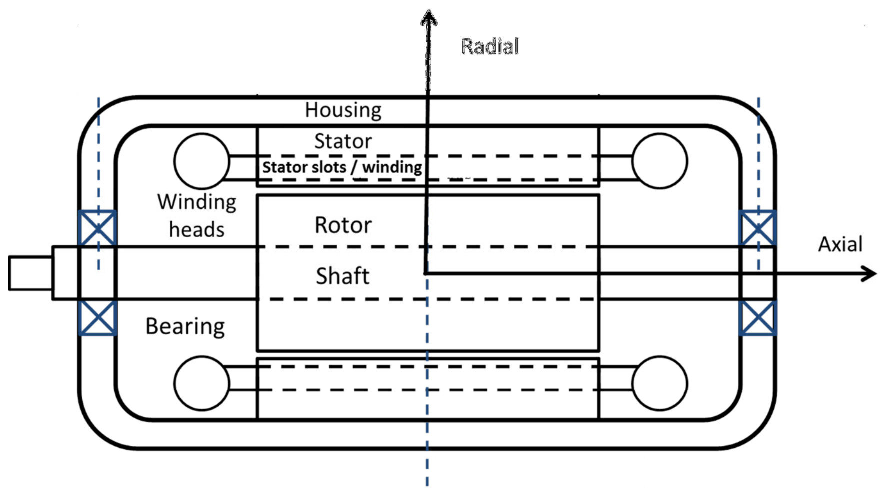

Figure 24: Sectional view of the permanent magnet assisted reluctance motor.

5. Mechanical model

An analytical model, based on material strength has been developed which takes into account both the maximum centrifugal force at maximum speed and mechanical fatigue due to speed cycling.

The rotor design is "monolithic" as shown in Figure 25. The flux barriers include bridges to ensure the robustness and the reliability of the motor, in particular at high speed and for cyclic speed operation.

It can be seen that each barrier has 2 radial and 2 tangential bridges.

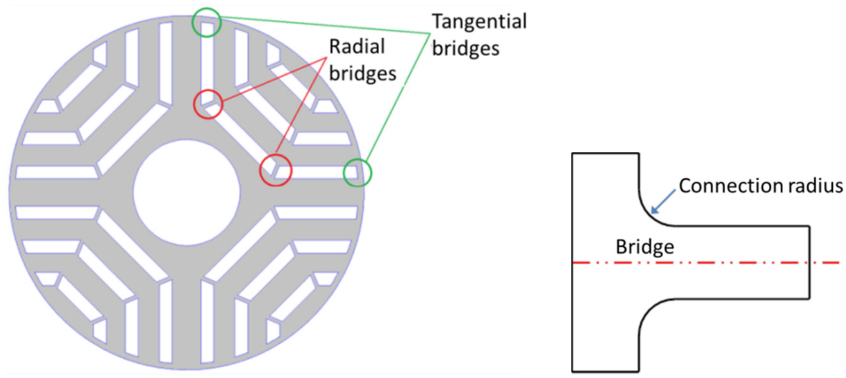

Figure 25: Rotor lamination of the permanent magnet assisted reluctance motor.

Once the bridge dimensions have been determined to ensure zero failure over the life duration of the motor for the expected speed cycles, particular attention is needed to the influence of the stamping process of the laminations at the bridge intersection. If the radius is too small, it produces additional stresses which can decrease the strength of the rotor. A factor has been chosen to taken into account this manufacturing constraint based on the expected worst case defect from the stamping process.

Other safety factors have been considered to take into account the material parameter spread as well as the model accuracy limits which have been validated during comparisons with endurance cycle test to failure.

6. Cost model

The geometry of the machine and the weight of all the components are known. The cost is estimated from the price per kg of the different materials.
A constant price per kg has been used for Ferrite magnets as this technology is very stable and sustainable. The use of NdFeB magnets is not excluded, depending on price and for applications where weight and size reduction are needed. Their cost per kg increases with the remnant flux density.

7. Multi-physic couple problem

The different models of the machine are connected together as shown in Figure 26.

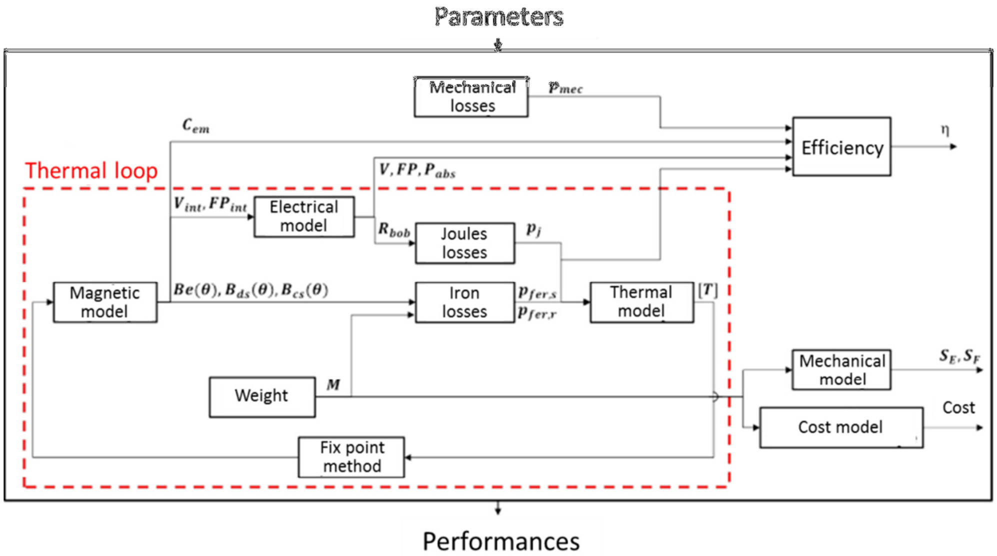

Figure 26: Coupling of the different models of the motor.

iii. Comparison with the finite element model

The machine used to validate the analytical model is a 4 pole Ferrite magnet assisted synchronous reluctance motor with a nominal current of 15A and a nominal speed of 3000rpm. The main characteristics of this machine are given by table 1.

Characteristic	Value
External stator diameter [mm]	150
Internal stator diameter [mm]	94
Shaft diameter [mm]	30
Air gap [mm]	0,42
Number of stator slots	48
Stack length [mm]	100
Winding overhang axial length [mm]	28
Number of pole	4
Number of flux barriers per pole]	3
Thickness of the barrier [mm]	4,25
Magnet thickness [mm]	4
Magnet type	Ferrite

Table 1: Main characteristics of the motor used for comparison with finite element model.

The results presented in the figures 27 to 32 validate the analytical model of the machine with the advantage that calculation step duration of 15s is used compared to 120s for the finite element method.

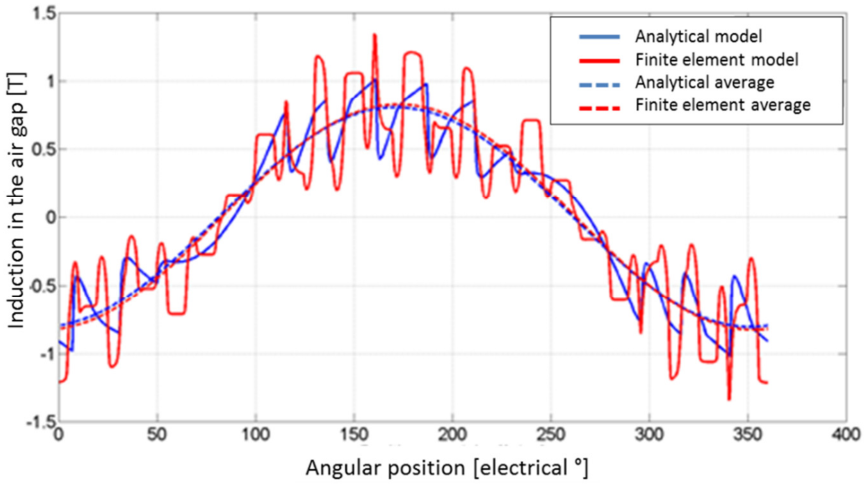

Figure 27: Air gap flux density calculated using the analytical and finite element models.

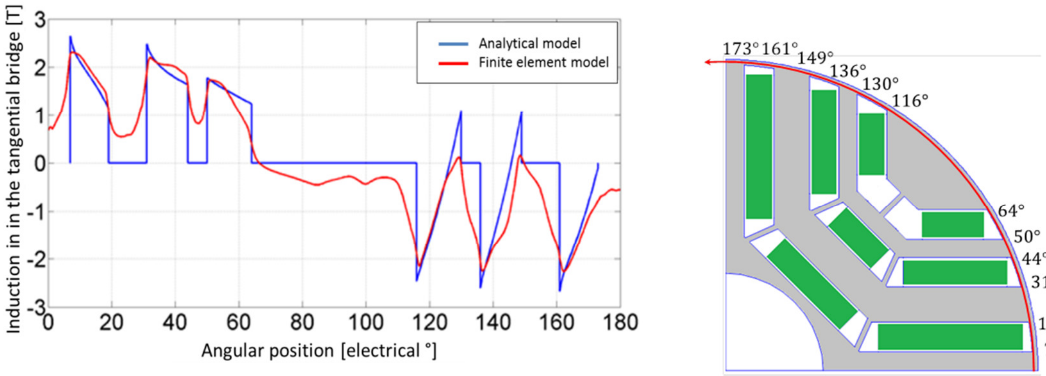

Figure 28: Tangential bridge flux density calculated using the analytical and finite element models.

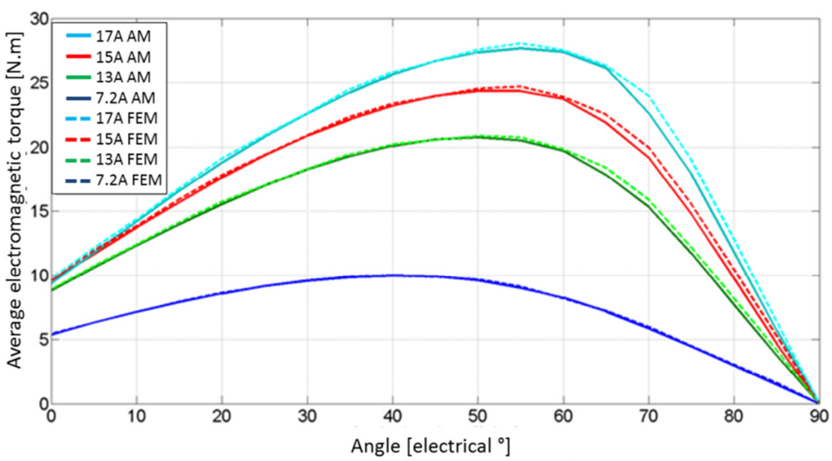

Figure 29: Electromagnetic torque calculated using the analytical and finite element models.

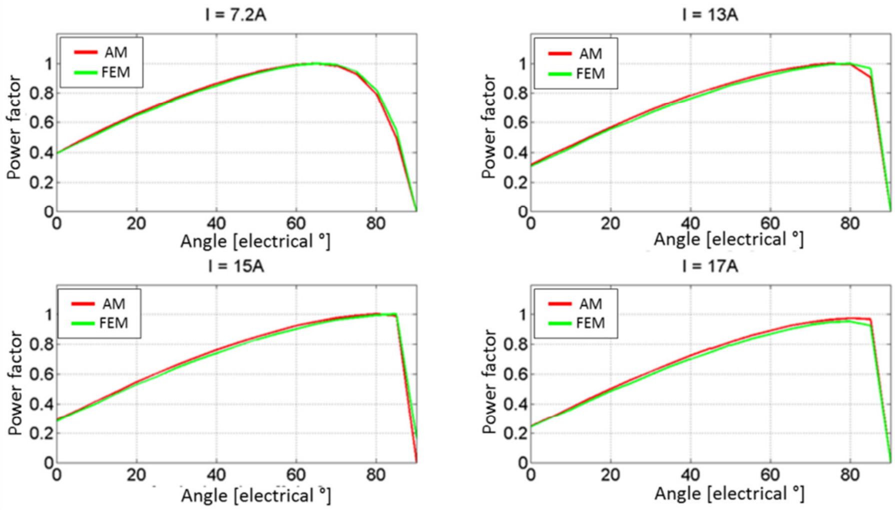

Figure 30: Power factor calculated using the analytical and finite element models.

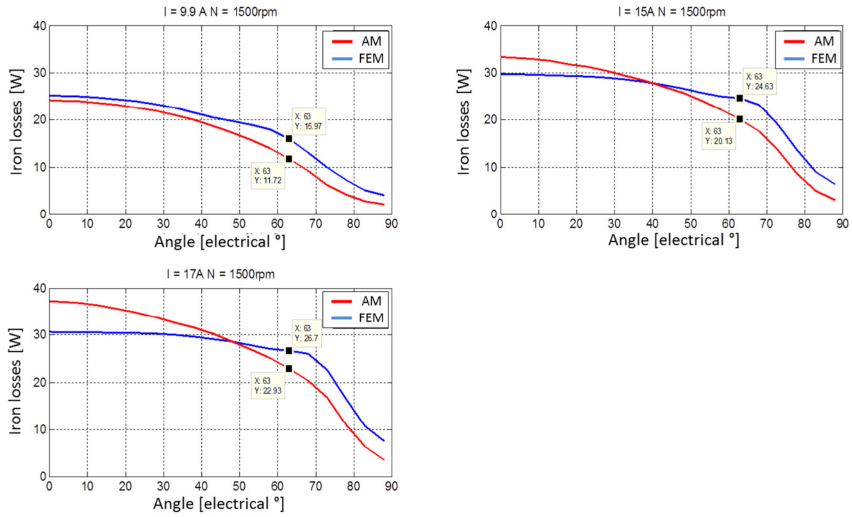

Figure 31: Stator Iron losses calculated using the analytical and finite element models.

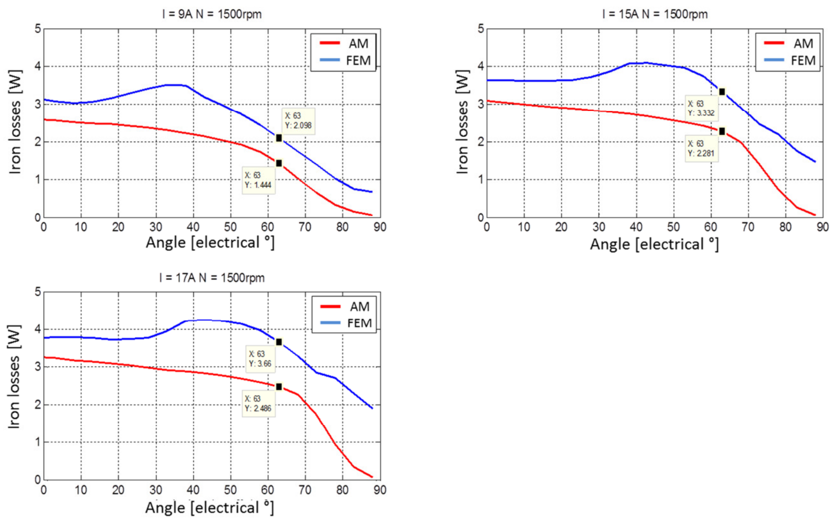

Figure 32: Rotor Iron losses calculated using the analytical and finite element models.

iv. Comparison with experimental results from a prototype

The machine used to validate the multi-physics analytical model is the same 4 pole ferrite magnet assisted reluctance motor already compared to the finite element model results.

The results presented in figures 33 to 36 validate the multi-physics analytical model using real test results.

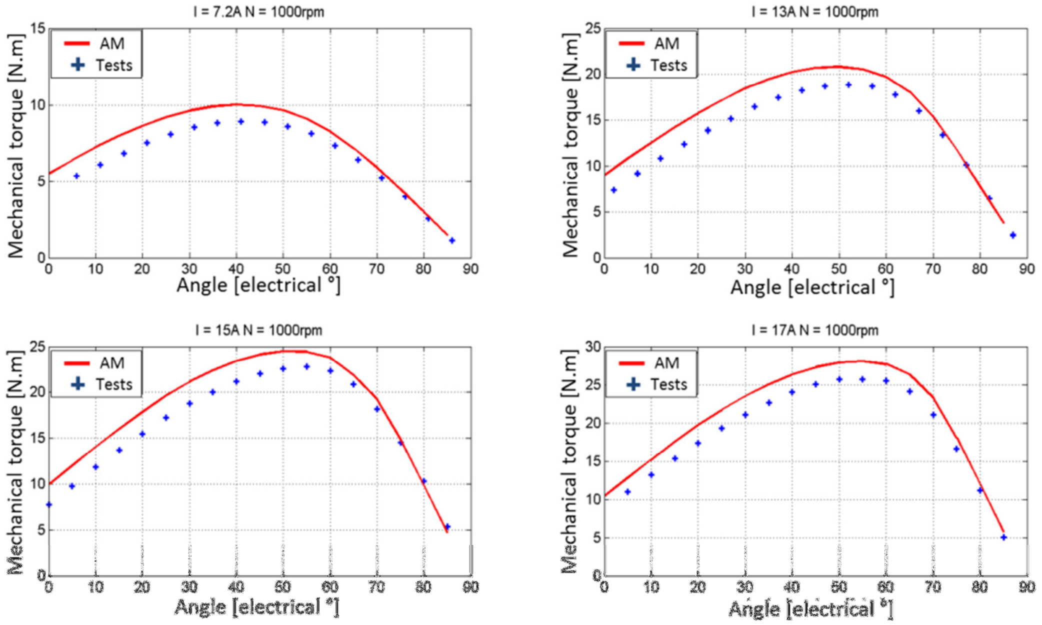

Figure 33: Mechanical torque calculated and measured on the prototype.

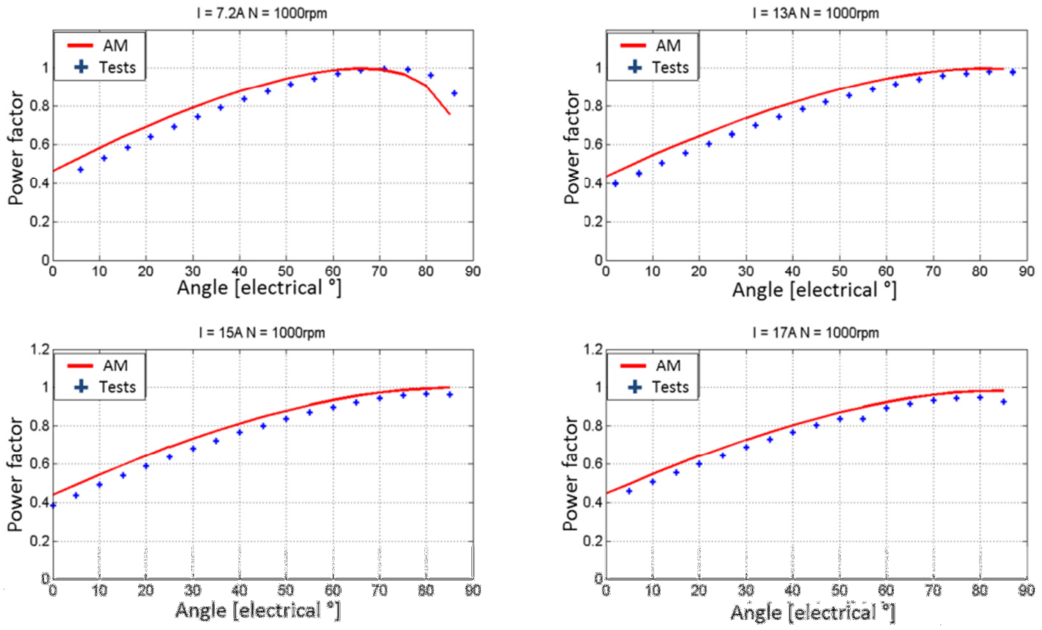

Figure 34: Power factor calculated and measured on the prototype.

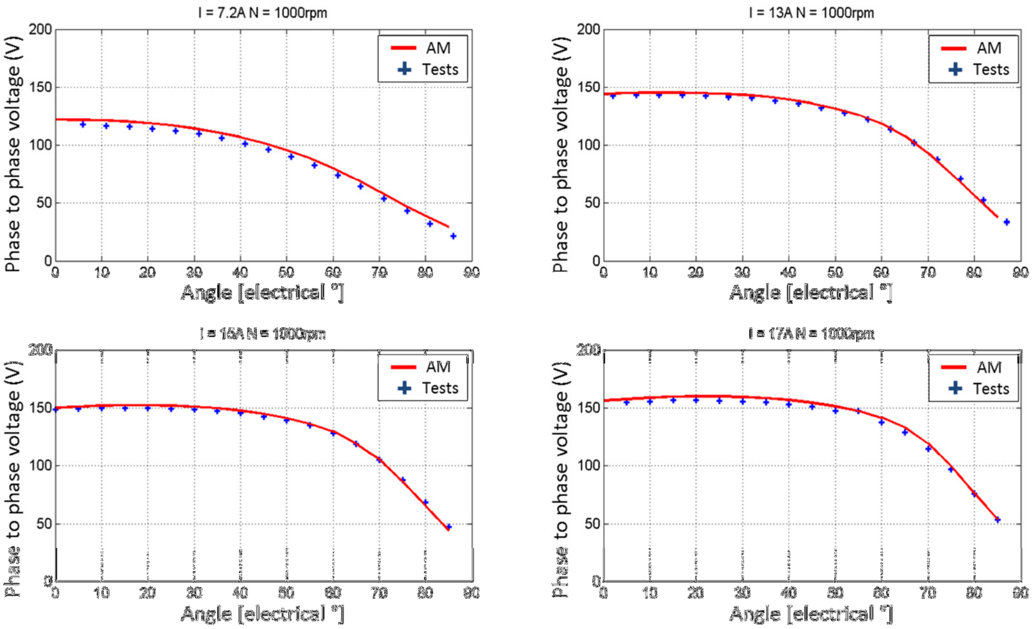

Figure 35: Phase to phase voltage calculated and measured on the prototype.

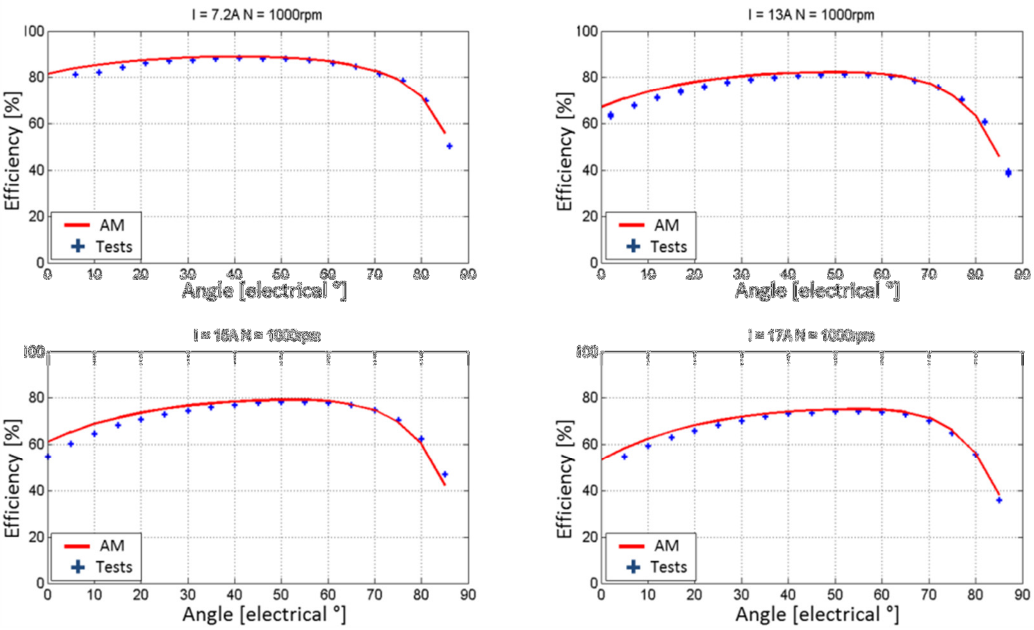

Figure 36: Efficiency calculated and measured on the prototype.

b. Machine and electronic drive range design optimization

In order to minimize the investments and the complexity, the objective is to have only one design for both process applications (where a standard size compared to induction motors and a high efficiency are required) and for manufacturing automation ones (where high power density and high peak torque are needed).

The selection of the design optimization algorithm will be presented followed by the technical specification of each application and an example of the optimized design.

i. Design optimization algorithms

Deterministic algorithms are the fastest. However, the results depend on the starting point and the objective function mathematical expression often needs to be known, which is difficult in this case.

Stochastic algorithms evolve toward the global optimum and thus are more adapted to this objective. The most well-known is the genetic algorithm where the process is similar to what would happen to a population who create babies who are subsequently tested and so on. The drawback of stochastic algorithms is that they are longer than deterministic algorithms. Nevertheless, the stochastic algorithms has been selected to take advantage of the reduced calculation step time of the analytical model.

ii. Objectives

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 table 2 for process and manufacturing / automation market segments.

User needs	Process	Manufacturing / Automation
Efficiency	IE4 to IE5	IE3 to IE4
Power density / Compactness	Interchangeable with induction	11 N.m/kg with rare earth magnets 5 N.m/kg with Ferrite grade 9
Constant power operation	No	Range speed 3
Short lead time	Component and manufacturing process re-use Lamination sheet and magnet standardization	
Easy and fast set-up as induction	Position sensor-less operation → saliency ratio > 1,3 Optimized control	
Robust and reliable as induction motor	Monolithic rotor → bridges design Motor and electronic components temperatures < Max ratings Position sensor-less operation → saliency ratio > 1,3	
Easy to maintain	Ferrite magnets	Less rare earth magnets Ferrite magnets
Environmentally friendly	Ferrite magnets	Less rare earth magnets Ferrite magnets
Power factor	Better than induction (> 0,9)	

Table 2: Objectives for process and manufacturing automation market segments.

iii. Results

The results are shown for a technical specification of 100 Nm at 3000 rpm.

Figure 37 shows the optimum geometries for each market segment. Obviously, they are quite different from one to the other.

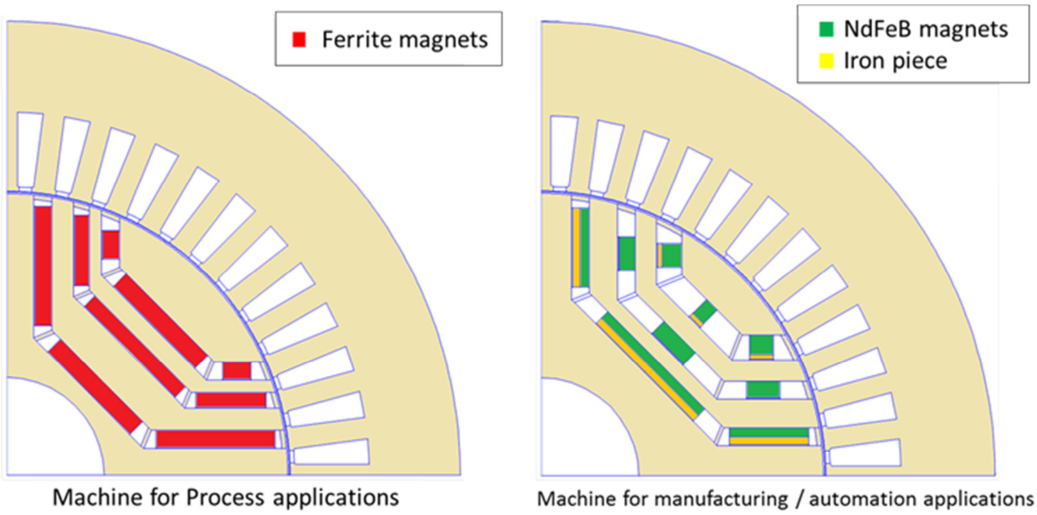

Figure 37: Optimum geometries for each market segment.

Figure 38 shows the optimum geometry which is the best trade-off for the 2 market segments. The laminations are identical. Only the magnets layout is different.

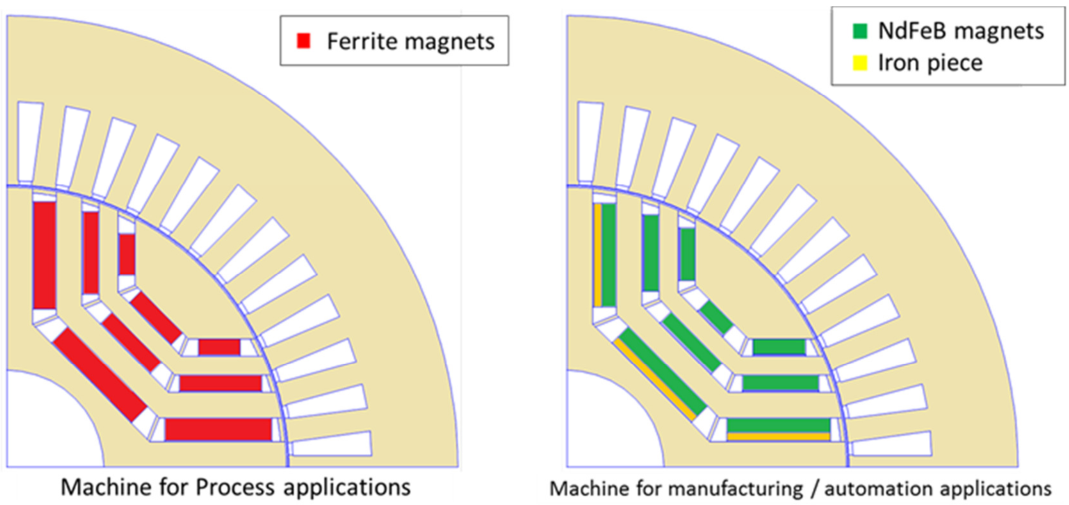

Figure 38: Optimum geometry for manufacturing / automation market segments.

Figure 39 shows a Pareto frontier with the optimum geometries for each market segment as well as the best trade-off for the 2 market segments.

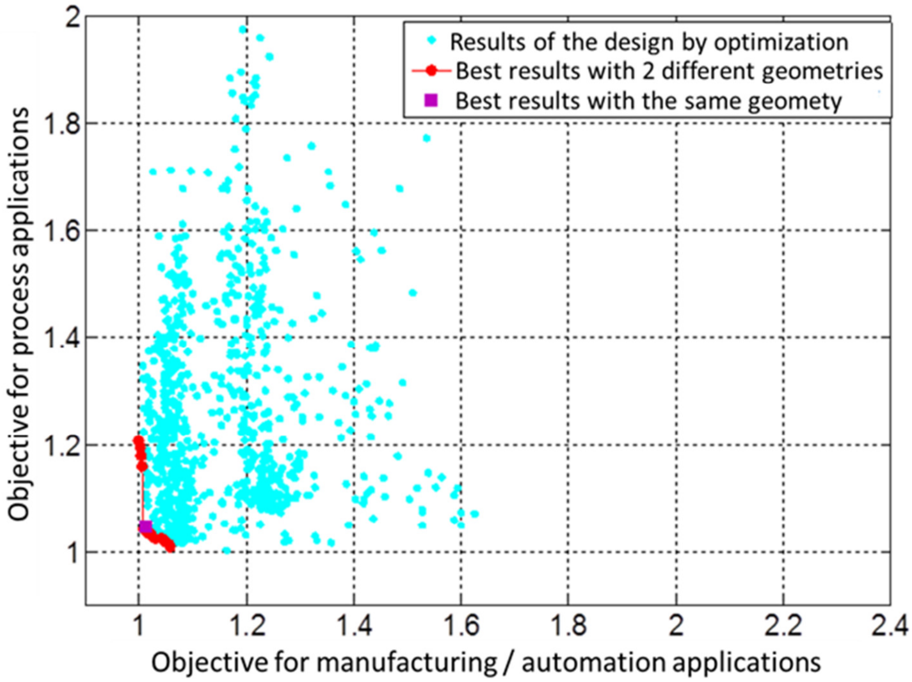

Figure 39: Pareto frontier of the optimum geometries for each application showing the best trade-off for both the process and manufacturing/ automation market segments.

c. Design for supply chain and manufacturing

The stator laminations have been standardized with one from the induction motor range in order to minimize the stamping tool and winding machine investments.

Mechanical components such as housings, shafts, bearings and flanges from the standard high volume induction motor range have been re-used for the process application permanent magnet assisted synchronous reluctance motor range.

For the manufacturing automation applications, as many parts as possible have also been re-used from the induction motor ranges, with smaller lamination diameters to reach the targeted power density.

The rotor laminations have been standardized and the high volume will allow flexible stamping tool investment and automation of the rotor stack assembly.

Finally, the magnet sizes have been standardized across different diameters. Only 9 different magnet part numbers will cover the entire range of permanent magnet assisted reluctance motors up to 500kW.

Conclusion

The rare earth permanent magnet assisted reluctance motor has already proven its superior torque density compared to the pure rare earth permanent magnet machine. An example for an electric battery powered vehicle is a water-cooled motor with a stator lamination diameter of 107mm and a length of 100mm which delivers a continuous torque of 38 Nm at 6000 rpm (24 kW) and a maximum torque of 75 Nm (49 kW). The maximum speed is 16 000 rpm.

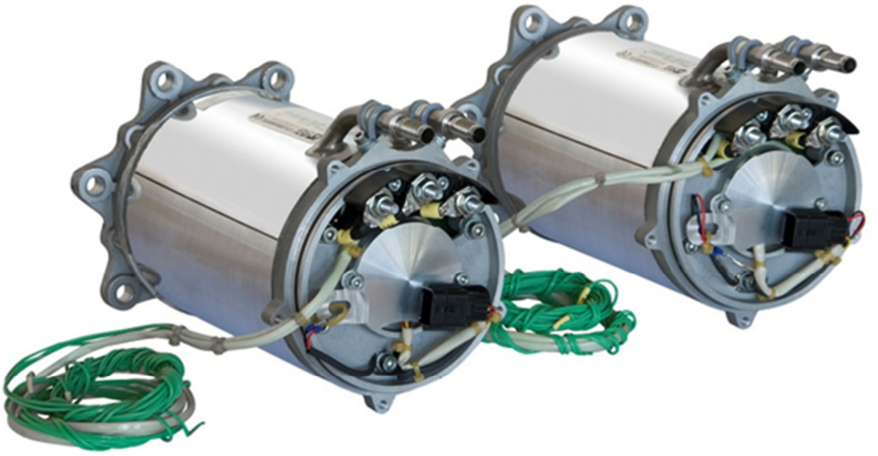

Figure 40: Prototype motors with a specific torque of 11 Nm/kg for an electric vehicle.

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.

A complete design process has been presented. Multi-physics analytical models of both the machine and the inverter and design optimization methods allow a complete motor range up to 500 kW to be optimized.

Both material cost and investment cost are used as constraints as along with component standardization and supply chain optimization to reduce the manufacturing lead times.

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ON THE EFFICIENCY OF HIGH SPEED PERMANENT MAGNET MOTORS WITH ACTIVE MAGNETIC BEARINGS DRIVEN BY A VFD FOR TURBO BLOWERS

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[1] SKF magnetic mechatronics

1. Abstract

In recent history the most common blower technology for supplying air at waste water treatment process (WWTPs) has been the multi-stage centrifugal blower, which is a blower where multiple impellers are mounted on a common rotor shaft. More recently, a new blower technology has come into use known as turbo blowers, which comprises a high-efficiency single impeller direct-driven by a high-speed permanent magnet synchronous motor (HSPMSM) and variable frequency drive (VFD) to achieve speed and airflow turndown.

This paper addresses the efficiency of air-air and air-water cooled HSPMSM with active magnetic bearings (AMBs) in the power range of 75 kW-300 kW. To estimate the efficiency, a dual supply back to back test was installed for each size. To reduce the uncertainties, highly accurate current probes (from Yokogawa and LEM) and power analyzers (from Yokogawa) were used. Moreover, to avoid discrepancies and uneven noise, the measurement was performed over a long time, recording the data each second. Unlike the method used on wound rotor synchronous motor, as described in IEC 60034-2 and IEEE 112, the efficiency was estimated with a small change on the approach. This is due to the permanent magnet technology that doesn't allow setting at the same time, voltages and currents identical in both machines (in the back to back test).

Keywords: efficiency, turbo blower, high speed permanent magnet motor, back to back test, high speed,

2. Introduction

Today, high speed turbo blowers (HSTBs) with active magnetic bearings (AMBs), become an integral piece of aeration system and a significant area of innovation in blower design, offering significant energy and cost savings for the wastewater industry [1]. The energy consumption of blowers is a function of air flow rate, discharge pressure, and equipment efficiency. Due to the HSPMSM and AMBs, together with respectively a VFD and amplifiers, HSTBs can operate at higher speeds, typically, between 18000 rpm and 60000 rpm with a high efficiency at rated operation and a good turndown capacity with little drop in efficiency. Besides efficiency, HSTBs present others advantages-small footprint, low vibration and low maintenance requirement. Figure (1) shows the usual range of power versus speed of turbo blowers installed in the market.

Since the last years, blower manufacturers think about ways to develop fair evaluation criteria and specifications that can be used to determine which blower technology offers the best energy efficiency. The industry is aware of the need for a new power evaluation and there are several efforts to present a "wire-to-air" specification to meet this need through ASME standards and ISO specifications. The term "wire-to-air" describes the total energy needed to produce the required flow and pressure [2].

There are many blower solutions and making an introduction of these technologies is upon this paper, however an overview of typical efficiencies achieved by blower technologies at full power is illustrated in figure (2).

Managing electric motor systems is one of the most important aspects of improving reliability and increasing energy efficiency in the industrial environment. There have been difficulties in accurately measuring the efficiency of electrical motors driven by VFDs [3]. While some experts claim accurate measurement of motor efficiency and shaft power is not feasible, others promote devices [4-5] and methods for loss determination [6-10].

Usually, methods of testing efficiency and temperature rise limits, using calibrated machine, torque measurement or back to back tests, is in accordance with the IEC 60034-2, IEEE 112 or NEMA standards. When direct testing is not possible, indirect testing such as the segregated losses method might be applied in accordance with the same standards. IEC 60034-29 summarizes the equivalent and indirect loading methods used for different machines (IMs, DC, and Synchronous).

The last decade has witnessed a substantial effort in harmonizing the different tests and classification standards (IEC, NEMA IEEE, CEMEP) resulting in major standards [11-15]. Besides Standards, a European regulation (EC) has established Eco design requirements for motors rated between 7.5 kW and 375 kW, by imposing an efficiency of at least IE3 for motor on grid and IE2 with a VFD [16-17]. However, none of the standards addresses HSPMSMs. Despite the increasing popularity of high speed applications, HSPMSMs were highly customized products without suitable standards. Today, the market for them has matured, it is then necessary to address these emerging technologies in more detail and develop standards accordingly.

The following section (3) recalls the main losses of a HSPMSM, it suggests a loss fraction of an air cooled HSPMSM and a comparison is done with a 4 pole squirrel cage induction motor (SCIM) [32] to highlight the loss trend.

Section (4) addresses the experimentation performed on different HSPMSM sizes. A dual supply back to back test has been performed at rated conditions and the efficiency has been deducted. In this section a change in the efficiency estimation method has been introduced to consider permanent magnet motor constraints.

In section (5), a global overview is given on the drive system efficiency usually obtained in the studied power range for blower technologies.

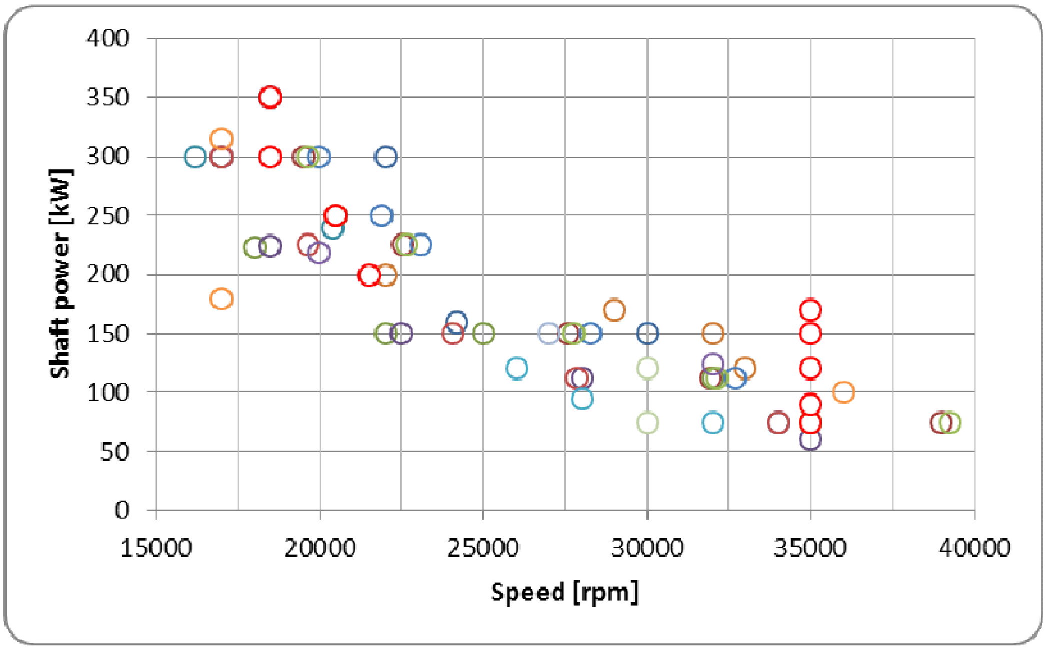


Figure 1 : Shaft power Vs speed trend in air turbo blower applications

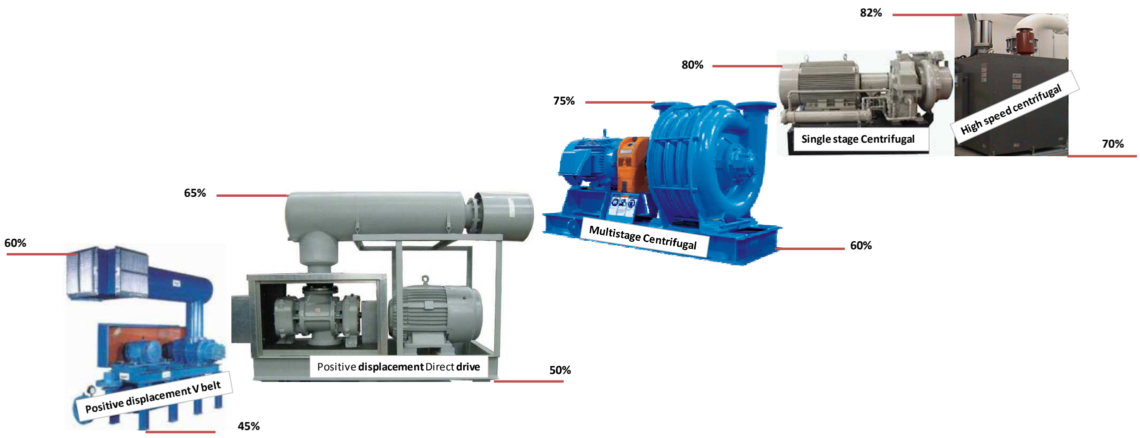


Figure 2 : Typical blower efficiencies (min and max) at rated conditions (power/speed)

3. Losses in HSPMSM

Drag and windage losses

Windage and drag losses are due to the velocity distribution in the airgap of electrical machines. They are controlled by the tangential flow due to rotor rotation, axial flow of the cooling gas through the airgap and the Taylor vortices due to centrifugal forces. Usually for high speed machines, the fluid is in turbulent flow conditions and then the windage coefficient C_w for rotating cylinders [18-20] or disk parts [20-21] can be expressed, by the inverse of Reynolds number $Re\delta$ powered by a fractional number. Besides windage coefficient and geometric dimensions, Drag & windage losses are proportional to the gas density and the cubic of rotational speed.

Rotor losses

In HSPMSMs with AMBs, rotor losses comprise both AMB rotor losses and magnet losses, these losses are purely electromagnetic losses.

AMB rotor losses

Usually active magnetic bearings use linearizing bias DC currents i_0 with superposed control currents i_c to obtain a linear characteristic of the AMB.

The AMBs rotor losses are mainly eddy and hysteresis losses due to rotational effects [22-23]. They both evolve with respect to the squared flux density. This flux density is proportional to $i_0 \pm i_c$. In steady state conditions, the behavior of the system (motor +AMBs) is assumed to be stable so that i_c is very small. Hence, the AMBs rotor losses are almost proportional to i_0^2.

Magnet losses

Magnets are subject to eddy current losses due to space harmonics, slotting and time harmonics of the stator current. Different approaches are usually adopted to reduce losses in magnets; circumferential segmentation [24-25] of PM has been considered as efficient methods of reduction of the eddy-current losses, in cases when pole-arc width and radial dimension of magnet segments are less than the skin depth of interest. Axial segmentation has also been proved beneficial for reduction of losses [26-27]. Analytical methods to optimize both circumferential and axial segmentation are proposed by some authors [28].

Stator Iron losses

In air cooled HSPSMS, iron/core loss plays an important role both in the improvement of the quality of electrical steels at the production stage and in the optimization of their operating conditions. These losses can represent more than 50% of the total losses in HSPMSM. Usually, in the frequency domain, loss separation is widely used with problems involving magnetic laminations. Loss separation splits the total core/iron loss into static hysteresis loss P_H, classical eddy current loss P_{Ec} and excess/anomalous loss P_{ex} [29].

Joule losses

Joule losses in HSPSMS can be dissociated in three parts as following:

Fundamental Joule losses

These losses are due to the electrical properties of the copper / aluminium and the fundamental (sinusoidal) component of the current flowing through it.

Time harmonic losses

HSPSMs driven by VFDs are subject of additional losses due to time harmonic components present in the current waveform. These harmonics are linked to the switching frequency. Despite the use of a sine filter, the minimum level of total harmonic distortion (THD) usually observed can achieve easily 5% and consequently at least 10% of additional (fundamental) Joule losses at rated conditions.

Circulating current losses

In high power high speed machines, skin effect and proximity effect increase power loss windings at high frequencies. Circulating currents flow in loops created by parallel conductor wires which form one turn per coil, it may be regarded as an increase of stator resistance for each current harmonic with ordinal number *k*. Analytical formulas exist only for rectangular shaped wires with distinguished placement of conductors [30]. For round wire winding with arbitrarily distributed conductors, the formula is almost empirical.

Litz wire is often used to reduce the impact of eddy currents in conductors. However, applying Litz wire effectively is not simple, such as, choosing the number of strands per turn, the number of strands that should be combined at each step of twisting and the strand diameter. Using the approach detailed in [31], the resistance increase factor k_c in a Litz wire, with insulated strand, can be given with respect to the frequency f.

In Litz wire configuration, the resistance increase factor can easily achieve 10% of the DC resistance at rated frequency.

Loss distribution in air /air and air/water cooled HSPMSM

In figure (3), case (1) and case (2) show typical loss repartition observed in air cooled HSPMSM with AMBs driven by VFDs at rated operating point. For the sake of comparison, case (3) shows the typical loss distribution of a squirrel cage induction motor (SCIM), running at 1500 rpm, for a shaft power (P_{shaft}) range between 90 kW and 300 kW [32]. While Joule losses (in both rotor and stator) are the most predominant in SCIM, in HSPMSM, iron/core losses can contribute to half of the total losses.

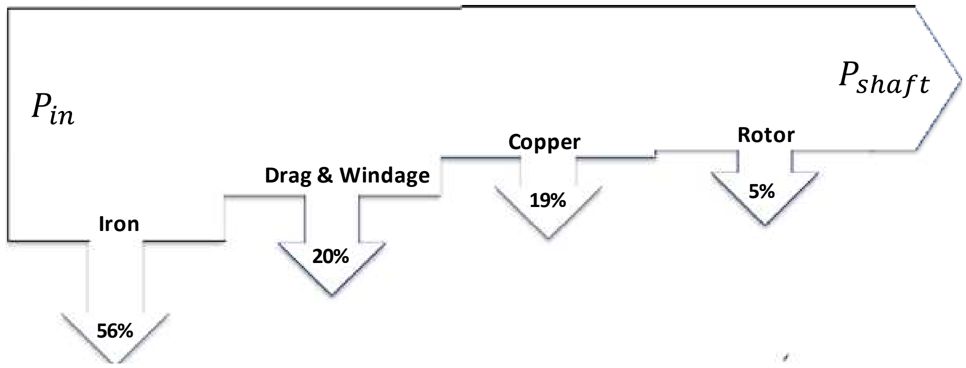
In the graphs for cases (1) and (2), we substituted Joule losses by copper losses since the studied cases consider copper as the main winding material.

In case (3) the loss definition are as following:

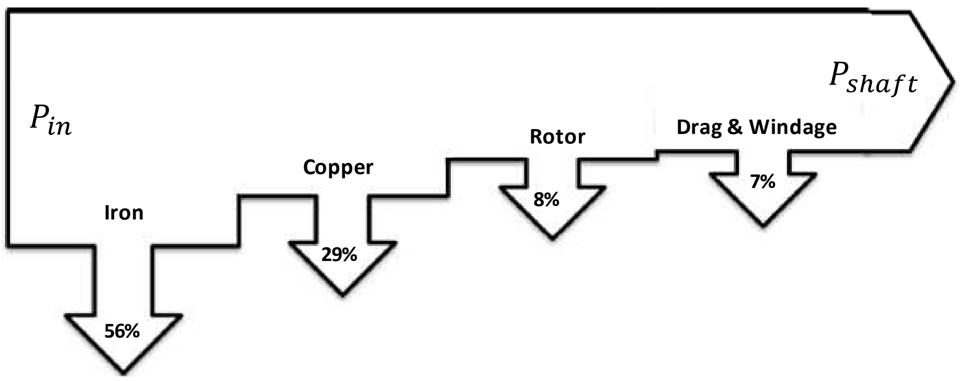
- Stator and rotor Joule losses are entitled respectively stator RI² and rotor RI².
- Stray losses are additional losses produced by the load current in active iron and other metal parts other than conductors as well as eddy current losses in winding conductors caused by load.

- Friction losses, group mechanical losses due to bearing and seal contact and windage losses.

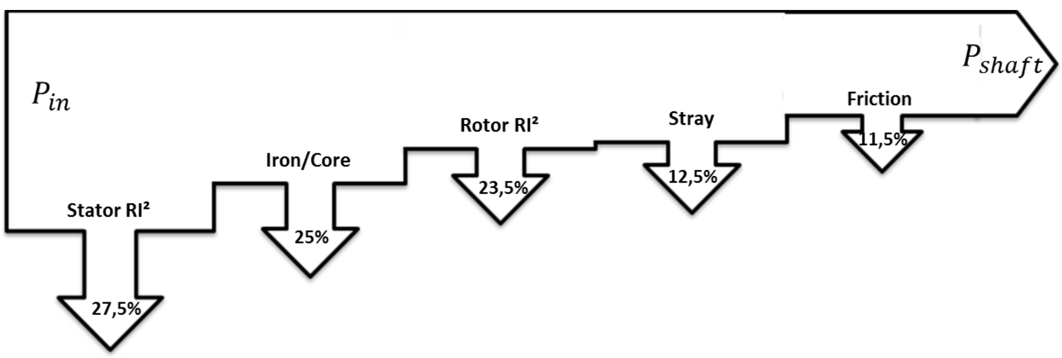
Figure (4) shows a typical loss fraction with respect to shaft power, in HSPMSMs equipped by AMBs. In figure (4), different sizes and speeds are represented. The figure highlights the predominant losses and the trend with respect to the shaft power in HSPMSMs with AMBs.



Case 1 : Air/air cooled HSPMSM with AMBs at 90 kW/35000 rpm



Case 2 : air/water cooled HSPMSM with AMBs at 300 kW/18500 rpm



Case 3 : Averaged distribution of an SCIM between 90 kW and 300 kW at 1500 rpm [32]

Figure 3 : Typical loss fraction between input power (P_{in}) and shaft power (P_{shaft})

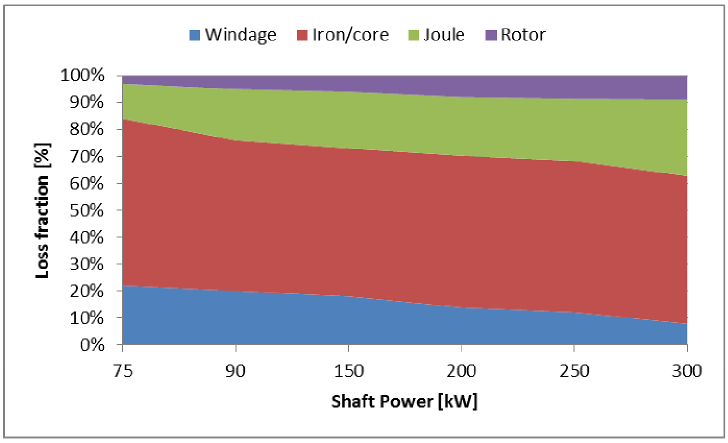


Figure 4 : Averaged loss fraction Vs shaft power for a 2 pole HSPMSM for turbo blowers

4. Experimentation

Set-up

The test bench consists of two identical machines tested in back to back configuration. As illustrated in figure (5), input power (of the motor) and output power (of the generator) are measured using two (2) precision power analyzers made by Yokogawa (Model WT 3000) having a claimed basic power accuracy of ± 0.02%. Both power analyzers are synchronized so that the measurement is recorded simultaneously. High precision current sensors are used as well (from Yokogawa and LEM companies). The input power from grid is also recorded by a Voltech power analyzer. Figure (6) represents some motor ranges tested in the described back to back configuration. The displayed/recorded results are averaged over several periods (in the device).

Tests are performed at rated conditions. The electrical data (power, voltage, current, power factor, total harmonic distortion of the current) are recorded after thermal steady state (steady state temperature in the stator winding and the rotor). The room temperature is around 35°C. The cooling system adopted for both machines is either air-air (for powers up to 150 kW) or air-water for powers above 150 kW.

Four sizes are tested, 75 kW, 90 kW, 150 kW and 300 kW, representing globally, the power range used in turbo blowers, as illustrated in figure (1).

The data (input power, output power, voltage, current, power factor, THDI) are recorded each second for a minimum of 10 minutes after thermal steady state achievement.

The two-wattmeter method approach has been used to measure powers and integrated filters (used in power analyzers) have been disabled.

Winding, rotor, air inlet, air outlet and ambient temperatures have been monitored. The rotor has been instrumented by temperature probes (embedded) and data are transmitted through a telemetry system. The end windings (overhangs) are instrumented in both sides (drive end and non-drive end) as well as the windings in the iron parts. Each phase is equipped with 6 temperature probes.

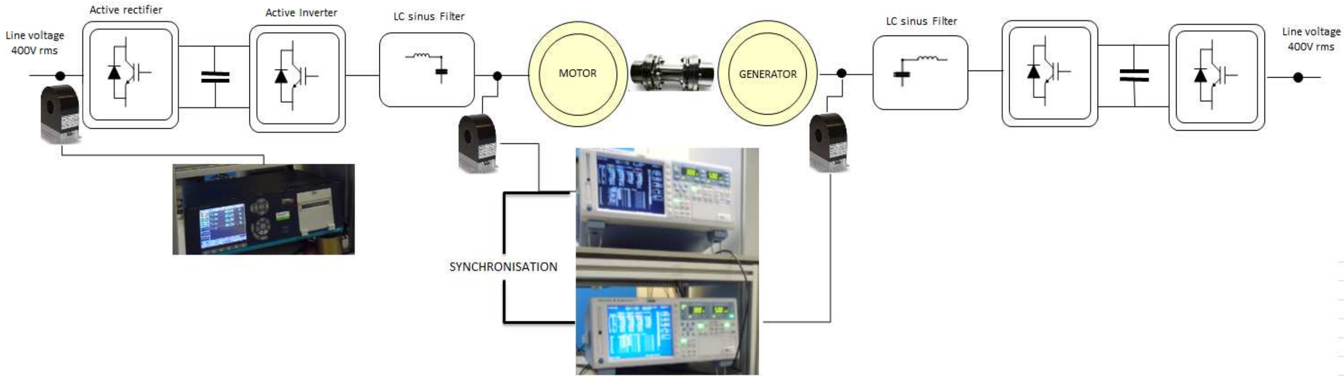


Figure 5 : Schematic representation of the back to back test bench

Figure 6 : Back to back test bench (left side: 90 kW range, right side: 150 kW range)

Shaft power and loss estimation

According to the definition given in [13] the dual supply back to back test is a test in which two identical machines are mechanically coupled together, and the total losses of both machines are calculated from the difference between the electrical input P_{in} (motor) and the electrical output P_{out} (generator). The VFD is set to deliver the same motor voltage for both machines. The carrier frequency is above 10 times the rated frequency.

In our case, dual supply back to back test are conducted ensuring the same input (motor) and output (generator) voltage. The input current (motor) and the output current (generator) are different. Even if the difference is not so big, the total losses in the motor are different from the generator's ones. So to be close to the reality, we have adopted some changes. The shaft power P_{shaft} is then obtained as following

$$P_{shaft} = \frac{P_{in}+P_{out}}{2} + \frac{P_{JGen}-P_{JMot}}{2} \quad (1)$$

Where P_{JMot} (resp. P_{JGen}) represents the Joule losses of the motor (resp. Generator) and are obtained as following:

$$P_J = \sum_1^3 R_i(T_{average}) \times \left(I_{i\_truerms}\right)^2 \quad (2)$$

$I_{i\,truerms}$: is the true rms current measured in the phase I, the true rms includes the harmonic content.

$R_i(T_{average})$: is the electrical resistance of the phase i (measured off line at room temperature) corrected at the averaged measured temperature (between the different probes located in the windings of the same phase i).

The losses per machine can be expressed as following:

$$P_{motor} = \frac{P_{in}-P_{out}}{2} - \frac{P_{JGen}-P_{JMot}}{2} \quad (3)$$

$$P_{generator} = \frac{P_{in}-P_{out}}{2} + \frac{P_{JGen}-P_{JMot}}{2} \quad (4)$$

Notice that the approach is quite different from the one recommended by standards IEC 60034-2 or IEEE 112. This can be explained by the conditions and freedom degrees that a classical DC wound rotor synchronous machine can afford. While in standards, for wound rotor synchronous machines, in a dual supply back to back test, it is recommended to have the same current and the same voltage for both machines by only changing the DC (rotor) supply, it's not possible for PM machines (no way to adjust the rotor field) to have the same voltage and current in both machines during back to back test.

Results

Figures (8-10) group four (4) results corresponding to the different motor sizes (power/speed). For each case, we have plotted the shaft power and the efficiency. We can observe the power fluctuation, especially for the 75 kW and 90 kW size, affecting then, the instant value of the efficiency. To reduce the impact of these discrepancies and fluctuations, the performances have been average over few minutes. The figures represent the different power sizes.

Figure (11) shows the efficiency evolution with respect to the shaft power for two motor sizes (90 kW and 150 kW). The efficiency estimation is performed at constant speed. As expected, the efficiency is almost constant above 50% of the rated power. The efficiency starts to fall below 50% of the power

Figure (12) shows the averaged efficiency at rated conditions for each 2 pole HSPMSM size, it is compared with the standard premium efficiency (IE3) that a direct on line three phase SCIM shall potentially achieve [12][17]. Up to 90 KW, the gap between HSPMSM efficiency and potential IE3 SCIM is not so big; this gap however becomes important from above 90 kW.

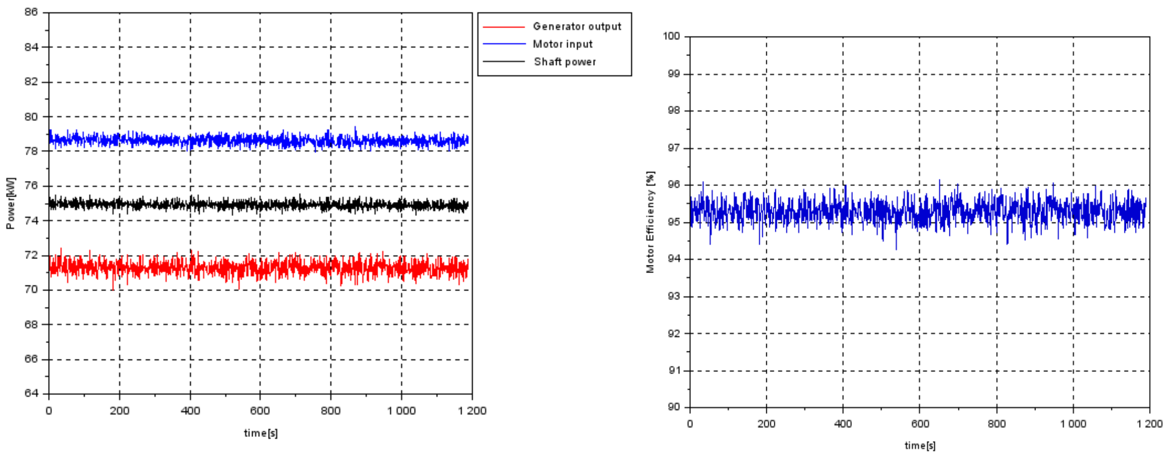


Figure 7 : Power measurement and efficiency estimation from measurement for the 75kW size

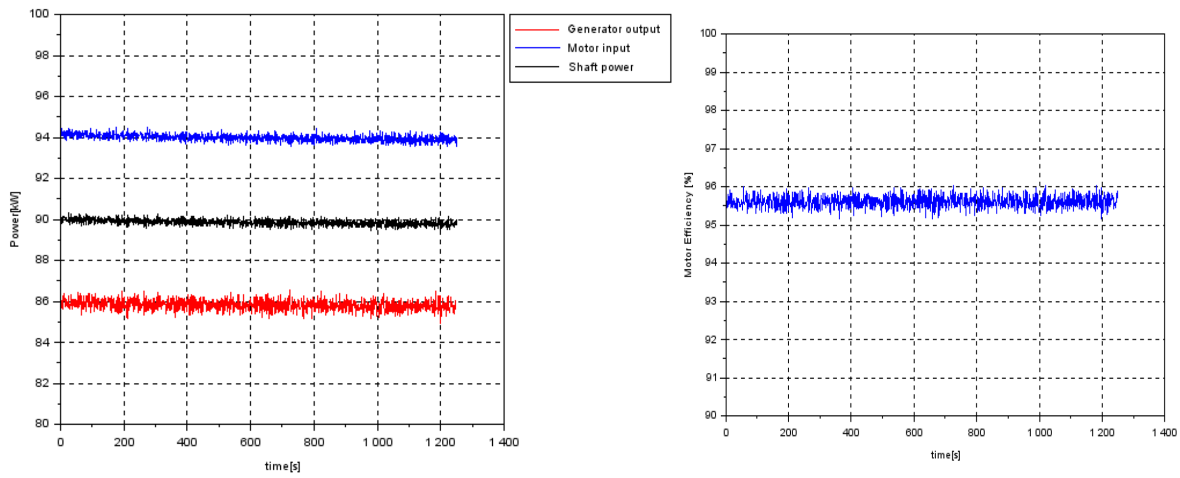


Figure 8 : Power measurement and efficiency estimation from measurement for the 90 kW size

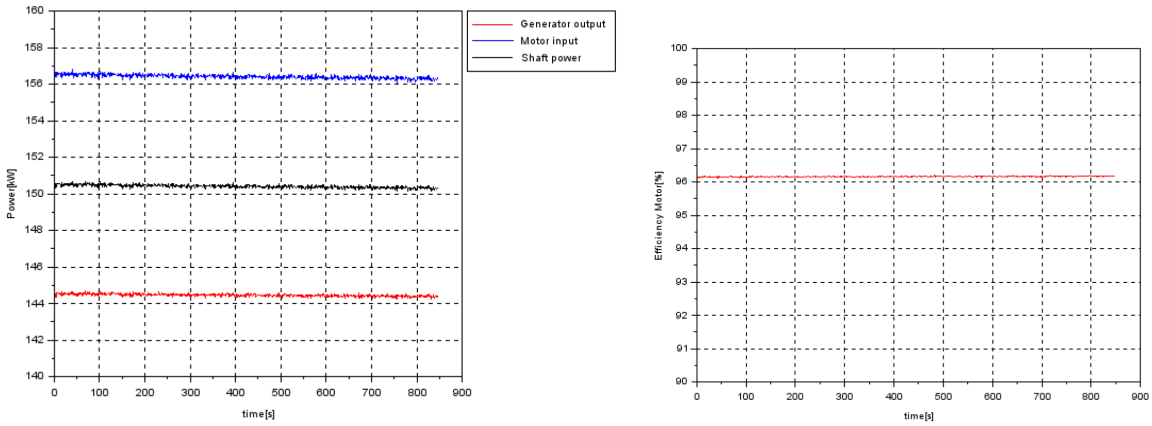


Figure 9 : Power measurement and efficiency estimation from measurement for the 150 kW size

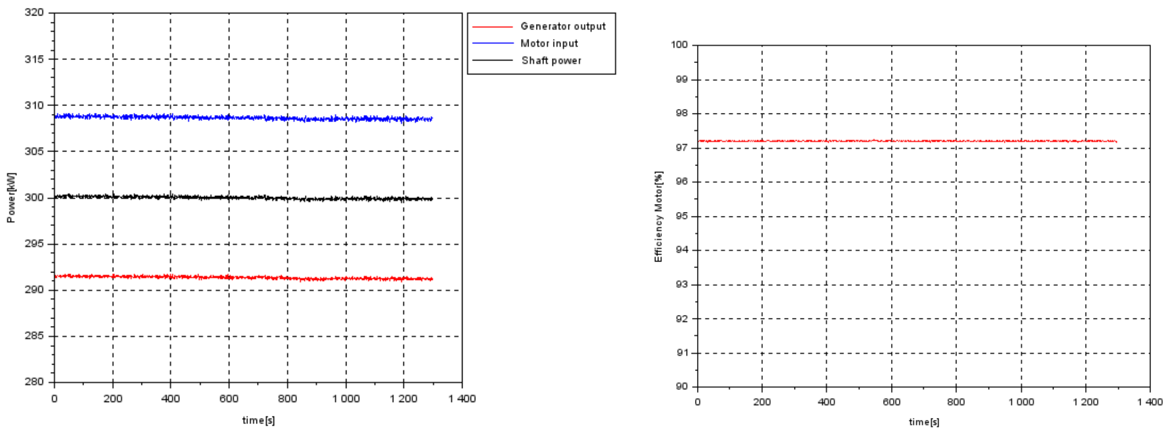


Figure 10 : Power measurement and efficiency estimation from measurement for the 300 kW size

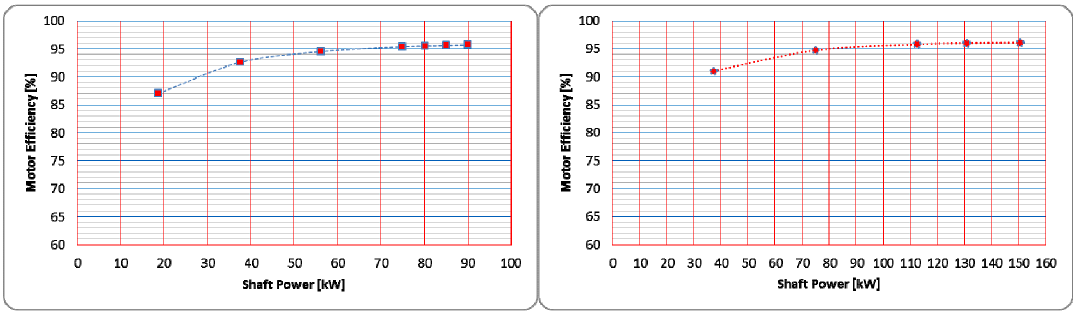


Figure 11 : Efficiency estimation from measurement for the 90 kW and 150 kW size at constant speed

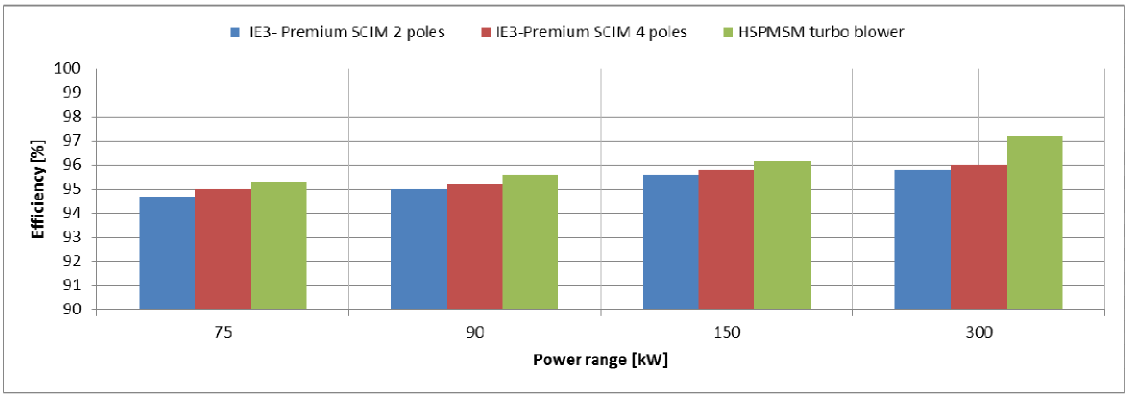


Figure 12 : Comparison between Premium (minimum) efficiency of SCIM with HSPMSM for turbo blowers

5. Overview of the drive system efficiency

During tests the focus was mainly on the motor efficiency. Unfortunately, we will not present the drive efficiency measured during back to back tests, since the used VFDs are not those used for the blowers ‘plant. However, it is interesting to give an overview of the drive system efficiency in blower technologies according to the lessons learned.

Figure (13) shows the usual efficiency of drive systems used in blower technologies

The blue area of figure (13) corresponds to the efficiency that could be achieved by a HSPMSM. For a given power design, the efficiency will depend on the chosen speed, the bill and quantity of material as well as the size of the machine.

If we add the VFD, the sine filter usually required for high speed applications and the AMB control board consumption, the efficiency will globally corresponds to the apricot colored area in figure (13). We can lose obviously about 4 “points” of efficiency depending on the drive size, the sine filter design (material core used) and the switching frequency.

Some improvements have been achieved in positive displacement (PD) technologies, for example some suppliers state that with an helical screw driven by a direct drive SCIM supplied by a VFD, the efficiency will be better (compared to a V belt technology). A 2/4 poles SCIM with VFD used in direct drive PD achieve an efficiency evolving in the auburn/red colored area (figure 13), while a DOL SCIM+ V belt drive has usually an efficiency in the green area range of figure (13).

It’s interesting to underline some constraints inherent to high speed applications. In the studied power range size, direct drive applications with motors running at 1500/3000 rpm (1800/3600 rpm) are supplied with VFDs that can achieve easily an efficiency of 98.5%, while in high speed applications (15000/36000 rpm) VFDs hardly achieve an efficiency of 96%.

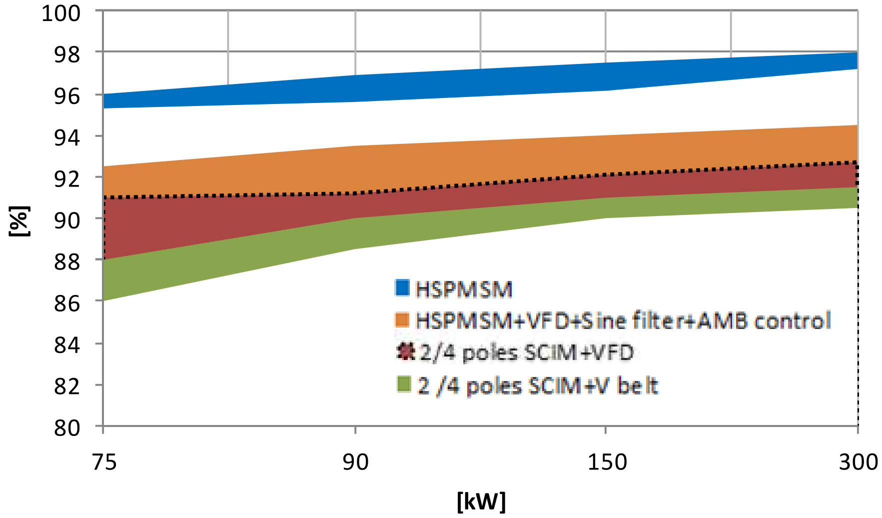


Figure 13 : Efficiency area of drive systems used in blower technologies

6. Conclusions

The paper addresses HSPMSMs with AMBs supplied by VFD for air-blower applications. Generally, in air cooling HSPMSMs, the most important loss is the iron/core losses while in SCIMs, Joule loss (rotor and stator) is predominant. Usually the classical balancing observed in SCIM loss repartition, is to have the same amount of rotor Joule, Stator Joule and stator iron losses. In HSPMSMs, having a balancing loss repartition means obviously an oversize of the machine.

The measurement of the efficiency, using a dual supply back to back test has been performed on different HSPMSM sizes. The method has been slightly modified compared to standards (IEC 60034-2 and IEEE 112) because of the particularity of PM motors. Moreover, the efficiency has been averaged over a large time duration (>10 min), recording data each seconds. This permits to avoid discrepancies and perturbations probably inherent to back to back configuration with VFDs and high speed.

Even though standards don't address HSPMSMs with VFDs, it was interesting to compare measured efficiency on HSPMSMs with required premium efficiency (IE3) potentially achievable by a direct on line (DOL) 3 phase SCIMs. Up to 150 kW, provided that a DOL SCIM can achieve IE3, the gap with a HSPMSMs is quite small, even more, if we add the VFD efficiency, we could imagine that the global efficiency (VFD+HSPMSMs) is lower than a DOL SCIM. However, one shall relativize, the wire-to-air efficiency will be better in HSPMSM with VFD, because of the non-use of gearbox, the use of variable speed and, last but not least, the use of centrifugal compressors, and then a better payback. Above 150 kW, the gap between HSPMSM efficiency and SCIM is quite obvious.

One point not addressed in this paper, is uncertainties due to the used devices (sensors, power analyzers), this topic has been addressed in [3] using the same power analyzer. The uncertainties of the measurement chain might strongly affect the readings especially when using a VFD. The challenge is to keep the uncertainties- quantified by loss fluctuation- introduced by the measurement devices below the loss margin "allowed" by IEC 60034-1 (15% for powers up to 150 kW and 10% for power above 150 kW).

For the 75 kW size the loss variation evaluated per machine is between 5.3% (generator side) and 6% (motor side) of the total losses. For the 90 kW size, the loss variation evaluated per machine reaches 5.9% (generator side) up to 6.4% (motor side) of the total losses. For the 150 kW size, the loss variation evaluated per machine fluctuates between 6.47% (generator side) and 6.82% (motor side) of the total losses.

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Policy 3

Development of a New Extended Motor Product Label for Inclusion in Energy Efficiency Programs

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Rob Boteler Nidec Motor Corporation

ABSTRACT

Energy efficiency program administrators have for many years been aware of the significant energy savings possible by managing the demand and consumption of motor driven systems versus a focus on component efficiency. Historically only larger systems were considered because of the cost of the resources required to measure and verify the savings. The recent move by the US Department of Energy (DOE) to regulate fans, pumps and compressors developments may change this. The development of specifications and labeling for motor-driven subsystems or packages known as "extended products" has defined a category of system that is limited to the motor, control and the driven load. By adopting this definition the suppliers of extended products can establish an "energy index" that reflects the potential energy savings achieved by managing demand (kW) rather than system efficiency.

In response to this market opportunity, manufacturers of electric motors, controls, pumps, fans, and compressors are developing voluntary labels for motor-driven systems (e.g., a fan, pump, or compressor and the motor and associated controls) based on test standards, metrics and MEPS "minimum efficiency performance standards" concurrently being developed with the DOE. The development of a driven component or "extended product" label combined with implementation data can become the basis for quasi- prescriptive rebate programs with deemed savings values. The intent of the high performance label is to identify these "extended products" to the program managers and power utilities who may then utilize them as the basis for programs. Providing incentives for labeled product will accelerate the adoption of more efficient motor-driven systems.

This paper explains the activities of a collaborative effort, the Extended Motor Product Label Initiative, to develop comparative metrics and labels for three categories of extended products. Also discussed are the ways its three working groups are ensuring the compatibility of these new extended-product labels with energy efficiency program measurement and verification needs. Finally, the paper describes the plan for development and public introduction of three or more efficiency program model proposals.

Background

Motor-driven equipment consumes one-fourth of all electricity sold in the United States each year (DOE 1998). Each year, facilities in the commercial, industrial, and institutional sectors purchase motor-driven products that total approximately 50 million horsepower in connected load (NEMA, 2013). As detailed in Table 1, electric induction motors are used predominantly to drive pumps, fans, compressors, and material handling and material processing equipment.

Electric utilities are constantly in search of new demand-side management program models that will help them reach their efficiency goals. Efficiency programs in the United States are spending an estimated $1 billion per year on industrial energy efficiency (Chittum and Nowak 2010). Many programs have realized the energy savings potential of motor-driven systems in the commercial and industrial sectors, but have been challenged to secure savings without requiring significant administrative resources and measurement and validation costs.

Table 1. Distribution of Motors by Application Percentage for NEMA Design A and B Motors

	Horsepower (hp)						
Application	**1–5**	**6–20**	**21–50**	**51–100**	**101–200**	**201–500**	**All hp**
Air Compressor	1.8	1.3	2.2	5.6	5.4	8.3	2.2
Fans	22.5	24.9	26.6	25.7	18.9	21.7	24.0
Pumps	22.3	31.6	33.0	34.2	36.0	25.5	28.5
Material Handling & Processing	12.0	9.4	6.8	10.6	7.8	7.6	10.0
Other	41.4	32.8	31.4	23.9	31.9	36.9	35.3
Fire Pumps	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: DOE 2012, Table 7.2.3

Program administrators must be able to document that the investments made with ratepayer funds produce energy demand and consumption reductions. If an incentive is provided for a project that in the end does not reduce load, the utility is still required to provide power to the customer. To avoid this, public utility commissions require programs to perform extensive measurement and verification (M&V) analyses of savings (Chittum, Elliott, and Kaufman 2009).

The cost of M&V is included when evaluating the cost-effectiveness of programs; therefore, if the resources needed to perform M&V are too great, the cost-effectiveness of the efficiency program suffers. Efficiency programs have addressed this issue by developing portfolios of programs. Two common types of program models are those that target simple equipment replacements with “deemed” savings and provide a prescribed, or “prescriptive,” rebate, [e.g. NEMA premium motors programs] and “custom” programs that target complex projects with incentives that are proportional to the energy savings. The latter can require extensive before-and-after measurements, making them cost-effective only for larger projects.

Between the simple types of projects covered by prescriptive programs and the complex projects covered by custom programs lay a great number of opportunities to save energy through the selection of the proper motor-driven systems.

Introduction

The optimization of motor-driven systems has long been recognized by efficiency program administrators for its energy-saving potential. As indicated in Figure 1 and in the second column of Table 2, besides the energy-saving potential of more efficient components (motors, drives, and driven equipment), significant additional savings can be achieved with this system optimization. Motor drive system optimization, simply put, is the condition met when all the components of a system or subsystem, inclusive of the motor, control and load, are operating in such a manner that reduced speeds and partial loads are controlled electronically rather than mechanically. A conventional motor-driven system will operate in only the on or off mode. The more ability a system has to adjust its performance to downstream demands, the less energy [input power] it will use.

Pursuit of these savings by efficiency programs has been limited to larger projects due to the challenges of quantifying the baseline energy use and measuring post-installation energy use. These activities can require specialists and be time-consuming—in other words, costly.

Recently, a number of developments offer the prospect of changing this reality. First, the development of specifications and labeling for motor-driven subsystems or packages by trade organizations (Table 2, column 3) provide a means for documenting some of the efficiency that results from system optimization and for making it readily available to end users and other interested parties, such as efficiency programs. Second, the emergence of low-cost intelligent sensors and control systems now allows these packages to achieve some degree of self-optimization.

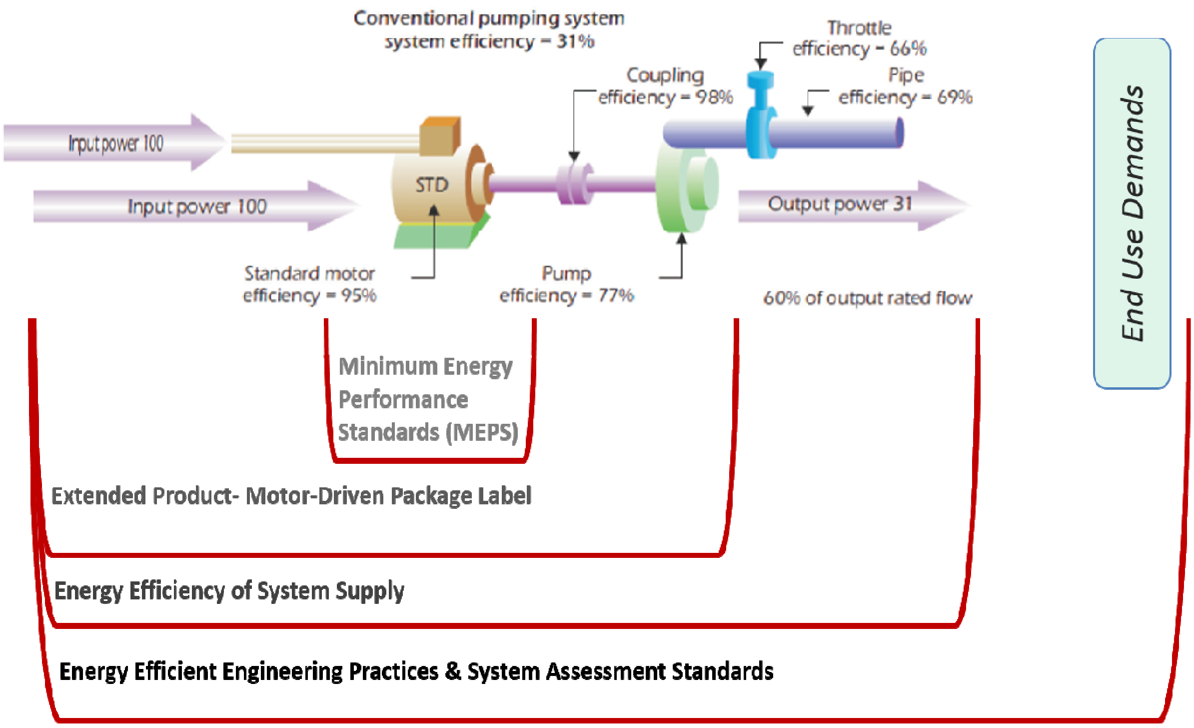

Figure 1. Extended-product example of a pumping system

Source: Rao 2013

In response to these developments, manufacturers of electric motors, pumps, fans, and compressors are developing voluntary labels for motor-driven systems (e.g., a fan, pump, or compressor that is connected to a motor and associated controls) to reflect the relative energy use of the equipment as it is installed in a motor-system application. The development of a driven component or "extended product" label combined with implementation data could be the basis for prescriptive rebate programs with deemed savings values. With motor-driven products totaling 50 million horsepower in connected load being sold every year in the United States, such programs would represent a significant new opportunity for efficiency program administrators.

This paper explores the state of development of these extended-product labeling efforts, proposes ways they can become the basis for new programs targeting the commercial and industrial sectors, discusses how they can be constructed to fulfill the measurement and verification needs of efficiency programs, and explains how they can help end users reduce energy consumption and operation costs.

Table 2. Relative Efficiency Gains for Labeled vs. Non-Labeled Motor-Driven Systems

Motor System Element	Sample % System EE Opportunity	How EE Opportunity Identified	Potential Program Response
Motor	2-5%	Label (MEPS, NEMA Premium)	Deemed Savings Eligible Product List
Drive	3 - 10%	Product class	Deemed Savings
Driven Equipment (Pump, Fan, Air Compressor)	10-25% for fans/pumps/ compressors*	Stated performance (AMCA label, CAGI data sheets, HI performance curves)	Deemed Savings Eligible Product Type Custom Program
Extended Product: Motor-Driven Package	15-35%	Label (proposed)	Eligible Product Type Custom Program
System Supply	15 - 40%	Performance Indicator (e.g. CASE) System Assessment	Technical Assistance Custom Program
Entire System	20 – 50%+	System Assessment (standards)	Technical Assistance Custom Program

Source: Rao 2013

The Extended Motor Product Label Initiative

The Extended Motor Product Label Initiative (EMPLI) is a US based 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. The participants from the trade organizations and manufacturers have expertise in performance testing and responding to U.S. and European rulemakings, as well as extensive market knowledge. The representatives from US utilities and programs have expertise in program design and implementation and knowledge of regulation and program evaluation.

The American Council for an Energy-Efficient Economy (ACEEE) has functioned as the convening organization and recruited several trade associations, their members, and utility sector energy efficiency programs into the collaborative. The trade associations are the National Electric Manufacturers Association (NEMA), the Hydraulic Institute (HI), the Air Movement and

Control Association (AMCA), the Compressed Air and Gas Institute (CAGI), and the Fluid Sealing Association. Efficiency programs that have participated to date include Pacific Gas and Electric (PG&E), Northeast Utilities, National Grid, the Energy Trust of Oregon, the Northwest Energy Efficiency Alliance, the Bonneville Power Administration, the Northwest Power and Conservation Council, Southern California Edison, and Consolidated Edison.

The collaborative approach facilitates communication between program administrators and the manufacturers of motor-driven equipment. The manufacturers and their respective trade organizations are interested in developing a label or comparative metric to simplify their customers' efforts to identify more-efficient products. The utilities and program administrators are interested in new methods for identifying potential energy savings.

The initiative has created three working groups (for compressors, fans, and pumps), with each being tasked with identifying a comparative performance metric for the primary component and/or the extended product. Each group includes representatives from the trade organizations, product manufacturers, utilities, and efficiency programs. The trade organization and manufacturer representatives, who are more familiar with their products and test methods, will determine the best comparative metric for inclusion in the label. A performance metric could be numerical (e.g., 40, 50, 60, and so on) or strictly comparative (e.g., "good," "better," "best").

Since each of the product manufacturers is at a different stage in its development of test standards, the ability to link a single overarching label for an extended product to a certified test is limited. Therefore, each of the teams will first develop a label relating the performance of their driven equipment. For example, the fan group may elect to develop a label just for fans and base it on a new performance metric such as the Fan Efficiency Grade. The pump team, challenged by the lack of a performance test for centrifugal pumps, may develop a new wire-to-water metric. In contrast, the compressor group has an existing wire-to-air metric that can be easily used for screw compressors. Labels based on any of these buckets still have the potential to be used in efficiency programs, the initial goal of the initiative was for each of the three teams to develop a unique label for an extended-product category, and develop program models [3] for each of the product teams.

Program Types

A goal of the collaborative is for the labels to enable projects (or at least parts of projects) currently covered only under custom programs to be eligible for inclusion in prescriptive or semi-prescriptive programs.

Prescriptive: Utilizes product description and performance to prequalify items for an incentive. Savings are "deemed" per piece of equipment or by size of equipment, such as per compact fluorescent lightbulb or per horsepower of a high-efficiency motor. These programs reach the most products and applications with the least amount of administrative cost.

Semi-prescriptive: Utilizes a deemed savings measure to evaluate a category of products used in specific applications. For example, if the load factor of a boiler in educational facilities is different from that of a boiler in multifamily housing structures, the program might have a different multiplier for each sector to determine the net incentive per boiler horsepower. Such programs require a greater level of administrative resources to evaluate and qualify applications than prescriptive programs do, but less than custom programs.

Custom: Requires before- and after-installation measurement to determine and verify savings. Applications can be elaborate, as can post-implementation measurement and validation. Custom programs tend to apply to larger customers and larger projects.

By including representatives from the efficiency program sector in the development of these new labels, the details of the labels and the documentation supporting them can be structured to be compatible with the needs of a prescriptive or semi-prescriptive rebate program.

Simplified Measurement and Verification

Efficiency program energy savings evaluation is very important in determining the success and influence of a program (Chittum 2012). A key motivation for utilities' involvement in this initiative is that these new labels will simplify the measurement and verification (M&V) for incentive programs by establishing straightforward eligibility requirements and the associated deemed energy savings. The coalition expects the results of this project to be usable and potentially accepted by a large number of utilities not directly involved with the project.

Scope of the Work

The working groups are in the process of identifying the criteria to be included in a label and collecting the supporting data that is required for product and efficiency program evaluation. The efficiency program representatives have shared their program development methodologies, which include an understanding of the variables that drive savings and the ability to predict the savings potential with acceptable accuracy. Performance test methods and metrics have been identified and the working groups are in the early stages of data collection. Development of program models has started as have plans to demonstrate programs in late 2015.

EMPLI Project Milestones

- Identify testing methods for each product category
- Identify performance metric for each product category label
- Collect field performance data and determine average savings. Categorize according to application and configuration
- Identify qualifying performance levels for each product category label
- Create label schemes for each product category
- Develop incentive program models based on labels
- Pilot one or more label-based efficiency program models
- Develop a common mark or brand for all product categories
- Initiate promotion effort to bring awareness to new labels

The working groups will start their development of program models focusing on one or two common products. The efficiency programs will take the data collected from the field, combine them with the associated program models, and then submit proposals to public utility commissions for authorization to conduct demonstration projects. The initiative plans to develop three or more program models and demonstrate two or more program models.

It is anticipated that after the conclusion of this initial phase, the working groups will continue within the scope of their supporting trade organizations to identify additional products and work with efficiency programs to develop additional program models.

Upon development of all program models and conclusion of the demonstration projects, the EMPL Initiative will conclude with a release of its findings and the launch of a promotional effort that will be continued in a new initiative.

Project Outcomes

The ideal outcome of the project is for each of the three teams to develop a label for an extended-product category and an associated program model proposal. As previously discussed, the current state of test procedures will not support this goal, and therefore the fan and pump teams are developing labels that assume a high-efficiency motor and appropriate drive (i.e., variable where appropriate) and provide the consumer with a wire-to-air or wire-to-water comparative metric, that is consistent with ongoing DOE rule making.

Each trade association will create its own label or mark for identifying highly efficient products. Each trade association will own and manage its respective energy performance label. The trade association may elect to include a memorandum of understanding or license agreement for their respective labels. They will be responsible for any registration or trademarking of their label. The four trade associations are discussing development of a common mark or brand that will identify for customers and efficiency program administrators qualifying product. Labeled products will be marketed to utilities, original equipment manufacturers, states, other trade associations, and end users.

The AMCA, HI, and CAGI are already American National Standards Institute–accredited testing organizations, and part of the value they provide for their memberships is performance testing and certification of member products. These new labels will add to this value, which will also accrue to the product sectors. It is hoped that, much as the Environmental Protection Agency's ENERGY STAR® logo has changed consumer purchasing of residential appliances, the establishment of an industry-supported and broadly accepted performance label will alter the purchasing habits of the commercial and industrial sectors, reducing their energy intensity.

Example

There is precedent for the development of programs based on voluntary performance labels and for integrated motor-driven products with variable energy consumption profiles. NEMA Premium® motors are often the basis of utility prescriptive rebate programs. PG&E "Pacific Gas and Electric" has developed a program for variable-speed pool pumps.

NEMA Premium Motors Voluntary Performance Label

This voluntary performance label became the basis for hundreds of utility sector programs, which was a catalyst for the EMPLI. Under the Energy Policy Act of 1992 (EPAct), DOE worked with industry to create a definition of electric motors and enact minimum energy performance standards (MEPS). Standards based on the "energy efficiency" level specified in NEMA's MG-1 standard (equivalent to the current levels in Table 12-11) were developed and instituted for certain electric motors of 1–200 horsepower (hp) in size. DOE adopted the Institute of Electrical and Electronics Engineers test methods for determining motor performance and adopted NEMA's performance metrics. The Energy Independence and Security Act of 2007 directed DOE to enhance those standards, and most motors covered under EPAct were required to meet higher standards as defined by NEMA MG-1 Table 12-12. As a result of DOE's rulemaking, manufacturers are now required to list the nominal efficiency of each motor on its nameplate and in published data. All motors sold in the United States must meet a minimum energy efficiency performance level.

To identify the most efficient motors on the market, NEMA used its existing reporting program to define a new efficiency level above the MEPS that the DOE had set. They trademarked that level as NEMA Premium. Shortly thereafter, the market and utilities began to adopt NEMA Premium as an incentive requirement in their efforts to accelerate the adoption of higher-performing motors. Because the difference in the energy use of a nominally efficient motor and a premium motor is relatively easy to calculate, utility programs were able to determine a likely energy savings per horsepower and design prescriptive programs around a rebate of a specified amount per horsepower.

Many companies and government agencies now require this label as a purchasing specification. So even though it continues to be a voluntary performance standard, most manufacturers make products to this standard and energy is saved that otherwise wouldn't be.

Next Steps

The next steps are for the groups to identify existing performance data sets that can support the performance metrics and to recommend pilot project designs for collecting additional field data. This information is needed to perform a cost–benefit analysis on whether the additional cost of the more efficient equipment is justified by the additional energy cost savings. Elements of a cost–benefit analysis will include:

- KWh saved by segment or product bin
- Site-specific field testing (M&V)
- Estimated administrative costs

Data collection for the initiative will conclude in July of 2015, though it is likely that data collection in support of specific program development will continue.

Late in the fourth quarter of 2015, the teams will convene a stakeholder meeting with peers to share findings, recommendations, and program model proposals. After feedback has been incorporated into the final product and additional participants added to the collaborative, a final report will be generated and shared with national stakeholders such as the Consortium for Energy Efficiency, the National Association of Regulatory Utility Commissioners, and the National Association of State Energy Officials. Following the release of the report, initiative participants will engage in promotional efforts over the balance of the year to create awareness and acceptance of the three labels.

It is anticipated that the trade organizations will expand the product scope to include additional categories once the initial product labels are launched. ACEEE will drop back into an advisory, support, and promotional role, talking with state energy offices, national efficiency organizations, and different departments of DOE to increase awareness.

Summary and Conclusions

The collaborative of manufacturers, trade organizations, and efficiency programs has been working together quite successfully and is well on its way to developing comparative metrics and performance labels. Each of the groups participating in the initiative has its own reasons for joining. The trade organizations seek to provide value to their members and to coordinate responses to DOE rulemaking. Manufacturers are seeking methods to achieve product differentiation and reduce regulatory burden. Efficiency programs are seeking new program models to cost-effectively acquire energy saving resources from the commercial and industrial markets. By working together, each group can satisfy its needs, and the initiative seems to have effectively created a space of trust and collaboration to make this happen.

The task of developing a performance metric for extended products has, as expected, proven to be more complex and challenging than for driven products. As a result, the fan and pump working groups are considering development a device efficiency metric first, before taking on a wire-to-air or wire-to-water metric that would capture the performance of an extended product. Since the goal of the initiative is to develop models for efficiency programs, initial program proposals may be built around the simpler metric and an assumed extended product. For example, a program might assume a high-efficiency motor and an appropriate drive, but the performance metric that will form the basis of the incentive will be for fan or pump efficiency only.

The initiative is on track to produce working papers proposing efficiency program models based on the respective comparative metrics. The participating efficiency programs have indicated a desire to pilot one or more of the program models before the end of 2015. If the collaborative is successful, as it appears it will be, within the next few years several efficiency programs around the US will deploy new prescriptive rebate programs with deemed savings for common industrial and commercial fan, pump, and compressor products. These programs will accelerate the adoption rate of more efficient integrated products and have estimated savings in the quadrillions of Btus over the next ten years.

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New European Ecodesign Regulation for Electric Motors and Drives

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Abstract

The importance of motors as a major electricity consumer, as well as its improvement potential, has long been recognized making this type of equipment a preferential target for Minimum Energy Performance Standards worldwide.

The European Commission also adopted minimum efficiency regulations for electric motors in Regulation No. 640/2009 of 22 July 2009, following a period of Voluntary Agreement with limited impact (in the year 2000 the EU motor market was dominated by low efficiency motors - IE0 represented about 70% of the sales).

This paper presents the major findings of the recent Lot 30: Motors and Drives Ecodesign Preparatory Study, carried out for the European Commission to evaluate the possibility of extending the scope of the Regulation to motors outside the current power range and to technologies other than three-phase induction motors.

The study is based on a methodology for the Ecodesign of Energy-using Products (MEEuP,) developed for the European Commission, which is common to all the EuP preparatory studies and will identify: a) Market characteristics for the products under consideration; b) Relevant environmental aspects of the products and their technical/economical potential for improvement; c) Existing relevant legislation and self-regulation by industry and standards; d) LCC assessment of average products; e) Technical analysis of the Best Available Technologies (BAT) and of the Best Not Available Technologies (BNAT); f) Scenario, policy, impact and sensitivity analysis. In this paper, a description and the main results of the study are presented.

The Lot 30 study identified a series of policy options that will lead to the reduction of environmental impacts taking into consideration the Life Cycle Cost and the best available technologies in the market. Scenario analysis projected the energy and economic savings for the period of 2013-2030 from each of these options. Six policy options (PO) were identified, as well as their possible implementation timelines. Innovative policies, such as raising Minimum Energy Performance Standards to IE4 (Super-Premium) and introducing MEPS for VSDs were proposed for the first time, making Europe the leading region in Motor systems regulation.

Introduction

Electric motors and motor systems have a high share of electricity consumption - they represent approximately 45% of the world electric energy use – and, therefore, have been signaled early on as a priority product group by policy makers.

Since the introduction of the 1997 US Energy Policy Act (EPAct) regulations for electric motors, other leading nations including the European Union (EC Regulation 640/2009) have introduced similar regulations with Minimum Energy Performance Standards (MEPS) globally now converging at the demanding IE3 premium efficiency level.

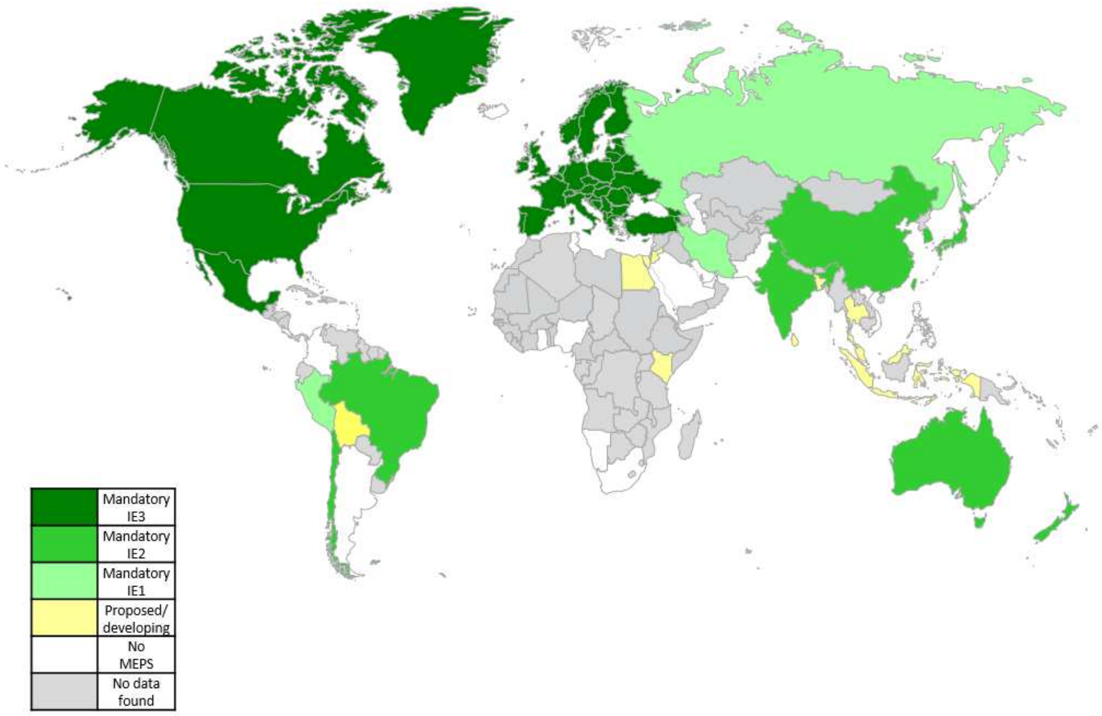

Figure 1 Overview of Minimum Energy Performance Standards (MEPS) Worldwide (Integral Polyphase Induction Motors)

Europe has also recognized the benefits of reducing the electricity consumption of electric motors systems and, following a period voluntary agreement supported by the European Committee of Manufacturers of Electrical Machines and Power Electronics (CEMEP) and the European Commission, also introduced MEPS for three-phase induction motors (0,75kW - 375kW).

The importance of introducing Minimum Efficiency Performance Standards (MEPS) relating to these products in Europe was highlighted by the 2008 Lot 11 EuP preparatory study on motors (de Almeida, et al., 2008).

Following the study, on July 2009, Commission Regulation 640/2009 (EC, 2009) was adopted, which specifies requirements regarding ecodesign of electrical motors and the use of electronic speed control (VSD). More recently the 640/2009 regulation was amended by Commission regulation 4/2014 (EC, 2014), to avoid loopholes created by the definition of operating conditions.

To help achieve European environmental goals (the aim is to reduce its greenhouse gas emissions by 20%, increase the share of renewable energy to at least 20% of consumption, and achieve energy savings of 20% or more, by 2020) one of the main strategies applied is improving the energy efficiency of the products used through measures such as energy labelling schemes, and enforcement of Ecodesign requirements for energy intensive products.

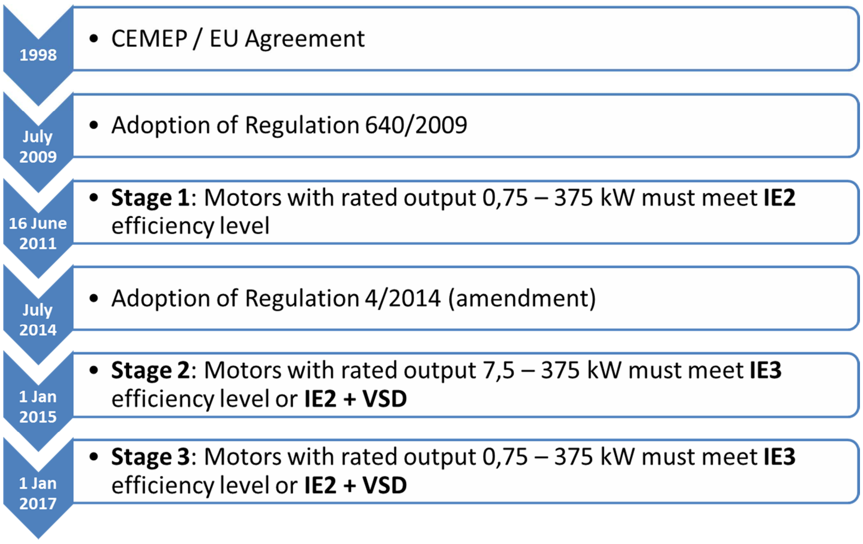

Figure 2 Timeline of EU motor policies

Nevertheless, the scope of the existing Regulation only covers part of the electric motors placed on the market. In order to evaluate the adequacy of covering motors not currently covered by legislation (e.g. in different power ranges or using different technologies) a new preparatory study - Lot 30: Special motors, 2014 - was launched in 2012. Electronic controllers, such as VSDs and soft-starters were also subject of the study.

The study is based on a methodology for the Ecodesign of Energy-using Products (MEEuP) (VhK, 2005) developed for the European Commission, which is common to all the EuP preparatory studies and identified: a) Existing relevant standards and legislation b) Market characteristics for the products under consideration; c) Relevant environmental aspects of the products and their technical/economical potential for improvement; d) Technical analysis of the Best Available Technologies (BAT) and of the Best Not Available Technologies (BNAT); e) LCC assessment; f) Scenario, policy, impact and sensitivity analysis.

The study proposes a list of policy options to remove inefficient motors and VSDs from the market but is unlikely to lead to big technological changes, therefore not overstressing the capabilities of manufacturers, particularly, of small and medium enterprises. This happens mainly because the improvement options identified in Lot 30 already exist in the market. The proposed MEPS can, in this way, be seen as an opportunity to drive the market towards more efficient products as well as an incentive for manufacturers to continue to search for innovative and efficient technological solutions.

The proposed policy options for improving the environmental impact of motors and drives, which resulted from the analysis carried out during the Lot 30 preparatory study, are presented in this paper, as well as the improvement potential associated with each of them.

The European Motor Market

Motor market data, relating to Europe, was primarily sourced from official EU statistics so that it is coherent with official data used in EU industry and trade policy. ProdCom (which stands for Production Communautaire) is the official Eurostat source of statistics on the production of manufactured goods. Where ProdCom data was found to be incomplete or inaccurate it was complemented with data provided by CEMEP[1].

[1] European Committee of Manufacturers of Electrical Machines and Power Electronics

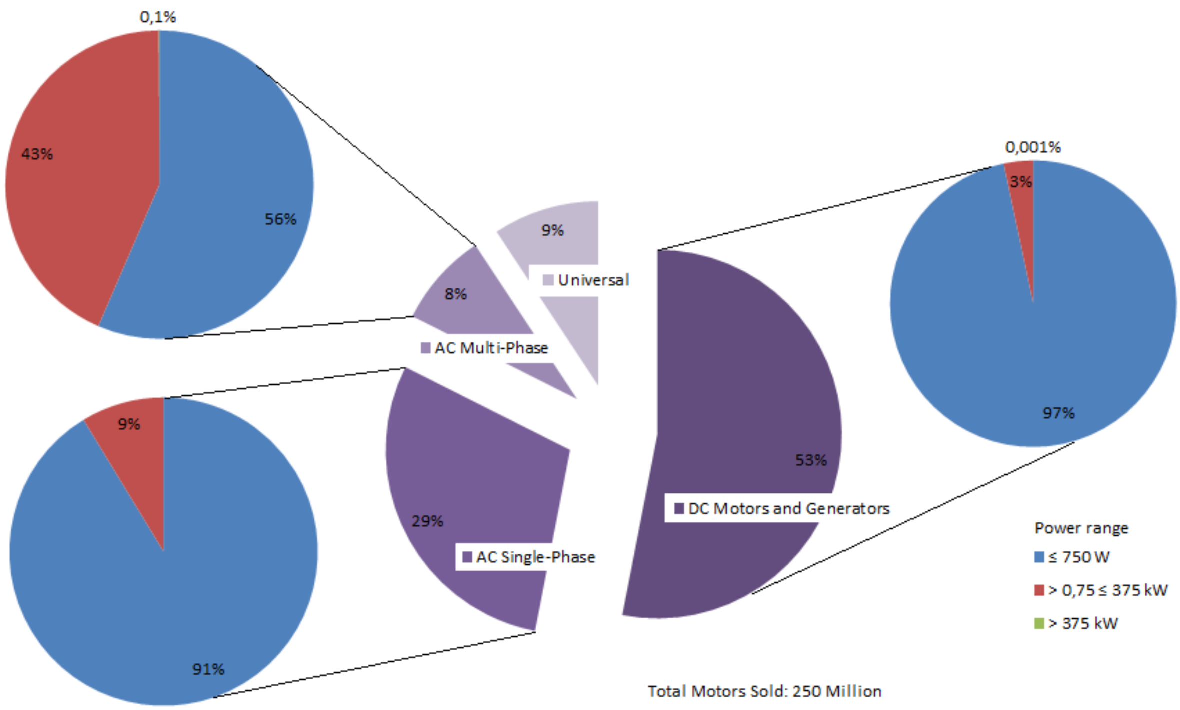

Figure 3 European Motor Market by technology and power range, 2010

In 2010 over 250 million motors were sold in the EU-27 [1], 91 % of which were in the small power range, that is, under 750 W, which are currently unregulated. The share of large motors is very small (only 0.01%) and the remaining 9% of motors sold are in the medium power range. These values are consistent with the available estimates of global sales of motors.

In the small power range (< 750 W), DC motors account for 56% of the number of units sold but more than 37% of this motors are used in automotive applications which are outside the scope of this study. There are two main reasons for this: automotive applications are outside the scope of the Ecodesign Directive and motors for off-grid applications were not included in the study due to their specificities.

The decreasing price of electronic controllers is expected to lead to the further decline in AC single-phase motor sales, and the increase in AC multi-phase motors and in DC brushless motors.

In the medium power range (0.750 to 375 kW), AC multi-phase motors are responsible for 50% of sold units (72% in value). The conventional Brushed DC motor market in this power range is expected to continue to decline as this technology is being replaced by three-phase induction motors. Very high efficient technologies (e.g. PM motors, LSPM motors), which until recently were considered customized products, are becoming available in the market in standard dimensions, as commodity products. [2]
Table 1 shows the VSD market data for the power ranges considered in the study.

Table 1. European VSD Market, 2012 (source: CEMEP)

	Power range					
	> 120 W ≤ 750 W		**> 0,75 kW ≤ 375 kW**		**> 375 kW ≤ 1000 kW**	
	n. units	Mio €	n. units	Mio €	n. units	Mio €
VSDs	1.13 Mio	200	2.89 Mio	2.500	7.000	260

Latest market trends show that the number of VSD units sold with power handling capabilities below 7.5 kVA has risen considerably in the last decade driven by developments in power electronics and by a decrease in prices. The market for VSDs sold integrated into small pumps and fans, particularly in HVAC high-efficiency applications, has also been increasing significantly.

Environmental Impact

For the evaluation of the environmental impact of motors and VSDs, the study collected data considered relevant for the evaluation of the environmental impact and of the LCC both for individual products and for the EU stock. Besides the market data presented above, the data collected included other relevant parameters, such as: Efficiency; Bill-of-Materials; typical number of hours of use; typical load factors / profiles; maintenance practices.

A total of 22 BaseBases[2] were modelled to ensure that the key characteristics of each group of products are adequately captured and are representative of the whole spectrum of products for each category. The results are shown for 12 BaseCases representative of motors and VSD as standalone products (not combined). The BaseCases are the reference point for further improvements, and therefore ideally represent the average new EU product. To evaluate the BaseCase environmental impacts, a reporting software tool named EuP EcoReport is used.

It was found that for all types of motor, the energy consumption (in the use phase) dominates in almost all types of environmental impact. This indicates that reducing the energy consumption should be the priority option for reducing the environmental impact of motors. Therefore, the environmental impact in other phases (production, distribution, end-of-life) was not further analysed.

The total environmental impact of VSDs is considerably less than that of motors, partly because they are inherently efficient at mid to high load, and because they are only used in some motor systems. However, particular attention should be given to this subject in order to identify any cost effective technologies that might be capable of reducing their losses, especially as the total stock is anticipated to keep increasing. It must be noted that the energy benefits from using a VSD always come from decreasing the losses of the system on the load side and that if this benefits can be achieved they largely surpass the losses in the drive itself.

[2] The BaseCase is the reference point for further improvements, and therefore ideally represents the average new EU product.

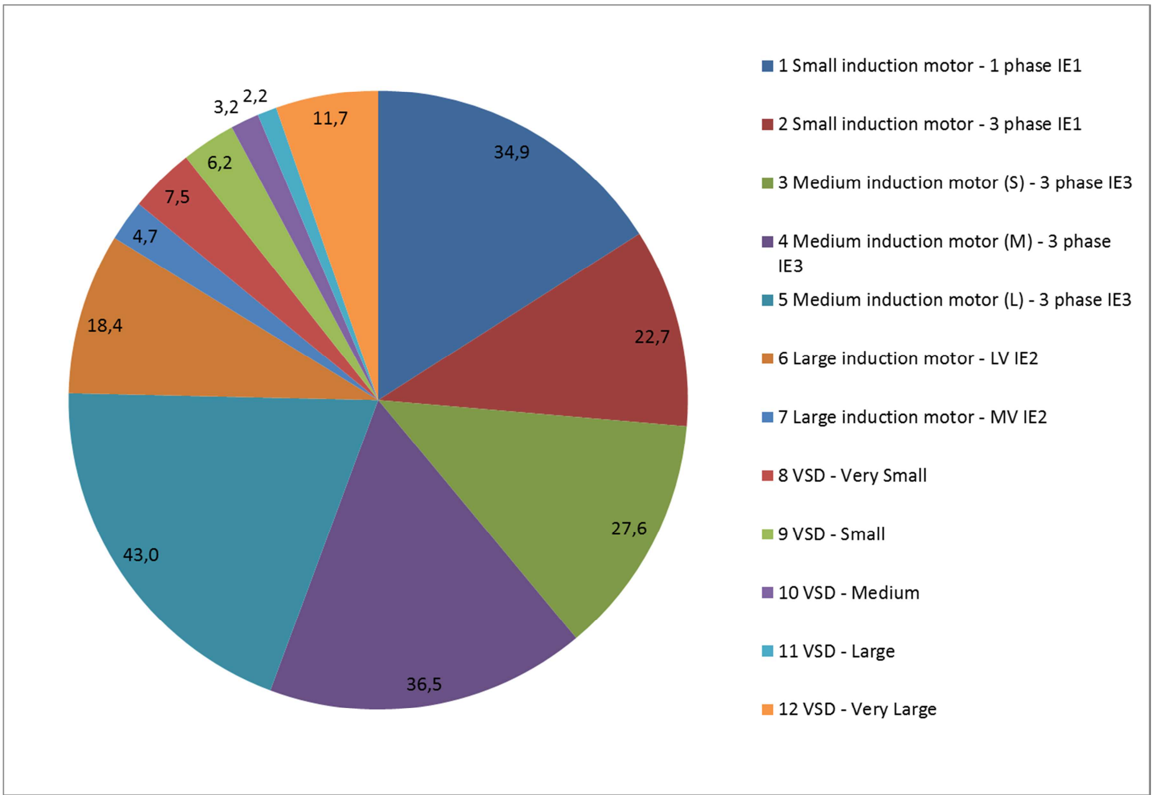

Figure 4. Breakdown of estimated energy losses (TWh/year), by product.

Best Available Technologies

Because of the gradually more stringent MEPS being introduced worldwide combined with the raised awareness towards the economic and environmental benefits of using high efficiency motors, in recent years manufacturers have been introducing in the market increasingly better solutions in terms of energy efficiency. The Lot 30 study analysed these new technological solutions in order to evaluate the possibilities for improvement.

The evolution in efficiency is reflected in the latest version of the IEC 60034-30-1 (2014) energy efficiency classification standard. In this updated standard the IE4 class (Super-Premium), which in the previous standard was only envisaged, is now defined. Furthermore, a new superior IE5 class is introduced although not yet defined in detail. It is the goal to reduce the losses of IE5 by some 20 % relative to IE4. The power range of motors covered was also broadened from 0,75kW – 375 kW to 0,120 kW -1000 kW which also better reflects regulatory trends.

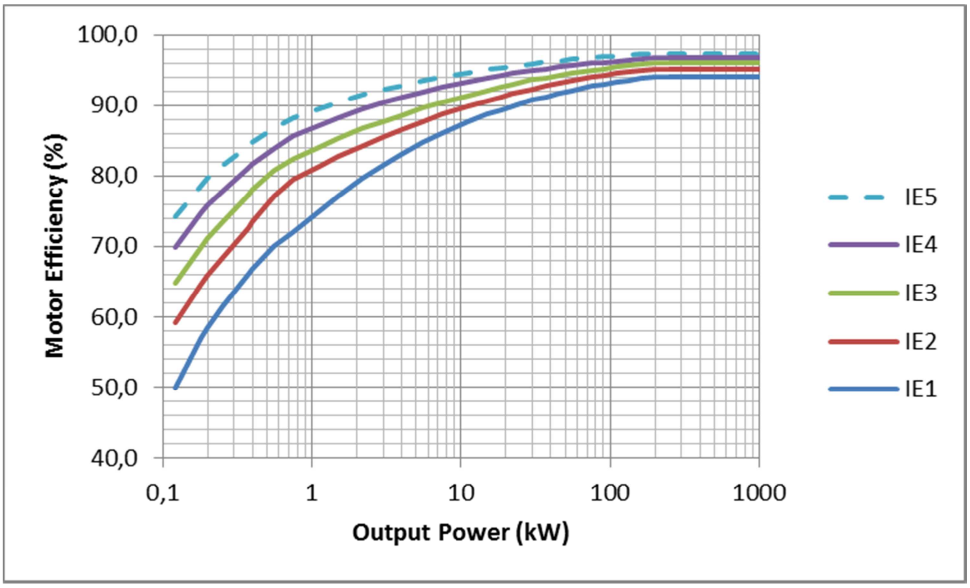

Figure 5. Efficiency levels in the IEC 60034-30-1 standard for 4 poled motors

At the time of the first edition of IEC 60034-30, in 2008, the efficiency levels of the Super Premium (IE4) class were believed to be too high to be achieved with standard induction motor technology, particularly for small motors. However, it was expected that advanced technologies would enable manufacturers to design motors for this efficiency class with mechanical dimensions compatible to existing motors of lower efficiency classes, making this motors commodity products. Today, induction motors have reached the market with IE4 efficiency levels and the use of advanced technologies can produce motors with efficiencies higher above the IE5 efficiency threshold. These technologies are expected to increase its market share in the near future (Figure 6).

Several strategies can be used to increase the efficiency of induction motors: advances in motor design (namely thermal), tighter tolerances, the use of superior magnetic materials, larger copper/aluminium 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 [3].

Additionally, other advanced technologies, such as permanent magnet synchronous motors and synchronous reluctance motors, have been developed that also reach these high efficiency levels and are actually candidates to IE5 class (De Almeida, et al., 2014).

For single-phase motors, adding a secondary “run” capacitor can also significantly increase efficiency. These motors, called capacitor start capacitor run motors, have two capacitors in series with the main stator winding.

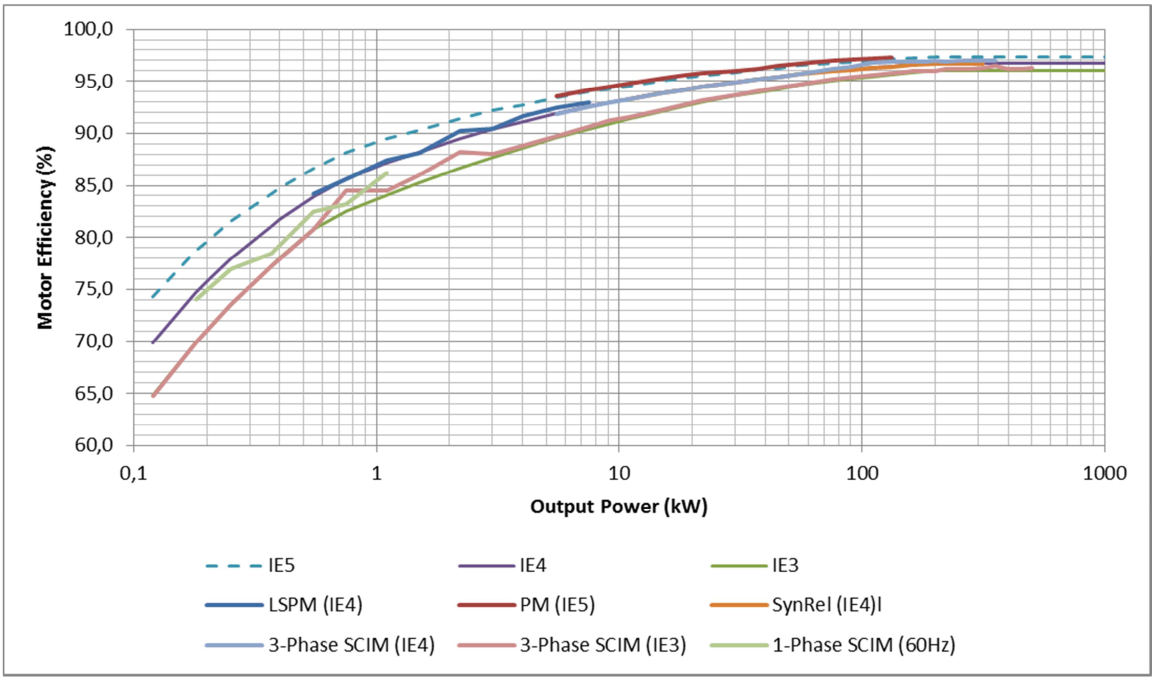

Figure 6. Overview on the motor efficiency classes defined in the IEC600-34-30-1 standard and on the commercially available motor efficiency (catalogue data)

VSDs

VSD 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%).

The most efficient VSDs present in the market today have approximately 25% lower losses than the average product on the market. Improved control algorithms also contribute to the increase in efficiency of these devices.

The functionality of the drive can also negatively affect its energy consumption but at the same time increase the capability of the system it is integrated into and its efficiency either by reducing the overall energy consumption or by increasing the production throughput. VSD capabilities can vary from simply varying motor speed with simple open-loop algorithms, to very complex enhanced on-board software features and embedded PLC functionality, network communications, etc.

It must be noted that the energy benefits from using a VSD always come from decreasing the losses of the system on the load side and that if this benefits can be achieved they surpass the losses in the drive itself.

Improvement potential

The following table shows the energy savings potential of introducing MEPS at higher efficiency levels, made possible by the use of the different technology option presented above. The improvement options are compared against a theoretical reference point - the BaseCase - for each of the product categories (1 to 12). The BaseCases are representative of the whole spectrum of products for each category and represent the average EU product. The improvement options are based on different Best Available Technologies (BAT 1, 2 and 3) which reflect different energy efficiency levels.

Table 2. Energy Savings from the introduction of different improved technology options, relative to each BaseCase.

Ref	Description	Size (kW)	BAT 1		BAT2		BAT3	
			Efficiency Level	Energy Savings (TWhPa)	Efficiency Level	Energy Savings (TWhPa)	Efficiency Level	Energy Savings (TWhPa)
1	Small induction motor 1 phase IE1	0,37	IE2	4.6				
2	Small induction motor 3 phase IE1	0,37	IE2	9.9	IE3	12.15	IE4	14.59
3	Medium induction motor (S) 3 phase IE2	1,1	IE3	0.87	IE4	4.73	IE5	6.80
4	Medium induction motor (M) 3 phase IE2	11	IE3	0.93	IE4	6.84	IE5	10.14
5	Medium induction motor (L) 3 phase IE2	110	IE3	1.07	IE4	6.96		
6	Large induction motor - LV IE2	550	IE3	3.12	IE4	4.19		
7	Large induction motor - MV IE2	550	IE3	1.14	IE4	1.53		
8	VSD - Very Small	0.37	IE2 VSD	0.75				
9	VSD - Small	1.1	IE2 VSD	0.62				
10	VSD - Medium	11	IE2 VSD	0.32				
11	VSD - Large	110	IE2 VSD	0.22				
12	VSD - Very Large	550	IE2 VSD	1.17				

It should be noted that:

- Not all measures in Table 2 are necessarily economic and so the most ambitious energy saving opportunities may not in practice be realizable. In some cases it was shown that the life-cycle cost of the improved technological option is greater than that of the BaseCase.
- Energy savings are in addition to those claimed for existing regulations.
- Energy savings are all relative to the BaseCase technology, not the preceding technology type.

Identified Ecodesign Policy Options

Based on the estimated potential savings a number of policy options are suggested in order to achieve the desired reduction of the environmental impacts of electric motors. These options and respective projected savings are summarised in the table below.

Policy Option 1 (PO1)

The current situation is that only motors between 0,75 kW and 375 kW are regulated. This option would introduce MEPS for motors with lower powers, between 120 W and 750 W, and higher powers, over 375 kW and up to 1000 kW.

IE2 would be the minimum requirement for motors with a rated power output between 120 W and 750 W (PO1a and PO1b). The study has identified an important cost effective energy saving potential on these motors, even while considering that a large number of the sales are motors that are integrated into products that are already covered by other Regulations.

For small motors, both the US and China have already passed a MEPS regulation. In the US case the performance limits are fairly high, as can be seen in

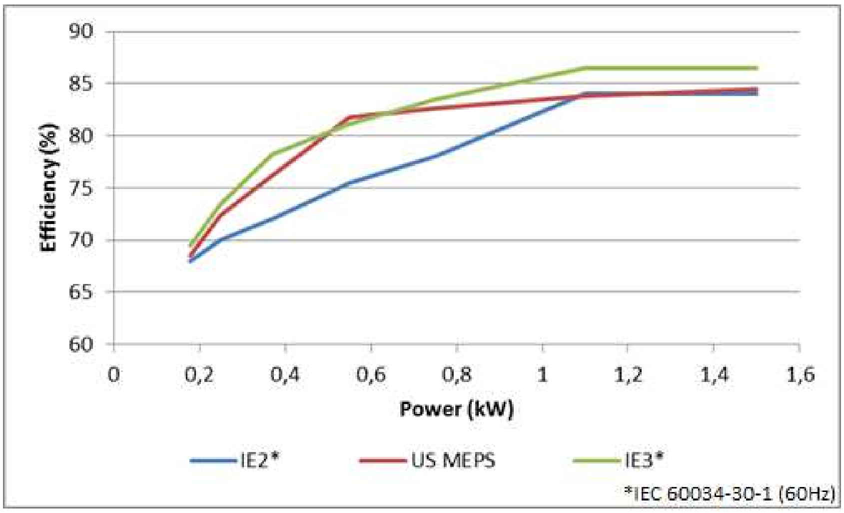

Figure 7 US single-phase MEPS and IEC 60034-30-1 standard levels

Regulations are only proposed for induction (both single phase and three-phase) and shaded pole motors. This is because universal motors have too low running hours to justify regulation, (the brushgear used only has a limited life). This exclusion does not lead to a loophole, as this limited lifetime means that it would not be practical to use universal motors in applications that currently use induction motors.

For large motors (375 kW -1000 kW), MEPS at IE3 level are proposed (PO1c). The current situation is that for large induction motors, China alone has a MEPS. However the savings are only small and most motors above 375 kW are specified based on total cost of ownership.

There is no technical or commercial reason why only Low Voltage motors should be in scope, and so under PO1 Medium Voltage motors up to 1000 kW would also be subject to the same regulations as LV motors to reach IE3 efficiency level. MV motors are defined as those operating from 1000 V and up to 6600 V.

Policy Option 2 (PO2)

This Policy Option would make IE3 the MEPS level for all motors 0.75kW to 375kW by removing the “IE2+VSD” alternative to the mandatory purchase of an IE3 motor.

Under the existing regulation 640/2009, substantial energy savings were claimed for the increased uptake of VSDs through the incentive of being able to use a lower cost motor. It may be considered that the publicity given to this measure will have been a major contributing factor in the ongoing growth in the sales of VSDs, which continue to grow as their energy saving and broader technical performance is appreciated. The higher sales volume, and the ongoing reduction in component prices, is leading to ongoing downwards pressure on VSD prices. It is therefore clear that the increase in sales of VSDs looks set to continue at a similar rate into the future. Furthermore, from an economic point of view, the combination of an IE2 motor and a VSD is more expensive than an IE3 motor, so, economic operators faced with fixed loads, the choice on an IE3 motor should be obvious.

At this stage of market development, the clause allowing the use of an IE2 motor when choosing a VSD is therefore considered to be of little benefit in further stimulating a market that is growing as fast as it is. Hence the proposal to yield further energy savings by moving the MEPS for all motors to IE3 level, which is now a very well established technology internationally.

Policy Option 3 (PO3)

This option would expand the types of motor included to explosion proof and brake motors which are currently specifically excluded. However, there appear to be no technical impediments for these motors to achieve efficiency levels similar to general purpose induction motors. The same is not true for increased safety motors (Exe) which have technical specificities, such as larger clearances, that do not enable them to reach high efficiency levels and should be specifically excluded.

Policy Option 4 (PO4)
Based on the analysis of the Life Cycle Cost curve, it can be justified to consider making IE4 the MEPS for all motors within scope of the current regulation in the power range 750 W to 1 000 kW.
IE4 induction motors are already available over a wide power range, although so far with limited manufacturer availability and very low sales. In addition there are practical considerations that will need to be taken into account, including the need to use non-standard frame sizes. So while it is true that it is technically challenging, especially in the small sizes, it is clearly possible to overcome these problems and produce commercial products.
If the IE4 market develops well in the next years IE4 could become the most adequate minimum requirement, the savings derived from such measure could be important, but its applicability should be re-evaluated in the future, as well as other policy options, such as financial incentives, to help pull the market towards these more efficient technologies.
As an example, the Life Cycle Cost and Payback analysis are shown in the next figures for an 11 kW three-phase induction motor, considering different electricity prices.

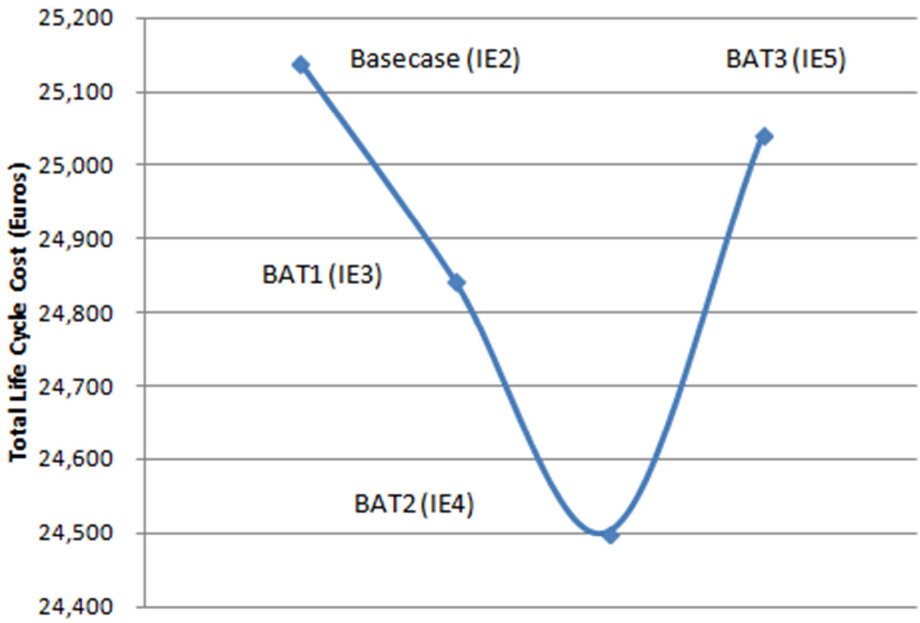

Figure 8 LCC Analysis: 3 phase induction motor, 11kW (3,000 hours/year; Lifetime: 15 years)

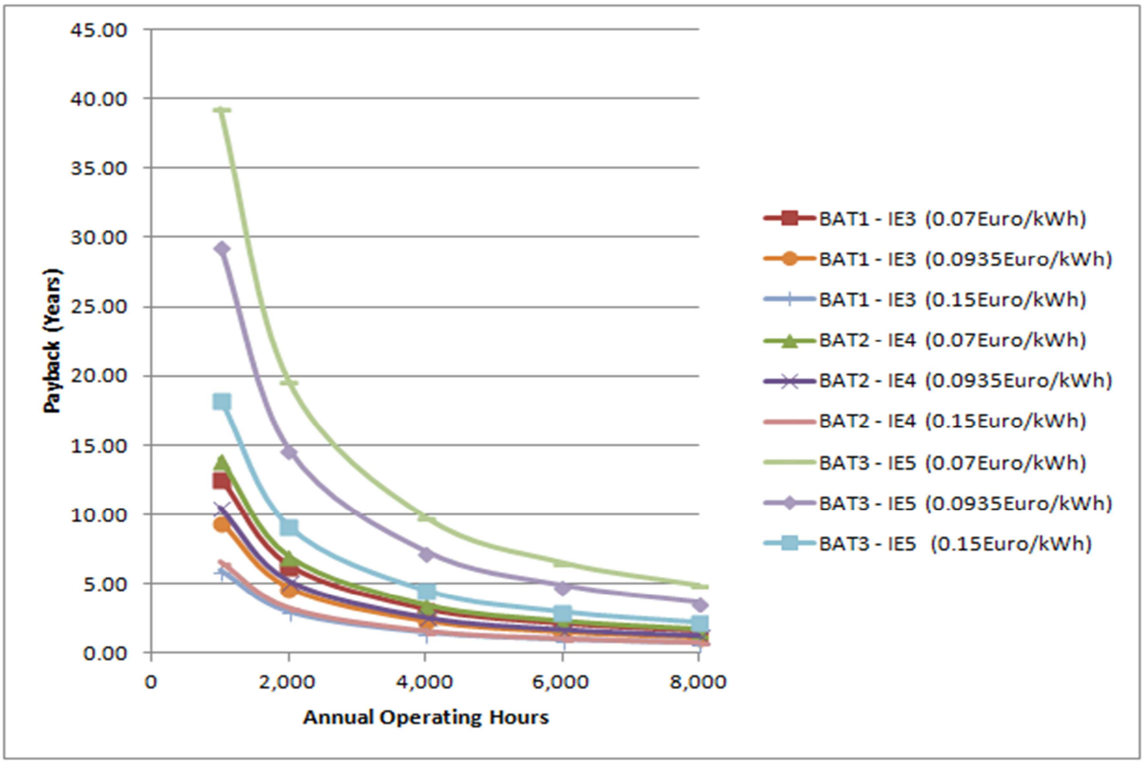

Figure 9 Payback Analysis: 3 phase induction motor, 11kW

Policy Option 5 (PO5)
Policy Option 5 is that VSDs must meet IE1 performance (as defined in CENELEC EN 50598-2 standard). Analysis has shown that it is not cost effective to require the introduction of a MEPS for VSDs at a higher level. However it would be beneficial to remove from the market VSDs with performance below IE1, mostly being imported into the EU.

There is the technical potential for further reduction in losses as technology improves, and as the understanding and characterisation of VSD losses improves. The following aspects in particular should be considered, with a view to introducing labelling requirements.

- The Extended Product Approach[3] for motor systems would require the part load efficiency of VSDs to be stated, based on EN 50598, giving the information required. The technical specification[4] IEC 60034-2-3, regarding the efficiency of converter-fed motors has recently been approved.
- New technologies such as Permanent Magnet and synchronous reluctance motors offer efficiencies beyond those of VSD driven induction motors, namely in the low power range. While it would not be justifiable to mandate the use of VSD+motor combinations of these types, it might be useful to indicate to the user the existence of these improved products through a labeling requirement. The recently approved classification standard IEC 60034-30-1 already includes technologies other than induction motors.
- It is noted that no other regulations on motor controllers elsewhere in the world have been identified.
-

There is insufficient data to estimate the energy savings from this improvement, but it is thought that they would be small (indicatively <1.0TWhpa), and so no specific energy savings are attributed to this measure.

Policy Option 6 (PO6)
Policy Option 6 is that the existing Product Information requirements within 640/2009 should be extended to include all types of motor within the proposed extended scope of this regulation.

[3] The EPA for motor driven units has been developed over the last decade as a means of characterizing and regulating common motor systems.
[4] Technical Specifications are often published when the subject under question is still under development or when insufficient consensus for approval of an international standard is available (standardization is seen to be premature).

These information requirements include, besides other technical information:

- nominal efficiency (η) at the full, 75 % and 50 % rated load and voltage (U_N);
- efficiency level: 'IE2' or 'IE3'

In particular, it is thought useful to include information on the standby consumption of VSDs in the technical documentation of these products.
Table 3 shows the projected energy savings of each of the listed policy options. Only in some cases is the 2030 time horizon sufficient for the total stock to be changed, and hence the 2030 and total energy saving are shown.

Table 3. Projected energy savings by Policy Option.

Policy Options	**Energy Saving [TWhpa]**		**Proposed date of coming into force**
	2030	**Total**	
PO1a. Small single phase motors (120 W – 750 W) - IE2	4.6		01/01/2018
PO1b. Small three phase motors (120 W – 750 W) - IE2	9.9		01/01/2018
PO1c. Large LV and MV motors (375 kW – 1 000kW) - IE3	2.9	4.2	01/01/2018
PO2. Removal of option to use an IE2 motor where a VSD is used	2.7		01/01/2020 Subject to review
PO3. Explosion proof and brake motors in the scope of the Regulation	0.9	0.95	01/01/2018
PO4a. Medium motors (750 W – 375 kW) - IE4	5.6	7.9	
PO4b. Large motors (375 kW – 1000 kW) - IE4		1.4	To be re-evaluated in the future
PO5. VSD MEPS at IE1			01/01/2018
PO6. Mandatory information requirements	Not Applicable		01/01/2018

Conclusions

Several of the identified Policy Options to promote energy efficient motors and drives are in line with current international best practice:

- PO 1: Expansion of scope of existing regulation to include MEPS at IE3 for large three phase induction motors and at IE2 for small three-phase and single phase motors.
  Saving 18.8 TWhpa.
- PO 2: Removal of the current option to use an IE2 motor + VSD instead of an IE3 motor.
  Saving 2.4 TWhpa.
- PO 3: Removal of the exemption given to explosion proof and brake motors under Regulation 640/2009.
  Saving 0.26 TWhpa.

In addition, the analysis has identified two further innovative options at World level that yield appreciable energy savings:

- PO 5: Set a MEPS at IE1 for VSDs so as to remove the poorest efficiency models from the market. Energy savings attributed to this measure are small (<1TWhPa)
- PO 4: Raising of MEPS for medium and large motors (0.75 to 1000 kW) to IE4.
  Saving 9.4 TWhpa.

Option PO 6, regarding information requirements, has no directly attributable energy savings but is necessary to increase the scope of the information requirements to support the expanded scope of proposed motor regulation.
Global harmonization of motor and drive regulations is an advantage to both producers and users of motors, with the important USA and Chinese markets having regulations that can be considered equivalent to PO1a (small motors only), PO2 and PO3.

IE4 motors are at an early stage of development, and currently most appropriate for applications with long running hours. However, the economics might change in the future, with price reduction through high volume production, and so it is suggested that PO4 is not adopted now but should be reconsidered at the time of first review.
The introduction of the proposed policy options would achieve environmental and economic improvements at EU level with potential cost-effective savings of up to **31.2 TWhpa**. of which **26 TWhpa** is achievable by 2030.

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A method to measure the cost-effectiveness of energy efficiency projects: a case study comparing US/Brazil efforts to improve Induction Motors' MEPS

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Abstract

Evaluating the cost-effectiveness of energy efficiency initiatives is essential to identify how much potential these projects have when compared with other forms of investments in energy. Defining cost-effectiveness helps energy efficiency programs compete with a broad range of other resource options in order for energy efficiency to get attention and funding necessary to succeed. Policy makers are aware of this and assessing potential cost and impacts is an essential step during the Minimum Energy Performance Standards (MEPS) definition.

This paper presents a graphical method to evaluate the cost-effectiveness of energy efficiency projects, the method is both Life Cycle Cost (LCC) and Net Present Value (NPV) based and it is open for economic and technical information. It also proposes the calculus of the cost of the saved energy (U$/MWh) so it gives a cost for energy efficiency projects that can be compared with other options of energy investment. This method also allows the uncertainty analysis by evaluating the impact of every parameter in the result (Sensitivity Analysis) and the limit values of each parameter to maintain the project viable (Breakeven Analysis). The method is actually available as an app for android mobile devices and it is currently under evaluation.

Actually, Brazil has mandatory MEPS for IR2 Induction Motors (IE2 similar) and it is expected to set higher ground (IR3/Premium) around 2017. The paper evaluates this scenario from the cost-effectiveness point of view and compares it with the transition the US is about to apply. It also tied the cost of the saved energy to achieve this efficiency improvement with other types of energy investments (thermal/wind generation, price of electricity).

Introduction

Energy Efficiency became a global concern as a result of the increase in energy prices and the awareness of the limitation of the natural resources. There have been initiatives around the world from governments and the private sector to use the natural resources in a more efficient way. The United States was one of the first countries to establish governmental programs to induce a gradual improvement in the efficiency of end-use equipment. Just after the 1970's energy crisis, the state of California defined an efficiency program which was a combination of voluntary labeling initiatives that gradually evolved to mandatory and then to efficiency standards (MEPS) of a large range of end-use equipment. Since then, similar programs have been implemented in a large number of countries around the world including Brazil. Actually, 60 countries have labeling program [1].

The policies to improve efficiency have a wide scope of actuation, since energy has various primary sources (fossil fuels, nuclear, hydro, solar, wind and others), passes through different phases before its final use (production, transmission, distribution), and has alternate destinations (buildings, industry, agriculture, residential, transportation) and use (heating and cooling, lighting, domestic appliances, motor driven systems, etc.). These policies also have different purposes (increase energy efficiency, reduce greenhouse gas emissions) [2], but they have in common the fact that the governments' response to this reality has been to centralize the efforts through national energy efficiency regulations. Table 1 summarizes the main national governmental policies that have been implemented around the world.

Table 1 – Summary of the national energy efficiency regulations around the world.

Country	Legislation	Year	Rules
Canada	Energy Efficiency Act	1992	MEPS Mandatory Labeling/Certification
France	Energy Efficiency Law	1992	MEPS Mandatory Labeling Thermal Regulation Buildings Performance
United States	Energy Efficiency Act	1992	MEPS reviewed every 4-6 years Mandatory Labeling for electro-electronics appliance Water conservation Renewable energy
Union Kingdom	Residential Energy Conservation Law	1996	MEPS Mandatory Labeling for all equipment
China	Energy Conservation Law	1997	MEPS Voluntary Endorsement Labeling Certification Programs
India	Energy Conservation Act	2001	MEPS Voluntary Labeling Energy Conservation Building Code Energy Conservation Fund
Brazil	Energy Efficiency Law	2001	MEPS Buildings Efficiency
Japan	Energy Conservation Law	2006	Voluntary Labeling
Russia	Energy Efficiency Act	2009	Buildings and Construction Performance Energy-efficient movement of goods Energy Audit
Europen Union	Energy Efficiency Directive	2012	Targets for energy consumption Buildings Renovation National Energy savings obligations National Funds Cogeneration for HC Systems

Source: **[3] [4] [5] [6]**

The United States' Energy Policy Act (EPAct) established several energy management goals: water conservation, labels and standards for equipment and buildings, energy audit, electric vehicles, federal funds, incentive programs for utilities, renewable energy, and others. It was revised in 2005 [6] including buildings performances and renewable energy requirements. At the same year, the government of Canada approved the Energy Efficiency Act (Energy Act CA, 1992), which had a less comprehensive scope, restricted to the trade of energy efficient products in the country and to the definition of standards and test procedures for end-use equipment. The Brazilian Energy Efficiency Law is similar to the Canadian with its restricted area of actuation. The most recent one, the European Union's Energy Efficiency Directive [5] amends previous legislations (EcoDesign) and has an even wider approach, bringing innovations like targets for primary and final energy consumption for 2020, yearly building renovation and obligation schemes for utilities and co-generation performances.

Brazil began the initiatives in this area with a voluntary labeling program in the 1980s, but a major crisis in the supply of electrical energy that occurred in 2001 forced the government authorities to raise investments in order to increase the electrical energy supply and also to hold down the consumption increase through efficiency programmes. In the same year, the National Congress approved the Energy Efficiency Law (10.295/2001), [4], which allowed the federal government to establish mandatory MEPS for energy driven end-use equipment manufactured or commercialized in the country. It also established an objective to improve the efficiency of buildings. This law, combined with the effects of the deregulation of the electrical sector occurred in the 1990s, gave a new dimension to energy efficiency policies, defining a national policy for conservation and rational use of energy, establishing the initial procedures to maximize the energy performance of equipment and buildings and other initiatives.

The one decade delay in applying national energy efficiency legislation is not the only difference between Brazil and United States. In fact, these continental American countries are in different stages of industrial development and energy consumption rates as Table 2 shows. Although Brazil's population is only 2/3 of the US, its GDP is seven times smaller, revealing a country in development process. The energy consumption numbers confirm this statement showing a Total Energy Consumption eight times smaller in Brazil and so is the Total Electricity Consumption. The analysis of the electricity consumption per capita, however, reveals a tendency of stabilization in the US, with a 71% growth during the last four decades [7], while in Brazil this increase was much more significant, 380% during the same period, which leads to an actual difference of five times between the numbers of Brazil and US.

The financial rates also reveal different stages of economic stabilization, the discount rate is ten times higher and its energy escalation rate is also superior. The prices for electricity for Residential and industrial consumers are higher in Brazil, although a recent depreciation on currency could change these numbers, but not enough to make electricity in Brazil cheaper than in the US.

Table 2 – Country Facts Comparison

	Brazil	**US**
Population	201 million	316,8 million
GDP	U$ 2,2 trillion	U$ 16 trillion
Energy Consumption	277,81 Mtoe	2.242,39 Mtoe
Electricity Consumption	526.167 GWh	4.293.889 GWh
Electricity Consumption per capita	2.617 kWh	12.947 kWh
Electricity Residential Tariff	U$ 0,208/kWh	U$ 0,116/kWh
Electricity Industrial Tariff	U$ 0,17/kWh	U$ 0,079/kWh
Estimated Ind. Motors Stock/2015	4,7 million	37,8 million
Mandatory IM MEPS Level	IR2	Premium
Discount rate (*d*)	5%	0.5%
Energy Escalation Rate (*e*)	3%	2%

Source: [8] [7]

All of the energy efficiency initiatives conducted by policy makers and other organizations have the objective to influence the market players (consumers, retailers, and manufacturers) to produce, commercialize and consume more efficient products. Amongst the methods proposed in those policies that affect directly the end-use equipment, the definition of voluntary or mandatory minimum efficiency performance standards (MEPS) is the one with better results so far. Since electric motors are responsible for the major part of the electricity consumption in the world (about 45% of the total) [9], and induction motors (IM) represents a share of more than 80% electric motors consumption [10], the analysis of IM mandatory MEPS in a country shows the stage of development of energy efficiency initiatives.

The process of efficiency improvement of energy driven equipment is associated with an increase in manufacturing cost and subsequently in the equipment's acquisition cost. This is expected to happen since the reduction of the losses is typically obtained with the use of more and/or better materials that are more expensive and innovative technologies that require some additional investment. Policy makers are mindful of this, since assessing potential cost and impacts is an essential step during the MEPS rule making process [2]. Evaluating the cost-effectiveness of energy efficiency projects/programs helps energy efficiency compete with the broad range of other resource options in order for energy efficiency to get the attention and funding necessary to succeed.

The goal of this paper is to assess the economic feasibility of setting higher efficiency standards for induction motors comparing the initiatives that are currently taking place in Brazil and in the United

States. It will be presented the economic analysis required to verify the viability of energy efficiency programs with the inclusion of the energy escalation rate as an additional input parameter. An android app to perform the economic analysis is presented including a tool for graphical visualization of the input data uncertainty. A survey of current products available in the US and Brazilian market are presented and analyzed under the perspective of increasing the MEPS levels in both countries.

Regulation, Induction Motors MEPS and Market

Traditionally, the Brazilian Government leads all the initiatives related to the energy area. Figure 1 illustrates the main entities that have the responsibility to manage energy efficiency policies in Brazil. The Ministry of Mines and Energy (MME) coordinates all the energy efficiency programs. The Management Committee of Indicators and Levels of Energy Efficiency (CGIEE) is formed by representatives of government agencies related to the energy sector and by energy experts, and has the objective to define: efficiency limits for end-use equipment; ways to monitor the equipment' efficiency; and methods to evaluate the results of these regulations. The Electrical Energy Conservation National Program (PROCEL) [11] conducts a successful endorsement labeling programme (PROCEL seal) and supports many energy efficiency initiatives, such as the site PROCELInfo. The National Institute of Metrology, Standardization and Industrial Quality (INMETRO) is responsible for the Labeling Brazilian Program (PBE) [12], certifies measurement laboratories and conducts the Conformity Assessment Programs related to the applications of the MEPS regulations. The Electrical Energy Regulatory Agency (ANEEL) is responsible for the regulation of the Energy Efficiency Programs (PEE) and the R&D programs, which are funded by the utilities of the electrical sector, and also for a law created during the electric sector deregulation (9.991/2000) [13].

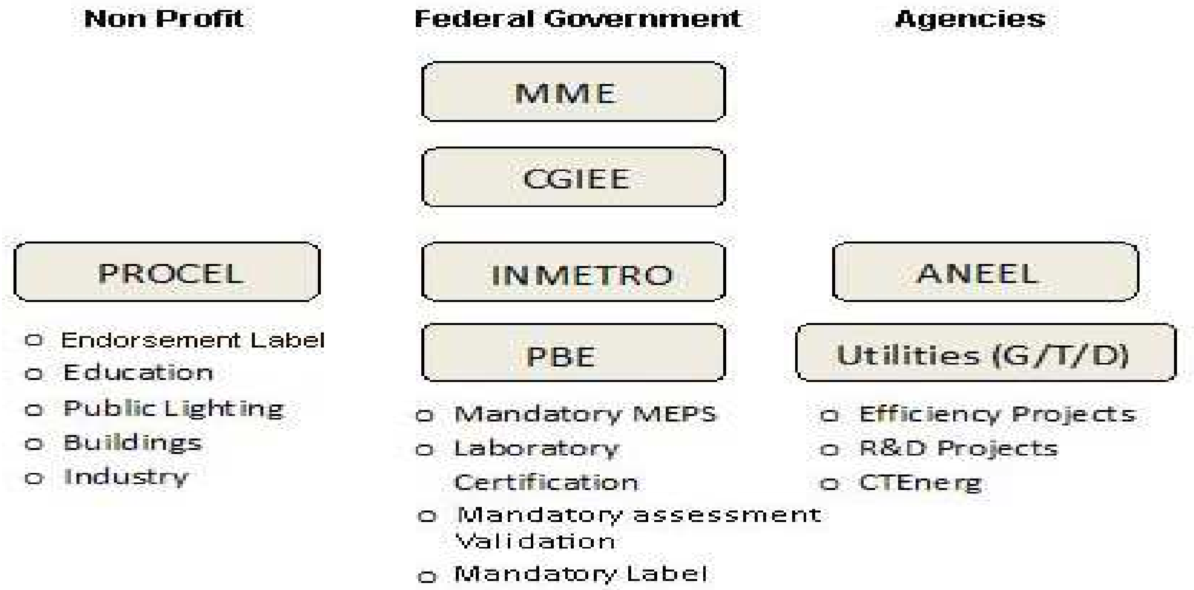


Figure 1 – Brazilian Energy Efficiency Organizations.

In the United States (US), the Department of Energy, through the Office of Energy Efficiency and Renewable Energy (EREN) [14], conducts the energy efficiency programs like the mandatory MEPS amongst other initiatives. The federal government also funds different agents and agencies in this area, like the Oak Ridge National Laboratory that conducts the Energy Efficiency and Renewable Energy (EE/RE) Program since 1978 to facilitate the Laboratory's research and development on energy efficiency and renewable energy technologies, and the Lawrence Berkeley National Laboratory's Environmental Energy Technologies Division, which performs research and development leading to better energy technologies and reduction of adverse energy-related environmental impacts. The labeling program called EnergyStar [15], which is a reference around the world, is conducted by the U.S Environmental Protection Agency (EPA), a Federal government agency whose mission is to protect human health and to safeguard the natural environment — air, water, and land. Figure 2 summarizes the Energy Efficiency Organizations operating in the United States to promote energy efficiency programs and projects.

Figure 2 – United States Energy Efficiency Organizations.

Induction Motor MEPS

The efficiency of electrical motors in the market has been increased during the last two decades as a result of a combination of public policy, higher energy costs and consumer awareness. Table 2 shows the actual estimated stock of IM in Brazil and in the US inferring a eight times smaller market in Brazil. It also shows that the US is one step higher in mandatory MEPS level for induction motors.

Premium efficiency (per NEMA MG-1 Table 12-12) standards for certain electric motors have become mandatory in the US since December 2010. The US Department of Energy is mandated by law to determine if there is need to set higher standards than the one currently in effect within 24 months of coming into effect of a current standard. In the European Union, IE2 efficiency level has been in effect since June 2011 [16]. In January 2015 motors rated 7.5kW to 375kW are expected to meet IE3 level or IE2 level if fitted with a variable frequency drive and in 2017, motors rated 0.75kW to 375kW are expected to meet IE3 level or IE2 level if fitted with VFD. For comparison purposes, IE3 and IE2 efficiency levels are equivalent to NEMA Premium and EPACT efficiency levels found in NEMA MG-1 Table 12-12 and Table 12-11, as it can be seen in Figure 3.

In Brazil, induction motors were selected to be the first equipment to have mandatory MEPS since 2002. The minimum levels of motor efficiency became mandatory since August 2003 (4508/2002 Decree) [4]. The regulation established two standards with minimum efficiency levels one for standard motors (mandatory, similar to the European IE1 and to US Pre-Epact MEPS) and other for high efficiency motors (voluntary, similar to IE2/Epact values). The MEPS were valid for three-phase induction motors from 1 to 250 hp, 2, 4, 6 and 8 poles, continuous operation, 600 V maximum, stand alone or as part of end-use machinery, imported or manufactured in the country. This regulation was revised at the end of 2005 (Ministerial Order 553/2005) [4], when the mandatory MEPS were restricted to the High Efficiency levels, initially up to the year of 2010, but due to a high number of Standard motors in distributors' stock, this decision had to be postponed until 2012. Currently, the motors manufactured and commercialized in Brazil must adhere to the High Efficiency levels, now called IR2 levels.

The next step for Brazilian MEPS for induction motors is to reach the values of Premium Efficiency levels already defined in Europe (IEC, 2008) and mandatory in the US since 2010 [17] (Table 12-12). CGIEE discussed and studied for more than a year to create new MEPS for induction motors and decided to enlarge its scope adding efficiency levels for 8 poles motors. The Brazilian Technical Standard Association – ABNT published these new levels (called IR3) at in the end of 2014 [18]. Although the standards are quite similar to the IEC standards, the efficiency test method is similar to IEEE 112-B. Figure 3 shows a comparison between these efficiency levels for all the range of rated output power.

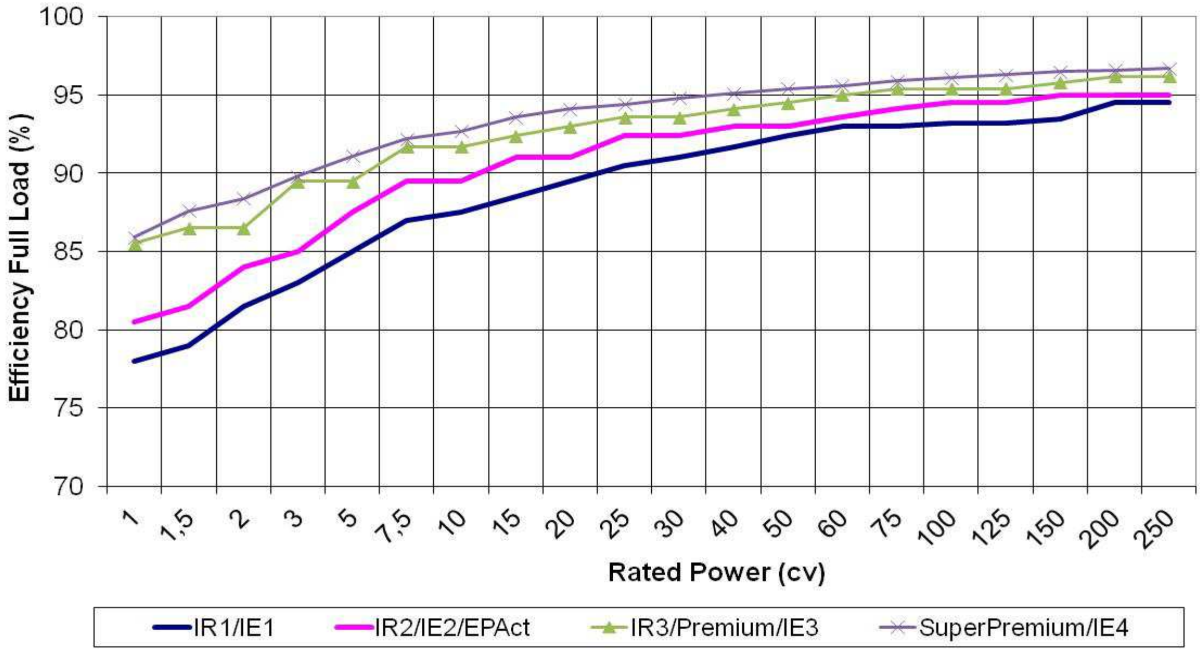


Figure 3 – MEPS for 4 poles Induction Motors. *Source:* [16]

IM Market

Figures 4 and 5 show the full load efficiency levels of some electric motors (induction and PM motors) that are currently available on the US and on the Brazilian market, respectively. The data was pulled from different manufacturer catalogues and marketing material and is displayed as dots on the plot. Figure 4 also displays the NEMA Premium MG 12-12 efficiency levels, the actual mandatory MEPS level in the US, as well as the proposed IE-4 efficiency level, which would likely be considered as a super-premium level. According to [16] the IE-4 super-premium level can hardly be achieved with induction motors. A look at the efficiency levels displayed in Figure 4 indicates that the IE-4 level may have already been reached or exceeded for some induction motors and also for PM motors; at least on the face value of the data available in manufacturer catalogues.

The Brazilian numbers indicates a similar scenario, the actual IR2 mandatory MEPS level is exceeded for most of the power range available, and the manufacturers also offers option in the next band of MEPS, the IR3 level, expected to become mandatory from 2017 [19]. However, these manufacturers' brochure data should be submitted to select testing laboratories to have the data checked under regulated specifications.

Economic Analysis and App

Energy efficiency (EE), like any other energy related area, must have a cost-effectiveness reference to identify how much of the potential for energy efficiency resources will be effectively realized. Defining cost-effectiveness helps energy efficiency programs compete with a wide range of other energy resource options. The cost-effectiveness tests evaluate the cost and benefits of the investment in a monetary basis.

The basic financial method for cost-effectiveness tests is the Net Present Value (NPV) applied over the costs and benefits of the EE project its lifecycle (LCC), which is the primary method for the perspectives of any participant in the initiatives [20]. The implementation of this method, altogether with a definition for lifecycle savings per unit of energy covers the entire perspective for the different players to check the cost-effectiveness of the energy efficiency initiatives.

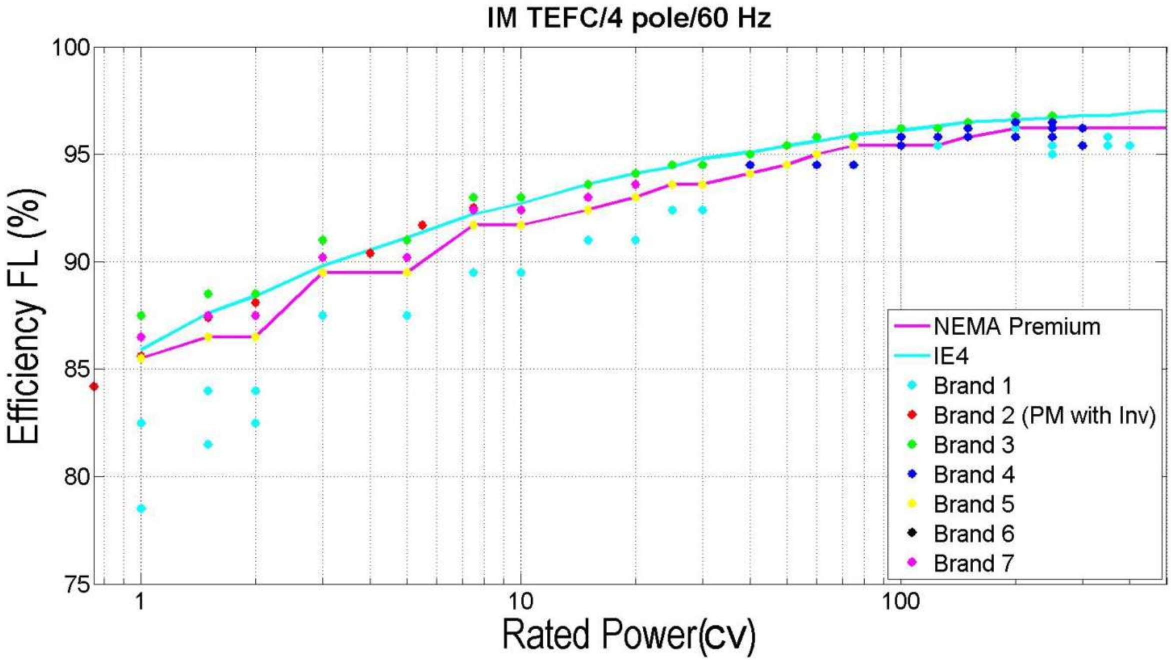


Figure 4 - Full Load Efficiency for Three-Phase Induction and PM Motors/4 pole/60Hz (US Market)

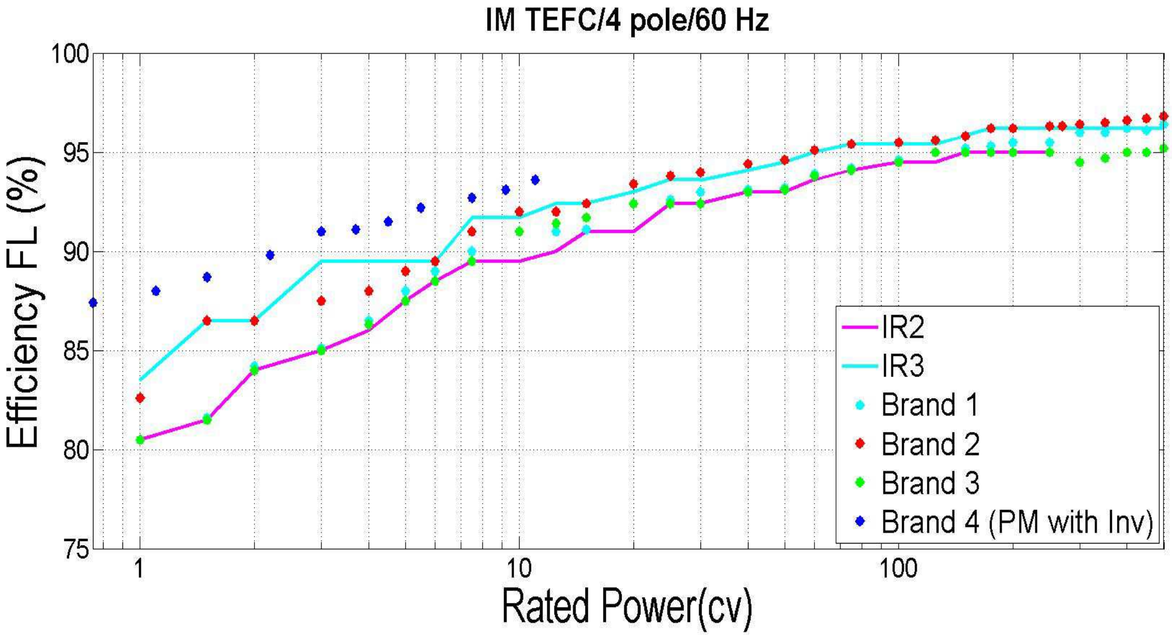


Figure 5 - Full Load Efficiency for Three-Phase Induction and PM Motors/4 pole/60Hz (Brazilian Market)

In order to apply the NPV, the costs and benefits of the energy efficiency program must be represented at the present time value. The discounted cash flows method is used to value the present value of the future expected cash flows for an investment. The expression used in the California standard [21] refers to the present time value for annually recurring uniform amounts. The energy related costs, however, have a behavior of its own during the project’s lifecycle, It occurs as a consequence of the variation on the energy price, which depends on different factors, as the type of generation (Hydro, Thermal, Wind, etc.), availability of primary resources and the dependency of energy import. This behavior must be reflected into the economic analysis of energy efficiency projects with the inclusion of the energy escalation rate (e) in the analysis in order to represent the increasing of the energy prices above inflation during the life cycle of the project.

An EE project is basically a project to improve efficiency in a energy driven equipment or system, or even in a building, and it is an alternative for a less efficient solution with a reduced or no investment at all. For these projects, the most suitable financial evaluation method to be used in an economic analysis is the Net Savings (NS) [22], since it uses the LCC and the NPV cash flow in a simpler way, dealing with the differences between the costs and benefits under analysis and, doing so, it discards the similar costs for both options under analysis (O&M, Replacement, Residual) and focuses in the variations on the investments and on the energy costs. Expression (1) represents the method and the viability analysis is as follow.

$$NS = \sum_{t=1}^{n} \Delta E \left(\frac{1+e}{1+d}\right)^{t} - \sum_{t=0}^{N} \frac{\Delta I}{(1+d)^{t}} \quad (1)$$

The first part of expression (1) represents the energy costs saved during the life cycle of the motor (*n*, in years), with NPV values. The second part is the difference between the investments required to purchase the motors with different efficiency levels, it is usually simplified by a simple subtraction, since the investment is made in the present time: if the result of the expression is equal or bigger than 0, the efficiency improvement project is economic viable, if not, it is non-viable. NS = 0 is the viability limit for the project.

Energy Costs (*E*) represents 96,7% of the motor's Life Cycle cost (LCC) [23] and its calculation depends on the operation characteristics of the machine: Load (*L*, % of the rated load, Pnom), Annual operating hours (*H*, hours) and efficiency (η). As expression 2 shows, it also depends on the energy tariffs (*C*, U$/kWh). The decreasing in the energy costs (Δ*E*) is expected as a result of the option for the equipment with higher efficiency.

$$E = \frac{P_{nom} \times L \times C \times H}{\eta} \quad (2)$$

Investments costs (*I*) include the acquisition equipment, installation and commissioning, and may even include the cost of engineering (project design), testing and inspection, and any training, or the acquisition of protection and control devices. This is the simplest cost to be calculated and it is usually simplified to the equipment's cost of acquisition. An Increase in the investment cost (Δ*I*) is expected with the option for equipment with higher efficiency.

Figure 6 represents graphically the economic analysis using the NS method. The cost-effectiveness limit is shown as curve defining the region of operation of the project where the improvement of efficiency is cost-effective.

This approach also make It possible to implement the deterministic methods of uncertainty analysis (Sensitivity and Breakeven analysis).The graphical method allows showing the impact of the imprecision of the values used in the analysis (Sensitivity Analysis) and with the information of the operating points of the equipment/project, it can be visualized how a parameter is critical to the economic viability of the project (Breakeven Analysis) [22]. Figure 7 shows the impact in the viability limit when some of the input data varies for electric motor efficiency improvement.

Figure 7 reveals the efficiency level as the parameter whose imprecision causes a crucial difference in the final results. It also can be seen in the Figure that the discount rate (d) and the energy escalation rate (e) have opposite effects on the viability limit, the firs, in a negative way to the viability limits (decreasing the operating points' area of economic viability), and the second in a positive way (increasing viability area) . The increase in Energy Price and in the projects lifecycle (*n*, in years) has almost the same effect positive on the viability limit, increasing the region of viability.

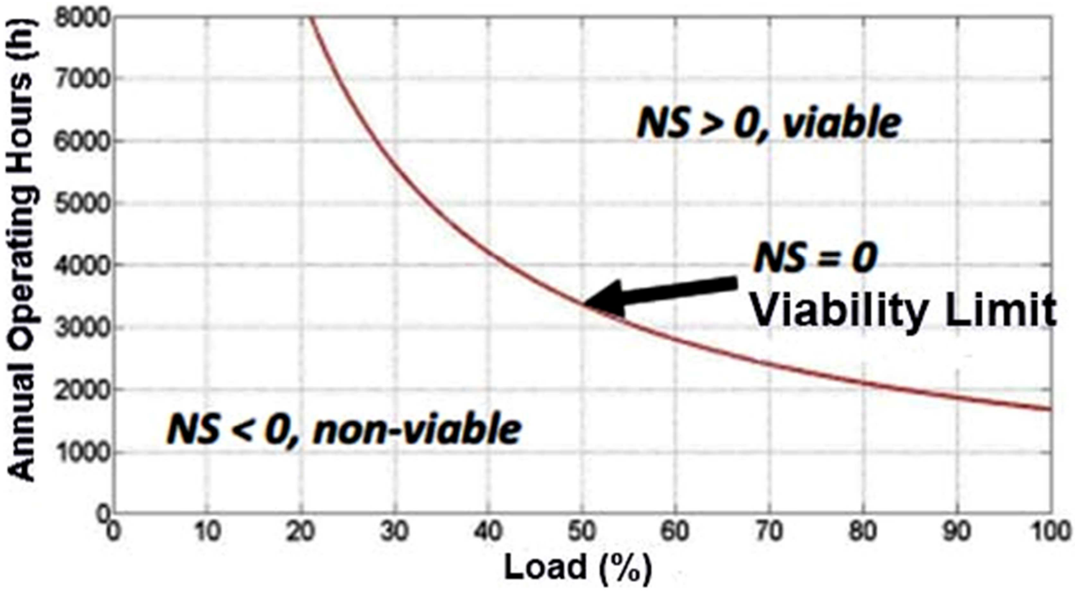


Figure 6 – Cost-effectiveness limit for the whole range of operation of a project/equipment *(Own elaboration)*

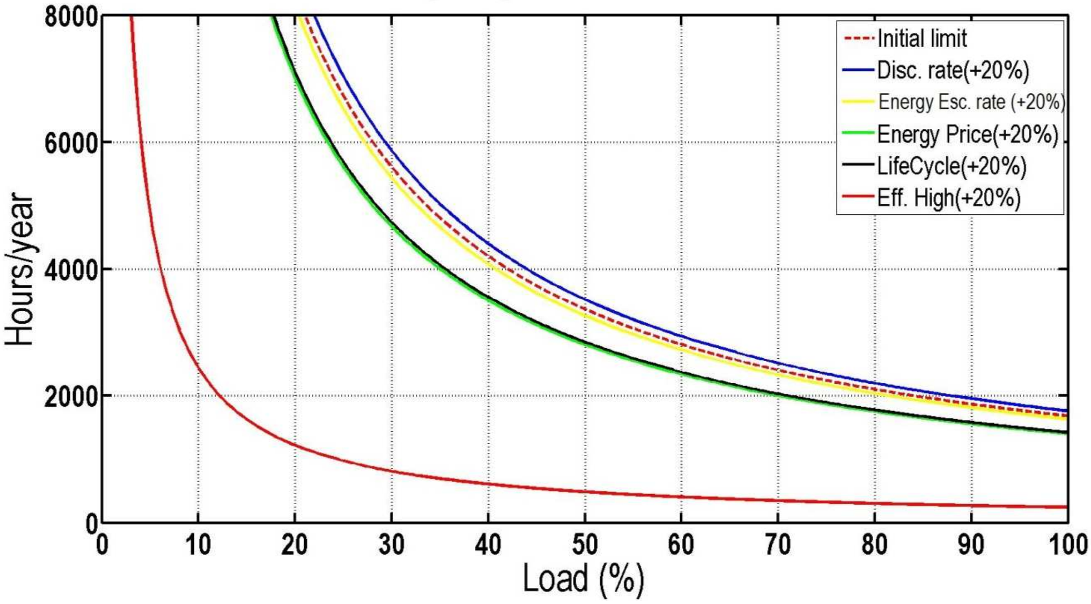


Figure 7 - Sensitivity analysis of the improvement of efficiency in an induction three-phase electric motor from IR2 to IR3 efficiency levels *(own elaboration)*.

Another cost-effectiveness test method that is required for the EE project's economic analysis is the Lifecycle revenue impact per unit of energy, which is basically the cost of the energy saved during the lifecycle of the EE project presented in expression (3) for electricity driven equipment as the Saved Energy Cost (Saved MWh, U$/MWh). This cost allows the comparison of the energy efficiency investment with other types of energy related investments. The Saved MWh is the relation between the increased investment for the improvement of the efficiency (ΔI, U$) and the reduction of energy (ΔMWh,Mwh) that is expected during the lifecycle of the energy efficiency project.

$$Saved\ MWh = \frac{\Delta I}{\Delta MWh} \qquad (3)$$

App General Description

Viability Analysis is an Android app developed to be a graphical tool for the economic evaluation of projects involving energy efficiency improvement. The main advantages of this approach are: to provide a solution for the economic viability analysis of energy efficiency projects linking technical and financial characteristics; and to allow a graphical display for the input parameters' uncertainty (Uncertainty Analysis). This version of the application presents one of the facilities of this tool that is to verify the economical viability of the energy efficiency improvement of a project/equipment in comparison with other option (with lower efficiency and lower initial investment). The application is customized to analyze the decision to purchase a new electric motor, but it can also be used to compare two efficiency projects with different costs and efficiencies. Future versions of the application will include analysis regarded the replacement of equipment in operation, retrofitting projects and energy efficiency rebate programs.

Figure 8 shows the opening screen of the app, where the input parameters are previously filled out with data from an 11 cv induction motor. The required parameters are: efficiency (higher and lower), rated power, investment cost (higher and lower), discount rate, energy escalation rate and energy price. A click in the VIABILITY CURVE box generates a curve based on expression (1), which shows the economic viable area (above the curve) and the non-viable area (below the curve). The OPERATING POINT box allows the input of the Operating characteristic of the Project/motor under analysis (e.g., 50 for Load (%) and 3000 for Annual Operating Hours (h)). The screen will display a red dot as the operating point and the result of the Saved MWh Cost (expression (3)) appear at the top right of the screen alongside with the result viability (or not) of the project under analysis, as it can be seen in Figure 8.

There are explanatory texts for every input parameter accessed with a click on the question mark at the side of every input box and the press and hold at each box opens standardize tables for each parameter, including average operating points (Figure 9)

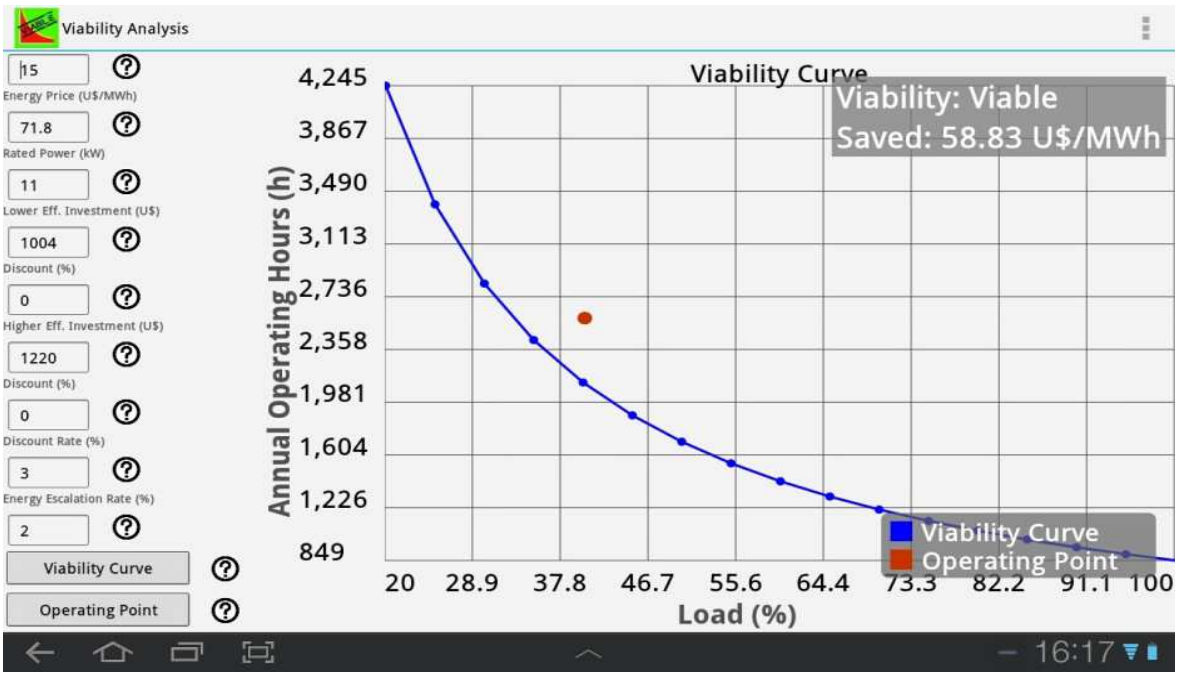
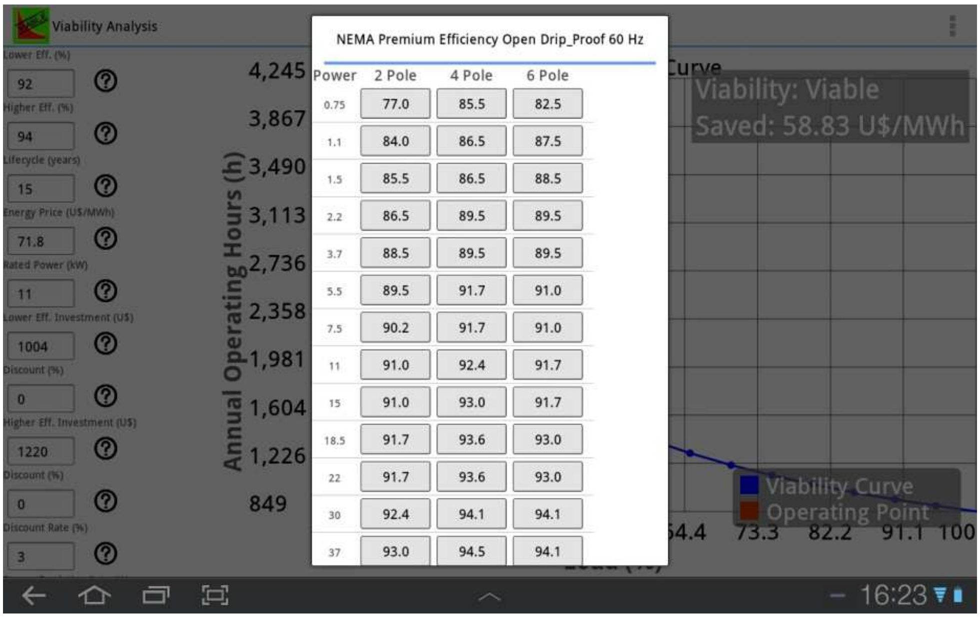


Figure 8 – Main screen of the Viability Analysis app with the results of an analysis of an efficiency improvement in a 15 cv induction motor.



Power	2 Pole	4 Pole	6 Pole
0.75	77.0	85.5	82.5
1.1	84.0	86.5	87.5
1.5	85.5	86.5	88.5
2.2	86.5	89.5	89.5
3.7	88.5	89.5	89.5
5.5	89.5	91.7	91.0
7.5	90.2	91.7	91.0
11	91.0	92.4	91.7
15	91.0	93.0	91.7
18.5	91.7	93.6	93.0
22	91.7	93.6	93.0
30	92.4	94.1	94.1
37	93.0	94.5	94.1

Figure 9 – Example of a table with NEMA Premium efficiency levels for induction motors.

The Uncertainty Analysis is shown with a click in the UNCERTAINTY ANALYSIS box and a new screen appears. The value of each parameter can be changed and the effect on the analysis is graphically displayed in a new viability curve, alongside with the original curve, as it can be seen in Figure 10. The app runs in any android device and is currently available for download.

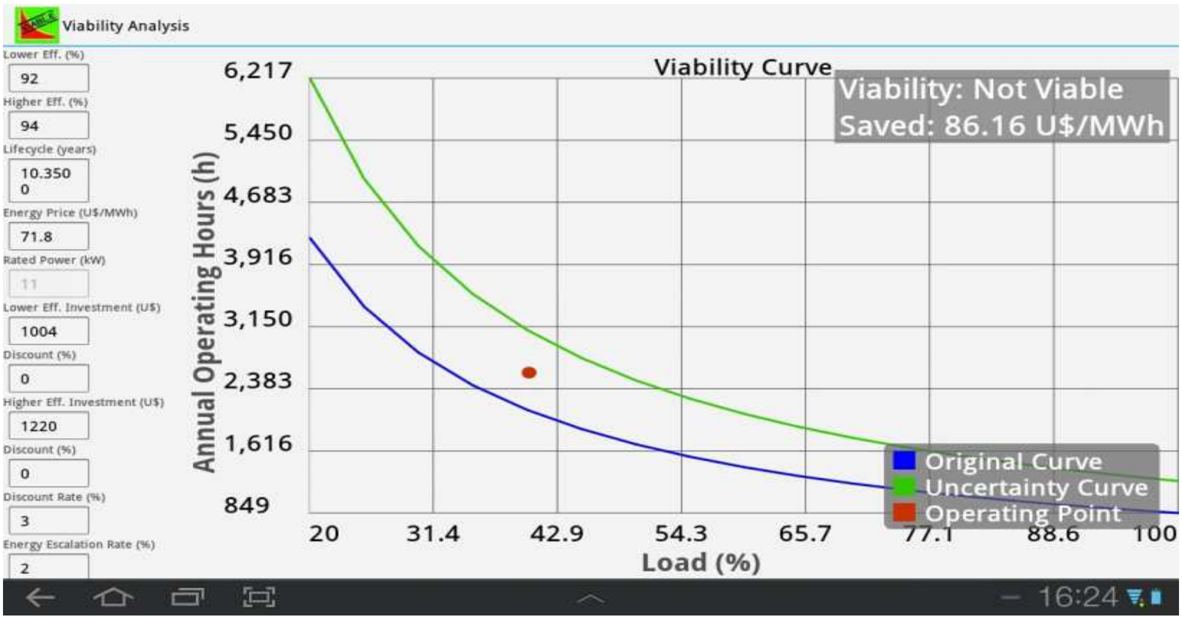


Figure 10 – Screen of the sensitivity analysis after the change in the value of the efficiency parameter.

Results

The induction motor efficiency improvement is achieved by the reduction of losses through design and manufacturing. This efficiency improvement affects the costs of the equipment's LCC: the energy costs are supposed to be reduced, the motor price (investment cost) will increase, and in the cases when the decision implies changes in the motor technology (Induction to Permanent Magnet motor, for example), the O&M and the replacements costs will also be affected.

The economic analysis for induction motors MEPS improvement in Brazil and in the US is made comparing the improvement of the mandatory MEPS from IR2 to IR3/Premium level that is supposed to occur in 2011 in Brazil with the improvement from Premium to Superpremium level that is under study by policy makers in the US.

In order to implement the economic analysis, the parameters used are based in the rates and industrial tariffs presented in Table 2 and also in the following:

- Period of life of the machine (n) is 10 years (for motors 1-1.5cv), 12 years (for motors 2-15cv), 15 years (for motors 20 to 150cv) and 20 years (for motors above 150hp) (DE ALMEIDA, FERREIRA, et al., 2008)
- Average motor prices for the Brazilian market compiled from market survey at January 2015 and for the US market compiled from list price from manufacturers' brochure with a discount of 20% for premium efficiency models and 10% for superpremium efficiency models;
- Technical data for the motors under analysis (power, efficiency) are from manufacturers` data sheet.
- The currency trade is 1 U$ = R$ 2,3, from January, 2015.

The analysis is based on the average operating characteristics of induction motors. Figure 11 shows the average operation characteristics (operating load and run-hours) of electric motors in the United States (US) and in Brazil (BR) for different rated power ranges. It can be seen that the motors from the Brazilian industry are being operated in a higher level of load and operating than US regions shown. An explanation for this fact is the size of the sample used for these data; in Brazil it is based in a survey of 8.119 motors from 209 plants [24], while in the US the survey encloses hundreds of facilities. The US data came from [25].

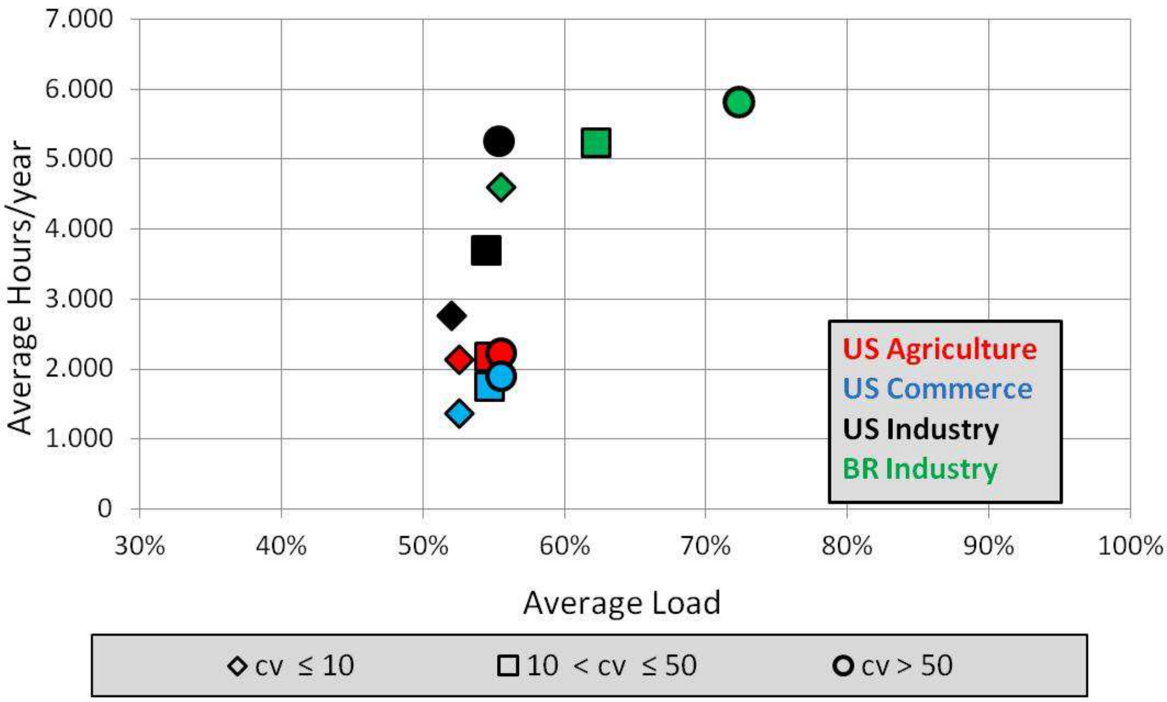


Figure 11 – Operation points for electric motors in the US and Brazil. *Source:* [25] [24].

Figures 12 to 15 show a comparison between the induction motors (IM) efficiency improvement from IR2 to IR3/Premium levels in Brazil and from Premium to Superpremium levels in the US for 60 Hz small (1,5 cv, Figure 12), medium (15cv and 50cv, Figures 13 and 14, respectively) and large power IM motors (150cv, Figure 15) . An overall view of the Figures reveals an increase in the viability area with the increase on the power range of the motors; the limits of cost effectiveness tend to go down as the rated power increase. For small rated power, the transition to IR3/Premium level is viable for the average operating point of the Brazilian industry. For the same rated power, the transition for Superpremium level in the US is not cost effective for all of average operating displayed (industry, commerce and agriculture), revealing a very hard task for policy makers. In this scenario, the 6 pole cost effectiveness limit does not even appear in the graphic.

For medium rated power motors, the situation in the US transition remains difficult but with a sight of improvement (Figures 13 and 14). In the Brazilian MEPS transition, the situation for medium rated power motors is still viable, as it is for large rated power motors. The transition for superpremium in the US for large rated power motors is not viable for most of the sectors in the US, except for industry. Figure 13 reveals a smooth transition in Brazil for the IR3/Premium in medium rated power IM motors and a difficult transition for the Superpremium level in the US, which is viable for industry but still shows difficulties for agriculture and commerce sectors. For these sectors, the average operating is viable only for the 2-pole motor, which has a share of less than 10% of the total IM motor stock in the US [10].

A look in the influence of the numbers of poles in the viability limits reveals that the 2 pole motor is frequently the lowest limit and the largest number of poles (6 in the US and 8 in Brazil) usually presents the smallest area for viability. The 4 pole limits should be considered as a reference, since it represents the biggest share of motors (between 60-79%, according to [10].

The effects of an error in the input data can be visualized in the sensitivity analysis presented in Figure 7, where it can be seem the effect on the viability limits with positive variations in the parameters. Errors in the discount or energy escalation rates have little effect in the limits, where the energy price and the lifecycle push down the limits in a similar weight. The efficiency data is the one that affects the most the limits, hence the importance of validate the available information through certified laboratories measurements.

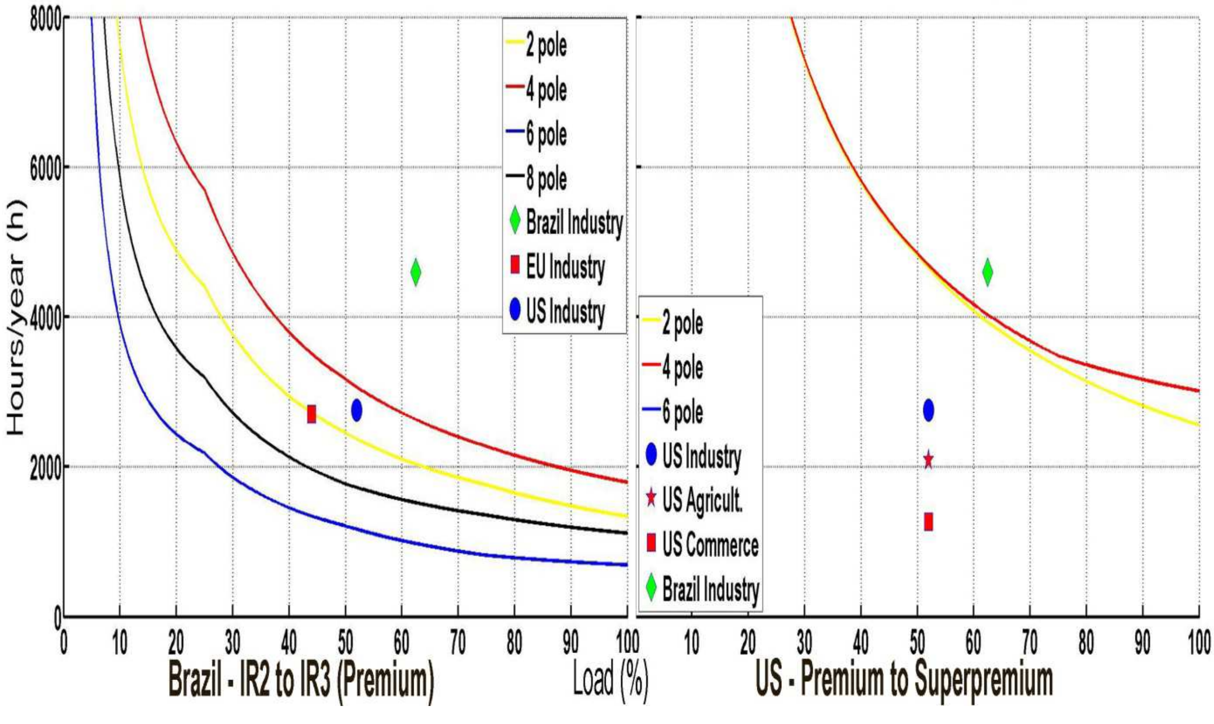


Figure 12 – Cost Effectiveness limits for the increase in efficiency of a low voltage MIT/1,5 cv/60 Hz from IR2 to IR3 level (Brazil) and from Premium to Superpremium level (US) (*Own elaboration*).

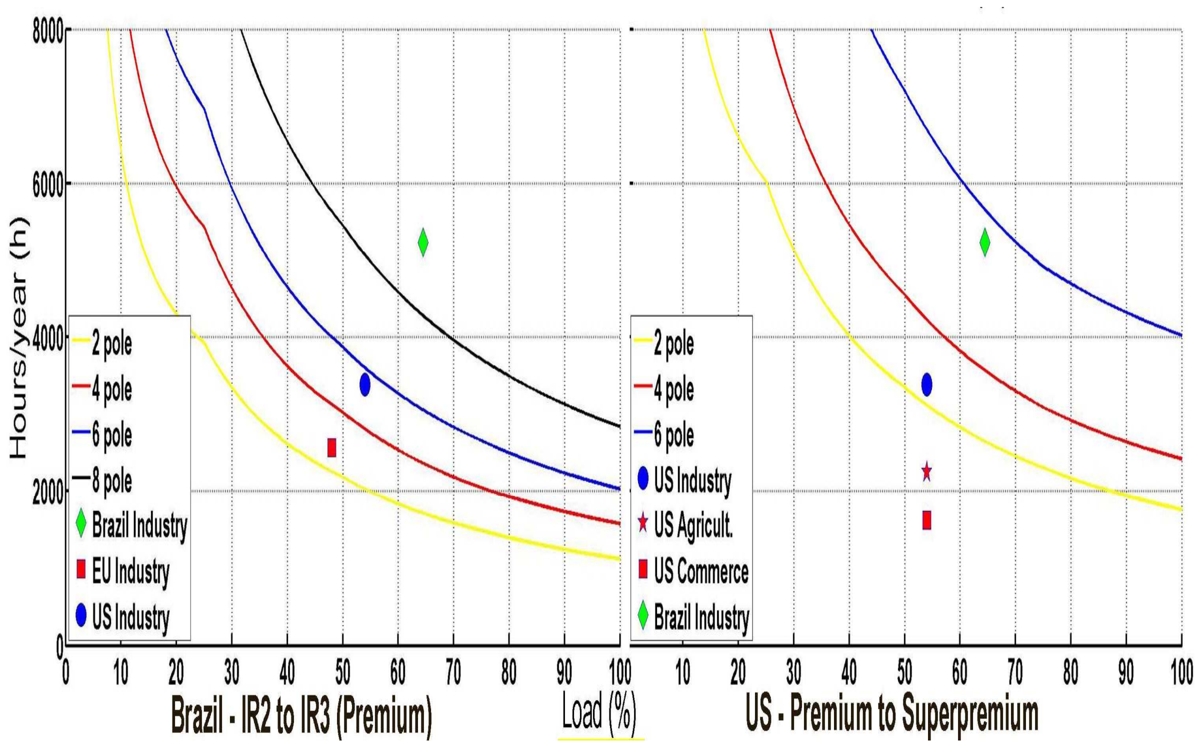


Figure 13 – Cost Effectiveness limits for the increase in efficiency of a low voltage MIT/15 cv/60 Hz from IR2 to IR3 level (Brazil) and from Premium to Superpremium level (US) (*Own elaboration*).

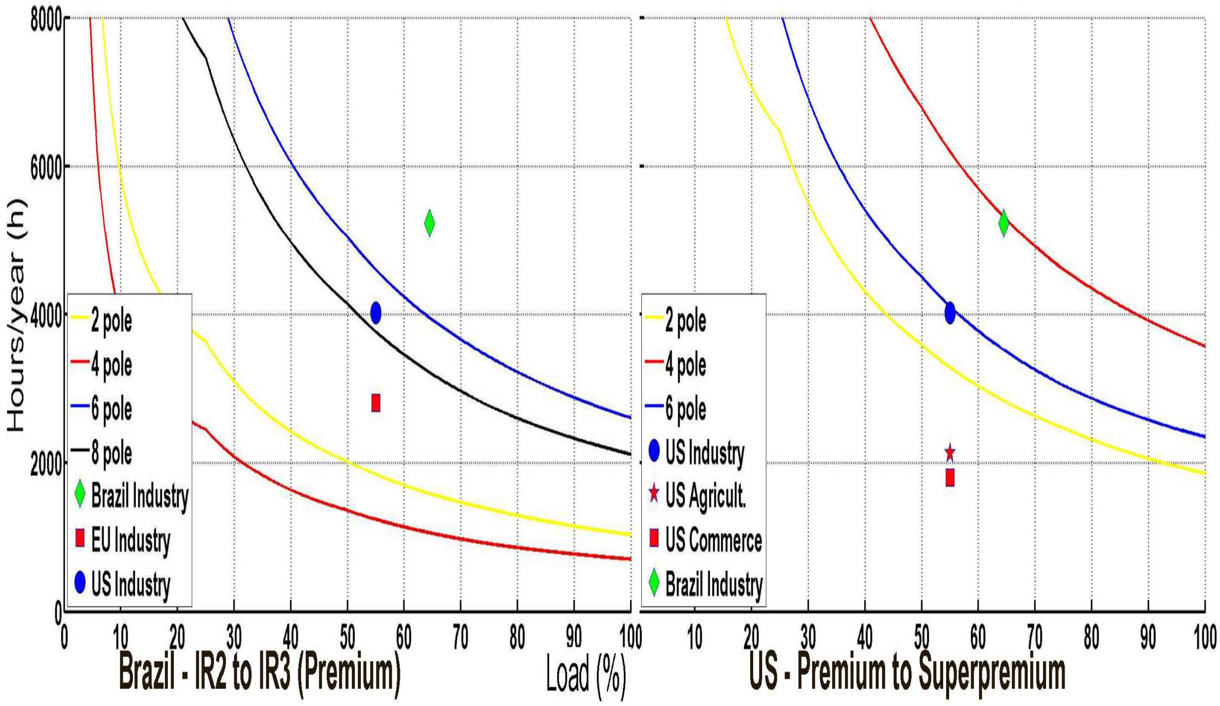


Figure 14 – Cost Effectiveness limits for the increase in efficiency of a low voltage MIT/50 cv/60 Hz from IR2 to IR3 level (Brazil) and from Premium to Superpremium level (US) (*Own elaboration*).

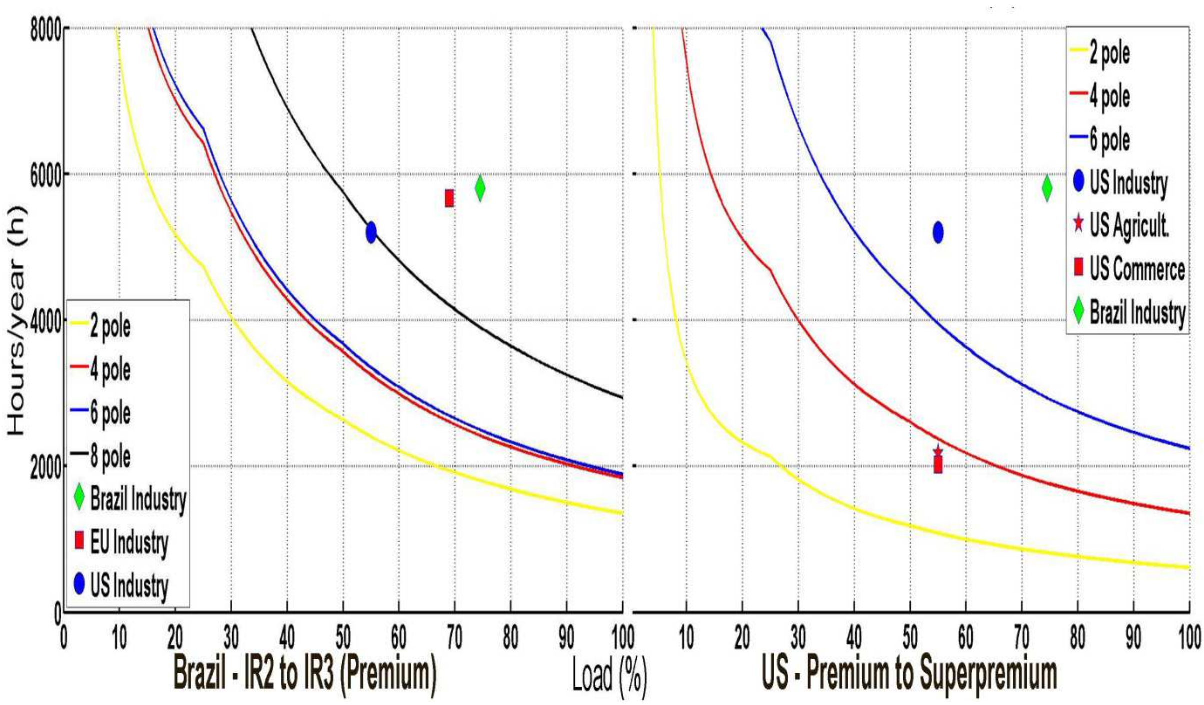


Figure 15 – Cost Effectiveness limits for the increase in efficiency of a low voltage MIT/150 cv/60 Hz from IR2 to IR3 level (Brazil) and from Premium to Superpremium level (US) (*Own elaboration*).

Figure 16 compares the average Saved Energy Cost (U$/MWh), from expression (3), for both MEPS levels transitions (IR2 to IR3/premium in Brazil and premium to superpremium in the US) and the results reveals that the transition in Brazil has a lower saved energy cost, even with the Brazilian average Industry operation points higher than the US. It also shows a decrease in the Saved Energy cost with the increase of the power range, confirming the results from the viability limits that revealed a more comfortable area for economic viability with the increase in the rated power. The numbers of the saved energy cost, when compared with the cost of purchasing energy from different generation types, shows that the investment in energy efficiency for induction motor is competitive.

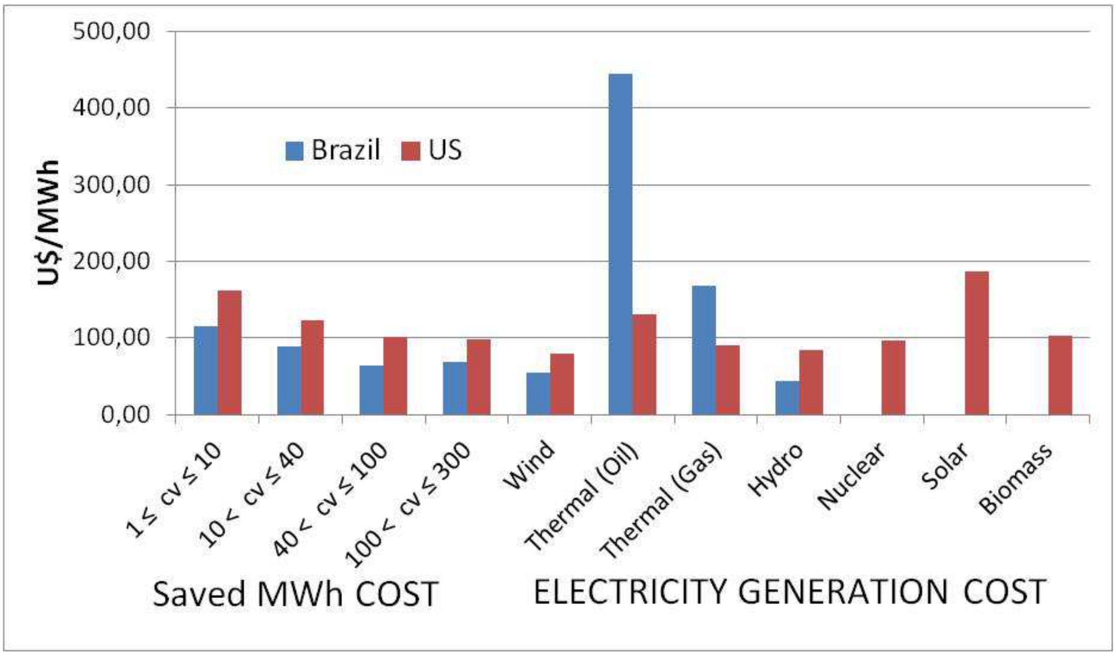


Figure 16 - Comparison of the energy saved cost in U$/MWh for the MEPS levels transitions with different types of electricity generation in Brazil and in the US. *Source:* [11] [15]

Conclusions

The United States of America is the strongest economy of the world and uses its capacity in a very positive way in the energy efficiency area. The country was among the first to implement energy efficiency programs nationwide and right now is one of the front-runners in this area. Regarding electric motor, the stand alone load that consumes most of the electricity in the world, the US has the highest mandatory MEPS level in the world, alongside with Canada, and right now is studying to adopt the next step level (superpremium) [26]. The manufacturers are ready for this stage, but the consumers have to approve the transition and the economic analysis of these motors reveals that most of the options available does not present cost effectiveness. Policy makers are facing quite a challenge at this moment.

Brazil is an emerging economy with growing energy dependency and for this matter is facing the challenges to increase the energy efficiency of the energy driven equipment and buildings. The mandatory IM MEPS had recently been raised for IR2 levels (one band below the premium efficiency) and the expectation is that the IR3/Premium levels, which actually are defined as voluntary levels, became mandatory from 2017. It is quite a challenge, but the economic analysis on the Brazilian market and financial numbers reveals that this transition is viable for all the range rated power using the average operating point of local industry. It should be noted that the average operating points from Brazil are based in a small sample and the results seem to be oversized, when compare with data from more industrialized countries. This matter requires a better look by the policy makers.

The results of the energy efficiency initiatives that have been adopted in both countries is showed in Figure 16. Although very similar in their implementation, the programs implemented in the US have achieved more significant results related to the total electric energy consumption of the country. The earlier implementation and even the size of the economy could explain this difference in the results achieved so far. It is important to emphasize that during this period, the electricity consumption in the US had a 1.4% annual increase rate, while Brazil had a 3.6% rate.

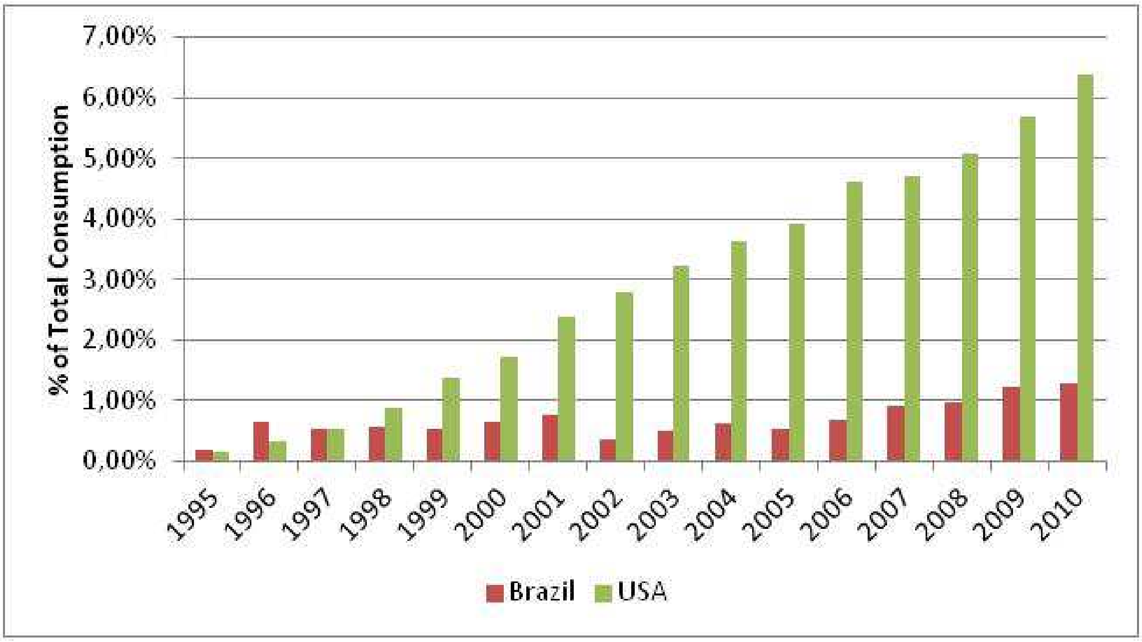


Fig. 17 – Percentage of the Total Electricity Consumption saved by energy efficiency programs. *Source:* [15] [11]

The app presented managed to accomplish the expectations, since it is simple to use and to visualize the results, but the main advantage is the possibility to implement the uncertainty analysis of the input data. In the economic analysis of energy efficiency projects it is important to verify which parameter is more vulnerable to errors and how to acquire this particular information with higher accuracy. The efficiency data is the one which affects the results the most in the economic analysis of EE projects, hence the importance of certify these data through credited laboratory measurements.

Acknowledgment

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One Manufacturer's View of MEPS for Electric Motors

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Abstract

Minimum Efficiency Performance Standards (MEPS) have been part of the United States government's motor efficiency regulations since first announced in 1992.The DOE announced a regulation affecting integral horsepower motors in May 2014 as the fourth such regulation introduced. This regulation sets the MEPS for 1 – 500 HP (0.75 – 370 kW) low voltage motors (<600VAC) to meet National Electrical Manufacturers Association (NEMA) MG 1 table 12-12 and 20B (IE3) while widening the scope of coverage compared to the previous regulations. This paper will discuss the advantages and disadvantages of the new regulations in the eyes of one motor manufacturer.

MEPS History in the US

EPAct92 [1] - The United States has been at the forefront of motor efficiency regulations since the Energy Policy Act of 1992 (EPAct92) was passed by Congress, although did not take effect October 1997. This initial act covered low voltage three-phase general purpose motors of 1 – 200 HP (0.75 – 150 kW), 2-4-6-poles with three-digit NEMA frame sizes (and IEC equivalents). The efficiency for these motors was set at NEMA MG 1, table 12-11 Energy Efficient (IE2). Base-mounted motors with C-faces (B14) and D-flanges (B5) were included but those without a base were exempt. Explosion Proof hazardous location motors and other variations requiring a third party certification were provided a two-year extension until 1999. The U.S. Department of Energy (DOE) created a list of common features and modifications that indicated which motor designs would be included or exempt. For example, motors with Non-NEMA dimension custom shafts or mountings were exempt.

When EPAct92 was enacted, this motor manufacturer's 1 – 200 HP (0.75 – 150 kW) portfolio needed to be raised to the compliant level of NEMA MG 1, Table 12-11 (IE2). Premium motors at higher efficiency levels did not have an official NEMA standard definition at this time but were being sold as an upgrade to energy efficient motors. By the end of EPAct, voluntary usage of premium motors was in the 20-25% range.

In 2001 the Consortium for Energy Efficiency (CEE) in Boston identified the level for premium efficient motors in the marketplace and created a table for 1-200 HP ratings that could be used for rebates by electric utility efficiency programs. NEMA released their defined Premium Efficient motor levels in MG 1 [2], Table 12-12 in August of 2001 and harmonized with CEE levels.

EPAct2005 [3] - A second Energy Policy Act was passed in 2005 that mandated use of Premium Efficient motors by US government agencies. The efficiency level for EPAct2005 was NEMA MG 1, table 12-12 (IE3). This act did not affect industry or commercial properties outside of the US government.

This was a case where the government decided to adopt the energy efficiency practices that they were hoping industry would do. Practice what you preach.

EISA [4] – The current regulation is part of the Energy Independence and Security Act of 2007 (EISA) which went into effect December 2010. General purpose 1 – 200 HP motors were split into two subtypes, Subtype I included those motors previously covered by EPAct92 that had efficiency raised to NEMA MG 1, table 12-12 (IE3). Subtype II included previously unregulated motors such as C-face or D-flange less base, close-coupled pump motors, NEMA Design C, U-frame designs and such at NEMA MG 1, Table 12-11 (IE2). Also included at table 12-11 (IE2) are 201-500 HP (150-377 kW) motors with NEMA Design B characteristics.

Both EPAct and EISA were laws that were wide-ranging and included many other energy saving regulations besides electric motors. These came through Congress and were enforced and regulated by DOE.

This manufacturer was actively involved in sales of premium efficiency motors and EISA changed usage to the 50-60% level.

Small Motor Rule [5] - This is the first motor regulation that was not part of a larger bill. The DOE studied what they believed was technologically possible for motor efficiency on small electric motors. DOE used NEMA Standard MG 1-1987 as their guideline which limited Small Electric Motors to NEMA 42, 48 and 56 frames in Open Drip-proof (ODP) enclosures, so when the rule was released in 2010, only general purpose ODP motors were included. The rule did not clearly identify the motor attributes that fall under the regulation. The regulation established DOE Average Efficiency levels for single and three phase motors ¼ through 3 HP in 2, 4 and 6-pole speeds. The rule went into effect March 9, 2015.

Motor manufacturers were not clear on the scope of coverage for the Small Motor Rule and petitioned the DOE for clarification, finally receiving an FAQ in May 2014. NEMA motor manufacturers however have interpreted certain aspects of the rule differently, so OEMs should contact their suppliers for further information.

Integral Horsepower Rule [6] – After receiving a confusing Small Motor Rule, manufacturers were not anxious to undergo another DOE study relative to integral motors. In a request for information, the DOE indicated they wanted to determine if motor efficiency could be raised above premium efficiency (IE3) by one or two NEMA bands (0.4-0.8%). This proposal was not popular with the motor manufacturers or the Energy Advocates since the present laws allowed motors to be exempted with simple modifications. So a coalition was formed that made a proposal to DOE to keep the efficiency at premium (IE3) but expand the scope of coverage to include many configurations that were at energy efficient levels (IE2) or exempted by previous regulations. The proposal also added NEMA 56 frame (IEC 80) enclosed motors.

The rule announced in May 2014 will take effect June 1, 2016. Almost all 1 – 500 HP (0.75 – 370 kW), including NEMA 56 frame and IEC 80 frame enclosed motors, will be covered. Most motor-designs that were exempt in previous rules will now be covered and required to be premium efficient. With such and expanded scope, the DOE issues a new testing rule [7] to provide for a clear way to take motors with non-standard mechanical configurations from commerce and test them. According to the DOE, this regulation has the potential for the greatest energy savings in electric motor regulations history.

This manufacturer expects usage of premium motors to be in excess of 90% after the latest Integral Rule goes into effect. The coalition's petition to the DOE to remain at premium efficiency level (IE3) rather than raising the efficiency by 1 to 2 NEMA bands relieves the manufacturer from redesigning the entire portfolio of over 300,000 motors, with an investment of several hundred million dollars. It has also not been shown that it is practical to increase the efficiency level further in all motor ratings and configurations. Premium efficient (IE3) designs will be standardized for almost all motor 1 – 500 horsepower (0.07 – 370 kW) designs.

Small Motor Rule #2 – As this paper is being written, the DOE has opened discussions and preparation for a revision to the Small Motor Rule. NEMA members expect to follow the way the integral horsepower rule was developed, perhaps adding additional input from industry associations for pumps and fans. The Small Motor Manufacturers Association (SMMA) is also involved since the regulation is expected to include motors from 120 watts (1/6 HP).

After initial discussions with DOE, a presentation to show the potential scope for the small motor rule was held at ACEEE. Many motor technologies outside of the current small motor rule were discussed along with standards and test methods for each type. This presentation illustrated that standards and test methods are not currently available for many motor types such as switched reluctance, ECM (electronically commutated motor) and others.

Method of analysis

When an efficiency rule is proposed, a motor manufacturer reviews their current portfolio to assess compliance. Are designs available that meet the required efficiency level? If not, what needs to change to design for compliance? What part of the portfolio will be required to change and what are those motor designs? There is the possibility that some designs may have to be removed from the portfolio as achieving the required level of efficiency may not be possible in that configuration or frame size.

At the beginning of the recent Integral Horsepower Rule, each manufacturer received a questionnaire from a U.S. Department of Energy (DOE) consultant. Some of the questions indicated that DOE was investigating raising the efficiency level above NEMA MG 1, Table 12-12 (IE3) by one or two NEMA bands (0.4 – 0.8%). A detailed analysis was required for the low voltage 1 – 500 horsepower (0.75 – 370 kW) portfolio of 2-4-6-pole motors, which include 75 different basic ratings in both enclosed and open designs. Electrical engineers studied what was required to reach potential efficiencies – more material, lower loss steel, new lamination designs, larger lamination diameters, larger frame size, etc. This was a detailed analysis that helped the DOE understand that reaching IE4 efficiency levels would not be an easy effort within the three year conversion time table. They eventually accepted a petition by a coalition of energy advocates and motor manufacturers to keep the efficiency at NEMA MG-1, Table 12-12 (IE3), but to expand the scope of coverage by adding more motor designs that were not general purpose and improve definitions to improve compliance and enforcement in the current regulations.

Since the survey was done with a confidentiality agreement with DOE's contractor, the information provided was not open to the public record. Only the aggregate of the motor manufacturers was published. During this survey, manufacturers provided an unprecedented amount of data for analysis.

A key part of the analysis was a discussion on design and production capabilities. DOE wanted to investigate die cast copper rotors and NEMA responded with an answer that there was no volume production capability to produce enough rotors in the US to meet industry needs. The DOE also investigated low loss electrical steel, but in the end this was dismissed due to lack of production capability in the mills to service the industry.

Rule Clarity and Testing

It is important that any regulation be clearly written and in terms well understood by that industry. Historically, motor rules in the U.S. have been written considering NEMA standards and nominal efficiency levels. The Small Motor Rule was written based on DOE Average Efficiency levels which DOE has yet to adequately define and continues to create confusion within the industry.

Clear definitions are required to avoid confusion and misinterpretation. A new rule on testing was required to cover the expanded scope of the Integral Horsepower Rule. The test method of IEEE 112 Method B and CSA 390 were continued. The rule added guidance on how to configure the various special mechanical motor designs for test. An example would be adding a "dummy" endplate to a partial motor from a gearmotor for test.

Compliance and Certification

Each manufacturer (or importer) is required to certify their portfolio of covered motors with the DOE. This may be done by testing a sample of five motors for each rating to prove the average total losses of those 5 motors is not more than a 5% greater than the total losses corresponding to the marked nominal efficiency and that the total losses of none of the 5 is more than 15% greater than that for the required nominal efficiency level for that rating. This must be done for each rating within the portfolio submitted by that manufacturer. With 1 – 500 horsepower (0.75 – 370 kW) covered, in 2, 4, 6 and 8-pole, enclosed and open enclosures – a total of 200 ratings. Tests must be performed in a National Voluntary Laboratory Accreditation Program (NVLAP) accredited lab. These test reports must be submitted to DOE who will issue a compliance certification "CC" number that must be displayed on the motor nameplate.

Another method for certification is to have the manufacturer's motor design program substantiated (i.e., verified) as an Alternative Efficiency Determination Method (AEDM). The EU refers to this method as a Semi-Analytic Model (SAM). This way of certification is often easier for motor manufacturers because it does not require testing of all designs. A group of five motors of several different ratings and configurations are tested as above to prove the accuracy of the design program.

Portfolio Assessment and Conversion

Once designs are available, what will the changes do to supply chain and production flow? A simple example is switching from an IE2 to IE3 motor, the laminations change. The steel grade changes and the gauge (thickness or steel lamination) becomes thinner. This means that more press stampings are required for the same amount of active material. Plus to make a premium motor, there may be an additional 15-20 percent of active material required. Each manufacturer is different with respect to their portfolio of stock (standard) motors and customized OEM models.

This manufacturer needed to increase stamping capacity by 40 percent when readying for the EISA regulation in 2010.

Each manufacturer is different with respect to their portfolio of stock (standard) motors and customized OEM models. All departments will need to take a proactive approach to meeting new regulations. Manufacturers need to be prepared to design new models of motors, complaint by the effective date of the new regulations as non-compliant motors can no longer be built for sale in the U.S.

The supply chain group needs to manage the materials for non-compliant motors so “obsolete” non-compliant components are coordinated with the date when the switch to the compliant designs occur. Motor manufacturers stamp their own laminations on a just-in-time basis, so this can be controlled. Specialty or low volume laminations may be from outside suppliers and purchased in minimum lot sizes, so these need to be carefully evaluated.

Sales, scheduling and production needs to plan the conversion to cut off order of non-compliant motors prior to the date set by DOE. If any orders are late in production, they cannot be built after the date for compliance. Existing finished goods inventory can be sold if built before the compliance date. Customers (distributors and OEMs) will expect availability of compliant motors in advance of the compliance date.

Training and Awareness

After the regulation gets published as a final rule, the DOE typically sets a three year window before the ruling goes into effect. In the case of the latest Integral Horsepower Rule, part of the coalition proposal was to expedite the effective time frame of the final rule to happen within two years of the final rule being published.

Within the 2 year period, manufacturers must identify the motors in their portfolio that are changing, design compliant motors for the stocked designs and educate customers on the new regulations. This means that product catalogs, website and pricing must be updated to show the new designs. Sales tools such as product configurators must be reprogrammed to match the new regulation scope of coverage.

Typically the motor manufacturer will have different levels of training so that internal engineering and sales support staff understand the new regulations to produce compliant quotes. The outside sales force will be required to understand the revised scope of coverage and also be provided with the list of motors that will become non-compliant so they can contact the customers they service.

Training must be conducted for OEMs, distributors and end users. All will be affected by changing regulations but in slightly different ways. Most manufacturers are distributing newsletters, whitepapers and hosting live training webinars to educate and bring awareness to these upcoming regulations. It is important to contact the OEMs early as a few new motors may be larger in size or have different performance characteristics that must be tested in application. Some OEMs require third party certification (UL, CSA) which requires additional time.

Industry trade magazines are anxious to offer their readers news and educational articles, webinars, whitepapers, etc. to help bring awareness to new regulations. Magazines on motor maintenance and those who focus on specific industries are good sources for help.

Large nation-wide distributors are interested in the rule as they support many large end users with national contracts. As part of the contract, these users measure the distributors' help with their productivity and efficiency and grade the distributor on how they help them achieve their goals.

Industry trade conferences can be a venue to provide guidance on new regulations. In the U.S., NEMA has participated in presentations at the IEEE Pulp and Paper Industry Conference and also at the IEEE Petroleum and Chemical Industry Refining Conference. At a recent conference, a program manager at DOE was a panel member discussing the new regulation.

Proactive Action is Required

Parties must remain active and engaged in monitoring of legislation affecting covered and related products. The motor manufacturers need to work with energy advocates and regulatory bodies to set achievable and realistic efficiency levels. Although it may be possible to design a motor with a very high efficiency level, the ability to produce that in volume at a price that is affordable and has a realistic payback is required. Some great ideas come from academics, but without a plan to produce the product at an affordable level, the idea must be shelved until it is feasible.

Because AC induction motors are nearing their technological design points at affordable price levels, there is a trend both in the U.S. and Europe to regulate systems. The DOE is working on system regulations for pumps, fans and compressor systems. The system will include the driven device, a motor, coupling or pulley and possibly an adjustable speed drive. A challenge here will be testing the efficiency of a motor driven system but new standards are being developed to do this such as CSA 838 [8], EN50598-2 [9] and IEC 61800-2 [10].

Many manufacturers currently offer super-premium (IE4) motors in technologies such as synchronous reluctance, switched reluctance, permanent magnet or particular squirrel-cage induction motors. These IE4 motor and drive systems are being offered today while NEMA and IEC are still writing standards to cover their construction, performance and testing. These technologies are viable voluntary efficiency upgrades for those who do not wish to install a complete extended system. Perhaps as these technologies mature and portfolios are expanded, IE4 could become a viable regulated level in the future for applications in which the technologies can be used.

Conclusion

Motor manufacturers must be proactive when addressing MEPS. One person involved in these regulations said "if you're not at the table, you're on the menu". These regulations do not need to be treated as limiting or negative factors if they are developed with good forethought. There must be a long term strategy to stair step to higher levels as designs and technology, materials, and production techniques become available at affordable costs.

Rather than component regulation, extended systems should become a focus of efficiency programs. Pump, fan and compressor systems offer the most efficiency savings because of centrifugal loads. "System efficiency" may be replaced by measurement of energy usage in terms of reduction of kWh usage. Productivity continues to be a major benchmark in the industrial sector with widgets produced per kilowatt hour.

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Fluid Systems 1

Best efficiency point of a multiple VSD pumps' equipment

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Abstract

When the process requirement is varying so largely that it cannot be handled by one only pump, a multiple pumps system, driven by variable speed drives (VSDs) and/or Direct-On-Line (DOLs), is used. A multiple pumps system also provides a redundancy capability useful to guarantee continuity of services. From a process point of view, we could consider a multiple VSD pumps system as a single "equivalent" pump, with a freedom degree which is how the process requirement should be shared between the multiple VSD pumps. This concept of "equivalent" VSD pump is interesting as we can separate the system energy efficiency optimization in two sub-problems: on the one hand the optimization of the system operating point, including system curves and single "equivalent" pump, and on the other hand, the optimization of the realization of this system operating point through a multiple pumps system. In this paper, we will show how to get optimal energy efficiency for multiple pumps system, accordingly to the freedom degrees available: number of running pumps, and their speeds. In particular, when pumps are similar, and the right number of pumps is selected according to the process demand, we will demonstrate the intuitive result that sharing evenly the process contribution, i.e. all pumps running at the same speed, is the most efficient solution. Simulation results for different types of application will support the theoretical demonstration.

Introduction

Generally in most of hydraulic applications (Booster control, level control …) the multiple pumps equipment is increasingly used [1], because it offers many advantages in terms of:

- Redundancy capability which is useful to guarantee continuity of services when one or more pumps becomes unavailable,
- Capability to answer for varying process requirements, such that the demand cannot be efficiently served by only one pump.

Energy savings are increasingly becoming important design target in many water distribution systems where the consumed electrical energy by the global installation (drives, motors, pumps, etc.) becomes more expensive [2]. Thanks to variable speed drives and motors, we can save energy consumption compared to a traditional Direct-On-Line, where pumps are directly connected to the mains [3]. In addition, in most of hydraulic applications, we have some constraints depending on the system (volume control, pressure control and many more …) and the equipment (single pump and multiple pumps equipment) that should be taken into account when we target to reach the system best efficiency operating point. That's why we need to define what system best operating point is, in terms of energy consumption according to these constraints. In this paper, we focus on the hydraulic equipment: the centrifugal pump and the system without taking into account the drive efficiency and the motor electrical losses.

First, we will present the notations to describe pump curves for a multiple pumps system. Second; we will address a multiple pumps equipment and how the best efficiency operating point can be obtained in this case with the available degrees of freedom: the number of running pumps, and their speeds. We will consider that multiple pumps equipment could be represented as an "equivalent" single pump and we will show how the process demand must be shared between pumps to get the best efficiency operating point in terms of energy savings. Third, the **B**est **E**fficiency **P**oint (**BEP**) for hydraulic applications depending on the hydraulic system type will be discussed. We will address specific use-cases: open system without constraints on process variables, system with pressure control, system with volume control. We will show what we may expect for this type of applications in terms of energy savings. Simulation-based results will support the theoretical demonstration.

Annotations and definition

Nomenclatures

The following table gives different nomenclature used in this paper.

Name	Description
H	Head [mH_2O]
Q	Flow [m^3/h]
P_w	Mechanical power [W]
ω	Mechanical speed [rpm]
η	Efficiency [%]
H_n	Nominal Head* [mH_2O]
Q_n	Nominal Flow* [m^3/h]
P_{wn}	Nominal Mechanical power* [W]
ω_n	Nominal speed [rpm]
η_n	Nominal efficiency* [%]
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)
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)
P-BEP	**P**ump **B**est **E**fficiency **P**oint
S-BEP	**S**ystem **B**est **E**fficiency **P**oint
P-BEC	**P**ump **B**est **E**fficiency **C**urve
α	Coefficient to calculate pump efficiency from physical unit
N	Number of pumps

*: Corresponds to the Pump Best Efficiency Point (P-BEP).

Pump curves and operating point with single pump system

First, the pump curves at different speeds may be represented by generic normalized equations as follows:

$$\begin{cases} h = x^2 \cdot f_{\omega n}\left(\frac{q}{x}\right) \\ p_w = x^3 \cdot g_{\omega n}\left(\frac{q}{x}\right) \\ \eta = \alpha \cdot \frac{h.q}{p_w} = n_{\omega n}\left(\frac{q}{x}\right) \end{cases} \quad where: \quad h = \frac{H}{H_n}; q = \frac{Q}{Q_n}; x = \frac{\omega}{\omega_n} \tag{1}$$

The system curve is defined by the set of losses provided by all the elements of the pumping system (tank, pipe, etc.) and it can be represented by the following normalized equation:

$$h_{sys} = \underbrace{h_{s0}}_{Static\ losses} + \underbrace{h_{s1} \cdot (q_{s1})^2}_{Quadratic\ losses} \quad where: \quad h_{sys} = \frac{H_{sys}}{H_n}; h_{s0} = \frac{H_{s0}}{H_n}; h_{s1} = \frac{H_{s1}}{H_n} \tag{2}$$

The system operating point is given by the intersection of the system curve and the pump curve, at a pump speed. In a feedback controlled system, the conditions of the system will determine the operating point, and those requirements will adjust the speed of the pump accordingly. When the speed of the pump is changed, the pressure, the flow, the power and the efficiency will also change.

For a given pump speed, ie $x = \frac{\omega}{\omega_n}$, the system operating point is deduced from the equations (1) and (2):

$$h = h_{sys} \Rightarrow x^2 \cdot f_{\omega n}\left(\frac{q}{x}\right) = h_{s0} + h_{s1} \cdot (q)^2 \tag{3}$$

The following figure gives the system operating point at different speeds [100%, 80% and 60%] of the nominal speed:

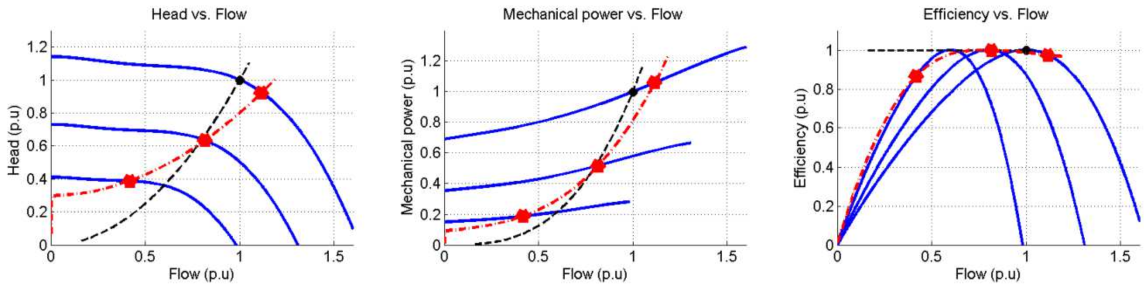


Figure 1: System operating point at different speeds
Pump curves (solid blue lines); System curves (dashdot red lines);Best Efficiency curve (dashed black line), System operating point (red diamond)

As shown in Figure 1, depending on the pump curve at different speeds (solid line) and the system curve (dash dot line), there are different system operating points (red diamond points). We can see also that the system curve crosses the best efficiency pump curve (dashed line) only on one operating point.

The obvious best operating point in terms of energy consumption (i.e. power consumption) is to switch off the pump. But this behavior cannot be possible because generally in a hydraulic system, we always have some process requirements:

- Keep constant the pressure,
- Keep constant the flow,
- Keep the pump at it best efficiency point,
- Fill or empty a volume in a minimum of time,
- Fill or empty a volume in a minimum of energy.

Pump curves and operating point with a multiple pumps system in parallel

In a multiple pumps system with identical pumps, the pump curves are expressed as follows:

$$\begin{cases} h_i = {x_i}^2 \cdot f_{\omega n}\left(\frac{q_i}{x_i}\right) \\ p_{w_i} = {x_i}^3 \cdot g_{\omega n}\left(\frac{q_i}{x_i}\right) \\ \eta_i = \alpha \cdot \frac{h_i . q_i}{p_{w_i}} = n_{\omega n}\left(\frac{q_i}{x_i}\right) \end{cases} \quad where: \quad h_i = \frac{H_i}{H_n}; q_i = \frac{Q_i}{Q_n}; x_i = \frac{\omega_i}{\omega_n}; i = [1 \cdots N\ pumps] \tag{4}$$

From a process point of view, we could consider a multiple pumps system as a single “equivalent” pump, with degrees of freedom based on how the flow demand is shared between the multiple pumps.

The equivalent pump curves may be represented by generic normalized equations as follows:

$$\begin{cases} h_{eq} = h_i & \text{where } i = [1 \cdots N \text{ pumps}] \\ p_{w_{eq}} = \displaystyle\sum_{i=1}^{N\text{ pumps}} x_i^{\,3} \cdot g_{\omega n}\left(\frac{q_i}{x_i}\right) & \\ q_{eq} = \displaystyle\sum_{i=1}^{N\text{ pumps}} x_i \cdot f_{\omega n}^{\;-1}\left(\frac{h_i}{x_i^{\,2}}\right) & \\ \eta_{eq} = \alpha \cdot \dfrac{h_{eq} \cdot q_{eq}}{p_{w_{eq}}} & \end{cases} \tag{4}$$

We have just to understand that the pump curves of the “equivalent” pump may vary accordingly to how the flow demand is shared between the multiple pumps. Figure 2 presents the system operating point with multiple pumps depending on the “equivalent” pump curves and the system curve, and how the overall system flow is shared between the pumps according to their speeds (Pump 1: 95% of nominal speed and Pump 2: 75% of nominal speed).

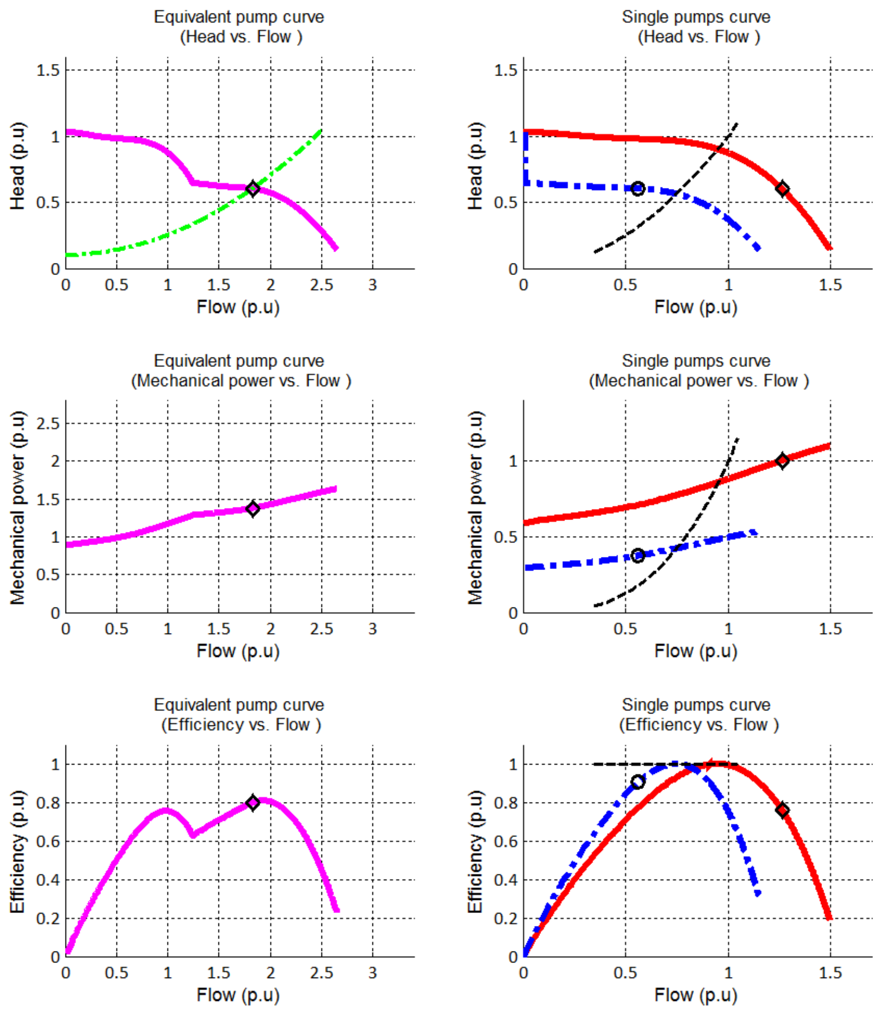


Figure 2: System operating point in a multiple pumps equipement: the equivalent pump curve and the system curve, for pumps at different speed.
Equivalent pump curves graphs: Equivalent pump curve (Solid magenta line), Multiple pump system operating point (black diamond), system curve (Dashdot green line).
Single pump curves graphs: Nominal pump 1 curve (Solid red line), Nominal pump 2 curve (Dashdot blue line), Efficiency pump curve (Dashed black line), pump 1 operating point (black diamond), and pump 2 operating point (black circle)

System Best Efficiency Point with Multiple Pumps Equipment

Theoretical demonstration

Multiple Pumps Best Efficiency operating point - Optimal pumps speed for $(\bar{H}, \bar{Q})$

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 (reference head $\bar{H}$ and process flow demand $\bar{Q}$).

From equation 1 and for the head reference $\bar{H}$ we have:

$$\bar{h} = x^2 \cdot f_{\omega n}\left(\frac{\bar{q}}{x}\right) \Rightarrow x = k(\bar{h}, \bar{q}) \tag{5}$$

Where:

- $\bar{h}$: ratio between the head reference $\bar{H}$ and the nominal head
- $\bar{q}$: ratio between the process flow demand and the nominal flow
- k : function of reference head and the process flow demand

For N pumps, equation 5 can be generalized to: $x_i = k(\bar{h}, q_i)$ where i: [1 … N] is indicating the i^{th} pump. The mechanical power consumed by each pump is then given by:

$$p_{w_i} = {x_i}^3 \cdot g_{\omega n}\left(\frac{q_i}{x_i}\right) \tag{6}$$

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

The relation between the flow of each pump and the global system flow is given by the following equation:

$$q_1 + q_2 + \cdots + q_{n-1} + q_n = \bar{q} \tag{7}$$

To solve the question, let us define the differential flow ε_{q_i} such that:

$$\mathrm{q_i} = \frac{\bar{\mathrm{q}}}{\mathrm{n}} + \varepsilon_{q_i} \tag{8}$$

Then, from equation 5, we get:

$$x_i = \mathrm{k}\left(\frac{\bar{\mathrm{q}}}{\mathrm{n}}, \bar{\mathrm{h}}, \varepsilon_{q_i}\right) \tag{9}$$

From equation 6, we get than the mechanical power is a function of the reference process flow, the reference pressure and the differential flow, let define a function p of three variables, such as:

$$p_{w_i} = {x_i}^3 \cdot g_{\omega n}\left(\frac{q_i}{x_i}\right) = p\left(\frac{\bar{\mathrm{q}}}{\mathrm{n}}, \bar{\mathrm{h}}, \varepsilon_{q_i}\right) \tag{10}$$

The total power is equal to a sum of N functions p:

$$p_{w_{Total}} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{p}\left(\frac{\bar{\mathrm{q}}}{\mathrm{n}}, \bar{\mathrm{h}}, \varepsilon_{q_i}\right) \tag{11}$$

with the constraint on the differential flows given from equation 8 and 9 by:

$$\varepsilon_{q_1} + \varepsilon_{q_2} + \cdots + \varepsilon_{q_{n-1}} + \varepsilon_{q_n} = 0 \tag{12}$$

Let us introduce the function q_3 that is the partial derivative function of p according to the third variable.

$$q_3 = \frac{\partial}{\partial x_3} p(x_1, x_2, x_3) \tag{13}$$

As the differential flows are linked by an algebraic relation, we can select for instance $\varepsilon_{q_n} = -\varepsilon_{q_1} - \varepsilon_{q_2} - \cdots - \varepsilon_{q_{n-1}}$ and then, the minimum is a solution of the system:

$$\begin{cases} \dfrac{\partial}{\partial \varepsilon_{q_1}}\left(p_{w_{Total}}\right) = 0 \\ \vdots \\ \dfrac{\partial}{\partial \varepsilon_{q_{n-1}}}\left(p_{w_{Total}}\right) = 0 \end{cases} \tag{14}$$

This system becomes:

$$\begin{cases} q_3\left(\dfrac{\bar{\mathrm{q}}}{\mathrm{n}}, \bar{\mathrm{h}}, \varepsilon_{q_1}\right) - q_3\left(\dfrac{\bar{\mathrm{Q}}}{\mathrm{N}}, \bar{\mathrm{H}}, \varepsilon_{q_n}\right) = 0 \\ \vdots \\ q_3\left(\dfrac{\bar{\mathrm{q}}}{\mathrm{n}}, \bar{\mathrm{h}}, \varepsilon_{q_{n-1}}\right) - q_3\left(\dfrac{\bar{\mathrm{Q}}}{\mathrm{N}}, \bar{\mathrm{H}}, \varepsilon_{q_n}\right) = 0 \end{cases} \tag{15}$$

That can be summarized into $q_3\left(\frac{\bar{\mathrm{q}}}{\mathrm{n}}, \bar{\mathrm{h}}, \varepsilon_{q_1}\right) = \cdots = q_3\left(\frac{\bar{\mathrm{q}}}{\mathrm{n}}, \bar{\mathrm{h}}, \varepsilon_{q_i}\right) = \cdots = q_3\left(\frac{\bar{\mathrm{Q}}}{\mathrm{N}}, \bar{\mathrm{H}}, \varepsilon_{q_n}\right)$. If we consider the pump for which the function q_3 defined by equation (13) is a monotone function, with the relation (15), we get that there is only one solution: $\varepsilon_{q_1} = \cdots = \varepsilon_{q_i} = \cdots = \varepsilon_{q_n}$. By definition of the differential flow, we get $\varepsilon_{q_1} = \cdots = \varepsilon_{q_i} = \cdots = \varepsilon_{q_n} = 0$. This demonstrates the fact that to be optimized in terms of power consumption, we just need to share equivalently the flow between the different pumps.

For the given pump curves on Figure 1, Figure 3 shows the function q_3.

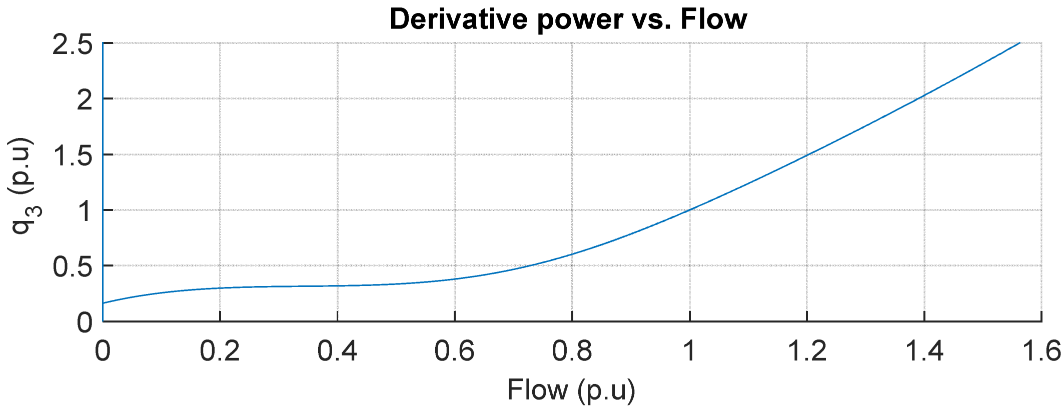


Figure 3: Derivative power function

The equivalent pump curves may be represented by generic normalized equations as follows:

$$\begin{cases} p_{w_{eq}} = \mathrm{N} \cdot {x_N}^3 \cdot g_{\omega n}\left(\dfrac{q_{eq}}{\mathrm{N} \cdot x_N}\right) \\ q_{eq} = \mathrm{N} \cdot x_N \cdot {f_{\omega n}}^{-1}\left(\dfrac{h_{eq}}{{x_N}^2}\right) \\ \eta_{eq} = \alpha \cdot \dfrac{h_{eq} \cdot q_{eq}}{p_{w_{eq}}} \end{cases} \tag{16}$$

where x_N represents the speed of the N pumps.

Multiple Pumps Best Efficiency operating point - Optimal Number of pumps for $(\bar{H}, \bar{Q})$

The objective of this part is to give a theoretical demonstration to choice the right number of pumps in multiple pumps equipment by considering the constraints on the process (head reference $\bar{H}$ and process flow demand $\bar{Q}$). All the pumps are running at same speed. The mathematical formulation is to find the value N that minimizes the power:

$$p_w = N \cdot x_N{}^3 \cdot g\left(\frac{\bar{q}}{N \cdot x_N}\right) = N \cdot \alpha \cdot \frac{\bar{h} \cdot \frac{\bar{q}}{N}}{\eta\left(\frac{\bar{q}}{N \cdot x_N}\right)} \tag{17}$$

The speed x_N is solution of $\bar{h} = x_N{}^2 \cdot f_{\omega n}\left(\frac{\bar{q}}{N \cdot x_N}\right)$, meaning a function of flow demand and pressure reference $x = k\left(\frac{\bar{q}}{N}, \bar{h}\right)$. By defining $q_N = \frac{\bar{q}}{N \cdot x_N}$, we may introduce the function m such that $q_N = m\left(\frac{N^2 \cdot \bar{h}}{\bar{q}^2}\right)$ is solution of $\frac{f_{\omega n}(q_N)}{q_N{}^2} = \frac{N^2 \cdot \bar{h}}{\bar{q}^2}$.

The mechanical power is given by

$$p_w = \alpha \cdot \frac{\bar{h} \cdot \bar{q}}{\eta(q_N)} \tag{18}$$

According to different value of N, we are able to compute the consumed power, and to sort them. The minimum one is the optimal one, and the number N corresponding is the optimal number of pumps to activate. The transition between N pumps and N+1 pumps is by the solution of the reformulated problem: find N such as $\eta(q_{N+1}) = \eta(q_N)$. As the efficiency function is a bell curve in function of flow with a maximum, for all values of efficiency η_T, it exists two values of flow q_{LOW} and q_{HIGH} such as $\eta_T = \eta(q_{LOW}) = \eta(q_{HIGH})$, and then we may define the function wb equals to the width of the bell curve for the $\eta_T$value.

$$q_{HIGH} - q_{LOW} = \mathrm{wb}(\eta_T) \tag{19}$$

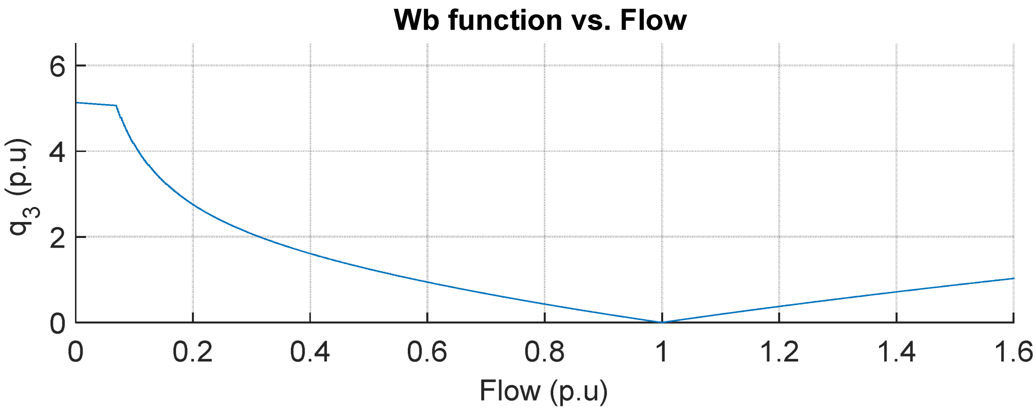


Figure 4: Width bell efficiency curve function

Using this function wb and the function m, we get the flow value $\bar{q}$, to change the number of pumps from N to N+1, by solving:

$$m\left(\frac{(N+1)^2 \cdot \bar{h}}{\bar{q}^2}\right) = m\left(\frac{N^2 \cdot \bar{h}}{\bar{q}^2}\right) - \mathrm{wb}\left(\eta\left(m\left(\frac{N^2 \cdot \bar{h}}{\bar{q}^2}\right)\right)\right) \tag{20}$$

Simulation results

After demonstrating that we can get the best efficiency operating point in multiple pumps system (all pumps should work at the same speed, selecting the optimal number of pumps). We will show in this part some simulation results got on a multiple pumps system with different hydraulic system constraints:

- Open system, without constraint on flow or pressure,
- System with pressure regulation constraint,
- System with volume constraint.

Thanks to the “equivalent pump” concept, we can demonstrate by simulation that the best efficiency operating point can be different from the pump best efficiency point but it still the best efficiency operating point from system point of view.

Open system, without constraint on flow or pressure

In this use case of hydraulic system, we haven’t constraints on process variables (flow and pressure). The objective is to put the pump in its best efficiency operating point.

Figure 5 shows how the operating point can change on the pump curves at different speeds (for 100%, 80% and 60% of nominal speed) and different system curves:

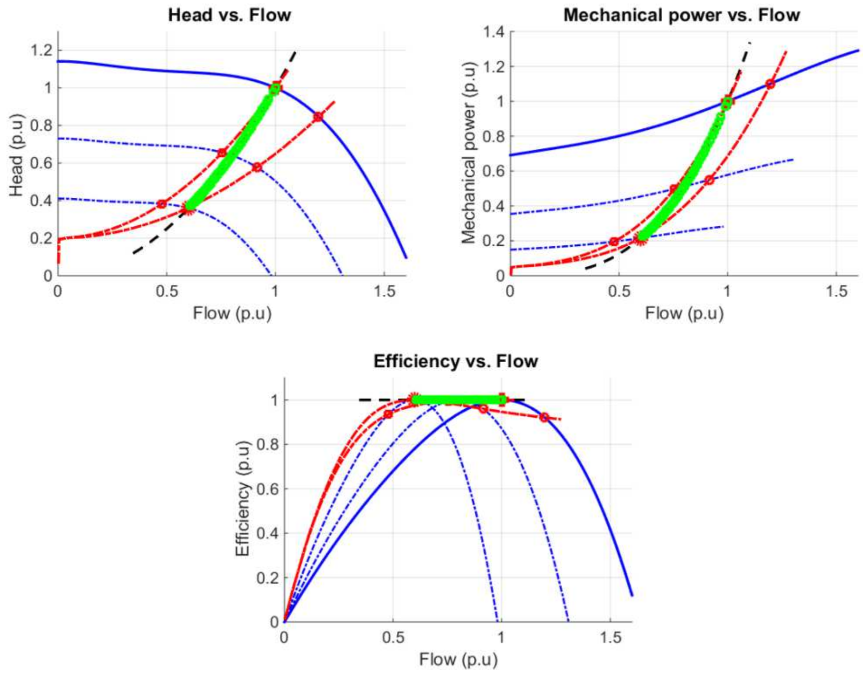


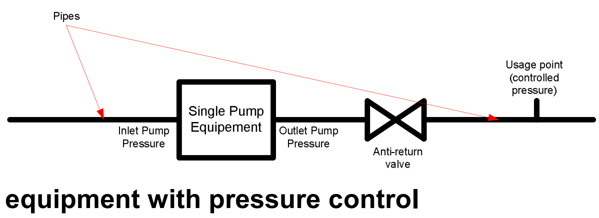
Figure 5: System Best Efficiency point on open system
Pump curves (Solid blue lines); System curves (dashdot green, red and brown lines);Best Efficiency curve (dashed black line), Best system operating point (brown square at 100%, red triangle at 80% and green circle at 60%

According to Figure 5 and depending on the pump speeds, if the system curve evolves (equivalently to close or to open a valve), the operating point will change on the pump curve at the same speed (from “square” to “circle” point). By reducing the pump speed we can put the system operating point on the best efficiency point of the pump (System-BEP = Pump-BEP).

If the system curve doesn’t cross the pump best efficiency curve, we cannot reach the optimal operating point (Pump-BEP), but the system best efficiency point is obtained at maximum reachable speed.

System with pressure regulation constraint

The objective is to maintain the pressure constant at usage point. Scheme 1 gives an example for this system:



Scheme 1: Single pump equipment with pressure control

The system operating point is then defined by pressure reference and system curve which is modified according to the demand in flow. Figure 6 shows how the operating point moved for a given pressure reference and according to the system curve evolution.

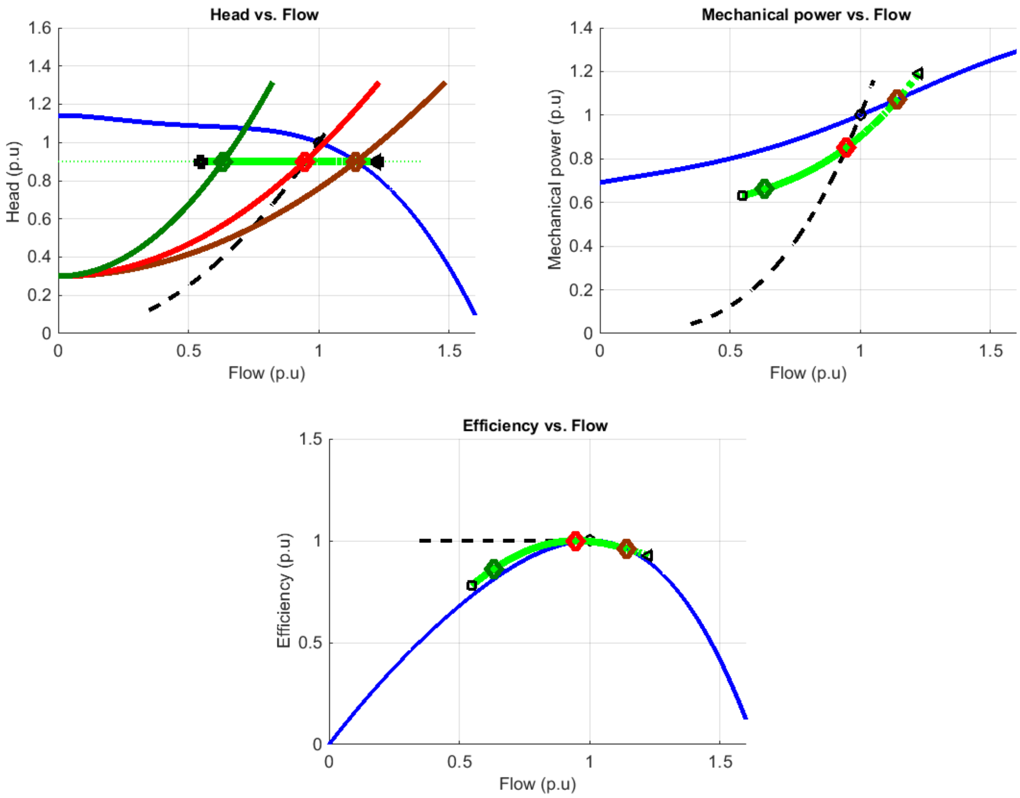


Figure 6: System operating point in Single pump equipment at different system curves and pressure reference

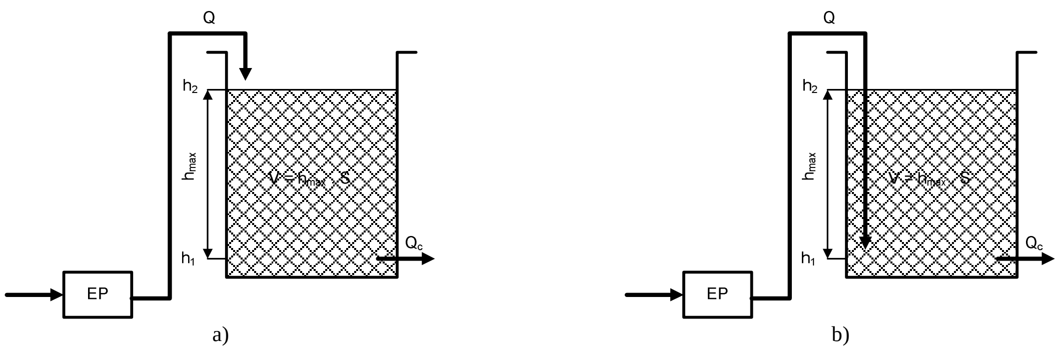
(Nominal pump curves (solid blue line); System curves (dashdot green, red and brown line); Best efficiency pump curve (dashed black line),Pressure reference (dotted green line); system operating point (green, red and brown diamond)

In case of pressure control, the operating point is imposed by the pressure reference and the system curve as shown in the figure 6. We can see that depending on system curve evolution, the operating point moves over the pressure reference (dotted line). For one particular case of system curve, the system operating point can corresponds to the Pump-BEP.

To conclude for this pressure control system, we can say that no way to set system best efficiency point (System-BEP) because there is no freedom degree, except by relaxing the pressure constraint.

System with volume constraint

In this use case, the objective is to fill or empty a given volume with a minimum consumption of energy. Scheme 2 presents different system configurations in case of volume control for filling process:



Scheme 2: Single pump equipment in volume control

According to scheme 2 we can define different forms of the system curve in this kind of system:

Constant system curve including only static head losses :

$$h_{sys} = h_{s0} \tag{21}$$

Quadratic system curve including static and dynamic quadratic head losses :

$$h_{sys} = h_{s0} + h_{s1} \cdot q^2 \tag{22}$$

Quadratic system curve including dynamic static and quadratic head losses :

$$h_{sys} = h_{s0}(h_{tank}) + h_{s1} \cdot q^2 \tag{23}$$

Where h_{tank} : is the measured level in tank [m].

Generally the consumed energy in single pump equipment (EP) is expressed as follow:

$$\frac{\partial e}{\partial t} = p_w \tag{24}$$

From system point of view, in case of filling process, we have the following expression:

$$\frac{\partial v}{\partial t} = q - q_c \tag{25}$$

Where q_c is a disturbance flow (p.u.) which counteracts to the flow provided by the pumping equipment. For the following calculation, we consider this flow equals to zero. We could demonstrate that this disturbance flow just introduces an offset in the speed corresponding to the best efficiency point. By introducing volumetric energy

$$e_v = \frac{\partial e}{\partial v} \qquad \Rightarrow \quad e = \int_0^{v_{max}} e_v \cdot \partial v \tag{26}$$

Reworking equations (7) and (8), the consumed energy can be expressed according to the volume as follow:

$$\frac{\partial e}{\partial v} = e_v = \frac{\mathrm{p_W}}{q} = \frac{\mathrm{h}}{\eta\left(\frac{q}{x}\right)} \tag{27}$$

The objective is to find the speed trajectory x=f(v) that minimizes the consumed energy e during a filling process, which can be translated by cancel the partial derivative function of the energy according to the speed:

$$\frac{\partial e}{\partial \omega} = \int_0^{v_{max}} \frac{\partial e_v}{\partial \omega} \cdot \partial v = 0 \tag{28}$$

The general solution can be expressed by a function g(x,v) with:

$$\frac{\partial e_v}{\partial x} = g(x,v) \;\; \textit{such as} \;\; \int_0^{v_{max}} g(x,v) \cdot \partial v = 0 \tag{29}$$

<u>For a constant system curve – particular case of a constant pressure system curve.</u>

We use the system curve defined by equation (21) and pump curves to calculate the operating point by solving the following equation:

$$x^2 \cdot f_{\omega n}\left(\frac{q}{x}\right) = h_{s0} \tag{30}$$

In this case, for a given tank volume v_{max}, there is a particular solution for the equation (28) which can be defined by:

$$0 \equiv \frac{\partial e_v}{\partial x} \tag{31}$$

According to equation (31), derivative function of the volumetric energy depending on the speed is expressed in normalized form as follow:

$$\frac{\partial e_v}{\partial x}=\frac{\partial}{\partial x}\left(\frac{\mathrm{h}}{\eta\left(\frac{q}{x}\right)}\right)=0\ \Rightarrow\ \frac{\partial e_v}{\partial x}=h_{s0}\cdot\frac{-\frac{\partial}{\partial x}\left(\frac{q}{x}\right)\cdot\eta'\left(\frac{q}{x}\right)}{\eta\left(\frac{q}{x}\right)^2}\ \Rightarrow\ \eta'\left(\frac{q}{x}\right)=0 \tag{32}$$

The optimum is obviously reached when efficiency is at maximum. Note that the pump best efficiency point (P-BEP) at nominal speed ω_n is given by (H_n, Q_n, Pw_n) and thanks to the affinity laws, the system best operating point (S-BEP) at constant system curve can be obtained with the optimal speed (ω_{opt}) which is calculated as follow for each constant system curve (h_{s0}):

$$\omega_{opt}=\omega_n\times\sqrt{h_{s0}} \tag{33}$$

In this case, we can say that that System-BEP is equal to Pump-BEP.

<u>For a system curve including quadratic losses – usual form of system curve in the most of hydraulic applications</u>

From equation (22) and the pump curves, we define the constraint between the flow (q) and the speed (x) as follow:

$$x^2\cdot f_{\omega n}\left(\frac{q}{x}\right)=h_{s0}+h_{s1}\cdot q^2 \tag{34}$$

This is meaning that flow is a function of system data $\mathrm{q}=\mathrm{k}_{\omega_n}(\mathrm{h}_{s0},\mathrm{h}_{s1},\mathrm{x})$. On a theoretical point of view, we are looking for the optimal speed that minimizes the volumetric energy expressed in equation (29) and which verifies the constraint between the flow (q) and the speed (x) in equation (34). This means it exist a solution (x_{opt}) that verify the following equation:

$$0\equiv\frac{\partial e_v}{\partial x}=\frac{\partial}{\partial x}\left(\frac{\mathrm{h}}{\eta\left(\frac{q}{x}\right)}\right) \tag{35}$$

By using equation (34) we get the relation

$$\eta'\left(\frac{q}{x}\right)=\eta\left(\frac{q}{x}\right)\cdot\frac{h_{s1}}{h_{s0}}\cdot x\cdot q\cdot\frac{2\cdot f_{\omega n}\left(\frac{q}{x}\right)-\frac{q}{x}\cdot f_{\omega n}{}'\left(\frac{q}{x}\right)}{f_{\omega n}\left(\frac{q}{x}\right)}$$

This is demonstrating that, for a decreasing pump curve (pressure vs. flow), the best efficiency operating point is moved to a lower flow value that the one expected by the best efficiency pump curve.

<u>For a system curve including quadratic losses and static head dynamically modified according to the tank level– typical usual form in the volume control system</u>

From equation (23) and pump curves, we define the constraint between the flow (q) and the speed (x) as follow:

$$x^2\cdot f_{\omega n}\left(\frac{q}{x}\right)=h_{s0}(h_{tank})+h_{s1}\cdot q^2\ \Rightarrow\ q=k_{\omega_n}(h_{s0},h_{s1},x,h_{tank}) \tag{36}$$

In this case, the static losses of the system curve evolve dynamically according to the tank level. Consequently we haven't one only best system operating point to fill the tank volume as seen previously in both use-cases of the system curve defined above, but there are different best system operating points. Therefore, we are looking for the optimal trajectory speed x=f(v) that verifies equation (28) during the filling process. A basic way to proceed is to re-calculate the optimal speed at each tank level.

Figure 7 presents the best efficiency operating point according to the pump curve and the system curve evolution in order to fill tank volume vmax.

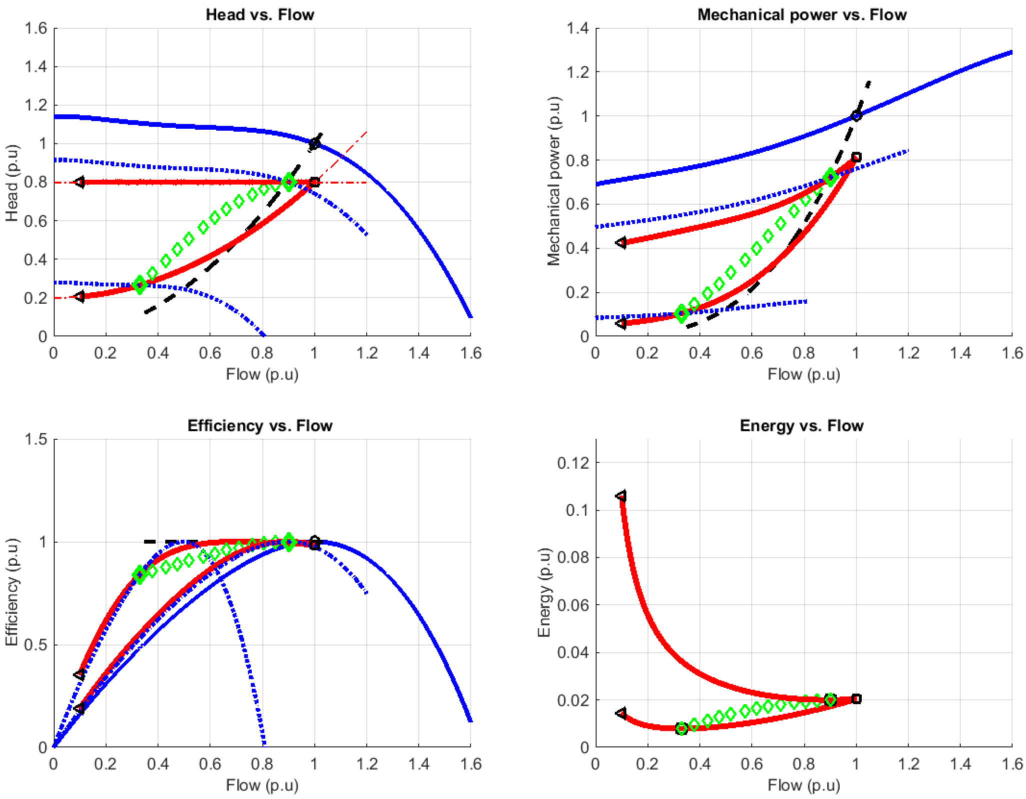


Figure 7: System Best operating point (S-BEP) at different system curves
Nominal pump curves (Solid blue line); Optimal pump curves (dotted blue lines), system curves (dashdot red lines); Best efficiency pump curve (dashed black line), Optimal speed trajectory (green diamond line)

In case of a constant system curve with no quadratic losses, the obtained system operating point (green diamond point) is placed on the pump best efficiency curve which is corresponding to the best system operating point in terms of energy saving as shown in the graphs (Energy vs. Flow).

When the quadratic losses are added in the system curve, we remark that system operating point moves away from the pump best efficiency curve, but it is still the best operating point for the global system in terms of energy savings as shown in the graphs (Energy vs. Flow). In this case of the system curve, we have one only system best operating point to fill the tank volume and which is different from the pump best efficiency point: System-BEP is different from Pump-BEP.

Conclusion

As demonstrated in this paper, in most of hydraulic applications, the system best efficiency operating point is not always corresponding to the pump best efficiency operating point. In fact, in single pump equipment, the system operating point is given by the system curve and one degree of freedom which depends on what we need to do in terms of system control:

- In efficiency control (open system without constraints on process variable : flow and pressure), the **S**ystem **B**est **E**fficiency **P**oint is equal to the **P**ump **B**est **E**fficiency **P**oint (**S-BEP** = **P-BEP**)
- In volume control (Level control applications), the **S-BEP** is given by minimizing the consumed energy during the filling or emptying process of a tank volume. Depending on the system curve form, we had demonstrated that the system operating point may be different from the **P-BEP.** In case of quadratic system curve with a static head varying dynamically with the tank level – typical system curve form in level control application – , we have the **S-BEP** that is

different from the **P-BEP**. There are different S-BEP's during the filling or emptying process which define an optimal speed trajectory.

- In pressure control (Booster control applications), there is no way to get the best system operating point in single pump equipment, because it is imposed by system curve and pressure reference. Therefore, as we had seen in this paper, it may be possible to define S-BEP in multiple pumps equipment.

We have demonstrated how we can define a single "equivalent" pump from the multiple pumps equipment. From energy savings point of view, there is one degree of freedom that can be translated by sharing equivalently the flow demand between the multiple pumps. Simulation-based support and a theoretical approach allow demonstrating that the optimal operating point is reached when the pumps are running at the same speed which is a key feature to use VSDs to control a multiple pumps equipment in hydraulic applications compared to a traditional DOLs.

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Motor-driven Systems: A Global Market Update on the Pump, Fan and Compressor Markets

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Abstract

This update highlights the findings of the latest analysis by IHS of the global markets for pumps, fans and compressors as well as detailed auxiliary research on the motor and drive markets. It summarizes how these markets are segmented by technology, geographic region, industry sector and other categories. In addition to presenting market data, the presentation will include an analysis of the current competitive environment for these products. A discussion of the projected impact of significant merger and acquisition (M&A) activity that has occurred in recent years is also included.

In addition to presenting detailed, reliable and impartial market statistics, the presentation discusses the major trends affecting these markets. Among the topics addressed are the impact of various regional minimum motor efficiency legislations being enacted by governments around the world as well as customer design preferences, changes in the supply chain, and minimum performance requirements for pumps, fans and compressors[1]. It provides the audience with a realistic view of how varying regions differ in their approach to systems efficiency and the realistic timetable for transition to higher-efficiency products. The update also includes a discussion of the effect that more expensive, higher-efficiency motors are likely to have on the repair versus replace decisions facing users of motor-driven systems, and the apparent disconnect between these decisions and the consideration of the total cost of system ownership, rather than its initial purchase price. This paper analyzes the increasing penetration rate of motor drives used to control the speed of motor-driven equipment and highlight the different approaches to total system efficiency used in North America, Europe, and Asia.

Introduction

This update is an overview of the latest findings by IHS from its analysis of the global markets for pumps, fans and compressors as well as detailed auxiliary research on the motor and drive markets. In 2014, the global market for fans, pumps and industrial compressors, with a combined value of nearly $91 billion[2], experienced a year of tempered growth due to a substantial economic slowdown in China, declining oil prices, overcapacity concerns and price declines in the process industries in which these products are heavily utilized. IHS believes that oil prices will continue to stabilize, and exploration and procurement activity will also increase from 2015-2017, though at a tempered rate [1]. This will lead to stronger growth for these motor-driven systems in process applications. Just as 2014 ended with uncertainty, 2015 began even more tumultuously, but the European market is continuing its push out of its economic crisis, large municipalities are increasingly more able to invest in much needed infrastructure projects, and investor confidence has begun to rise starting in mid-2015. Still, this market is in a period of uncertainty given the unknowns surrounding the potential exit of Greece from the European Union (EU) and other politically compromising situations. In 2015, IHS projects that unit shipments of these motor-driven systems will increase by about 1.5% from 2014. This slight increase can be directly attributed to the process industry's downturn being negated by the increase of worldwide construction spending as well as the increased size of commercial buildings. Land is becoming more and more of a scarce commodity in urban and urbanizing cities, meaning that taller buildings must be built and subsequently more pumps, fans and compressors will be required to meet the needs of today's comfort technology. The water, construction and HVAC industries already

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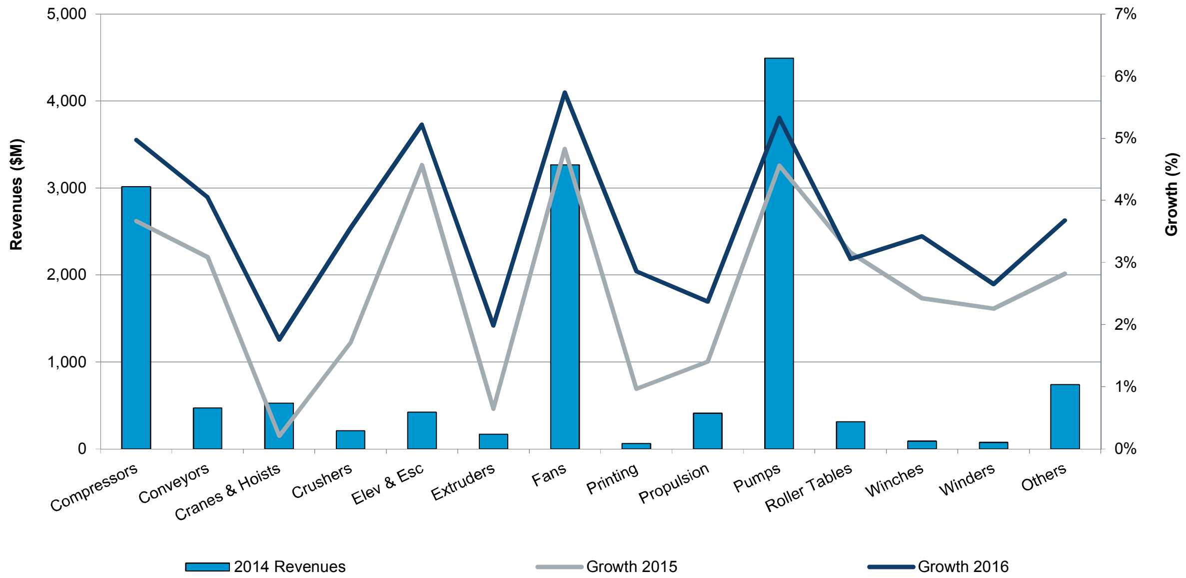
[1] The European Union (EU) is the only region to implement efficiency requirements for pumps, fans and compressors, but the US and several other countries are working to begin drafting or finalizing framework documents that would implement similar policies. This is a key focus worldwide.

[2] Based on data gathered from key suppliers as well as secondary sources published by IHS Economics and Country Risk Solutions.

accounted for more than 75% of these markets in terms of unit shipments in 2014, and that figure is expected to increase as urbanization and globalization continue to gain momentum.

Pump, fan and compressor manufacturers know that they are involved in a very mature market and that change often happens quite gradually in such environments. This update aims to capture the expected outcome throughout the forecast period of such mature markets when driven by demand for rapid change. These products accounted for more than two-thirds of motor applications (Figure 1) in 2014, so the adoption of efficiency regulations and minimum product standards has certainly been one of the most influential trends for more than a decade. Overall, each region has different priorities and separate timelines for such standards. The goal in each region, however, is to demonstrate the benefits of looking at the market as many components of a system. Looking at more than just one product and accounting for auxiliary equipment is referred to as the "extended product approach". Though many manufacturers still have an aversion for government intervention and incorporating the extended product approach, it has become more and more apparent that every equipment supplier (of motor, drive or motor-driven products) will be held to a minimum standard in the future, and only the companies that can adapt accordingly will thrive.

The World Market for Low-voltage Motors By Application - Market Breakdown and Growth



Source: IHS

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The European, Middle Eastern and African (EMEA) market for pumps, fans and compressors

The EMEA market for pumps grew by less than 2% in 2014, with more than 20 million units shipped. Of this, positive displacement pumps accounted for 20% of units and 25% of revenues. In Europe, the pump market was not as negatively impacted by the sudden decline of oil prices, but the Middle East and Africa have certainly experienced a contraction in their pump markets. Lower oil prices lead to a decline in the projects business, so this decline was much harder felt in the Middle East because of that region's reliance on heavier industries such as oil, gas and power generation. Furthermore, the Russian-Ukrainian conflict limited investment potential. Buoying the EMEA region's growth has been the rise in prices on account of higher standards for water pumps. In January 2015, many circulator pumps came under regulation that mandates they all reach a certain energy efficiency index (EEI), which has substantially increased their cost (more than 100% in many cases). While prices have increased for many standard-duty centrifugal pumps, municipalities are still dealing with low budgets. Therefore, infrastructure development has been timid in 2015, limiting growth of the vast water/wastewater industry for pumps in EMEA. There has been mixed feedback for 2015 growth expectations; overall, the large HVAC industry in Europe will buoy pump market growth despite the slowdown in the Middle East and Africa from the first half of 2015. Looking forward, the Middle East seems poised to begin investing more heavily in upstream projects again, offering a positive outlook for pumps and compressors in 2016 and 2017.

Industrial air and gas compressors follow a similar trajectory to that of pumps. This market had a value of $10 billion and more than 2 million units shipped in 2014. IHS did not include HVAC or refrigeration in its compressors research, so the projected market contraction in 2015 does not account for the rapidly growing compressor market in those industries. While fan and pump regulations have been on the forefront of many discussions in Europe, an effort to regulate compressor efficiency is also underway. The compressor market is also very mature, however, and IHS believes that compressor legislation will take the longest to implement based on how far these efforts are compared to the well-established pump and fan regulations in the region.

Europe will continue to experience increased average selling prices (ASPs) as a result of efficiency regulations designed to reduce the use of materials (in this case refrigerants) that are harmful to the environment and increase the use of variable-speed drives [2]. On the industrial side, both air and gas compressors suffered from modest unit shipment growth and price decreases in applications in which there is typically more revenue. However, low commodity prices limited profit losses last year, so compressor manufacturers remain optimistic for a bounce back in early 2016. For industrial air and gas manufacturers, IHS forecasts revenue and unit shipment growth of 4% and 3%, respectively, in 2016.

With a market value of almost $7 billion and well over 44 million fans sold, the fan market performed the strongest of the three applications in 2014. The second wave of the ErP directive for fans came into effect in January 2015 [3], and the market has adopted these higher-efficient products fairly well, though at a rate lower than previously expected. While no such standards exist elsewhere for fans, it will be interesting to see how other countries attempt to follow suit and incorporate their own regulations. Many fans that were sold in 2014 are no longer compliant with 2015 standards, and early accounts have shown that the top-tier suppliers are gaining even higher shares of the market. It is not yet clear what will come of the second- and third-tier manufacturers in the region, but this market is certainly scrambling to maintain market share while investing heavily in research and development (R&D). The average R&D investment in this region has increased from about 3% to almost 4% of revenues from 2013 to 2014. This very clearly highlights the nature of the fan market in Europe. As a direct result, the market has been introduced to (and has accepted quite well compared to other regions) EC (electrically commutated motors) technology in an increasing number of applications.

Strong growth is forecast to continue for the fan market as prices continue to increase in the residential and commercial markets. Though enforcement of these energy efficiency policies remains a concern, it appears that the more developed countries have not had as many issues with this.

The American market for pumps, fans and compressors

While the Eurozone has successfully implemented motor-driven systems efficiency standards, the American market has no such standard in place just yet. Specifically in the United States, this has created a stigma that the manufacturers are not keen to adopt the aforementioned extended product approach. While there is not a lack of energy-efficiency initiatives in the US, there is certainly a different way of thinking in the country. Since the NEMA/IEC motor regulations began, the US has always been the leader of this transition into using higher-efficiency, low-voltage (LV) motors. Over time, the motor-driven product manufacturers want to establish something similar for their products, so the US is looking at minimum efficiency ratings for clean water pumps and myriad fans. Fan efficiency grades (FEG) currently exist and are in effect (established via AMCA), though it has become increasingly clear to suppliers and regulators alike that there needs to be a consideration for part-load efficiency concerns. At the same time, sacrificing systems like FEG leads to much more uncertainty with regards to the reporting of a product’s energy efficiency. It is not plausible to calculate the energy saved when manufacturers do not always know into which applications their product is going. It is possible to calculate based on peak performance, but motor-driven systems seldom operate at that level for extended periods of time. This delay has led to a bit of uncertainty regarding the future of efficiency regulations for pumps, fans and compressors in the Americas, particularly in the US. Despite the stereotype, research has shown that there are many similarities between the European and US markets. In fact, it is believed that future Department of Energy (DOE) regulations on this equipment will likely be of a similar mold to those of the ErP directives. What has become clear is that the US market seems to have more focus on enforcement, which understandably results in delays when developing a system to enact such dramatic, though necessary, policies.

The American pump market was valued at more than $13 billion in 2014 with almost 9 million units shipped. The year 2014 was a very slow year as a result of the drop in oil prices, and by all accounts 2015 is poised to be another relatively flat year. Whereas a little more than 20% of revenues for the pump market are associated with oil and gas, the industry accounted for 27% of compressor revenues in 2014 (much more when only considering gas compressors). From the third quarter of 2014 until recently, pump and compressor manufacturers have been forced to sell their products at a discount of anywhere between 15-30% in order to move product. The past couple of years have seen a rapidly consolidating market, indicative of a time when cost-cutting and efficient production is paramount. As evidence of a push towards consolidation, ITT acquired Bornemann Pumps, a positive displacement pump manufacturer; Siemens acquired Rolls Royce Energy and Dresser-Rand; GE acquired Alstom and Cameron (reciprocating compressors); and Ingersoll Rand acquired Cameron's centrifugal compressor division. The consolidation of these markets is expected to shift pricing in favor of the suppliers in the midterm.

There is currently a clean-water pump efficiency regulation being reviewed by the Department of Energy (DOE), and HVAC pumps such as circulators are likely to be considered next. However, the market size for circulator pumps in the Americas is dwarfed by that of Europe, so there is less urgency because the energy savings from this product are minimal in the United States. Also worth noting, Grundfos, Xylem and Wilo only comprised less than 5% of the American circulator market with their ErP-compliant pumps as of the end of 2014. Furthermore, pump, fan and compressor OEMs are beginning to see the benefit of selling energy-efficient extended products (pumps with premium efficient motors and/or drives). Only 10% of water treatment facilities utilize VFDs despite being run mostly all day. Rebate programs are on the rise for efficient fan systems in commercial buildings, and leakage remains a huge problem for water handling, even in the most developed US cities. Coupled with leakage concerns, storms have ravaged the US East Coast over the past few years, and revamps are needed in order to handle storm water and boost much of the outdated infrastructure. Projects such as these bode well for the motor-driven systems markets in the Americas, specifically that of the US.

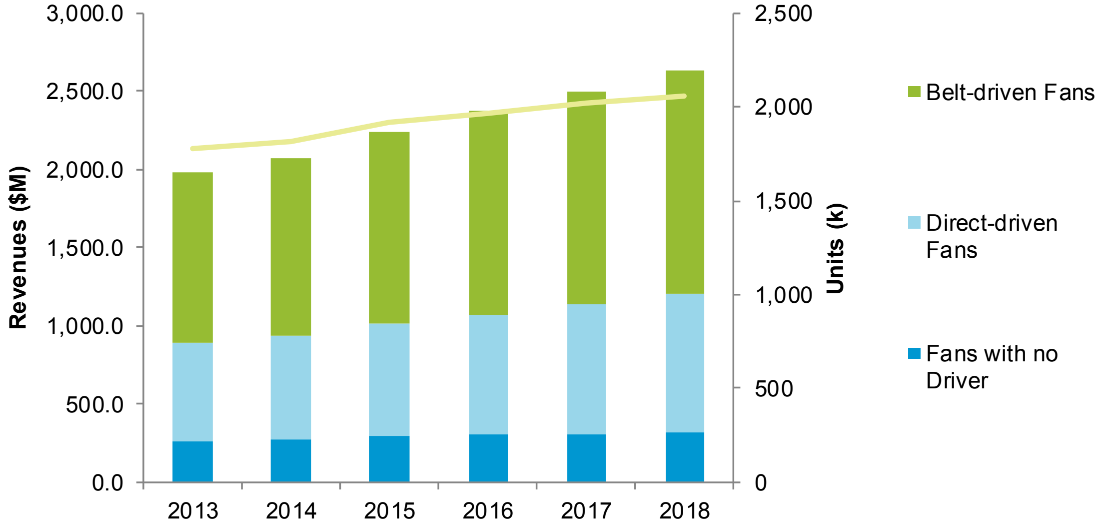
Similar to the pump market, the American market for industrial air and gas compressors (valued at $6.2 billion with 1.3 million units shipped in 2014) is forecast to experience a year of flat growth in 2015. On the other hand, the American market for fans and blowers was valued at $4.7 billion with over 31 million units shipped in 2014 and is forecast to experience near double-digit growth as a result of advanced technology, a rapidly growing housing market as well as increased commercial construction investments. Fan arrays now require multiple fans, and noise and efficiency concerns have reportedly led to a strong market for replacements and retrofits.

The industrial fan manufacturers in the US are the least keen to optimize the full systems approach of selling more than just a stand-alone fan. Many industrial manufacturers and lower-tier commercial suppliers do not want to be held accountable for the efficiency of products that they did not manufacture themselves, which is what originally led to the development of the FEG standards in place today. That sentiment, however, is fading away fast; in fact, only 13% of units sold in the Americas were stand-alone, compared to less than 9% in EMEA in 2014 (Figure 2). The difference is that only 32% of American fan shipments were direct-drive (and the subsequent 55% were belt-driven), whereas in EMEA those figures are 79% and 12%, respectively.

Figure 2a

The American Market for Commercial & Industrial Fans

By Sales Package

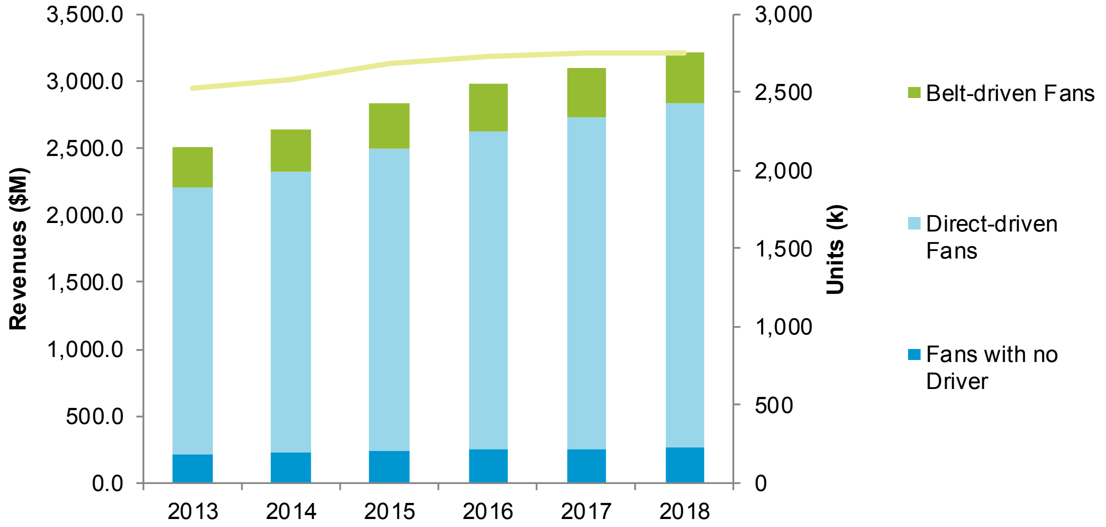


Source: IHS

Figure 2b

The EMEA Market for Commercial & Industrial Fans

By Sales Package



Source: IHS

Just as R&D costs have risen in Europe, they are increasing just as rapidly in the US for all product markets. Trade associations appear to be pushing the full systems approach as much as possible, and are even going so far as to regulate and certify products and suppliers' testing facilities. This is the extent to which the American market is committed to adopting standards that are both adaptable from the European standards and also enforceable. Though not all manufacturers are fully supportive, it is becoming clearer that they do not have much of a choice but to adapt to these rapidly changing markets in which customers are becoming more aware of the need to save energy, reduce downtime and prevent costly maintenance.

The Asia-Pacific Market for Pumps, Fans and Compressors

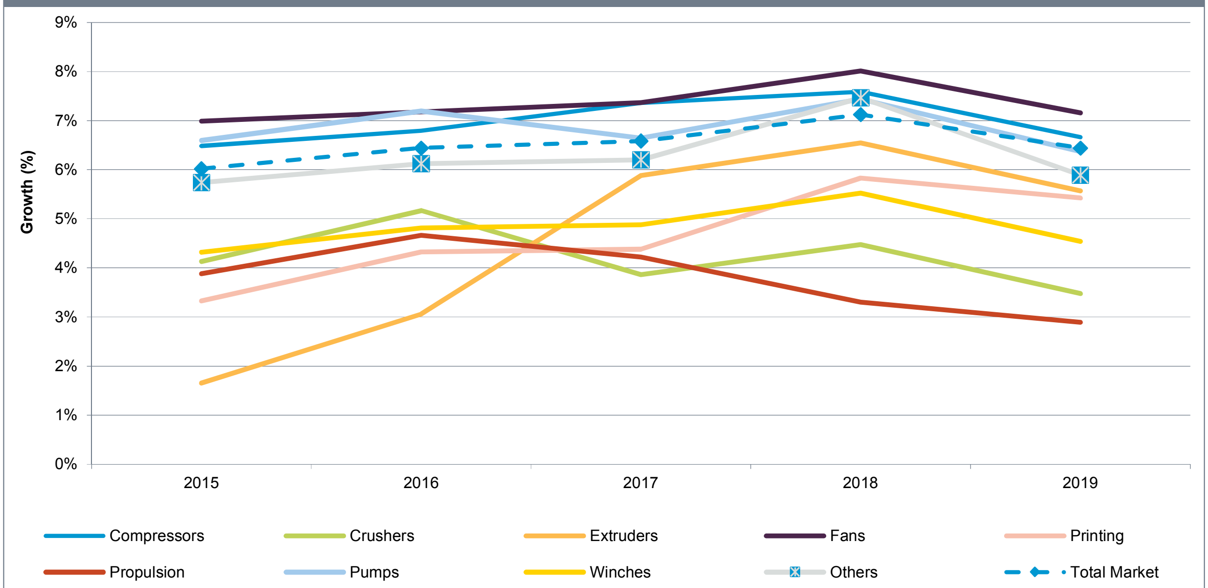
The Asia-Pacific pump market was valued at $15 billion in 2014, with more than 25 million units shipped. The year 2014 was a year of contraction for pumps and compressors. The Asia-Pacific market for compressors was worth more than $10 billion in 2014, with 2.5 million units shipped. As EPCs experienced profit losses, those losses reverberated back to OEMs at a great detriment. Since the larger projects were the hardest hit, this actually had a negative impact on American OEMs almost just as much as the domestic Asia-Pacific suppliers since large projects normally require American equipment.

Aside from the larger projects, China experienced substantial economic tribulations that slowed growth throughout the entire industrial automation sector. As a result, the fan market in Asia Pacific (valued at more than $13 billion with 215 million units shipped in 2014) experienced flat growth, but is poised for strong bounce-back years in 2015 and 2016, with close to double-digit revenue growth due to China's heavy investments in infrastructure and a growing residential and commercial market.

Because China accounted for roughly 60% of these products' country split in Asia in 2014, its economic direction is very telling of the performance of suppliers in Asia Pacific. The past few years have seen government incentives for higher-efficiency pumps, fans and compressors, but Chinese end users have remained very price-conscious initially. The top-tier Chinese suppliers have begun to focus more on exporting because of the domestic economic slowdown as well as that they can sell more expensive equipment in other countries such as Australia and Japan. These companies have also found a competitive advantage in Eastern Europe and the Middle East by exploiting economies of scale. The manufacturing capabilities of Chinese manufacturers are also quite impressive. The top few Chinese pump suppliers, for example, have the manufacturing capacity to produce more than seven million pumps annually, underscoring the massive size of the Chinese pump market. Overall, though, Chinese pumps, fans and compressors are typically much less efficient and there is much room for improvement in this regard. There is a severe lack of enforcement for motor regulations as it is, so the push for pump, fan and compressor standards has not been adopted as readily as initially imagined. This has made it difficult for foreign companies to eke out a sizable share of this market, though all signs indicate that multinational companies are steadily gaining brand recognition. By all accounts, brand recognition is the most important driver for growth in China, and as minimum energy performance standards (MEPS) for motors are more widely accepted, so will efficiency increases in motor-driven equipment throughout the region.

Overall, the Asia-Pacific market is poised for the fastest growth of the regional markets from 2014-2019. The revenue CAGR for pumps, fans and compressors is projected at more than 7% (Figure 3), compared with 4.5% for the Americas and 4% for EMEA.

The Asia Pacific Market for Low-voltage Motors By Application - Revenue Growth Profiles - 2015 - 2019



Source: IHS

Conclusion

IHS has paid close attention to an inherent disparity in the industrial automation arena over the past five years: the person purchasing the equipment is seldom the person who pays the energy bills at that facility. This of course leads to a conflict of initial price concern versus total life cost awareness. Many efficiency standards have taken place, from motors to drives to the equipment that they control, but few suppliers feel that these policies have been as effective as they could be. This is of no fault to the regulating agencies or the suppliers. This push to save energy and therefore save customers money will apparently take a substantial amount of time. While it is true that progress will not come about until governments begin to act, it does not end there; the suppliers are just as responsible to drive that point to their customers.

We have seen that when an energy-efficiency policy is enacted, it may take several years to be fully realized. This is on account of loopholes, gradual scope changes to regulations and old, non-compliant inventory that needs to be sold. Furthermore, a customer can buy the most efficient products on the market but misuse or improperly size the equipment for the desired application. This is where suppliers can make a name for themselves and combat lower-cost competitors. Pump, fan and compressor suppliers in all regions have begun to incorporate sizing software, training programs, premium-efficient designs as well as lean production techniques in order to get closer to the customer. Any effort that these suppliers can make to reach the customer and show how to properly size and utilize the right equipment for the right job will yield more benefits than just gaining a sale. This is how manufacturers increase their profit margins via the extended product approach because this connection with the customer allows for the incorporation of their supply chain and gives the supplier a better understanding of the applications in which the customer is involved. Overall, the market for pumps, fans and compressors has a positive outlook, with increasing sales prices and multiple projects on the horizon. Despite a rocky past twelve months, these manufacturers have expanded their service capabilities as well as R&D investments, so the push for new technology and support methods will continue to shape these markets for the better in the future.

References

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[3] European Commission *Commission Regulation (EU) No 327/2011.*

Update on Pump Efficiency and System Assessment Standards

Abstract

Since the 1970's, increasingly three-phase electric motors have been subject to comprehensive voluntary and mandatory energy standards, but for pumps, standards setting minimum efficiency have just been introduced in 2013 and are limited to selected rotodynamic models handling water. In both Europe and the United States, however, regulatory authorities have initiated plans to expand covered pump scope by types, power and fluids.

Pump efficiency standards will apply to manufactured product and gradually will raise the net efficiency of the installed universe, but net efficiency improvement will follow a slow curve driven by new constructions, process changes and pump/motor replacements.

Recognizing the above, using a team of industry experts, in 2009, ASME published EA2-2009, Energy Assessment for Pumping Systems. The Standard sets processes for conducting and reporting the results of pumping system assessments for the purpose of identifying energy performance improvement opportunities.

Seeing a similar global requirement, ISO TC-115 (Technical Committee Pumps) formed WG7 for the purpose of developing an ISO version of the topic, and this paper covers the history of ISO/ASME 14414 from 2010 till today with an overview of the contents, differences with ASME E2, and a review of topics added, including positive displacement pumps and drivers.

It further updates the reader on the progress of regulatory activity for pumps in the United States and Europe, along with the global status of the "extended product" concept (which includes electric motor, pump, variable speed drive and controls) as an opportunity for energy reduction.

Overview

EEMODS11[1] and 13[2] presentations included several that dealt with the issues surrounding pump and motor standards. Over the intervening years, we have seen concepts advance from voluntary to regulatory standards, broaden from regional to global standards and from product to a combined pump-driver-control concept. This paper is structured around these steps, outlines the progress in each, and envisions future stages.

Likely, there are few people alive who can remember a time when there was not a pump or motor standard. For decades, industry organizations have developed standards on nomenclature, definitions, application, operation and dimensions. And as these two vital industries matured, the sophistication of standards increased in a continuing effort to simplify commerce between manufacturers and users while promoting valuable goals such as safety or dimensional commonality.

None of these were regulatory (derived from law), nor typically did they deal with establishing efficiency minimums, as efficiency was felt to be an element of the marketplace competitive process. Industry groups, however, developed generalized efficiency guidelines for users' use. They also promoted use of their standards with guidelines and companions to broaden the knowledge base of users and its members. With, however, the advent of regulatory agencies focused on energy reduction, there came a new player in the standards process.

History shows that the electric motor industry led the pump industry in development of standards dealing with efficiency. These initially were voluntary, but evolved to an industry-government collaboration to today's regulation. Electric motors have characteristics that more easily lead to efficiency standards. There is, however, application criteria that are similar; proper setting of the process requirement, proper sizing for the application, and minimization of safety margins.

Pumps have numerous subcategories, come in a variety of mechanical configurations, and handle a ubiquitous list of liquids in systems with boundless variables such as inlet and discharge conditions, pipe sizes, liquid temperatures, sealing requirements and economic importance of hydraulic efficiencies. These lead to regulators' early selection of motors to be targeted for efficiency standards.

Pumps, however, are a high priority for energy saving since they are estimated to consume 27% of energy used in industrial plants, and the U.S. DOE report their studies show energy accounts for 40% of a pump's lifetime operating costs.

When one considers the efficiency process, it is important to highlight it is established in legislation and regulation. In Europe, that is European Commission Regulation 547/2012/EC implementing Directive 2009/125/EC[3]. In the United States, it is the National Energy Conservation Policy Act of 1978 implemented by the Energy Policy Act of 1992 (ECPA).

In the US, the proposed rules for Energy Conservation Standards for Commercial and Industrial Pumps are being developed by the Department of Energy, Building Technologies Program, Appliance Standards and Rulemaking Committee. This is the agency that has done energy regulations on items such as washing machines and walk-in coolers, so industrial pumps require very different skills; therefore, there was needed considerable product education for NGO and DOE administrators. The regulation development also depended on data collection which is neither collected nor transparent in the pump industry.

Pump Energy Conservation Regulatory Standards Implemented

There is a great deal of credit due the leaders of the European pump industry, their technology groups, and the senior technical educators in Europe for their contribution in developing the groundbreaking processes involved in advancing concepts dealing with the challenge of pump energy conservation and the introduction of removal of low efficiency pumps from the market. The first of the products were home circulators and rotodynamic water pumps.

Circulators and Rotodynamic Water Pumps

Circulators: Currently implemented and in place are the European Ecopump circulator and rotodynamic water pump regulations, which will be recognized as the forerunner programs for regulating pump efficiency. Circulators based on Eco-design directive 2005/32/EC revised by 2008/125/EC, covered by EC regulation 641/2009[4] was the first pump product to be regulated for efficiency.

These cover "glandless circulators with a related hydraulic output power between 1 and 2500W designed for use in heating systems or secondary circuits of cooling distribution systems". Circulators were early candidates due to the substantial annual manufacturing volumes for which the industry in 2005 had launched a voluntary commitment to efficiency label products (A thru G) and by 2012, remove products greater than E from the market.

The regulation introduced the concept of an "Energy Efficiency Index" of a circulator to be confirmed by declaration of CE conformity. The EEI is the ratio between the weighted average of the power for a specific circulator based on a four-point standardized load profile and the power rating of a reference pump with the same hydraulic power times a "calibration factor".

Acceptable EEIs for standalone circulators are established on EEI<0.27 from 1.1 2013 and a circulator in a product as EEI<0.23 from 1.8.2015. This regulation therefore provides market leading concepts:

- Acceptable product efficiency minimums
- Power calculations based on established load curve
- Energy savings in variable speed drives
- Industry participation

This regulation is in place with wide acceptance; however, some noncompliant imported product may be leaking in the market. Note: Compliance to requirement is a national responsibility.

Rotodynamic Water Pumps: On 1 January 2013, this regulation came into force concerning minimum required efficiencies of certain rotodynamic water pumps. It, too, is established by European Directive 2005/32EC[5] and is commission Regulation (EU) No 547/2012. This body of pumps has been known for some time as Lot 11. It covers pumps designed for water in the following mechanical configurations:

- End suction own bearing (ESOB)
- End suction close coupled (ESCC)
- End suction close coupled inline (ESCCI)
- Vertical Multistage (MS-V)
- Submersible multistage (MSS)

The regulation sets minimum efficiency requirements for pumping clear water in the following operating envelopes:

- "End suction water pumps" means a glanded single stage end suction rotodynamic water pump designed for pressures up to 16 bar, with a specific speed between 6 and 80 rpm, a minimum flow of 6 meters cubed/hour, a maximum shaft power of 150 kW, a maximum head of 90 m at normal speed of1450 rpm and a maximum head of 140 m at normal speed of 2900 rpm.

- "Vertical multistage water pump" (MS-V) means a glanded multistage rotodynamic water pump in which the impellers are assembled on a vertically rotating shaft, which is designed for pressures up to 25 bar, with a nominal speed of 2900 rpm and a maximum flow of 100 meters cubed/hour.

- "Submersible multistage water pump" (MSS) means a multistage rotodynamic water pump with a nominal axial dimension of 4" (10.16 cm) and 6" (15.24 cm) designed to be operated in a borehole at nominal speed of 2900 rpm, at operating temperatures within a range between 0C and 90C and a maximum shaft power of 40 kW.

Finally, it is of interest to note that along with the European water pump regulation, there are motor efficiency standards that have had efficiency upgrades in 2015 to IE3 or IE2+VSD. These products are in the market today with broad acceptance from users. Also, there are in the U.S. related energy standards that are not regulatory, such as ASHRAE 90.1[6], which when used with building codes, become regulatory, or AHRI 1210 (I-P)[7] voluntary standard covering Variable Frequency Drives for energy conservation in buildings.

Regional to Global Standards

Not a regulatory energy reduction standard, but an important family of standards, is the ISO 50000 series. The core standard is the June 2011 ISO 50001 Energy Management Systems. The standard specifies the requirements for establishing, implementing, maintaining and improving an energy management system, whose purpose is to enable an organization to follow a systematic approach in achieving continual improvement of energy performance, including energy efficiency, energy use and consumption. The standard aims to help organizations continually reduce their energy use, and therefore their energy costs and their greenhouse gas emissions. Other standards in the series are:

- ISO 50002, Energy Audits
- ISO 50003, *Energy management systems — Requirements for bodies providing audit and certification of energy management systems*
- ISO 50004, *Energy management systems — Guidance for the implementation, maintenance and improvement of an energy management system*
- ISO 50006, *Energy management systems — Measuring energy performance using energy baselines (EnB) and energy performance indicators* (EnPI) — General principles and guidance

Within the reference standards in ISO 50002[8] is ISO/ASME 14414[9], *Pump system energy assessment.* The regulatory standards have been focused at manufacturers of pump products, implementation of which over time create sustainable improvement in energy consumption, but ISO 50000 series of voluntary standards attacks the massive installed universe of pump systems. In addition, it adopts the position long promoted by pump manufacturers. Greatest energy reduction can be obtained by proper pump sizing, system improvements, and controlled operation than in demanding hydraulic improvements in mature pump designs which have been developed within a competitive industry marketplace.

The US Department of Energy, *Industrial Technologies Program,* supported this position and granted funding to the ASME, the American Society of Mechanical Engineers, to develop a portfolio of four Energy Assessment Process Documents. Using a core group of knowledgeable industry experts, in 2009, working under the 23-member ASME, Industrial Systems Energy Assessment Standards Committee, with audits from the 19-member EA 2 project team, published ASME EA-2, Energy Assessments for Pumping Systems standard. Using an ANSI, American National Standards Institute process it also received an ANSI designation.

A companion document was published by the committee in 2010, ASME EA-2G-2010, an excellent extensive Technical Report covering the base document. Both documents are available from ASME publication channels, including the Hydraulic Institute in the US and BPMA in the UK, both of whom offer training courses in the subject and material.

In 2011, ISO TC 115 (Technical Committee for Pumps) voted to create a pump energy reduction audit document that would embrace the subject and be referenced with the ISO 50002 Energy Audits Framework. For that purpose, WG7 was established to develop CD 14414. The workgroup recognized the excellent work within the ASME E2 document and drafted portions or near portions into their document. This, however, was the core of conflict when ASME warned of violations of their IP and copyrights, causing the WG to halt work on the draft.

Numerous efforts across multiple channels worked toward a resolution, which eventually was accomplished at both organizations' executive level, with an ISO-ASME collaborative agreement that formed a joint workgroup and parallel ISO and ASME approval channels. The details of operation developed operating procedures for an ISO/ASME document.

The WG, using ISO editorial rules, developed the 14414 document, distribution for comments and comment resolution, an activity that took place in meetings held on three continents. FDIS 14414 was distributed for approval on 9 September 2014 and final vote by 25 November 2014; approved by ISO members and open ASME issue resolved by Chairman's negotiation in February 2015.

The processes in either ISO 14414 or ASME E2 appear similar, and both likely can provide satisfactory results. Being ISO formatted, there are differences within the documents. ISO 14414 is broader in pump types including positive displace pumps. There is no Technical Report Companion such as exists in ASME-EA-2-TR; however, there are eight annexes with additional materials:

- Annex A (Normative) Report Contents
- Annex B (Informative) Recommendations on efficient system energy reduction
- Annex C (Informative) Expertise, experience and competencies
- Annex D (Informative) Recommended guidelines for analysis software
- Annex E (Informative) Example of prescreening worksheet
- Annex F (Informative) Specific Energy
- Annex G (Informative) Pumping system parasitic power
- Annex H (Informative) Example of pumping system efficiency indicator

Standards in the Final Stage of Development

For US manufacturers, suppliers and users, this category is of major importance. As described in the following paragraphs, this is a process approaching a key milestone, the publication of the DOE NOPA, Notice of Proposed Rulemaking. It was anticipated that the NOPA would be published by this date (1 March 2015) but that has not yet occurred. Follows is the history and scope that has occurred to date.

On 13 June 2011, the US Department of Energy (DOE) published in the Federal Register[10] the intent to enter into pump efficiency rulemaking to establish Energy Conservation Standards for industrial and commercial pumps. This activity was authorized under the National Energy Conservation Policy Act of 1978 (NECPA). NECPA was amended by the Energy Policy Act of 1991. The DOE department driving this proposed regulation is the Appliance Standards Rulemaking Committee. This group develops standards, test procedures, certification, enforcement and product labeling for residential and commercial equipment.

This department has broad experience in the appliance area, but commercial and industrial pumps were new grounds. Its processes are controlled by the above acts and published processes, which are lengthy, extensive and complex, covering a period of approximately five to ten years. Below are the major process segments for the Energy Conservation Standard and the Test Standard:

- Framework Document (2013)
- Preliminary Analysis (2014)
- NOPR Notice of Proposed Rule (2015)
- Final Rule (2016)
- Final Rule Effective Date (2019)

The EPCA directs the DOE to consider seven factors to analyze for a feasible and economically justifiable standard.

EPCA Requirement	Corresponding DOE Analyses
1. Economic impact on consumers and manufacturers	• Life-Cycle Cost Analysis • Manufacturer Impact Analysis
2. Lifetime operating cost savings compared to increased equipment cost	• Life-Cycle Cost Analysis
3. Total projected energy savings	• National Impact Analysis
4. Impact on utility or performance	• Engineering Analysis • Screening Analysis
5. Impact of any lessening of competition	• Manufacturer Impact Analysis
6. Need for national energy conservation	• National Impact Analysis
7. Other factors the Secretary considers relevant	• Emissions Analysis • Utility Impact Analysis • Employment Impact Analysis

The years from 2011 till today involved heavy support of the Hydraulic Institute members in pump training for NGO and the DOE team of administrators, engineers and regulators, plus intense exchange of industry data; however, the pump industry collects only a limited portion of the data necessary to support the EPCA requirements.

Based on several open public meetings and document exchanges, the DOE team developed the Framework Document, which was responded to by interested parties in a 20 February 2013 DOE-hosted Framework public meeting. The prepared Framework document contained over 100 questions (119 by actual count) requesting material, answers and opinions prior to 2 May.

It did, however, present some items under consideration by DOE: the possible product regime, the MEI concept, and areas they had already ruled out of consideration. The chart below covers the pump types proposed for consideration.

Pump Type	Sub-Type	Stages	DOE Terminology	Design Speed
End Suction	Close Coupled	Single	End Suction Close Coupled (ESCC)	3,500
				1,750
	Own Bearings/ Frame Mounted	Single	End Suction Frame Mounted (ESFM)	3,500
				1,750
In-Line		Single	In-Line (IL)	3,500
				1,750
Axial Split		Single	Double Suction (DS)	3,500
				1,750
		Multi	Axially Split Multistage (AS)	3,500
				1,750
Radial Split		Multi	Radially Split Multistage (RS)	3,500
				1,750
Vertical Turbine	Non-Submersible	Any	Vertical Turbine	3,500
				1,750
				3,500

	Submersible	Any	Submersible (VT-S)	1,750
Axial/Propeller and Mixed Flow		Any	Axial/Propeller and Mixed (A-M)	3,500
				1,750

Products no longer under consideration: Wastewater, Sump, Slurry, API 610[11], Positive Displacement Pumps, Fire Pumps.

There was discussion of consideration or outright adoption of the European MEI material, but the 50 vs. 60 cycle operation halted that consideration. The Framework document did raise the potential of inclusion of (VSD) variable speed drives. This was strongly supported by industry participants as such a concept had been proposed in the form of “Extended Product”.

Collaborative activity moved toward the Pump Test document with a separate DOE team. Hydraulic Institute began work on a modified HI 40-6 Test Standard. At this point, DOE went silent on the Framework document, but continued active pursuit of the elements required by EPCA, including visits to pump plant facilities. The many activities involved are shown in two process documents attached.

The DOE, recognizing the assistance of the Hydraulic Institute and NGOs in the process, suggested an alternate negotiated process. On 23 July 2013, the Federal Register (78 FR 44036)[12] announced the establishment of ASRAC (Appliance Standards Rulemaking Advisory Committee) with parties invited to reach consensus on a proposed rule for energy efficiency of commercial and industrial pumps. From this, a balanced committee of 14 members were certified and met in a series of two-day monthly meetings from 18 December 2013 to July 2014. As a completion safety reason, DOE kept traditional rulemaking in a parallel process.

DOE targeted Jan/Feb 2015 to move to the next phase, NOPR, Notice of Proposed Rulemaking, with regulation implementation set for the 2019 to 2020 period. As of this date (1 March 2015, however, the NOPR has not been released.) Although a final agreement was not reached, the Working Group agreed and published thirteen “Term Sheets”.

- 1. Defined pump
- 2. Defined components of a pump
- 3. Rating does not include motor metrics
- 4. Defines mechanical construction of pumps
- 5A. Sets action plans and calendar for circulators, ASRAC and NOPR
- 5B. Recommend exclusion of pool pumps
- 6. Explicitly excludes seven styles of water pumps
- 7. Lists process rating conditions that apply
- 8. Lists specific types of pumps not included, i.e., API 610, ASME/ISO chemical
- 9. Recommends test standard be HI 40.6
- 10. Defines PEI and PER
- 11. Provides labeling recommendations
- 12. Recommendation for certification report data
- 13. Recommends testing method for multistage pumps

These are expanded on the DOE website[13], which also provides PowerPoints with data developed in support of the ASRAC and to comply with EPCA requirements:

- Engineering Analysis Update

- PER C-Value Update – Comparison of DOE and HI data
- Manufacturer Impact Analysis for C&I pumps
- Comparison of HI, DOE, and EU lot 11 MEI C-Values
- LCC Impact on Consumers, Shipment models, National Impact Analysis

Also the Test Standard workgroup has finalized work and is awaiting publication of the NOPA for that document, which is believed to closely parallel the revised HI Pump Test Standard HI 40.6.

Standards and Energy Regulation Under Development

Europe: In this category are the next lots of the Ecodesign legislation that are undergoing evaluation for value and scope:

- Lot 28 – Waste Water Pumps (Dirty fluids)
- Lot 29 – Other pumps (Range of Lot 11 pumps extended)
- Lot 30 – Other Motors (Provide an "IE" rating for motors between 120 and 1MW[14]

Both Lots 28 and 20 are candidates for the Extended Product Approach, which is a methodology to calculate the energy efficiency index (EEI) of an Extended Product (EP) (Assembly of physical components), which incorporates load profiles and control methods[15].

United States:

HI Pump Test Standard: HI 40.6: While HI pump test standards, particularly ANSI/HI 14.6, are well known among pump end users, EC firms, pump OEMs and distributors, the DOE would have to reference its own specific pump test procedure as the foundation of its rulemaking. HI offered to write that standard with the DOE, and invited DOE experts as part of the standards-writing team. Unlike the 14.6 standard, the standard that DOE will adopt will be based on only one test tolerance known as 2B.

Minimum Efficiency Index (MEI) Standard: The purpose of the MEI is to develop a methodology for reducing the energy consumption of pumping systems. The MEI concept takes into account the factors of pump type, size (flow rate @ BEP), head, and specific speed to predict the efficiency cut-off level. The MEI provides a decimal index value (<1) indicating an efficiency class.

Pump Test Lab Approval Program: This committee is developing a pump test laboratory audit and inspection standard to approve a pump test laboratory's ability to test the performance of certain products to applicable HI and other performance test standard(s), as well as to adhere to the requirements of an international test lab accreditation standard (ISO 17025). The scope of the committee's work encompasses all pump test laboratories testing pumps and extended products.

Extended Product Standard: The HI Extended Product Committee is working on a publication to identify and verify optimized energy usage of extended products, defined as the pump-motor-drive assembly and control. Working collaboratively with its European counterpart, Europump, HI intends to create a standard for the pump/motor assembly and motor control from the perspective of a subsystems approach (European Extended Product Approach).

Extended Product & Pump Labeling Initiatives: A collaborative effort on Extended Product Labeling was organized by the American Council for an Energy Efficient Economy (ACEEE) to work with electric power utilities, energy efficiency advocates and other trade allies to develop new concepts for pump and extended product labeling to recognize higher efficiency products or extended products. Other trade organizations involved include the Air Movement and Control Association (AMCA), the Compressed Air and Gas Institute (CAGI), the Fluid Sealing Association (FSA), and the National Electrical Manufacturers Association (NEMA).

Summary

Author's opinion: One can easily see from the summary there has been a massive amount of work extended in the area of pump energy standards. Still in the US, until the NOPA is published and analysis made, it is impossible to deter the work ahead. Clearly there will be within government and the pump industry extensive ongoing efforts required to transition to minimum efficiency standards. That effort likely will be continual from this date forward, but at a minimum, it is a task for the next decade. It is still too soon to assess the impact on the industry and commercial and industrial energy consumption.

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Progress in energy efficiency in fluid handling systems

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Abstract

Efficient Energy Use (EFEU) program was founded in 2011 to assess industry-level problems in energy efficiency in Finland. The current focus is in improving fluid handling systems with systems-level approach through pump control and also by developing next-generation equipment, such as pumps, agitators and pulpers for the paper industry. An important aspect of EFEU program is the co-operation between universities and equipment manufacturers to realize new systems-level results instead of just focusing on individual devices. As an example of research work in EFEU, this paper focuses on three research topics.

Variable-speed drives (VSD) have been identified to have one of the greatest potential for energy savings in various fields of industry as they allow energy efficient operation of fluid handling systems. As an example process, we present the pumping of a given amount of fluid between two tanks with the minimum energy consumption and fixed time. This process can also be a part of a larger system with in- and outflow from either tanks. The optimal control law for the pump rotational speed can be easily implemented in programmable VSDs.

Another case aims to assess the efficiency improvement potential in electric motors. We review the best available current technology and point out some weaknesses. We evaluate different future technologies according their cost and reliability and present our view of an ideal future motor for pump applications.

Finally, we present a case study from forest industry. In pulping process bales of pulp are broken down and mixed to produce a homogeneous water-fibre suspension. The rotor, which is responsible for breaking down bales, mixing the suspension, and cleaning the screen, has been redesigned based on CFD-simulations. We demonstrate considerable energy savings in this application.

These cases summarize the goals, results and also the future of EFEU project. Our new results provide control engineers appropriate tools to operate and control their processes and demonstrate considerable reduction in energy consumption in pulping process. The newly developed methods and equipment are set against the old ones to demonstrate the increased efficiency in each case.

Introduction

Fluid handling systems including pumps, fans and different kind of mixers are the most common end-use application for electric motors, making them a notable contributor to the global energy consumption [1]. As an example, single paper mill is operated with hundreds of electric motors driving pumps, fans, mixers, agitators and different kinds of conveyors with each one having power consumption in the range of tens to hundreds kilowatts (see Fig. 1). Operating costs are the single most important source of costs in fluid handling systems. Because of the high energy demand of fluid handling systems, small improvements in efficiency can lead to significant reduction of the life cycle costs [2]. Especially energy intensive equipment is found in forest industry for example in refining and pulping processes and in pumping of fiber suspensions.

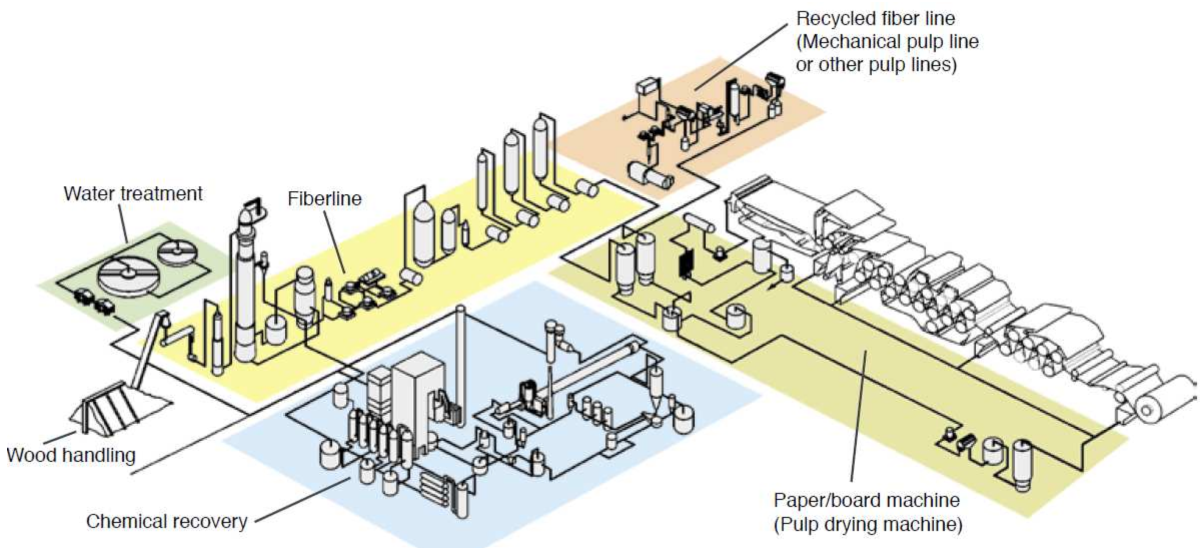


Fig. 1. End-use applications for electric motors in a paper mill [3].

Improvement of system component efficiencies and their variable-speed operation are key factors in energy efficient operation of systems, as the improved component efficiency should not be wasted by inefficient control method [4]−[5]. This kind of systems approach is one of the main ideas behind Efficient Energy Use (EFEU) program founded in 2011, which provides solutions for industry-level problems in energy efficiency in Finland [6]. Since its starting, EFEU project has provided means to design next-generation equipment, such as pumps, agitators and pulpers and to control fluid handling systems as energy efficiently as possible with the help of a variable-speed drive [7]. The conducted work is supported by the co-operation between universities and equipment manufacturers to realize new systems-level results instead of just focusing on individual devices, which is an important aspect of EFEU program.

The object of this paper is to introduce research results obtained in EFEU research program on three separate research topics (control of fluid handling systems; efficiency improvement potential in electric motors; efficiency improvements in pulpers). Since the research program is studying both the system components and their overall control, each case introduced in this paper is summarized with their expected energy savings potential. When possible, the effect of component efficiency improvement potential on total system energy efficiency is also analyzed with the concept of specific energy consumption E_s (kWh/m^3). Figure 2 shows how the improvement effect of component efficiency on the system E_s will gradually get lower, when the component efficiency is improved. For this reason, the focus of EFEU research program is set to the systems level and to the flow devices and their motors, which have the largest efficiency improvement potential available.

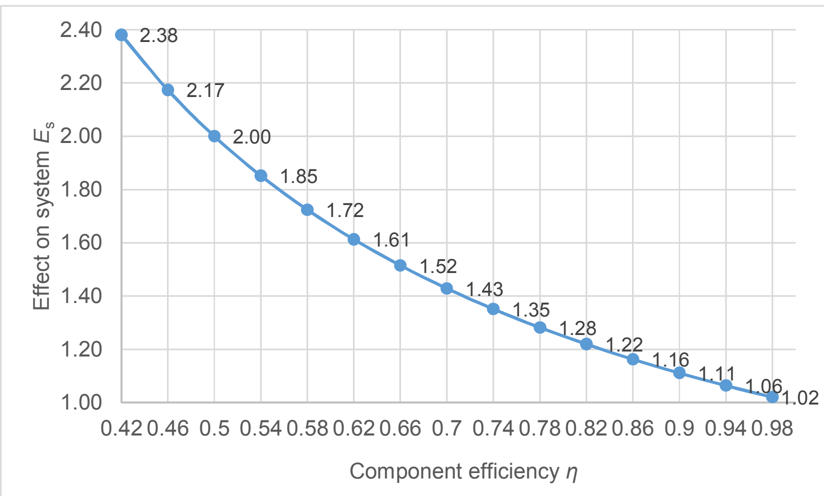


Fig. 2. Relative magnitude of system E_s as a function component efficiency η [4].

Energy efficiency improvement potential in electric motors

Fluid handling systems are most often operated with asynchronous induction motor (IM) which can be considered as the workhorse machine for the paper industry. Simple and mature construction of the induction motor combined with a rotor having short-circuited copper or aluminium bars makes this motor type cost-efficient and reliable. IM can also be driven with any frequency converter and it generally has good overall efficiency characteristics over the whole speed range, which is why the IM has been preferred option for driving a fluid handling system. Depending on their age and other selection criteria, induction motors currently operating in fluid handling systems mostly follow the IE efficiency classification in levels IE1 (previously known as EFF2 in Europe) and IE2 (previously known as EFF1). For a four-pole (1500 rpm), 15 kW motor these classes mean minimum efficiencies of 88.7 and 90.6 percent [8], see Fig. 3.

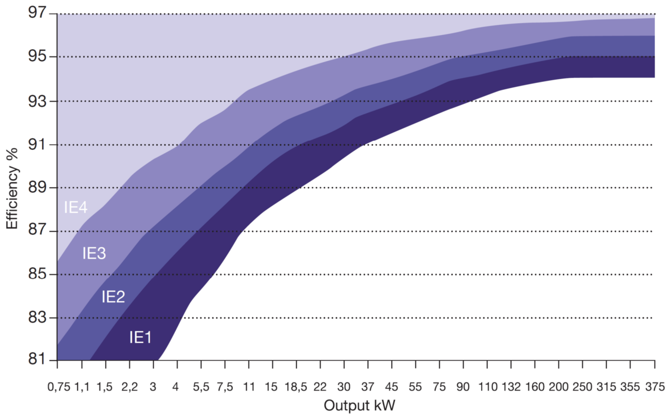


Fig. 3. International efficiency classes given for four-pole electric motors according to IEC standards IEC/EN 60034-30:2008 and IEC/TS 60034-31 [8].

Since the induction motor is neither the most efficient nor the most compact motor technology available nowadays [9], it gives room for the energy efficiency improvement in electric motors. Modern circulator pumps are a good example of energy efficient and integrated pumping systems, where permanent magnet synchronous motor (PMSM) is applied as the default motor technology. Compared to IM, permanent magnet motors have better power density due to the magnets in the rotor, so they can reach higher operating efficiency with more compact dimensions. As a practical example, first commercial PMSMs with IE5 level have been introduced in 2014 [10]. For the 15 kW four-pole motor, this would mean the minimum efficiency of over 94.3%.

Another higher-efficiency alternative for IM is the synchronous reluctance motor (SynRM) that can be considered as a combination of IM and PMSM. The advantage of basic SynRM is that it is cheap to manufacture as it only needs iron and copper. They are also available in IE4 efficiency level, meaning 93.9% motor efficiency with a VSD supply according to [11]. As downsides, SynRM requires a variable-speed drive for its operation and it has a small torque density and poor power factor which can be, however, improved by placing magnets in the flux barriers. Then, the machine is called PM-assisted SynRM (PMASynRM), which are also able to reach IE5 efficiency class in the power range of 1-15 kW [12].

When the above motor efficiency values are compared to E_s values shown in Fig. 2, one can see the relative E_s improvement potential to be around 0.1 units when the component efficiency is improved from 88% to 94%. A more detailed analysis on the energy saving potential with the motor efficiency improvement from IE3 to IE4 level was carried out in [13] for IE3 IM, IE4 SynRM and nearly IE5 PMSM by analyzing their measured efficiency maps. Results shown in Fig. 4 also illustrate the resulting pump operating points, when a Sulzer APP 31-100 centrifugal pump (1460 rpm, 47.5 l/s, 21.7 m and 12.9 kW as nominal operating values) was operated according to the standardized load profile for closed loop systems [10]. When efficiency maps are compared with each other, the efficiency benefit of PMSM seems clear with the motor efficiency of and over 92%. At all operating points, the motor efficiency improves with a graduation from IM to SynRM and from SynRM to PMSM.

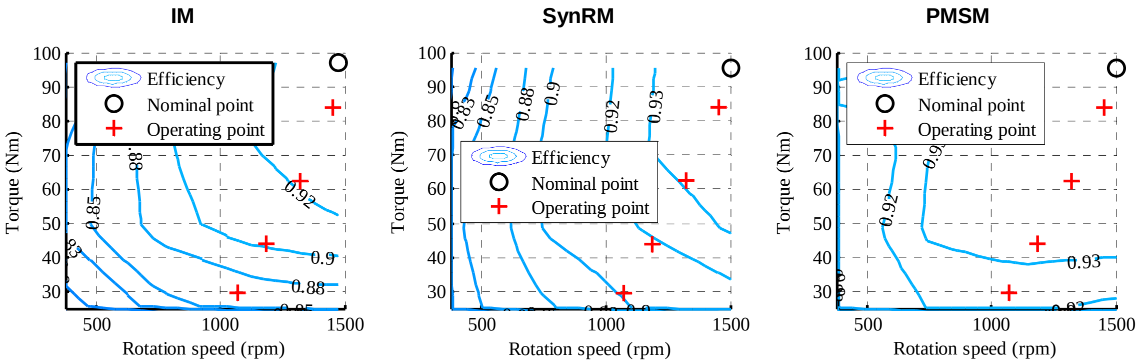


Fig. 4. The resulting pump operating points, when it is driven with an IM, SynRM and PMSM according to the load profile for closed loop systems.

The study was summarized by calculating annual energy consumption for the motor alternatives, which are given in Table 1. Compared with induction motor, the energy saving potential of SynRM and PMSM are in the range of 2 to 4%, as the studied motors have at least IE3 efficiency classification. When these values are converted to financial savings with 0.1 €/kWh electricity price, the resulting annual savings with the use of PMSM are around 200 € per single pumping system.

Table I. Energy consumption of the different motor types for the closed and open loop system loading profiles according to [13].

	IM	SynRM	PMSM
Closed loop system			
Annual energy consumption	54 987 kWh	53 659 kWh	52 886 kWh
Energy consumption compared with IM	100 %	97.8 %	96.4 %
Open loop system			
Annual energy consumption	58 771 kWh	57 521 kWh	56 779 kWh
Energy consumption compared with IM	100 %	98.0 %	95.8 %

If the comparison would have been carried out with IE1 or lower efficiency IM, the improvement potential would have been larger. Nevertheless, energy savings obtained with improved motor efficiency are clearly lower compared to the measured energy savings obtained with improved control of the system or with improved efficiency of the pump or pulper rotor.

Energy efficiency optimizing control methods

In reservoir pumping applications, for example in the process of Fig. 5a and in sewage pumping [14], a given amount of fluid is pumped from one reservoir to another. When the process time is flexible, the pumping process can be optimized quite freely with respect to the specific energy consumption, $E_s=E/V$, where E is the energy consumption and V is the total volume of fluid. A sensorless method to realize this E_s-based operation was described in [15]. In sensorless control, the operational point is determined based on the information retrieved from the VSD system and the estimate can be refined by combining the information from both VSD and system measurements [16].

Often the optimal pump control is limited by certain practical constraints such as a time limit and minimum and maximum flow rates recommended by the pump manufacturer. The energy-efficiency-based control of reservoir filling in [15] is also possible with time constraints as explained in [17]. An example is given below.

The energy consumption (E) and time (T) of a reservoir filling process can be defined as the following integrals:

$$E = \int_0^t E_s \mathrm{d}V \quad (1)$$

$$T = \int_0^t Q^{-1} \mathrm{d}V \quad (2)$$

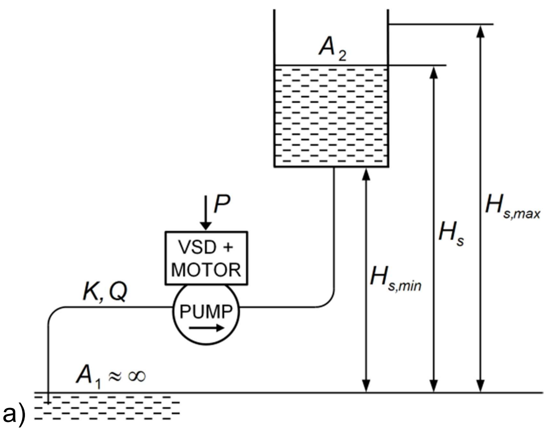
where Q is the flow rate (m3/s). During filling the tank in the process in Fig. 5a, the surface levels in the tanks change and the pump rotational speed must be constantly controlled so that E_s is minimal. However, when the time limit $T=T_0$ is imposed, the optimal operation cannot be found by a simple minimization procedure. By following the principles of the Calculus of variations, the following optimal control law can be derived for the rotational speed [17]:

$$\frac{dE_s}{dn} = C\frac{dQ^{-1}}{dn} \quad (3)$$

where C is a constant which depends on the process time limit. Equation (3) is applied as follows: the rotational speed is constantly changed in small steps dn and the changes dE_s and dQ^{-1} are monitored. Rotational speed is controlled such that Eq. (3) is satisfied. Few process runs are needed to find the correct value of C which corresponds to the desired process time.

As an example of the new control procedure, consider a process where a A_2=20 m^2 tank is filled with 240 m^3 of water. The initial and final static heads are $H_{s,init}$=2 m and $H_{s,final}$=14 m and the system curve is $H=H_s+9000Q^2$. The pump characteristics are shown in Fig. 5b. When we ignore the time limit and control according to the minimum specific energy, this process consumes 42.9 MJ energy and requires 11168 s to complete. However, with a time limit of T=9000 s, the process energy consumption is 45.7 MJ. Thus the process time can be reduced considerable with only a small increase in energy consumption. The optimal flow rate and head is shown in Fig. 6.

Energy saving potential of optimized control greatly depends on the surrounding system and set process requirements. Compared with constant speed operation of pumps at their nominal speed, optimization methods are able to decrease system energy consumption even by 30…40 %. Also compared to the use of best constant rotational speed for the reservoir emptying (or filling), which also requires the use of VSD, the method proposed in [7] for identifying the optimum speed profile could further decrease the energy consumption by some percentage units. Compared with energy savings potential in motor efficiency, these results underline the importance of good control for a fluid handling system.



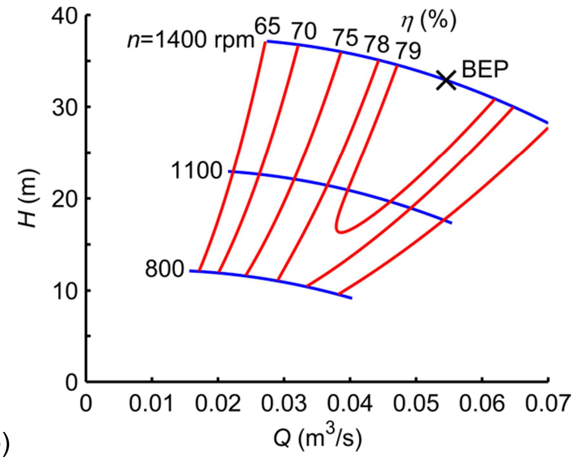


Fig. 5. Process layout (a) and pump characteristics (b) in the example.

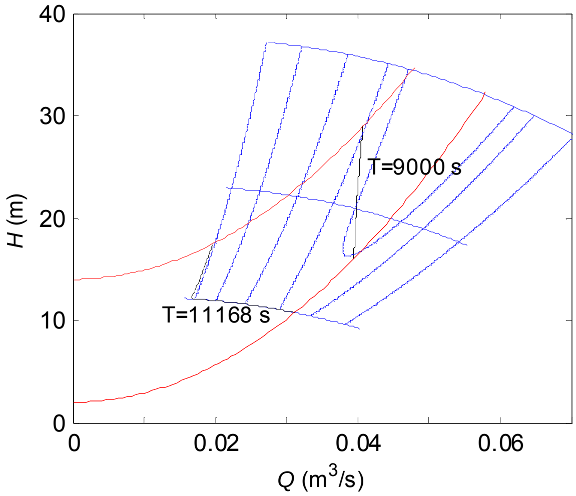


Fig. 6. Optimal operation in reservoir filling.

Energy efficiency improvements in pulpers

With reference to Fig. 1, in *Pulping process*, dry bales of pulp are mixed with water to produce a homogeneous water-fiber suspension. Bales are dropped into water filled tank, which is agitated by the rotor located at the bottom of the tank. The rotor is shown in Fig. 7. The process can run either in batch wise or in continuous mode. In batch operation bales of 250 kg are fed to the pulper, and process is run until the suspension becomes homogeneous. This process consumes 12-20 kWh of energy per ton of pulp.

The function of the rotor is three-fold: the rotor 1) agitates and mixes the suspension, 2) produces mechanical stresses sufficient to the break down bales and fiber bundles, and 3) clears the screen at the bottom of the tank shown in Fig. 7a. Because rotor is responsible for pumping, processing and screening, it must be carefully designed. At the project start up, the goal was to reduce the process energy consumption by 30 %. The design was constrained by the requirement that the quality of the produced pulp must remain the same.

New rotor was designed based on CFD analysis. Pulper flow fields were simulated using ANSYS CFX 14.5 software using water as a fluid. SST-k-omega turbulence model was used with the curvature and rotation correction terms. A steady state solution was calculated for a periodic computational domain consisting of one blade and its surroundings. The vat and rotor domains were connected with a frozen rotor interface with an appropriate pitch change.

Whereas the calculation of the energy consumption is straightforward with CFD, the calculation of the pulp quality is not. We thought of different criteria that could represent the quality. Fiber treatment is clearly proportional to the stresses and strains induced to them during the process. Also the high level of turbulence can indicate fiber bundle breakdown. Sufficient fiber treatment was guaranteed by requiring that the total shear force of the rotor blades was higher than in the original design.

The original and new rotors were tested at Valmet Fiber Technology Center (FTC) in Inkeroinen, Finland. Figure 8 shows the calculated and measured power versus rotational speed for the original rotor. The affinity law for pump power predicts that rotor power increases as the cube of rotational speed. This behavior was expected and also observed with the original rotor, see Fig. 8. Because of such a predictable behavior, we designed the new rotor by performing simulations only at 300 rpm. There is an unexplained 30 % difference between the measured and simulated power. We proceeded by ignoring the difference and assuming that the even though the absolute values are not correct, the changes in the design are predicted correctly. In other words, we assume that both the actual and simulated power consumption change in the same direction upon a change in the rotor geometry.

The results of preliminary test runs with the new rotor were promising. Even though power consumption of the redesigned rotor was practically the same as that of the original rotor, the intensity of the mechanical treatment was increased considerably and pulping could be carried with 50 % less time. Thus, with the same product quality, the energy consumption of the process could be reduced by 50 %. Fiber treatment was enhanced because flow velocities were generally higher in the new design which caused stronger impacts. The new rotor shape is also such that the area of impacts is larger. We estimate that further savings of 10 % might be possible by reducing the rotor's rotational speed. Research is being done to determine the rheological properties of water-fiber suspensions to be able to provide more accurate CFD predictions.

Fig. 7. Original rotor.

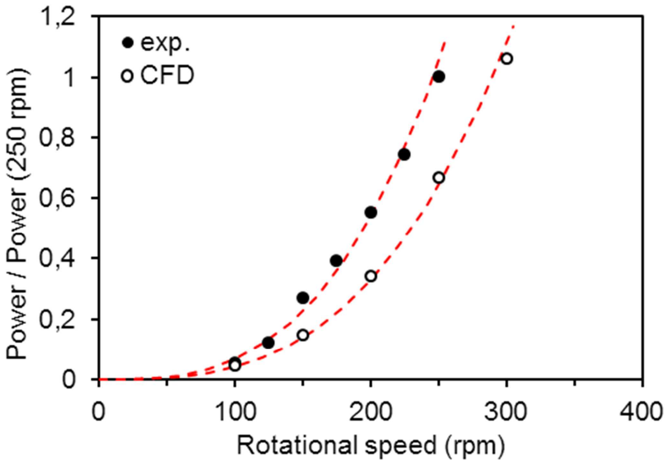


Fig. 8. Pulper power measured at Valmet FTC in Inkeroinen (exp.) and calculated with CFD (CFD). Dashed lines show cubic fitted curves.

Summary

The Finnish paper industry consumes a vast amount of energy in pumping fluids and in processing of fiber suspensions. EFEU project has focused on realizing energy efficiency improvement both in equipment and systems level. Pumping system consume up to 50 % of industrial energy consumption in industrial countries. With the use of optimal electrical motors, the energy consumption of pumping systems could be reduced approximately 2-4 %. Variable speed control can be applied for example in reservoir pumping application with approximately 30-40 % energy savings. We have demonstrated how the time constraint can be taken into account while energy consumption is minimized, which extends the applicability of energy minimizing speed control. The energy consumption of pulping process is 12-20 kWh/ton of pulp. New energy efficient pulper designed in this project consumes 50 % less energy than the old one. We estimate that further 10 % savings are possible using variable speed control also in this application.

Acknowledgments

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Motors 5

Measurement uncertainty of direct and indirect efficiency testing of induction machines

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Abstract

The paper is about uncertainty in the determination of losses and efficiency of air-cooled three-phase induction-motors according to the modified and improved procedures included in the 2nd edition of the international standard IEC 60034-2-1 [1]. A formal analysis is carried out to compare the spread of efficiency test values (reproducibility) obtained by direct measurements (input / output – method 2-1-1A) and by summation of losses with residual losses (indirect test – method 2-1-1B) of [1].

The analysis is based on the Monte Carlo method [2] assuming the worst possible measurement errors of all measurement instruments according to the requirements of the standard [1].

The analysis showed that the variation of the indirect test results is generally much lower compared to the direct test. The difference in accuracy increases for higher efficiencies. The currently defined tolerance of -15% of (1-η) for motors up to 150 kW and -10% above seems to be acceptable for indirect testing. It cannot be achieved with direct testing at the higher efficiency classes (IE3, IE4). There is certainly no room to reduce these tolerances in future editions of IEC 60034-1.

Introduction

Uncertainty in the determination of efficiency of high efficient electric motors has always been a challenge for industry and academia. Already decades ago, the International Electrotechnical Commission published the first edition of the standard IEC 34-2, which contained measurement procedures for losses and efficiency. Complementing the procedures was the allowed tolerance on efficiency of -15% (for machines up to and including 150 kW) or -10% (for larger machines) of (1 – η) as published in IEC 60034-1 [3].

This tolerance is designed to compensate two different factors of influence:

Firstly, tolerance must cover unavoidable variations in measurements when the test is repeated in different laboratories with different ambient conditions, different instrumentation and different personnel (reproducibility = inter-laboratory variability [4]).

Secondly, tolerance must cover production variability. A manufacturer cannot test every individual specimen of a mass production, which can easily run for many years and include thousands or even millions of pieces. Unavoidable variations due to changes in material properties (for example in the electric sheets) or changes in the production tools (for example the stamping tool) must be included in the allowed tolerance. Obviously, regular re-testing of current production samples will be required. However, according to IEC and CENELEC philosophy, it is the manufacturer's decision how to confirm the continuing quality of his production. Re-testing intervals and sample sizes are not specified in international motor standards.

In recent years IEC 34-2 has evolved to IEC 60034-2-1 edition 2.0 [1], which was released in 2014. Many technical changes have been introduced into the testing procedures. All are aimed at making efficiency testing more precise and improve repeatability and reproducibility.

This has raised the question in the relevant IEC working groups, if the tolerance of IEC 60034-1 could now be reduced.

For this purpose, an error analysis based on real world test data has been carried out to compare the direct measurement method (2-1-1A) with the indirect measurement method (summation of losses 2-1-1B) and to determine the spread of the efficiency test results (uncertainty).

The analysis is based on the Monte Carlo method [2]. Each individual measurement value is being altered randomly (even distribution) within a band of assumed measurement error based on the requirements for instrumentation given in IEC 60034-2-1. This random variation is then repeated one thousand times for each test motor. The individual results are recorded and presented as a histogram of possible test outcomes.

The direct measurement is a test method in which the mechanical power of a machine is determined by measurement of shaft torque and speed. A power analyzer measures electrical input power to the stator (voltage, current and phase angle). The ratio of output power over input power at full load gives the efficiency of the motor.

The summation of losses method is a test method in which the efficiency is determined by the summation of all individual loss components. In particular, iron losses, windage and friction losses, stator and rotor copper losses and additional load losses are determined. Since this method in principle does not need the determination of output power, its accuracy should be much better than a direct measurement, especially for motors with very high efficiencies above some 90%. However, output power testing is still required for the determination of additional load losses by residual losses and that compromises the quality of this test to some degree.

In real world scenarios, measurement errors should be lower than what has been found in the analysis presented in this paper. This is because measurement instruments are usually better than required by the standard. In particular, errors of torque measurement shafts are likely not randomly spread (as assumed in the following analysis) but consist instead of an offset error and a much smaller individual variation of the readings. Offset errors, however, are compensated by the determination procedure for the most part.

Variations of supply voltage, supply frequency and ambient temperature during the testing have not been taken into account in this analysis, as they are usually very small.

Requirements of instrumentation

It is assumed that all measurements are taken with digital instruments.

The IEC standard gives the following requirements for electrical quantities ([1], chapter 5.5.2): “The measuring instruments shall have the equivalent of an accuracy class of 0,2 in case of a direct test and 0,5 in case of an indirect test in accordance with IEC 60051. The measuring equipment shall reach an overall uncertainty of 0,2 % of reading at power factor 1,0 and shall include all errors of instrument transformers or transducers, if used.”.

The following analysis was therefore carried out under the assumption of a maximum deviation of 0,2% of the reading and no further errors based on the selected measurement range.

Torque measurement accuracy is assessed in chapter 5.5.3 [1]: “The instrumentation used to measure the torque shall have a minimum class of 0,2. The minimum torque measured shall be at least 10 % of the torque meter’s nominal torque. If a better class instrument is used, the allowed torque range can be extended accordingly.”

In the following analysis, a suitable torque meter was selected for each motor from following types: 10, 20, 50, 100, 200, 500, 1000 Nm. The measurement error was assumed to be distributed randomly with a maximum of 0,2% of the selected range.

As an alternative, the standard also allows testing by a dynamometer. Since this is an old technology rarely used in modern laboratories, it has not been analyzed further.

Speed and frequency measurements are defined in chapter 5.4.4 [1]: “The instrumentation used to measure supply frequency shall have an accuracy of ±0,1 % of full scale. The speed measurement should be accurate within 0,1 revolution per minute.”

Frequency is not used in the procedure. As stated above, a variation of frequency during the testing is not taken into account, as errors are likely very small.

Finally, the accuracy of temperature measurement is given in chapter 5.5.5 [1]: “The instrumentation used to measure temperatures shall have an accuracy of ±1 K.”

Test and motor data

In total, tests of ten different motors were available for analysis, see table 1.

Motor	Rated Power [kW]	Poles 2p	Frequency [1/s]	Efficiency [%]	IE-Class
1	0,37	2	50	77,20	IE3
2	2,2	4	50	88,57	IE3
3	15	4	50	93,10	IE3
4	30	4	50	94,94	IE4
5	37	2	50	94,78	IE4
6	45	2	50	94,56	IE3
7	45	4	50	95,62	IE4
8	110	4	50	96,33	IE4
9	290	4	50	95,96	IE3
10	315	4	50	96,47	IE3

Table 1: Summary of available test motor data and efficiency determined by the indirect test method

Selection of measurement ranges

Obviously, the selection of instrumentation and measurement ranges has a significant influence on measurement uncertainty.

As a basic approach, this paper assumes that all instruments to measure voltage, current, electrical power, electrical resistance and torque are available in steps of 1, 2, 5, 10, 20, 50, … of the measurement ranges. Table 2 summarizes the measurement ranges that were selected for the motors in the subsequent simulations.

In all cases, the smallest possible range was selected that would fulfill the requirements of all individual tests of the indirect testing method of IEC 60034-2-1 (in particular the heat-run and the 125% load test). It was assumed that these measurement ranges were unchanged during all tests (including the no-load tests) of each motor.

Motor	Rated Power [kW]	Meas. range used for power [kW]	Meas. range used for voltage [V]	Meas. range used for current [A]	Meas. range used for resistance [Ohms]	Meas. range used for torque [Nm]
1	0,37	1	500	2	50	2
2	2,2	5	500	10	5	20
3	15	50	500	50	0,5	200
4	30	50	500	100	0,2	500
5	37	50	500	100	0,1	200
6	45	100	500	200	0,1	200
7	45	100	500	200	0,1	500
8	110	200	500	500	0,05	2000
9	290	500	500	1000	0,05	2000
10	315	500	500	1000	0,01	5000

Table 2: Summary of measurement ranges used in the following simulations

It is further assumed that temperature measurement is accurate to 1 K, speed measurement is accurate to 0,1 /min and frequency measurement is accurate to 0,1% in accordance with the requirements of IEC 60034-2-1 (see previous chapter).

In real testing laboratories, in particular the expensive torque meters may not be available in such fine granularity. The impact of measurements with oversized torque meters and oversized current sensors will be discussed in a separate chapter of this paper.

Correction to reference ambient temperature

The indirectly determined efficiency value can be corrected to an ambient cooling temperature of 25 °C. The procedure is described in chapter 5.7.3 [1]. However, this is not a normative requirement: “When required, the winding resistance values … shall be referred to a standard reference temperature of 25 °C.”. In the following analysis, an ambient temperature correction of the indirect test was always performed.

The direct test is described in chapter 6.1.2 [1] and does not contain an ambient temperature correction.

However, such a correction has been proposed in IEC TC2 working group 28, which is responsible for this standard. The correction is based on temperature measurements before and after the load test. The electrical input power will be corrected by differences in stator and rotor losses based on the variation of resistance with temperature. Other influence factors (for example changing of the friction losses with temperature) cannot be compensated.

The following analysis will therefore present three results: Indirectly determined efficiencies corrected to an ambient of 25 °C, directly determined efficiencies at an assumed ambient temperature of 20 °C and directly determined efficiencies corrected to 25 °C. Obviously, greater deviation from 25 °C will result in greater compensations. However, operation of a testing field below 20 °C or above 30 °C is rather uncommon and should be avoided anyhow.

Results

This chapter presents the so-called *expanded uncertainty* of the determined efficiency of the ten test motors. Expanded uncertainty is the "*confidence interval, which allows to calculate the minimum and maximum value where average measured result may be found when the measurement is re-done at any other laboratory following the reproducibility conditions*" [4], which are defined in IEC 60034-2-1 [1]. Reproducibility is also given as standard deviation.

Motor number 10 has the highest efficiency and is therefore the most critical in testing.

The results of 1000 simulated indirect tests are shown in figure 1.

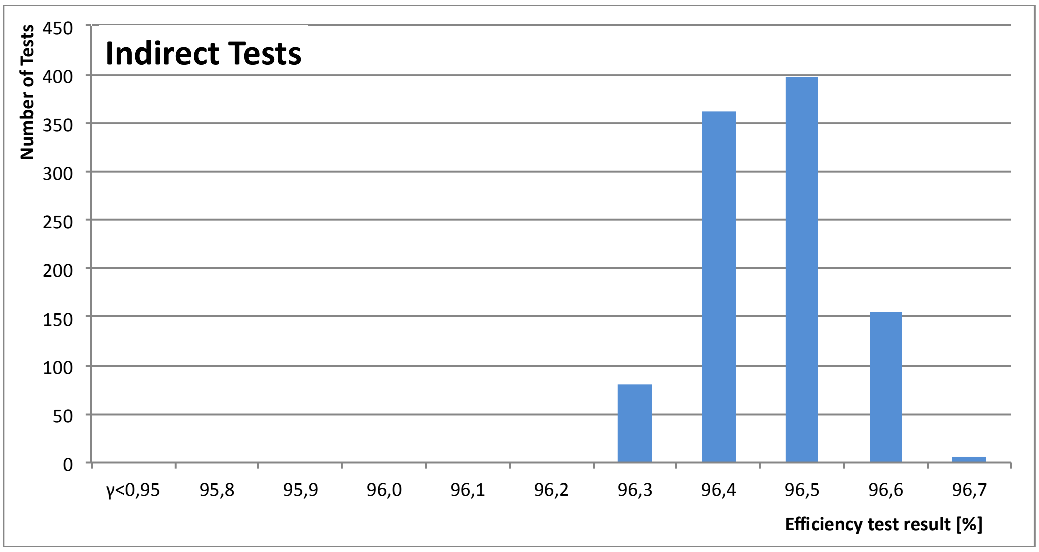

Figure 1: Spread of efficiency test results based on 1000 simulated measurement runs of motor number 10 – indirect tests

The average efficiency of all tests is 96,46 %. The single lowest obtained result was 96,29 %, which is equivalent to a tolerance of -5,2 % relative to the average value.

IEC 60034-1 [3] permits a tolerance band of -15% of (1-η) for motors up to and including 150 kW output power and -10% above.

The single highest result was 96,74 %, which is related to a tolerance of +7,6 %.

In a worst case scenario, the manufacturer might measure and declare 96,74% on the rating plate while a check-test performed in an independent testing laboratory might measure 96,29 %. This is would compute to a tolerance of -13,8%, which is very close to the allowance of -15%.

The results of the direct tests (with and without temperature correction) of the same motor can be found in figure 2.

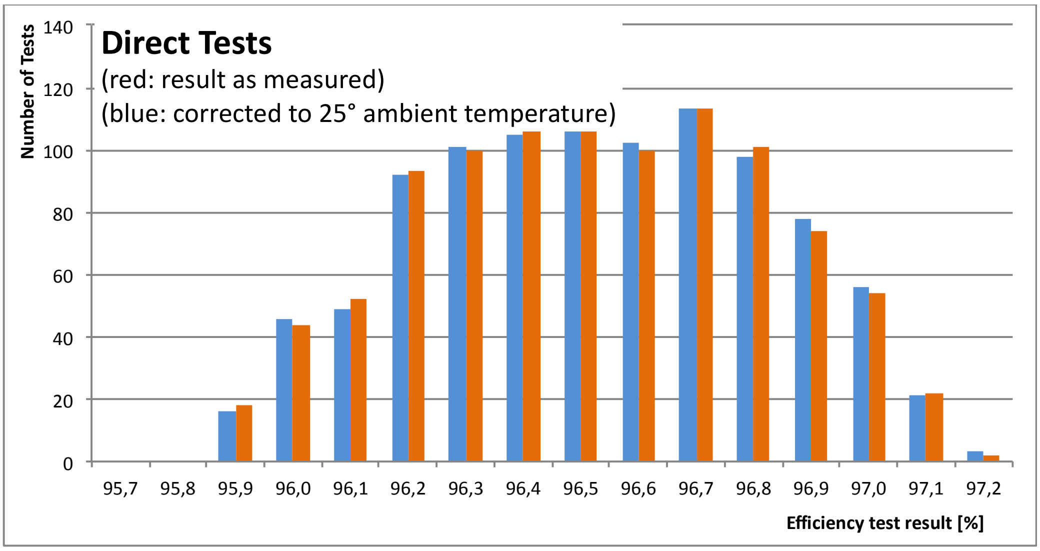

Figure 2: Spread of efficiency test results based on 1000 simulated measurement runs of motor number 10 – direct tests

Not surprisingly, the direct tests show a much larger spread of results. The average was 96,52%. The single lowest value was at 95,88%, which is equivalent to a tolerance of -18,0% relative to the average value, which is significantly above the allowed tolerance.

Table 3 and figure 3 summarize the findings of all ten motors.

Motor No.	Indirect Efficiency Test			Direct Efficiency Test			Direct Efficiency Test at 25°C		
	Aver-age %	Low-est %	Toler-ance % of (1-η)	Ave-rage %	Low-est %	Toler-ance % of (1-η)	Ave-rage %	Low-est %	Toler-ance % of (1-η)
1	77,20	76,96	-1,1	77,88	77,51	-1,7	77,73	77,35	-1,7
2	88,57	88,37	-1,7	87,97	87,56	-3,4	87,86	87,44	-3,5
3	93,09	92,90	-2,8	93,00	92,46	-7,8	92,94	92,42	-7,6
4	94,93	94,68	-5,2	94,64	94,01	-11,8	94,65	94,02	-11,8
5	94,78	94,58	-3,9	94,48	94,00	-8,7	94,46	93,98	-8,7
6	94,56	94,37	-3,6	94,36	93,95	-7,2	94,34	93,93	-7,3
7	95,62	95,45	-3,9	95,25	94,76	-10,4	95,23	94,74	-10,4
8	96,32	96,13	-5,4	96,25	95,53	-19,1	96,25	95,52	-19,2
9	95,90	95,70	-6,3	95,77	95,39	-8,8	95,76	95,38	-8,9
10	96,47	96,27	-5,6	96,49	95,88	-18,1	96,49	95,88	-18,2

Table 3: Summary of the test results based on 1000 simulated measurement runs each

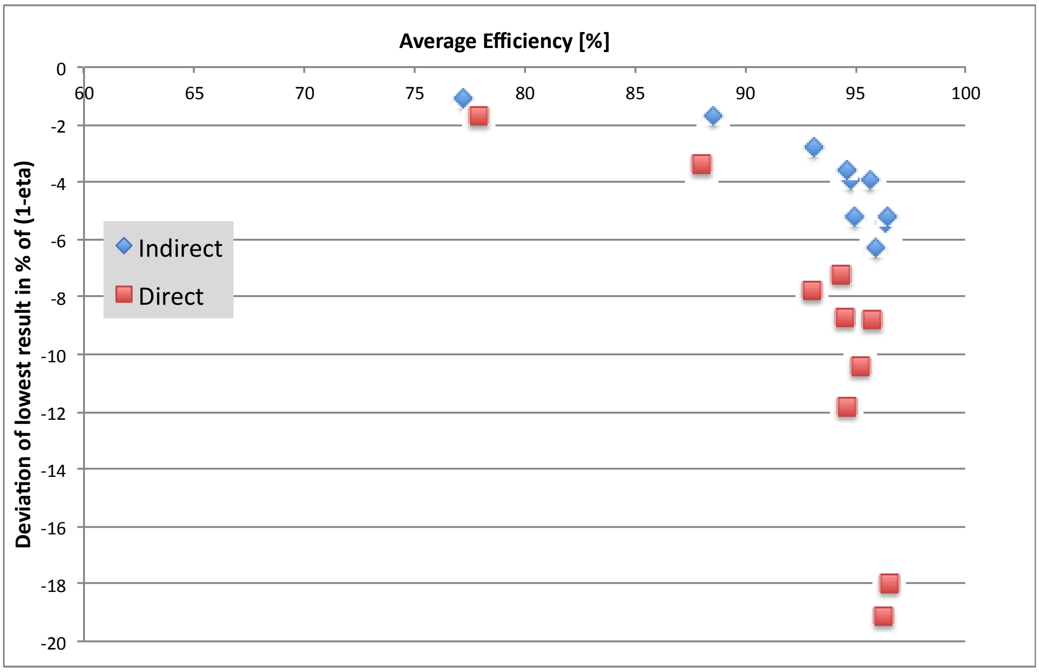

Figure 3: Deviation of the lowest result of indirect and direct testing from the average of 1000 tests in percentage of (1-η).

The results clearly indicate that the uncertainty of the direct test is much higher than that of the direct test in general. Also, there is an obvious (and expected) tendency to higher uncertainty associated with higher efficiency.

It is generally accepted that about half of the tolerance of IEC 60034-1 (i.e. -7,5% of (1-η) up to 150 kW and -5% above) should be available for variations of material and process during mass production while the other half is available for measurement uncertainty.

Figure 3 shows in particular for the high power /high efficiency motor range that a tolerance of -5% may not always be enough to compensate measurement uncertainty.

The current practice of IEC 60034-1 of allowing a lower tolerance on higher-powered motors having better efficiencies is very questionable.

Instrumentation with oversized measurement ranges

Due to cost constraints, torque meters and current sensors may not always be available in fine granularity in all laboratories.

The following tables 4 and 5 show the increase in measurement uncertainty when these devices are oversized by one step. For example, a torque meter of 20 Nm would be used where 10 Nm would suffice or a current meter of 100 A would be used where 50 A would suffice.

Motor No.	Indirect Efficiency Test			Direct Efficiency Test			Direct Efficiency Test at 25°C		
	Aver-age %	Low-est %	Toler-ance % of (1-η)	Ave-rage %	Low-est %	Toler-ance % of (1-η)	Ave-rage %	Low-est %	Toler-ance % of (1-η)
1	77,2	76,9	-1,3	77,87	77,14	-3,3	77,73	76,97	-3,4
2	88,57	88,37	-1,8	87,96	87,21	-6,3	87,86	87,1	-6,3
3	93,09	92,89	-2,9	93,03	91,9	-15,8	92,97	91,84	-15,9
4	94,93	94,69	-5	94,67	93,49	-21,5	94,67	93,49	-21,6
5	94,78	94,59	-3,6	94,47	93,53	-17,3	94,45	93,5	-17,3
6	94,56	94,36	-3,6	94,34	93,55	-14,3	94,33	93,54	-14,2
7	95,62	95,44	-4,3	95,25	94,43	-17,4	95,23	94,41	-17,3
8	96,32	96,14	-5,1	96,27	94,74	-40,2	96,26	94,74	-40,1
9	95,9	95,7	-6,4	95,78	95,07	-16,3	95,76	95,06	-16,4
10	96,47	96,25	-6,2	96,51	95,4	-31,8	96,51	95,4	-32

Table 4: Summary of the test results based on 1000 simulated measurement runs each; Torque meter oversized by one step compared to tables 2 and 3.

Motor No.	Indirect Efficiency Test			Direct Efficiency Test			Direct Efficiency Test at 25°C		
	Aver-age %	Low-est %	Toler-ance % of (1-η)	Ave-rage %	Low-est %	Toler-ance % of (1-η)	Ave-rage %	Low-est %	Toler-ance % of (1-η)
1	77,21	76,92	-1,3	77,88	77,49	-1,7	77,74	77,32	-1,8
2	88,57	88,36	-1,9	87,97	87,55	-3,5	87,86	87,44	-3,5
3	93,1	92,9	-2,8	93,02	92,47	-7,7	92,97	92,42	-7,6
4	94,93	94,69	-4,9	94,61	93,97	-12,5	94,62	93,97	-12,7
5	94,78	94,54	-4,5	94,47	94	-8,7	94,45	93,98	-8,6
6	94,56	94,34	-4	94,34	93,92	-7,8	94,32	93,9	-7,7
7	95,62	95,45	-4	95,24	94,76	-10,3	95,23	94,74	-10,4
8	96,32	96,15	-4,8	96,24	95,53	-19,1	96,23	95,52	-19,2
9	95,91	95,69	-6,7	95,76	95,38	-9,1	95,75	95,37	-9,1
10	96,46	96,29	-5,2	96,51	95,85	-18,8	96,51	95,86	-18,7

Table 5: Summary of the test results based on 1000 simulated measurement runs each; Current meter oversized by one step compared to tables 2 and 3.

Some interesting conclusions can be drawn from these tables:

An oversized torque meter and its associated increase in measurement error have almost no effect on indirect test results. The effect on direct test results, however, is dramatic. Even an increase by just one step practically doubles the measurement uncertainty.

An oversized current sensor and its associated increase in measurement error have a very small influence on the accuracy of the indirect or the direct tests.

It is commonly assumed among experts that real world torque meters behave better than in this simulation, which uses random errors. Oversizing should mainly lead to additional offset errors, which would be mostly compensated by the testing methods of IEC 60034-2-1. Linearity errors, which cannot be compensated, should increase much less.

Summary

The paper analyzed indirect and direct efficiency testing of several three-phase cage-induction motors with the direct (2-1-1A) and indirect (2-1-1B) procedures contained in the new edition of IEC 60034-2-1 [1].

When using measurement instruments according to the requirements of the standard, the spread between the average and the lowest indirectly determined efficiency was up to about half of the available tolerance (-15 % / -10% of (1- η) depending on motor output power according to [3]).

Even though the tolerance leaves room for product variation in mass production (variations in electric sheet quality etc.) there is no margin to reduce the tolerance in future editions of the standard.

It was found that the determination of efficiency of higher efficient motors (IE4) is associated with considerable higher uncertainty. It may therefore be reasonable to increase the tolerance for IE4 motors and lower it for IE1 and IE2 motors.

The influence of output power on measurement uncertainty is reflected in the higher efficiency normally associated with larger motors. The current setup of tolerances in IEC 60034-1, where motors of higher output power have a lower allowance, seems to be questionable.

The direct tests generally showed a much larger spread of the results, often exceeding the available tolerance by far. Direct testing is therefore not recommended for the determination of efficiency of induction motors.

The indirect test is stable against increased torque and current measurement error. The application of oversized torque meters in testing laboratories seems to be acceptable. In case of direct testing, however, the accuracy of the torque meter plays a very dominant role and the smallest and most accurate torque meter must always be selected for the test.

References

[1] IEC 60034-2-1 (ed. 2.0): 2014-06; "*Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)*"

[2] Doppelbauer, M.; "*Accuracy of the determination of losses and energy efficiency of induction motors by the indirect test procedure*"; EEMODS'11 Conference – Energy Efficiency in Motor Driven Systems; 12-14 September 2011; Alexandria (VA), USA

[3] IEC 60034-1 (ed. 12.0): 2010-02; "*Rotating electrical machines – Part 1: Rating and performance*"

[4] CEN/CENELEC ECO-CG N 087; "*Draft guide to assess measurement uncertainties for products and services under the Ecodesign Directive 2009/125/EU*"; Eco-design Coordination Group; 2015-01-06

Evaluation of a new high efficiency motor and drive solution for current and emerging applications

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Abstract

In the United States, about 90 million electric motors are in use, out of which approximately 40 million are in the commercial and industrial sectors [1]. The U.S. Department of Energy (DOE) has estimated that electric motor-driven systems consume about 23% of all energy produced in the United States [2]. Globally, these numbers are even more significant. Worldwide, electric motor-driven systems are the largest consumers of energy, consuming about 43-46% of all energy sold [3]. Thus electric motors play a significant role not only in industrial by other sectors as well. This paper presents the results from an U.S. laboratory evaluation of a high efficiency motor technology, namely, synchronous reluctance motor and drive system. The laboratory testing answers key research questions such as:

• What is the operating principle of the technology?

• What are the customer benefits?

• What are the current and new applications?

• Can this technology qualify for electric utility rebates?

The U.S. laboratory test results showed that the synchronous reluctance motor and drive system has significant energy efficiency improvements over the traditional or super premium induction motor. A holistic approach was taken during the testing, so the efficiency of the motor and drive as a system was computed. The results of the efficiency test are presented in this paper. A theoretical attempt has been made to compare the new motor and drive system efficiency against an adjustable speed drive and induction motor system efficiency.

Background

Electric motors have been around for over 100 years. Until the end of the 20th century electric motor demand was primarily driven by the demand from industrial sector. The AC induction motor was and continues to be the workhorse in many industrial, commercial, as well as residential applications. Historically, horsepower (HP) and torque have been the driving criteria for selecting an electric motor. However, the present decade has seen the growth of a number of new age technologies. These new technologies include electric vehicles, variable speed air conditioning and refrigeration, and multi-functional portable appliances (washers, dryers, power tools, and so on). This coupled with rising demand for electricity have altered the technical requirements for electric motors. As a result, in addition to the traditional HP and torque requirements, new driving factors have emerged as criteria for selecting an electric motor for a particular application, namely efficiency across a wide torque and speed range, control, power density, volume, and weight.

Due to the large number of motor-driven systems in use, energy savings potentials in motor driven systems are large. According to DOE estimates, potential industrial motor system energy savings, using mature, proven, cost-effective technologies range from 11-18 percent of current annual usage or 62 to 104 billion kWh per year in the manufacturing sector alone [4]. The motor-driven systems have been the focus of standards and policy making aimed at improving motor energy efficiency.

While the AC induction motor continues to improve in efficiency, new motor technologies are rapidly emerging that can provide a viable alternative to the induction motor, providing higher power/torque densities, and higher efficiency over a wide torque/speed range. With the introduction of new technologies, the electric motor industry is seeing resurgence. Several promising motor technologies have recently emerged. One such promising technology is the Synchronous Motor or SynRM motor technology. This report provides the results from the laboratory testing and its implications in real world applications and how this results could be utilized by electric utilities.

Operating Principles

The invention of the synchronous reluctance motor concept dates back to 1923. However, the motor type was not industrially adapted primarily due to the lack of a direct online starting capability. Now, with the use of new generations of variable speed controllers this problem has been addressed.

The rotor of a synchronous reluctance motor runs in synchronism with the applied stator vector field, striving to minimize reluctance in the magnetic circuit, hence the name synchronous reluctance. The torque produced by the motor is proportional to the difference between the inductances on the d- and q-axes: the greater this difference, the greater the torque production. The synchronous reluctance motor is therefore designed with magnetically conductive material, iron, in the d-axis and magnetically insulating material, air, in the q-axis.

Magnetic reluctance is the magnetic equivalent of the resistance in electrical circuits. The rotor consists of one direction of least possible magnetic reluctance (or equivalent resistance) (d) and a perpendicular direction (q) with a high magnetic reluctance or good magnetic “insulation”. The current in the stator cause a Torque to be produced, as the rotor attempts to align the magnetically conducting direction to the stator field. The strength of the produced torque is directly related to the saliency ratio, i.e. the inductance ratio between the two magnetic directions of the rotor. This is shown in Figure 2. Figure 3 shows the cross-sectional view of the SynRM motor [5].

In Synchronous reluctance motors, the stator construction is identical to the induction motor with no salient poles. Figure 1 shows the single laminate of the SynRM motor and the rotor of a switched

Figure 1 Single Laminate of the Synchronous Reluctance Motor

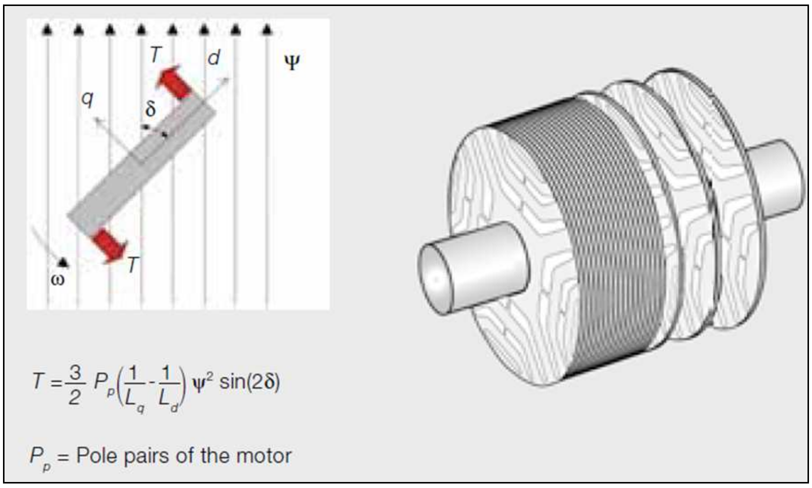

Figure 2 Rotor (Right) and Torque (Left) in a Synchronous Motor

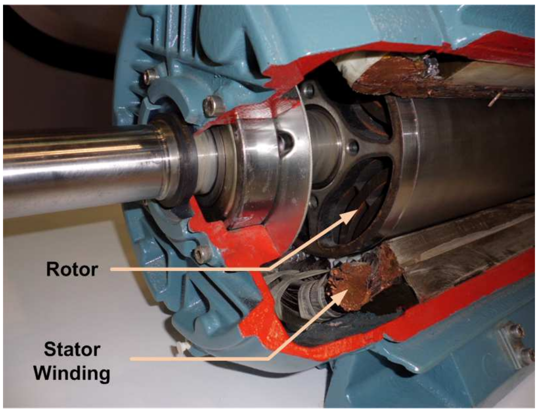

Figure 3 Cross-sectional View of the Synchronous Reluctance Motor

Test Setup Description

The objectives of the laboratory tests are listed below:

1. To validate manufacturer's statements such as efficiency, speed (rpm), temperature at rated power (or torque) of the motor
2. To perform the efficiency analysis for the whole motor and drive system – a holistic approach
3. To perform power quality analysis to look at input power quality characteristics of the system
4. To verify non-energy benefits of the motors such as reduced operational noise and lower bearing temperature
5. To determine applications for this new and emerging motor technology for U.S. markets

The SynRM motor was originally configured for European operational voltage and frequency, namely, 400Vac and 50Hz. However, it was found that the motor could be powered at U.S. operating voltage and frequency of 460Vac and 60Hz and therefore the tests were conducted at U.S. operating conditions. The schematics of the test setup is shown in Figure 4. One important thing to notice is that the SynRM motor does not operate alone, it requires an adjustable speed drive to run. Hence as shown in the figure below, the SynRM motor and the adjustable speed drive are connected to the three phase AC power supply. The motor is then connected to the DC brake load via the motor shaft. The brake load provides an opposing torque proportional to the dc voltage supplied to the field winding. This is used to vary the loading of the motor and drive system. The torque and speed sensor is connected at the shaft coupling which provides the torque and speed signal to the power analyzer. The Yokogawa WT2030, used with this test setup, is a power analyzer capable of monitoring ac input power (electrical) and the output shaft power (mechanical) and calculate efficiency of the overall motor and drive system. A Hioki 3196 power quality (PQ) meter is attached to the input of the drive to monitor the power factor, voltage and current harmonics of the system.

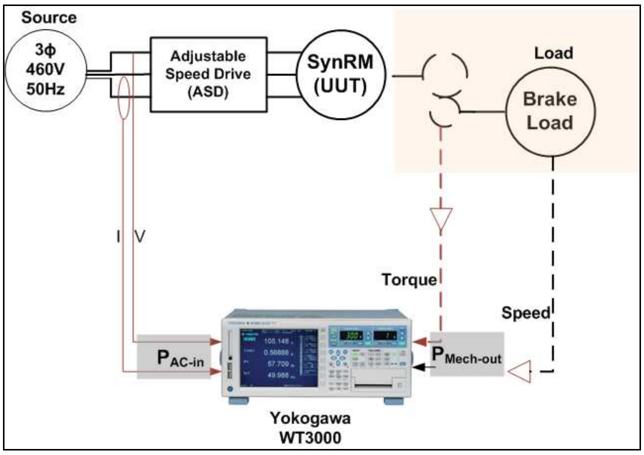

Figure 4 Schematics of Laboratory Test Setup

Energy Efficiency Measurements

Traditionally the efficiency measurements were calculated only for the motor under test, based on ac input power to motor and mechanical output power delivered by the motor. However for the test that was performed at the laboratory, the overall system efficiency was calculated, which is given by Eq. 2-1.

$$System\ Efficiency\ (\eta) = \frac{Mechanical\ Power\ Output\ of\ the\ SynRM\ Motor}{Electrical\ Power\ Input\ to\ the\ ASD} \qquad \text{Equation 0-1}$$

Mechanical power output is calculated my measuring the torque (τ) and angular speed (ω). The unit of torque is Nm and that of angular speed is radians. To calculate the mechanical horsepower output in Watts from torque (Nm) and speed (rpm) the following equation (Eq. 2-2) is used. The electrical input power is measured by the meter using Eq. 2-3 where V_L is the line-line voltage, I_L is the line current and the power factor is given by Cosθ.

$$P_{mechanical}(W) = \frac{\tau(N.m) * 2\pi * n\ (rpm)}{60} \qquad \text{Equation 0-2}$$

$$P_{electrical}\ (W) = \sqrt{3} V_L I_L Cos\theta = 3 V_{Ph} I_{Ph} Cos\theta \qquad \text{Equation 0-3}$$

The overall system efficiency is then calculated by simply dividing Eq. 2-2 by Eq. 2-3. The load of the motor was varied from 25% to 100% of the rated horsepower in increments of 25%. The system efficiency is calculated at each loading point of the motor to develop an efficiency vs. load curve.

Power Quality Measurements

Adjustable speed drives (ASDs) like any other nonlinear load are a potential source of harmonics in the electrical system. The harmonic current injected by an ASD in the system causes voltage distortion. Both the harmonic current and the resulting voltage distortion can cause potential problems. Possible symptoms of ASD harmonic related problems are fuse blowing in facility power-factor-correction capacitor banks, overheating of transformers and cables, and in some cases the interference with the operation of other equipment that requires a stable sinusoidal voltage waveform for operation. However, the end user needs to realize that just the presence of harmonics does not necessarily mean that there is a problem. Harmonics only means trouble if the power system is not designed to handle them. Even some voltage distortion below 8% THD at the point of utilization is acceptable as long as sensitive equipment is not affected. During the lab testing a Hioki 3196 power quality meter, capable of capturing harmonic content of voltage and current waveforms, is connected to the input of the ASD and the input current and voltage waveforms are monitored at various load conditions.

Noise Measurements

The audible noise generated by motors can sometimes be loud and may cause noise pollution inside commercial and industrial facilities. For the scope of this testing, the electric noise or the electromagnetic radiation noise is not considered. An Exetech HD600 was used to measure and monitor the noise levels generated during the motor testing at various loads. IEC 60034-9 defines the noise limits for rotating electrical machines. The standard specifies test methods for determination of sound power level of rotating electric machines. Also it specified a maximum A-weighted sound power levels for factory acceptance testing. According to the standard, for speed less than 1900 rpm and power less than 22 kW the maximum A-weighted sound power level in DB at no load is 94dBA (refer to Table-1 in IEC 60034-9). At rated load the maximum allowable noise level in dB is 98dBA. The results were compared against the IEC 60034-9 standard.

Rotor Bearing Temperature Rise Measurement

Typical induction motors running at rated load operate at higher temperatures and this is reflected in the bearing temperature rise. According to NEMA and IEC standards, the allowable temperature rise at full load is defined for each class (refer to Table 2 1). The induction motors typically operate at Class F level and the allowable temperate rise on 105^{o}F. The test was conducted with a thermal camera by FLIR, model E60.

Table 1 Standard NEMA Insulation Systems Classified by Maximum Allowable Operating Temperature

Temperature Tolerance Class	Maximum Temperature Allowed		Allowable Temperature Rise at Full Load (motor service factor 1)	
	°C	°F	°C	°F
A	105	221	60	140
B	130	266	80	176
F	155	311	105	221
H	180	356	125	257

Results from the Efficiency Testing

Energy Efficiency Test Results

In energy efficiency testing, typically the efficiency of the motor will be discussed and documented. However, in this paper a holistic system approach was considered and hence the efficiency of the overall motor and drive system was measured. According to the manufacturer, the SynRM and Drive system efficiency of the 18.5 kW motor with 1800 rpm (nominal) is 91.9%. When tested, the efficiency of the SynRM motor and drive system was able to exceed this by 1% to reach 92.9% at rated full load condition. However, the maximum efficiency was attained at 75% motor load which corresponds to 93.6% efficiency (Figure 5). Having a system efficiency of 93.6% is significant because it is the product of motor efficiency and drive efficiency and not just motor or drive efficiency. For example, in **Error! Reference source not found.**, below the system efficiency is given by Eq. 3-1 [6].

$$\eta_{SYSTEM} = \eta_{ASD} \times \eta_{motor} \qquad \text{Equation 0-1}$$

If the system efficiency has to be 93.6% at 75% load, then one possible combination of the ASD and motor efficiency could be 96.74%, respectively(since 96.74% x 96.74% = 93.59%). In real world, induction motors don't have that high efficiencies at even full load conditions. For example, even an 18.5kW induction motor (IE4 – Super premium efficiency) at full load has an efficiency of 94.2%. Assuming a high efficiency for ASD and motor, say 93% each at 75% load, the system efficiency would be 86.49%. Hence, the higher system efficiency (greater than 91%) at greater than 50% loading demonstrates significant energy savings in real world applications.

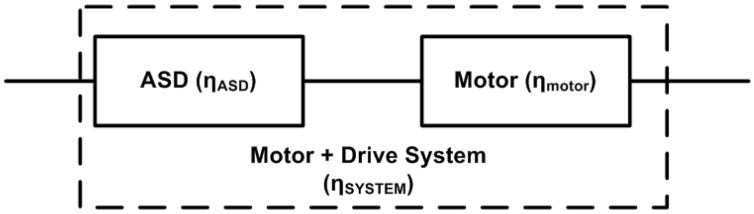

Figure 5 Representation of System Efficiency

Table 2 summarizes the results for 10%, 50%, 75% and 100 % load conditions.

Table 2 Summary Table of Energy Efficiency Test Results

Summary of Efficiency Test Results SynRM Motor and Drive System			
10% Load			
U (V)	463.24	Torque (Nm)	10.83
I (A)	4.06	Speed (rpm)	1755
P (kW)	2.35		
S (kVA)	3.26	Output Power (kW):	1.99
Q (kVAR)	2.25	Input Power (kW):	2.35
Cos θ (PF)	0.72	**Efficiency (%):**	84.7%
50% Load			
U (V)	462.94	Torque (Nm)	43.56
I (A)	17.09	Speed (rpm)	1755
P (kW)	8.77		
S (kVA)	10.08	Output Power (kW):	8.01
Q (kVAR)	4.95	Input Power (kW):	8.77
Cos θ (PF)	0.87	**Efficiency (%):**	**91.3%**
75% Load			
U (V)	463.72	Torque (Nm)	77.46
I (A)	20.49	Speed (rpm)	1755
P (kW)	15.22		
S (kVA)	16.45	Output Power (kW):	14.24
Q (kVAR)	6.24	Input Power (kW):	15.22
Cos θ (PF)	0.93	**Efficiency (%):**	**93.6%**
100% Load			
U (V)	464.69	Torque (Nm)	103.09
I (A)	27.01	Speed (rpm)	1755
P (kW)	20.40		
S (kVA)	21.74	Output Power (kW):	18.95
Q (kVAR)	7.49	Input Power (kW):	20.40
Cos θ (PF)	0.94	**Efficiency (%):**	**92.9%**

As a theoretical exercise to compute the energy efficiency of a motor and drive system with traditional induction motor, let us consider the part load efficiencies of a similar size motor as given in Table 3 [7]. The overall system efficiency is calculated as per Eq. 3-1. This overall efficiency is then plotted against the results of SynRM and drive system, as shown in Figure 6. It can be seen that the SynRM motor and drive efficiency is higher than the traditional induction motor and drive pair over the entire load range.

Figure 6 shows two curves, one is the overall system efficiency of the SynRM and drive pair and the other curve is the overall system efficiency of the traditional induction motor and drive pair of similar size. The efficiency curves for induction motor and drive system is shown here for illustration purpose only; actual test was not conducted for this pair.

Table 3 Theoretical Part Load Efficiencies of a Traditional Induction Motor and an Adjustable Speed Drive

System Load	Induction Motor Efficiency	ASD (Drive) Efficiency	Overall System Efficiency
10%	45.0%	75%	34%
50%	90.9%	90%	82%
75%	91.0%	92%	84%
100%	89.7%	91%	82%

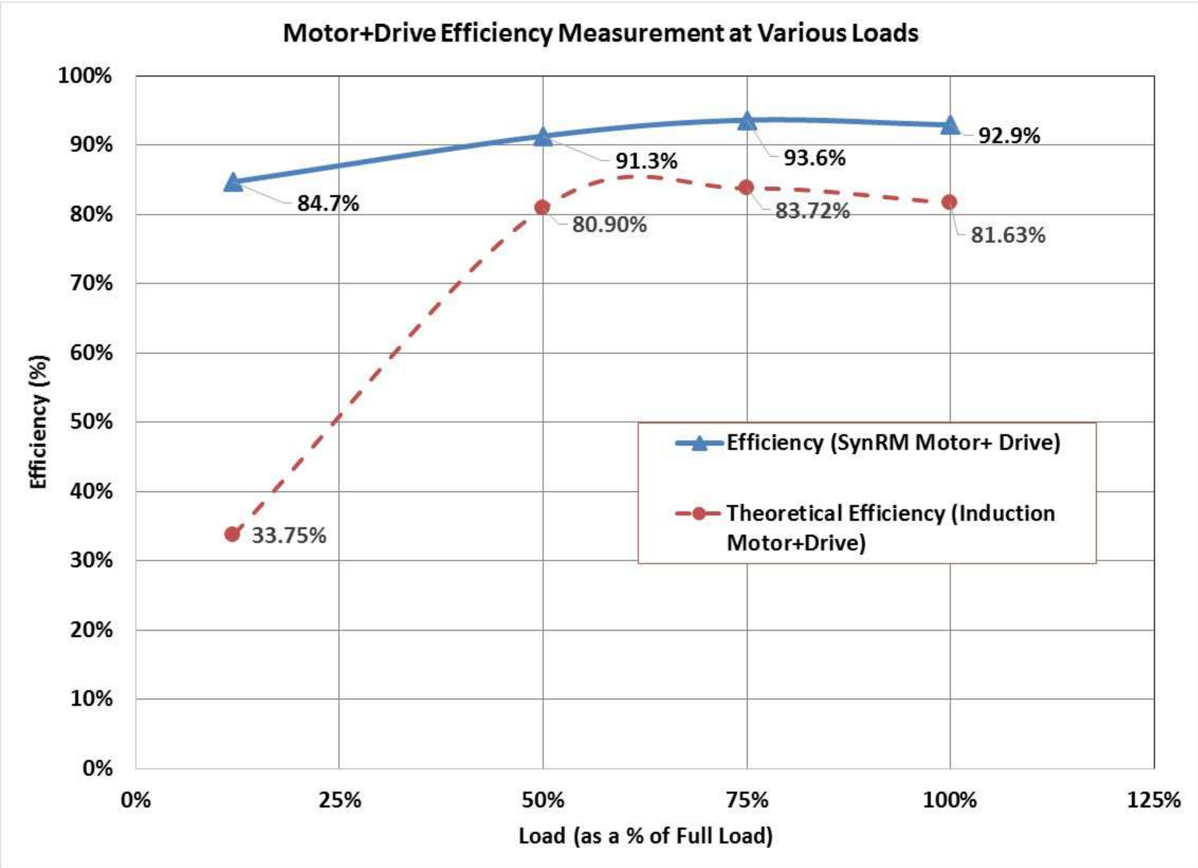

Figure 6 Efficiency Measurement Test Results

Power Quality Test Results

Power electronics based devices such as adjustable speed drives tend to introduce non-linearity to the electrical system. They often times introduce harmonics to the electrical distribution systems and hence they are approached with caution even though they show energy efficiency benefits. Hence, during the energy efficiency testing of the SynRM motor and drive system, power quality (PQ) measurements were also taken with the help of Hioki PQ analyzer. PQ measurements were taken at various load conditions along with energy efficiency measurements. Table 4 summarizes the PQ measurements showing the total harmonic distortions for both voltage and current waveforms at various loads. It should be noted that at loads greater than 50% the THD is below 40%. This is also clearly shown with higher power factor, greater than 0.91, at these higher load levels. This shows that there may be no problems that is caused by the use of ASDs. The three phase current and voltage waveforms under full load conditions are shown in Figure 7.

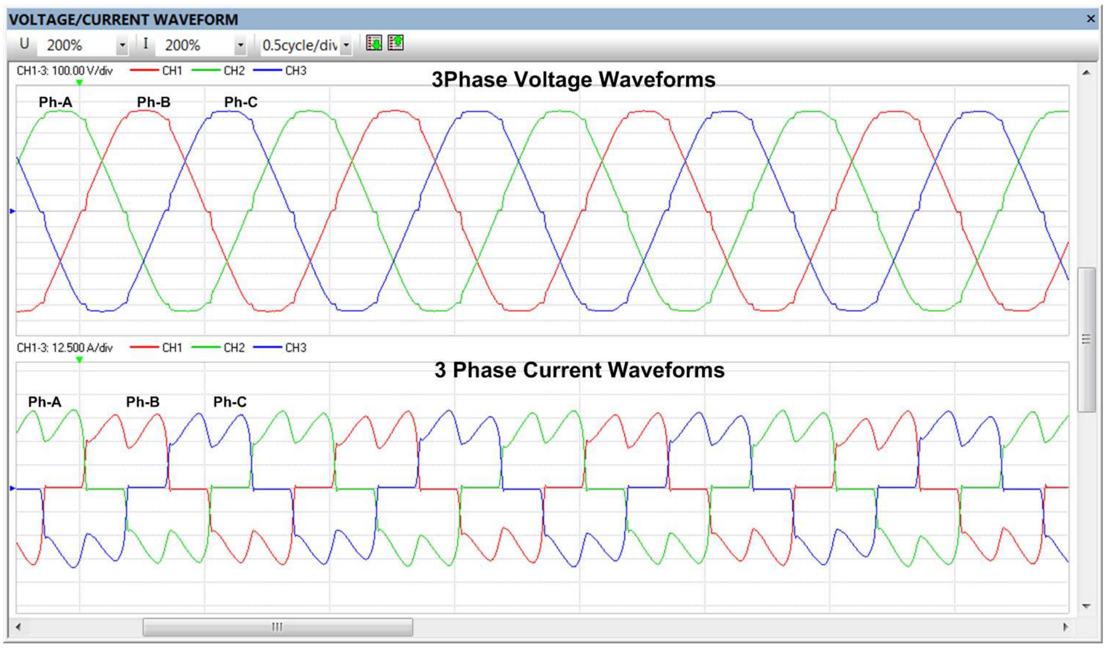

Figure 7 Three Phase Voltage and Current Waveforms Measured at the Drive (ASD) Terminal

Table 4 Voltage and Current Total Harmonic Distortion (THD) at Various Loads

Load	V_{THD} (%)	I_{THD} (%)	PF
11.50%	2.05%	90.54%	0.72
50%	2.64%	58.02%	0.87
75%	2.86%	39.93%	0.93
100%	3.08%	34.80%	0.94

Noise Measurement Test

According to IEC 60034-9, noise limits for rotating machinery, maximum A-weighted sound power levels for motor running at less than 1900 rpm and less than 22 kW is 94dB-A (at no load) and 98 dB-A (at rated load). The laboratory measurements showed that the SynRM motor was well within this limit. In fact the noise levels were approximately 20dBA lower than the required limits. The noise level remained flat for various operating load conditions. Some facilities such as hospitals, child care facilities, and even some industrial facilities would be benefited by lower audible noise from this new motor technology. To give an example of what this noise level is comparable – a vacuum cleaner at 3m is about 75dBA, a jet take off at 100m is about 125dBA and loud conversation in a hall at 1 m is about 60dBA. In U.S., the occupational safety and health administration (OSHA) allows 8 hours of exposure to 90 dBA[1] bur only 2 hours of exposure to 100 dBA sound levels. So having lower noise improves worker conditions in an industrial facility and helps reduce noise pollution in a medical facility, to name a few.

Temperature Rise Measurement Test

Since there is no current induced in the rotor because of the construction of the rotor laminates, the rotor I^2R losses are eliminated. This results in rotor running at lower temperature than its equivalent induction motor. For a same size motor, the SynRM motor can operate at Class A temperature rise while the induction motor may operate at Class F (refer to Table 1).

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[1] https://www.osha.gov/SLTC/noisehearingconservation/ Link visited on August 10, 2014

Summary of Laboratory Test Results

The laboratory tests demonstrates that the SynRM motor and drive system meets and in some cases exceeds the manufacturer specifications. In a laboratory setup, all the variables are controlled and hence there is no adverse impact on the testing from other systems. However, that is not the case in real world conditions. Hence laboratory testing provide a good firsthand knowledge of the operation of the system. The evaluation of the system, in this case the SynRM and drive system, is considered to be complete when the laboratory testing is followed by a field demonstration. The laboratory assessment has highlighted the strength areas of the SynRM motor and drive. The actual savings and other constraints of this system needs to be explored further through an actual demonstration at a customer facility. At the time of completing this paper, we are actively looking to find a site for demonstration at one of our member utilities customer locations.

Limitations of Laboratory Tests

In the laboratory test setup, care has been taken to include as many tests as possible to comprehensively gather the entire operating range of the motor and drive system. However, the tests have been conducted in a controlled environment hence the actual results may vary based on the application, operating conditions, operating personnel and other variables. Hence, the results discussed in this paper should not be taken as complete; however, important characterization tests are completed to be as comprehensive as possible. A natural extension of the laboratory testing would be to install in an actual field demonstration at a facility. The test results from the laboratory can then be used to compare the results from the field and determine any deviations. The field demonstration helps create awareness of this technology to several customers. These new and emerging motor technologies could help utilities meet their efficiency goals as well.

Non-Energy Benefits

The motor also exhibited a low noise profile, nearly 20dBA lower than the requirements set forth by the IEC 60034-9 standard. Because of lower noise, they could be a candidate for low noise environment applications such as health care facilities and school buildings. The temperature rise test revealed that the synchronous reluctance motor was running at relatively low temperature rise (Class A) as opposed to its competing counterpart (Class F or H). This low temperature rise has several advantages such as higher bearing reliability, higher insulation life, increased motor life, reduced maintenance and greasing of bearing as well as reducing the space cooling costs because of motor temperature. Finally no adverse impact on power factor or any major power quality (PQ) concerns could be found during the tests. This motor can be used in traditional induction motor applications such as fans, pumps, compressors and extrudes to name a few.

Conclusions

The laboratory test results showed that the SynRM motor and drive system has significant energy efficiency improvements over the traditional induction motor. The efficiency of the system was greater than 90% for 50%, 75% and full load. The motor also exhibited a low noise profile, nearly 20dBA lower than the requirements set forth by the IEC 60034-9 standard. Because of lower noise, they could be a candidate for low noise environment applications such as health care facilities and school buildings. The temperature rise test revealed that the SynRM motor was running at relatively low temperature rise (Class A) as opposed to its counterpart (Class F or H). This low temperature rise has several advantages such as higher bearing reliability, higher insulation life, increased motor life, reduced maintenance and greasing of bearing as well as reducing the space cooling costs because of motor temperature. Finally no adverse impact on power factor or any major power quality (PQ) concerns could be found during the tests. The SynRM motor can be used in traditional induction motor applications such as fans, pumps, compressors and extruders to name a few. Some of the key features of this technology are:

- Higher system efficiency
- High line-side power factor
- Simple rotor construction

- No permanent magnet or rare earth magnets used
- Lower temperature rise
- High power density
- Improved power factor

The laboratory testing of the SynRM motor highlighted several key features of the motor in comparison to the induction motor.

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Market Surveillance Challenges for complex motor systems

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Abstract

The European Commission and leading motor system product suppliers are working towards the launch of an Extended Product Approach scheme that will set out maximum energy consumption values for different types of common motor systems. This will at last enable the much larger energy systems known to be available in the system to be captured, by both ensuring the correct choice of components for the application, and in particular the best type of controls.

This paper summarises some key developments and new issues identified since the 2013 Rio de Janiero EEMODS workshop on "Practical implementation of the Extended Product Approach"[i], which it is hoped will stimulate further discussion. This subject remains important, as it is essential that the Market Surveillance Authorities (MSAs) have clear guidance in applying supporting regulations to enforce an imagined future EPA Directive.

The Extended Product Approach

The Extended Product Approach (EPA) is detailed in other sources[ii] and supporting technical standards, but in summary it is described in the following diagram. This shows how the overall Energy Efficiency Index (EEI) is calculated as the sum of the individual component efficiency values or indexes. In this diagram the controller is shown as a VSD, but in some cases the optimum control method might be an alternative control method such as on-off control. To take account of real life performance, a generic load profile is assumed for different load types, with the energy use at each load point calculated and then weighted by typical time at each to give the total annual energy consumption.

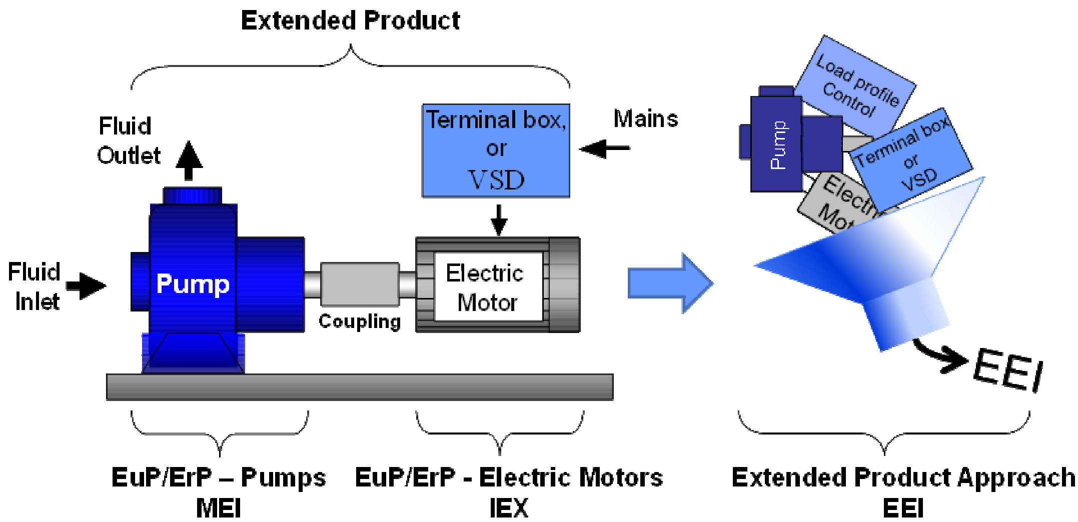

Figure 1 Illustration of Extended Product Approach Methodology based on summing the performance of the individual components, (Europump).

The EPA will impact the following products already regulated under Directive 2009/125/EC, and future products (including VSDs and an extended range of motors and pumps):

- 640/2009 Ecodesign requirements for electric motors[iii].
- 641/2009 Ecodesign requirements for glandless standalone circulators and glandless circulators integrated in products[iv].
- 327/2011 Ecodesign requirements for fans driven by motors with an electric input power between 125 W and 500 kW[v].
- 547/2012 Ecodesign requirements for water pumps[vi].

Although not finalised, the working assumption is that there will be a website that contains component data, which the Supplier then selects and the website then returns the appropriate EEI value(s). One of the important side-effects of this is that this website would effectively create a listing or register of EUP compliant products, which does not currently exist.

EU clarification on Responsibility for placing on to the market complex products

There are many detailed questions regarding the interpretation of existing Ecodesign regulations that have caused some confusion within the EU supplier base of lighting and motors in particular, which are both products that might be modified or integrated into a large product by another body.

The European Commission has now issued firm guidance on this, which answers many of the questions identified in the 2013 EEMODs meeting. The following guidance is taken from a 2015 European Commission Discussion paper[vii], based on the content of the “Blue Guide” to European product policy[viii]:

1. When the product is transferred from the original equipment manufacturer to the final manufacturer in the EEA, it is being placed on the market. In consequence, it has to fulfil any legal requirement that might apply and bear the CE mark.

2. When the final product is placed on the EEA market including the 'integrated product' (e.g. motor, fan), the final manufacturer is responsible for the legal compliance of the complete product, including integrated products, vis-à-vis market surveillance authorities.

3. The final product manufacturer can rely on the DoC (Declaration of Conformity) and CE mark of the integrated products in order to build the DoC and CE mark of the final product.

4. In the case of imported final products, the integrated products regulated under Ecodesign also need to comply with the minimum requirements, and be accompanied by the DoC and bear the CE mark.

5. An additional consequence of a “placing on the market” that happens during the transaction between the original equipment manufacturer and the final product manufacturer is that the product has to comply with the requirements applicable at that point in time. New requirements coming into force before the final product is placed on the market (but after the transaction between OEM and final manufacturer has taken place) have no relevance.

6. If the final product is intended to be exported outside the EEA, the conclusions presented above do not apply.

Implications for the Motor products supply chain

This makes clear that in all cases it is the body placing a product on to the market who is responsible for ensuring compliance with Product Directives. Where these products contain components that are also subject to regulation, the suppliers of these components must also ensure that they are compliant, but with the body putting that component on to the market as part of the integrated product assuming responsibility. The wider principle is that all bodies in the supply chain must individually be responsible, and that there should be a transparent trail based on a Declaration of Conformity at each stage of the chain. In the event of prosecution by an MSA, this would presumably mean that the body putting the product on the market would be responsible for the non-conformity of a component that they used in good faith, and so to minimise the severity of any findings against them, they would need to demonstrate that they had made reasonable effort to verify the validity of the Declaration of Conformity made by the component supplier.

Further in the case of an extended product with components integrated into it, not only does the whole extended product as put on to the market have to comply, but so do the individual components from which it is created. If the whole Extended product meets Directive criteria, this is not in itself sufficient – all the components of which it comprises must also comply. This in theory at least reduces scope for manufacturers to look for trade-offs in the performance of different components. For example under the fan regulation, the use of a VSD would reduce the calculated FEG (Fan Efficiency Grade) requirement sufficiently to theoretically allow the use of a non-compliant motor and still meet this criteria, but this is not permitted.

In practical terms this means that the MSA can take action against any component found for sale, whether or not it is intended for integration into another product.

Part Load Performance

The EPA calculation of EEI includes a weighting of performance at different loads, corresponding to a different application based weighting profile. For pumps, four generic profiles are currently considered, which are thought to be representative of all common types of pumping system. But this means that the same product can have different EEI values according to application.

System Type	EEI
1	0.75
2	0.77
3	0.70

Figure 2 Hypothetical nameplate detail for a pumpset suitable for use with three different generic load profiles, showing the inclusion of three different EEI values.

Figure 2 illustrates what the EEI descriptor might look like on an Extended Product nameplate. The systems for which EEI values are shown must cover all reasonably possible intended applications, and the EEI value must be above the minimum for each case. The MSA will verify that this is the case, with a failure for one meaning that the EPA is non-compliant, regardless of where it is used. This distinction is important as it preserves the simplicity of a product not being available where the acceptability of its performance is dependent on the application. There is so far no mechanism for identifying which load profiles a pump can reasonably be used for, and so this represents a loophole since a supplier could simply fail to suggest a product is used in a particular application, even where they know that it is likely that it will be.

Market Surveillance of Extended Products

For Extended products, the MSA will check that the actual EEI values equal or exceed the minimum efficiency criteria set in the Directive. Both the Supplier putting the product on to the market, and the

MSA, will verify this by performing a calculation. This is unusual in that it means that compliance will be by calculation only, there will therefore be no physical testing of the Extended Product.

This reinforces the need for the Supplier to be satisfied that all regulated components have a valid Declaration of Conformity, and to know the declared energy performance value or efficiency being declared for each.

The lack of a need to perform laboratory tests will greatly reduce the cost and administrative complexity of procuring, shipping and testing products, which will be enable more inspections to take place within limited MSA budgets.

Part load performance

A weakness with the EPA is that it relies on part load data on many motor system components, for which there is not currently a requirement to collect this data. And so where this data is not available, the semi analytical method can instead be used, which calculates part load performance based on extrapolation, rather than actual data.

What is not known is how much variation there is in the actual part load efficiency of similar practical products. Given the convergence on very similar designs of motors, and to a slightly lesser extent of motors and VSDs, it may be supposed that the differences in part load performance between different products are only minor. This will in turn suggest that the relative EEI values of similar products with different load profiles will show little variation.

Who is responsible for placing the product on the market?

For integrated products using regulated components, such as motors, pumps and VSDs, it is clear that the Supplier is responsible for placing the final integrated product on to the market. For “off the shelf” integrated products, it is clear who the Supplier is. But where there is any element of custom design, the situation is not so clear:

A simple example would be the installation of a water supply pump where the motor and pump are connected together by the local supplier; who would be responsible for compliance?

- The Organisation that provides the requirements specification for the pumpset?
- The Supplier that suggests the parts to meet the specification?
- The Organisation that assembles it?

An alternative scenario is where the site engineer might purchase the components direct from a supplier, and then assemble and hence create the Integrated Product.

Later in its life, a component within an integrated product might need replacement. Would this new integrated product need to be checked for compliance?

Clarification on these points will be useful.

Creating regulated products out of older pre-regulation components

EUP regulations only apply to when products are first put on to the market, they are not retrospective. This means that once sold, regulated components can be re-used and repaired either until they fail, or for as long as the User wishes. But in the case of sites which carry stocks of spares, and keep no longer needed components for re-use, what will be the situation when they are later assembled to create a regulated product? Will the regulations still apply in this case?

A working assumption is that the Directive applies to when an assembly of components is assembled and made into an integrated product intended for use in the EU, irrespective of whether the components were subject to regulation when they were themselves placed on to the market.

Clarification of this point would also be useful.

Identification of imported products

Many regulated components are imported as part of Integrated products, of which there is currently little visibility to MSAs. This category presents several interesting challenges:

- Identification of which integrated products contain regulated components.
- The cost of buying a complete product in order to just extract the required components.
- For integrated products destined for direct delivery to an end user, the practicality of the interception, purchase, dis-assembly and testing of an integrated component?

The first EU activity in this area took part within the Ecopliant[ix] project.

By contrast, for legislatures where there is a product registration scheme, it will at least be known whether the components are compliant.

Conclusions

Welcome clarification on many of the fundamentals of Compliance, Certification and Enforcement of Motor system products has been given by the European Commission in a Discussion paper, which answer many of the questions previously raised that relate to the introduction of the proposed Extended Product Approach regulation.

But further questions relating in particular to who is finally responsibility for placing a product on to the market still need to be addressed. Present regulation is targeted at the Supplier of the product, but now that Extended Product units are being custom or semi-custom built, the responsibility moves down the supply chain towards the actual installer. Ensuring that the Extended Product calculation method is sufficiently simple for this much expanded group of responsible bodies in the supply chain to apply, is an important next step.

Such a simple paperwork based method of demonstrating and checking compliance should reduce the burden on both the supply chain and the Market Surveillance Authorities, which is critical for gaining further acceptance of this new method of gaining system energy savings.

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Permanent Magnet Motor and AC Induction Motor Efficiency in Variable Speed Fan Applications

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Abstract

Permanent Magnet (PM) Motors operated with Variable Speed Drives (VSDs) are now being employed in variable speed fan applications. This paper will present data on PM motor efficiency in fan applications for motor sizes of 1.5kW to 7.5kW. Comparisons of PM motor efficiency to NEMA Premium® AC Induction motors will be presented. Measurement of motor efficiency at varying speed and load will comply with CSA Standard C838-13. The efficacy of IEC 60034-30-2 Energy Efficiency Interpolation for variable speed and part load motor efficiency testing will be assessed.

Introduction

Variable speed motor systems are widely used in fan applications to meet demand flow requirements that can vary with ambient temperature, humidity, air pressure, CO2, or airborne contaminant levels. Applications often have a high duty cycle, creating an opportunity for high efficiency, energy-saving motors. In the US, the Energy Independence and Security Act ("EISA") has mandated the NEMA Premium® level of efficiency for general-purpose AC Induction motors of 1-500 horsepower (0.75-375kW) since December 2010. More recently, new permanent magnet motor technologies offering high operating efficiency over a broad range of speed and load have become commercially available, presenting an attractive option for use in variable speed fan applications. This paper examines the motor efficiencies of 1.5kW to 7.5kW NovaTorque permanent magnet motors and AC Induction motors for fan application operating scenarios.

The IEC 60034-30-2 Energy Efficiency Classification Standard (Draft 2/1782/CD) for motors operated with variable speed drives includes an interpolation method whereby motor efficiency can be estimated at any operating point up to 100% speed and 100% load. Following an initial motor efficiency measurement at seven specified speed and load points (See Figure 3), efficiency at other speed/load points can be calculated using expressions that utilize the measured points along with coefficients representing the loss profiles of the test motor. This paper assesses the accuracy of the 60034-30-2 interpolation method by comparing measured efficiency to interpolated values for NEMA Premium® AC Induction motors and Permanent Magnet motors operated at speed and loading representative of fan applications.

A large percentage of variable speed fan applications in the 1.5kW -7.5 kW range are implemented as direct drive solutions, where the fan is installed directly on the motor shaft without transmission system (gearing or pulleys). The advantages of direct-drive are simplicity of installation, reduced system cost, and reduced maintenance. A disadvantage in some cases can be that the motor is less likely to operate near its region of maximum efficiency. Adjustment of pulley size in a belt and pulley system provides the ability to match motor output more closely with the fan delivery requirement.

The selection of test motors and fan operation test points in this paper are intended to cover a representative range of commercial applications. Low static pressure, ductless applications will typically employ a large diameter fan with low speed operation (as low as 300-500 rpm). Higher static pressure, ducted applications employ fans of lesser diameter operated at higher speeds, often exceeding 1800 rpm.

Motors Tested

Measurement of efficiency at fan application test points was conducted on motors of four different output ratings as shown in Table 1. The Permanent Magnet motors tested were NovaTorque PremiumPlus+® TEFC models, the AC Induction motors were Baldor TEFC models; all motors are commercially available. For a given rating category, the same ABB ACS355 variable speed drive was used for testing, with parameter changes as needed to operate the type of motor under test.

Note: As of July 2015, NEMA Frame 8-pole AC Induction motors were available only at the Epact Efficiency level, not at NEMA Premium® efficiency ratings. Where high motor efficiency at low speeds (900 rpm and below) is desired, a NEMA Premium® 6-pole motor is often used preferentially to an Epact-efficient 8-pole AC Induction motor. Consequently, both an Epact-efficient 8-pole ACI motor, and the closest-matching NEMA Premium® 6-pole motor were used in efficiency comparisons for the 3.7kW-900 rpm, and 1.5kW – 900 rpm rating categories.

7.5kW(10hp) – 1800 rpm	
NovaTorque NTQPM-27-1018-4	(7.5 kW – 1800 rpm Rating)
NEMA Premium 4-pole AC Induction	(7.5 kW – 1800 rpm Rating)
3.7kW(5hp) – 1800 rpm	
NovaTorque NTQPM-13-0518-4	(3.7 kW – 1800 rpm Rating)
NEMA Premium 4-pole AC Induction	(3.7 kW – 1800 rpm Rating)
3.7kW(5hp) – 900 rpm	
NovaTorque NTQPM-26-0509-4	(3.7 kW – 900 rpm Rating)
Epact-Efficient 8-pole AC Induction	(3.7 kW – 900 rpm Rating)
NEMA Premium 6-pole AC Induction	(5.0 kW – 1200 rpm Rating)
1.5kW(2hp) – 900 rpm	
NovaTorque NTQPM-19-0209-4	(1.5 kW – 900 rpm Rating)
Epact-Efficient 8-pole AC Induction	(1.5 kW – 900 rpm Rating)
NEMA Premium 6-pole AC Induction	(2.2 kW – 1200 rpm Rating)

Table 1. Output Levels and Test Motors

Methodology

Motor Efficiency Determination

Motor efficiency measurements were conducted on a dynamometer test system following the output-input test method described in the CSA C838-13 standard for efficiency measurement in three-phase variable frequency drive systems.

Interpolation Calculation

The calculation of motor efficiency at interpolated speed and load points follows the method described in the Interpolation section of the IEC 60034-30-2 Standard: Efficiency Classes of Variable Speed AC Motors. IEC 60034-30-2 Edition 1 is in progress; the Draft 2/1782 CD was circulated on 2015-3-13 with content that may undergo improvements or modifications.

Fan Application Test Points

For each motor, four fan application scenarios were tested. The maximum output operating conditions for each fan application are given in Table 2. The maximum output conditions are 100% rated motor torque, at 50%, 75%, and 100% rated motor speed, and 100% rated motor power at 125% motor rated speed.

Fan Application	Percent of Rated Motor Speed	Percent of Rated Motor Torque	Percent of Rated Motor Power
1	50	100	50
2	75	100	75
3	100	100	100
4	125	80	100

Table 2. Maximum Fan Application Operating Conditions

As a close approximation, motor torque varies as the square of the speed, and output power as the cube of the speed in variable-speed fan applications. For each fan application, the selected measurement points are based on 12.5% torque increments of maximum motor torque for the application. A minimum torque level of 12.5% of rated motor torque was used for application scenarios 1, 2 and 3. A minimum torque of 10% of motor rated torque was used for application 4.

The fan application test points are shown in the graphs below. Figure 1 shows the test points as a function of motor speed and torque (percent of rated). Figure 2 shows the test points as a function of motor speed and output power (percent of rated).

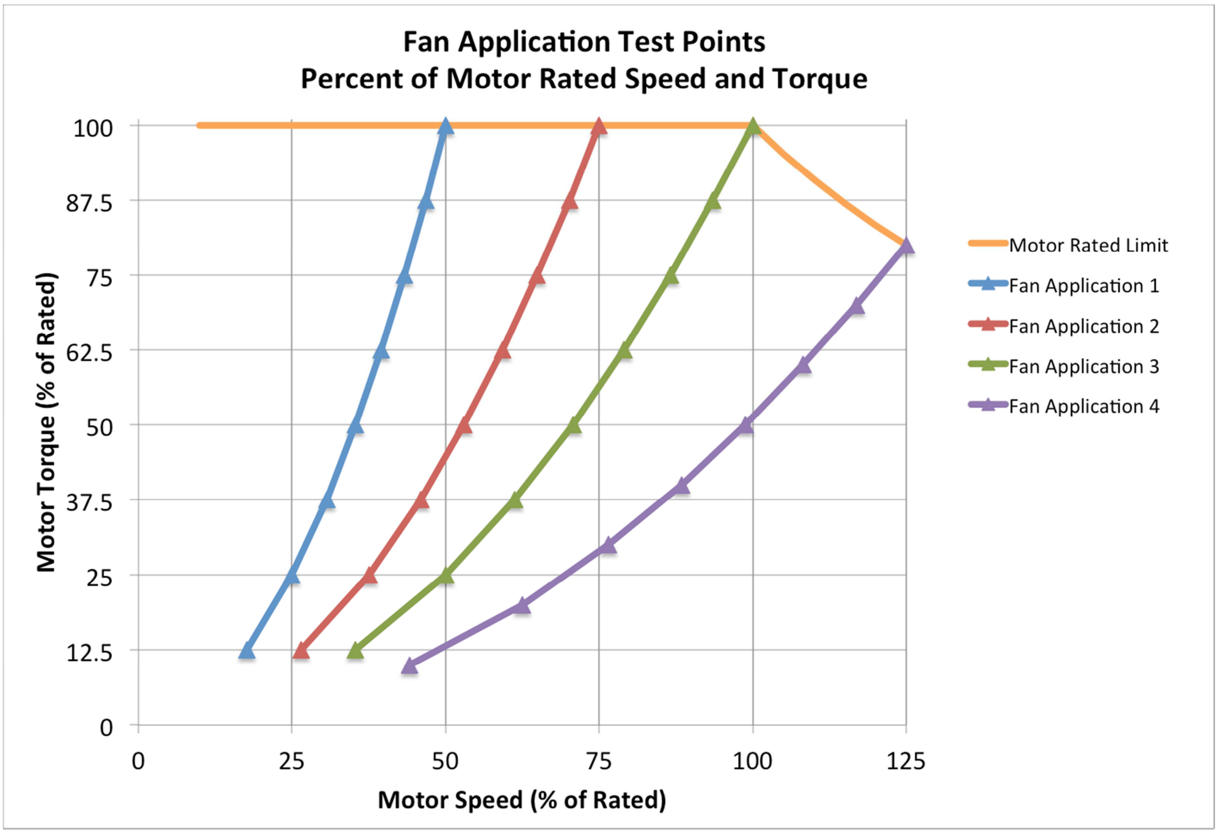


Figure 1. Fan Application Test Points (Percent Motor Speed and Torque)

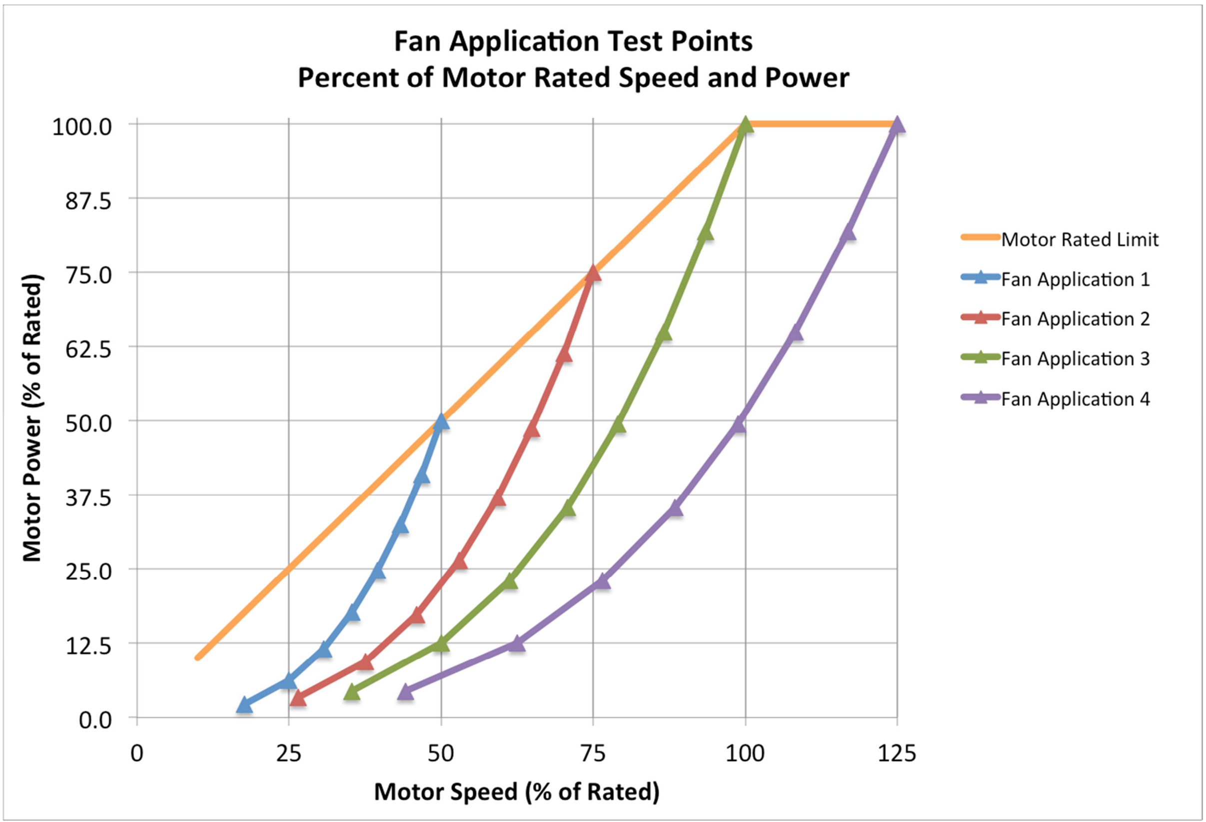
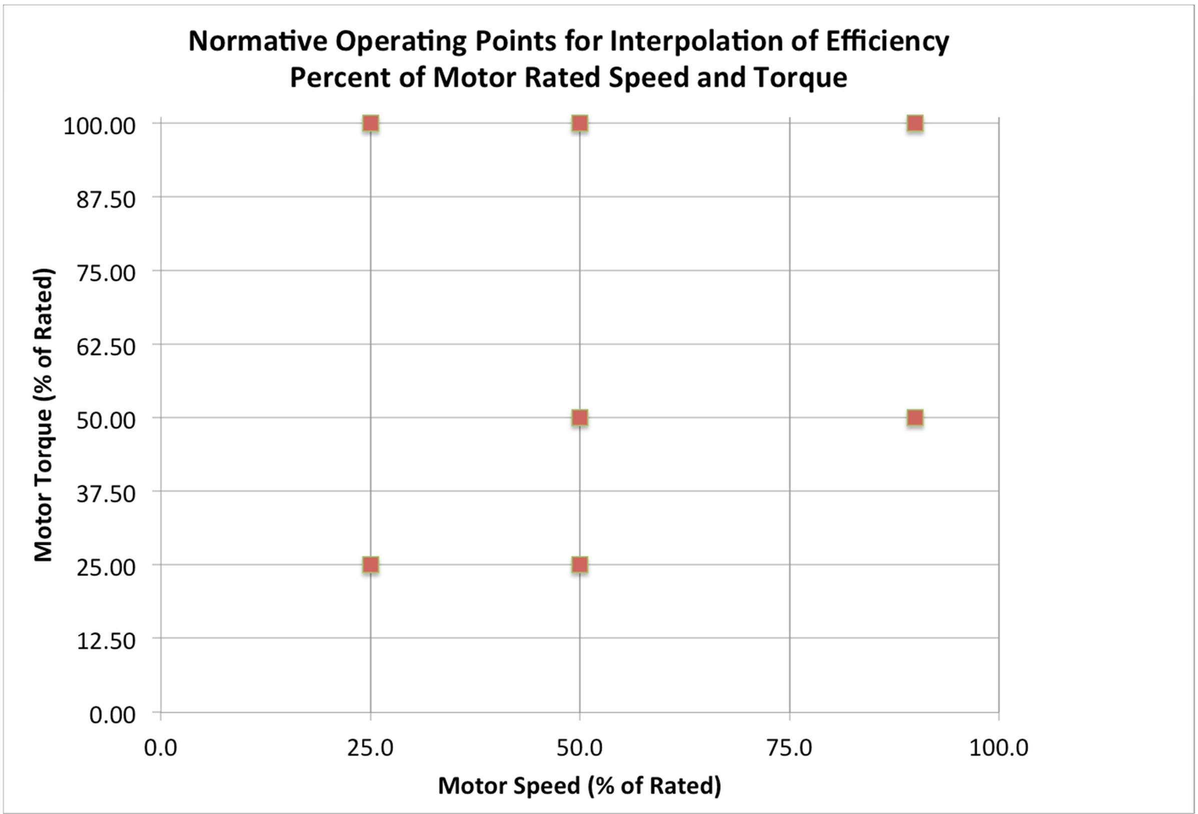


Figure 2. Fan Application Test Points (Percent Motor Speed and Power)

Interpolation of Motor Efficiency – IEC 60034-30-2

Figure 3. Normative Test Points for IEC 60034-30-2 Interpolation



Measurement Results – Tabular

Note: For all interpolated motor efficiency data, the interpolation coefficients were analytically determined from normative interpolation point data. Refer to 'Interpolation of Efficiency', pages 12-13.

7.5kW(10hp) – 1800 rpm Rated Motors

Speed (rpm)	Motor Torque (Nm)	Output Power (Watts)	NovaTorque Motor Efficiency (%)	NEMA Premium Motor Efficiency (%)
1620	39.56	6711	94.9	91.1
900	39.56	3728	93.8	86.8
1620	19.78	3356	94.3	91.7
900	19.78	1864	94.0	88.8
450	39.56	1864	91.0	78.0
900	9.89	932	91.0	86.1
450	9.89	466	90.3	81.2

Table 3: Measured Efficiency at 60034-30-2 Interpolation Points, 7.5kW-1800rpm Motors

Fan Application	Speed (rpm)	Motor Torque (Nm)	Output Power (Watts)	NovaTorque Measured Motor Eff. (%)	NovaTorque Interpolated Motor Eff. (%)	NEMA Prem. Measured Motor Eff. (%)	NEMA Prem. Interpolated Motor Eff. (%)
1	900	39.56	3728	93.8	93.8	86.8	86.8
	842	34.62	3052	93.9	93.9	86.9	86.9
	779	29.67	2422	93.9	94.0	86.9	86.9
	712	24.73	1842	93.7	93.9	86.8	86.8
	636	19.78	1318	93.3	93.5	86.3	86.2
	551	14.84	856	92.5	92.7	84.9	84.8
	450	9.89	466	90.2	90.3	81.1	81.2
	318	4.95	165	85.2	82.4	69.3	69.8
2	1350	39.56	5593	94.7	94.7	90.0	90.0
	1263	34.62	4578	94.7	94.7	90.0	90.0
	1169	29.67	3633	94.6	94.7	90.0	90.0
	1067	24.73	2763	94.5	94.5	89.7	89.7
	955	19.78	1977	94.0	94.0	89.1	89.1
	827	14.84	1284	93.1	93.1	87.8	87.7
	675	9.89	699	90.6	90.8	84.3	84.3
	477	4.95	247	84.9	83.2	74.2	74.3
3	1800	39.56	7457	95.1	95.0	91.2	91.6
	1684	34.62	6103	95.1	95.0	91.6	91.6
	1559	29.67	4843	95.0	94.9	91.5	91.6
	1423	24.73	3684	94.8	94.7	91.3	91.3
	1273	19.78	2636	94.2	94.3	90.7	90.7
	1102	14.84	1712	93.3	93.2	89.3	89.3
	900	9.89	932	91.0	90.8	86.1	86.1
	636	4.95	330	85.1	83.4	76.6	76.7
4	2250	31.65	7457	95.2	95.1 *	90.5	92.9 *
	2105	27.69	6103	95.2	95.0 *	91.7	92.8 *
	1949	23.74	4843	94.8	94.7 *	92.2	92.6 *
	1779	19.78	3684	94.3	94.3	92.0	92.1
	1591	15.82	2636	93.5	93.6	91.1	91.1
	1378	11.87	1712	92.3	92.2	89.4	89.3
	1125	7.91	932	89.5	89.1	85.4	85.3
	795	3.96	330	88.2	80.5	74.2	74.2

Table 4: Measured Efficiency at Fan Application Points and Interpolation, 7.5kW-1800rpm

***** Extrapolation to *f* > 1.0 is not considered valid per 60034-30-2, Draft 2/1782 CD

Measurement Results – Tabular (Cont.)

3.7kW(5hp) – 1800 rpm Rated Motors

Speed	Motor Torque	Output Power	NovaTorque Motor Efficiency	NEMA Premium Motor Efficiency
(rpm)	(Nm)	(Watts)	(%)	(%)
1620	19.78	3356	94.2	88.7
900	19.78	1864	92.8	83.8
1620	9.89	1678	93.3	88.2
900	9.89	932	92.7	84.7
450	19.78	932	89.2	74.6
900	4.95	466	90.0	79.5
450	4.95	233	88.8	73.7

Table 5: Measured Efficiency at 60034-30-2 Interpolation Points, 3.7kW-1800rpm Motors

Fan Application	Speed	Motor Torque	Output Power	NovaTorque Measured Motor Eff.	NovaTorque Interpolated Motor Eff.	NEMA Prem. Measured Motor Eff.	NEMA Prem. Interpolated Motor Eff.
	(rpm)	(Nm)	(Watts)	(%)	(%)	(%)	(%)
1	900	19.78	1864	93.0	92.8	83.8	83.9
	842	17.31	1526	93.0	92.8	83.8	83.8
	779	14.84	1211	93.0	92.7	83.7	83.6
	712	12.36	921	92.9	92.5	83.1	83.0
	636	9.89	659	92.6	92.0	81.8	81.7
	551	7.42	428	91.7	91.1	79.0	79.1
	450	4.95	233	89.2	89.0	73.5	73.5
	318	2.47	82	83.3	82.8	56.9	58.0
2	1350	19.78	2796	94.1	93.9	87.5	87.5
	1263	17.31	2289	94.2	93.9	87.3	87.4
	1169	14.84	1816	94.1	93.7	87.0	87.0
	1067	12.36	1382	93.9	93.4	86.3	86.3
	955	9.89	989	93.2	92.9	85.1	85.1
	827	7.42	642	92.0	91.9	82.6	82.6
	675	4.95	350	89.8	89.7	77.4	77.5
	477	2.47	124	83.0	83.7	62.5	63.0
3	1800	19.78	3728	94.4	94.4	89.0	89.3
	1684	17.31	3052	94.4	94.3	89.2	89.2
	1559	14.84	2422	94.3	94.1	88.8	88.8
	1423	12.36	1842	94.1	93.8	88.2	88.2
	1273	9.89	1318	93.5	93.2	86.9	86.9
	1102	7.42	856	92.4	92.1	84.5	84.5
	900	4.95	466	90.0	89.9	79.6	79.6
	636	2.47	165	83.5	83.8	65.5	66.0
4	2250	15.82	3728	94.4	94.4 *	88.7	90.6 *
	2105	13.85	3052	94.3	94.1 *	89.5	90.3 *
	1949	11.87	2422	93.9	93.8 *	89.6	89.7 *
	1779	9.89	1842	93.3	93.3	88.6	88.7
	1591	7.91	1318	92.6	92.5	87.0	87.0
	1378	5.93	856	90.7	91.0	84.1	84.1
	1125	3.96	466	88.0	88.3	78.3	78.3
	795	1.98	165	80.2	80.9	62.7	63.0

Table 6: Measured Efficiency at Fan Application Points and Interpolation, 3.7kW-1800rpm

***** Extrapolation to *f* > 1.0 is not considered valid per 60034-30-2, Draft 2/1782 CD

Measurement Results – Tabular (Cont.)

3.7kW(5hp) – 900 rpm Rated Motors

Speed	Motor Torque	Output Power	NovaTorque Motor Efficiency	Epact-Efficient 8-pole Motor Efficiency	NEMA Premium 6-pole Motor Efficiency
(rpm)	(Nm)	(Watts)	(%)	(%)	(%)
810	39.56	3356	94.0	83.1	88.8
450	39.56	1864	91.3	77.0	85.0
810	19.78	1678	94.1	82.4	86.3
450	19.78	932	92.7	77.5	83.0
225	39.56	932	85.8	65.5	77.2
450	9.89	466	90.7	70.7	75.3
225	9.89	233	88.7	61.5	69.2

Table 7: Measured Efficiency at 60034-30-2 Interpolation Points, 3.7kW-900rpm Motors

Fan App	Speed	Motor Torque	Output Power	NT PM Measured Motor Eff	NT PM Interpol. Motor Eff	Epact Measured Motor Eff	Epact Interpol. Motor Eff	NEMA Premium Measured Motor Eff	NEMA Premium Interpol. Motor Eff
	(rpm)	(Nm)	(Watts)	(%)	(%)	(%)	(%)	(%)	(%)
1	450	39.56	1864	91.3	91.3	76.8	77.0	85.0	85.0
	421	34.62	1526	91.6	91.5	76.7	76.8	84.5	84.5
	390	29.67	1211	91.7	91.6	76.2	76.3	83.6	83.7
	356	24.73	921	91.8	91.6	75.4	75.3	82.5	82.5
	318	19.78	659	91.7	91.3	73.5	73.3	80.5	80.3
	276	14.84	428	90.8	90.6	69.6	69.5	76.5	76.6
	225	9.89	233	88.8	88.8	61.3	61.4	69.1	69.1
	159	4.95	82	81.8	82.0	42.4	42.7	51.7	51.4
2	675	39.56	2796	93.2	93.3	81.5	81.6	87.8	87.8
	631	34.62	2289	93.3	93.4	81.2	81.4	87.3	87.3
	585	29.67	1816	93.4	93.4	80.8	80.9	86.5	86.6
	534	24.73	1382	93.4	93.2	79.9	80.0	85.4	85.4
	477	19.78	989	93.0	92.9	78.2	78.2	83.4	83.4
	413	14.84	642	92.2	92.1	74.7	74.7	79.9	79.9
	338	9.89	350	90.0	90.1	67.4	67.6	73.1	73.1
	239	4.95	124	83.4	83.7	49.5	49.7	56.4	56.5
3	900	39.56	3728	94.2	94.3	83.4	83.9	89.4	89.3
	842	34.62	3052	94.2	94.3	83.6	83.7	88.8	88.8
	779	29.67	2422	94.2	94.2	83.1	83.3	88.0	88.1
	712	24.73	1842	94.0	94.0	82.2	82.5	86.9	87.0
	636	19.78	1318	93.7	93.6	80.6	80.7	85.1	85.1
	551	14.84	856	92.7	92.7	77.5	77.6	81.7	81.8
	450	9.89	466	90.7	90.8	70.9	71.0	75.2	75.2
	318	4.95	165	84.1	84.3	53.3	53.4	59.5	59.6
4	1125	31.65	3728	94.1	95.0 *	82.1	85.4 *	89.7	89.7
	1052	27.69	3052	94.5	94.8 *	84.1	85.0 *	89.1	89.1
	974	23.74	2422	94.5	94.6 *	84.3	84.3 *	88.1	88.2
	889	19.78	1842	94.3	94.2	82.9	83.0	86.7	86.7
	795	15.82	1318	93.6	93.5	80.8	80.9	84.4	84.4
	689	11.87	856	92.2	92.2	77.1	77.1	80.4	80.5
	563	7.91	466	89.5	89.6	69.9	69.8	73.4	73.6
	398	3.96	165	81.7	82.2	51.7	51.6	56.4	56.6

Table 8: Measured Efficiency at Fan Application Points and Interpolation, 3.7kW-900rpm

***** Extrapolation to *f* > 1.0 is not considered valid per 60034-30-2, Draft 2/1782 CD

Measurement Results – Tabular (Cont.)

1.5kW(2hp) – 900 rpm Rated Motors

Speed	Motor Torque	Output Power	NovaTorque Motor Efficiency	Epact-Efficient 8-pole Motor Efficiency	NEMA Premium 6-pole Motor Efficiency
(rpm)	(Nm)	(Watts)	(%)	(%)	(%)
810	15.82	1342	93.6	79.8	86.2
450	15.82	745	90.9	72.6	80.5
810	7.91	671	93.2	77.7	84.6
450	7.91	373	91.8	72.0	80.1
225	15.82	373	85.2	59.5	69.9
450	3.96	186	88.9	63.6	73.1
225	3.96	93	86.7	53.4	64.6

Table 9: Measured Efficiency at 60034-30-2 Interpolation Points, 1.5kW-900rpm Motors

Fan App	Speed	Motor Torque	Output Power	NT PM Measured Motor Eff	NT PM Interpol. Motor Eff	Epact Measured Motor Eff	Epact Interpol. Motor Eff	NEMA Premium Measured Motor Eff	NEMA Premium Interpol. Motor Eff
	(rpm)	(Nm)	(Watts)	(%)	(%)	(%)	(%)	(%)	(%)
1	450	15.82	745	90.4	90.8	72.4	72.5	80.5	80.4
	421	13.84	610	90.5	90.9	72.0	72.1	80.2	80.1
	390	11.87	484	90.5	91.0	71.2	71.3	79.5	79.4
	356	9.89	368	90.3	90.9	69.8	69.9	78.3	78.3
	318	7.91	264	90.0	90.6	67.2	67.1	76.4	76.3
	276	5.93	171	89.1	89.6	62.3	62.4	72.4	72.4
	225	3.96	93	87.2	87.0	53.1	53.4	64.5	64.5
	159	1.98	33	80.4	77.9	33.4	33.7	45.5	45.4
2	675	15.82	1118	92.8	92.9	77.8	77.9	84.7	84.6
	631	13.84	915	92.9	92.9	77.3	77.4	84.4	84.3
	585	11.87	726	92.8	92.8	76.4	76.7	83.6	83.7
	534	9.89	553	92.6	92.5	75.0	75.3	82.6	82.6
	477	7.91	395	92.1	92.0	72.6	72.8	80.6	80.7
	413	5.93	257	91.0	90.9	68.2	68.4	77.2	77.1
	338	3.96	140	88.9	88.3	60.0	60.3	69.9	69.9
	239	1.98	49	81.8	79.8	40.4	40.5	52.1	51.9
3	900	15.82	1491	93.5	94.0	80.3	80.7	86.9	86.9
	842	13.84	1220	93.5	93.9	80.1	80.2	86.6	86.6
	779	11.87	968	93.3	93.7	79.2	79.4	85.9	85.9
	712	9.89	737	93.1	93.3	77.8	78.2	84.9	84.9
	636	7.91	527	92.4	92.7	75.5	75.8	83.0	83.0
	551	5.93	342	91.2	91.5	71.6	71.8	79.9	79.9
	450	3.96	186	89.4	88.9	63.8	64.0	73.4	73.4
	318	1.98	66	82.4	80.9	45.1	45.0	57.2	56.9
4	1125	12.66	1491	92.5	94.6 *	79.6	82.1 *	88.2	88.2
	1052	11.07	1220	93.2	94.3 *	81.4	81.3 *	87.6	87.6
	974	9.49	968	93.3	93.9 *	81.0	80.2 *	86.7	86.6
	889	7.91	737	93.2	93.3	78.2	78.4	85.2	85.2
	795	6.33	527	92.2	92.3	75.4	75.5	83.0	83.0
	689	4.75	342	90.7	90.7	70.7	70.7	79.2	79.2
	563	3.16	186	87.3	87.4	62.5	62.2	72.0	71.9
	398	1.58	66	78.7	78.0	43.6	43.3	55.4	55.0

Table 10: Measured Efficiency at Fan Application Points and Interpolation, 1.5kW-900rpm

***** Extrapolation to *f* > 1.0 is not considered valid per 60034-30-2, Draft 2/1782 CD

Measurement Results – Motor Efficiency Graphs

Note: Measurement points at 25% rated torque and higher are shown in graphs.

7.5kW(10hp) – 1800 rpm Rated Motors

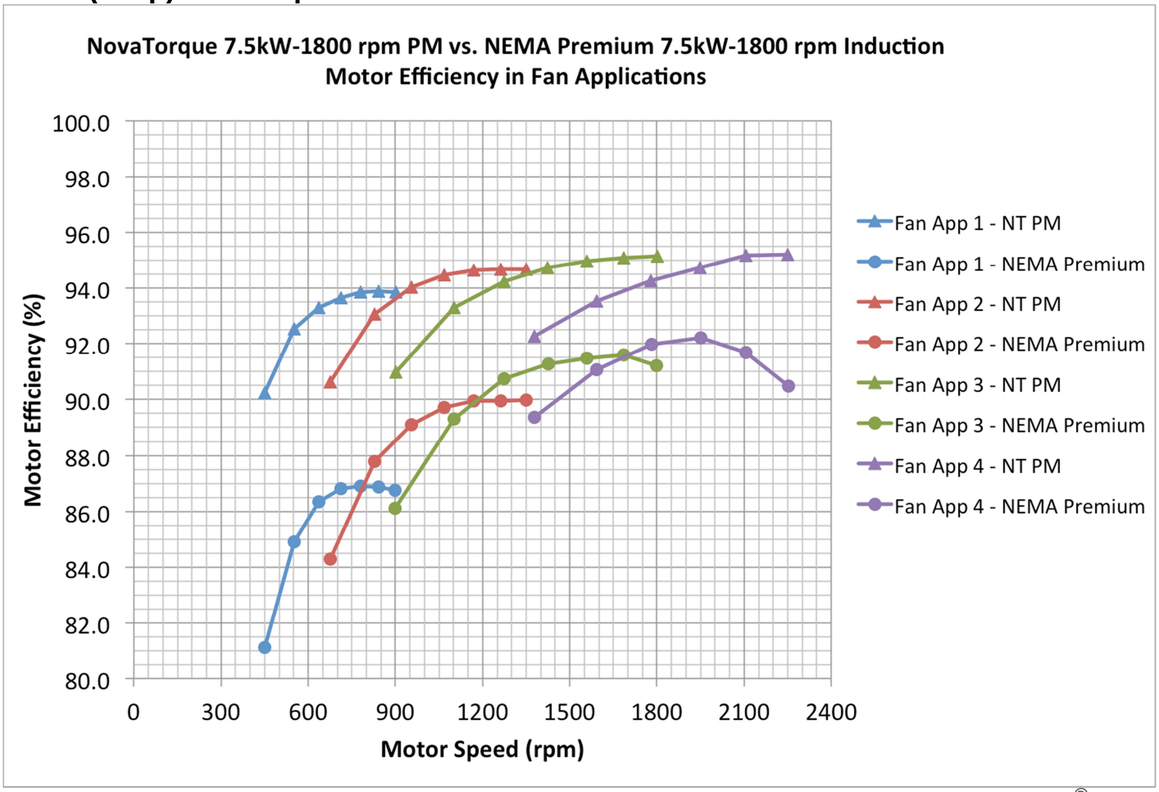


Figure 4. Measured Motor Efficiency for 7.5kW-1800rpm NT PM and NEMA Premium® Motors

3.7kW(5hp) – 1800 rpm Rated Motors

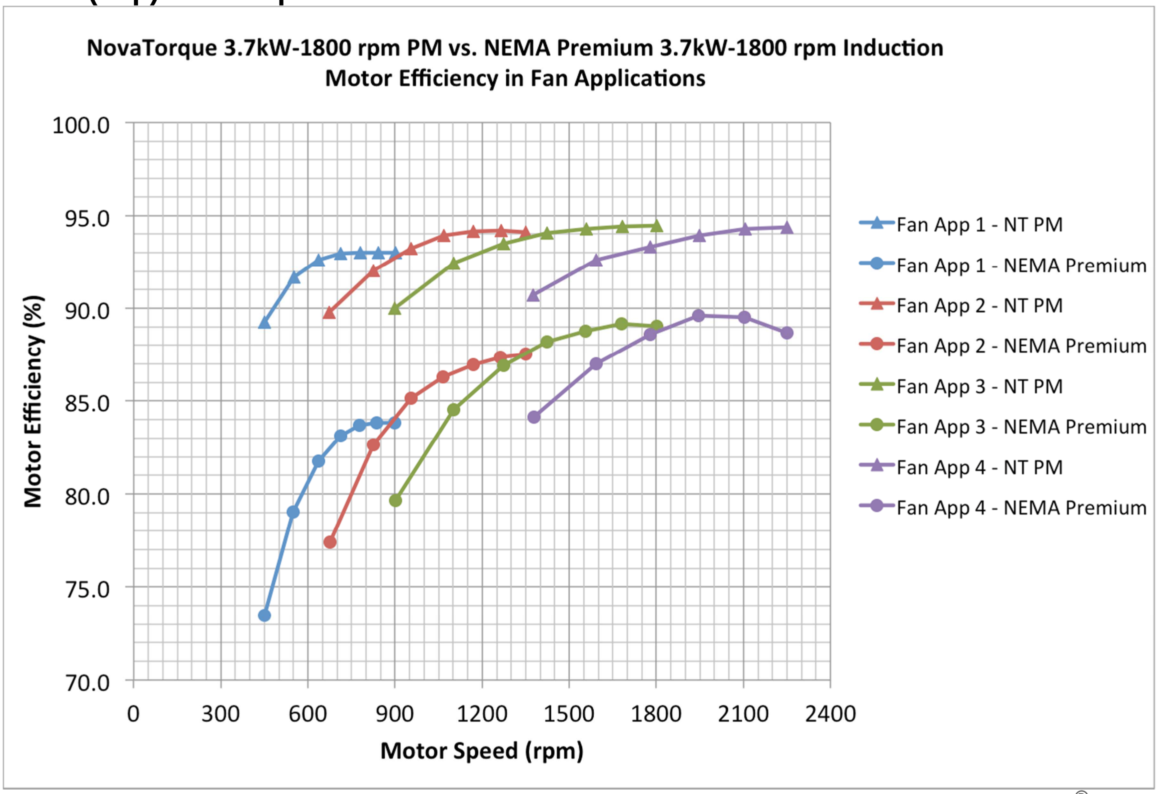


Figure 5. Measured Motor Efficiency for 3.7kW-1800rpm NT PM and NEMA Premium® Motors

Measurement Results – Motor Efficiency Graphs (cont.)

3.7kW(5hp) – 900 rpm Rated Motors

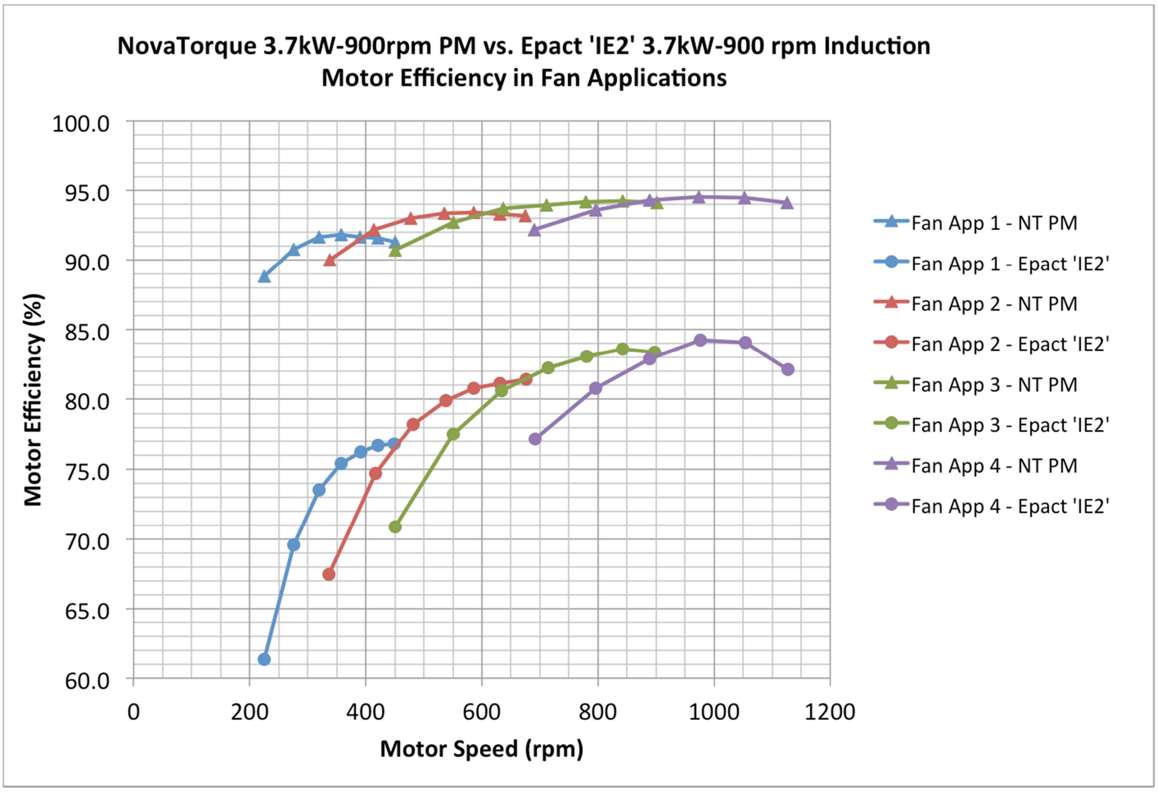


Figure 6. Measured Motor Efficiency for 3.7kW-900rpm NT PM and Epact Induction Motors

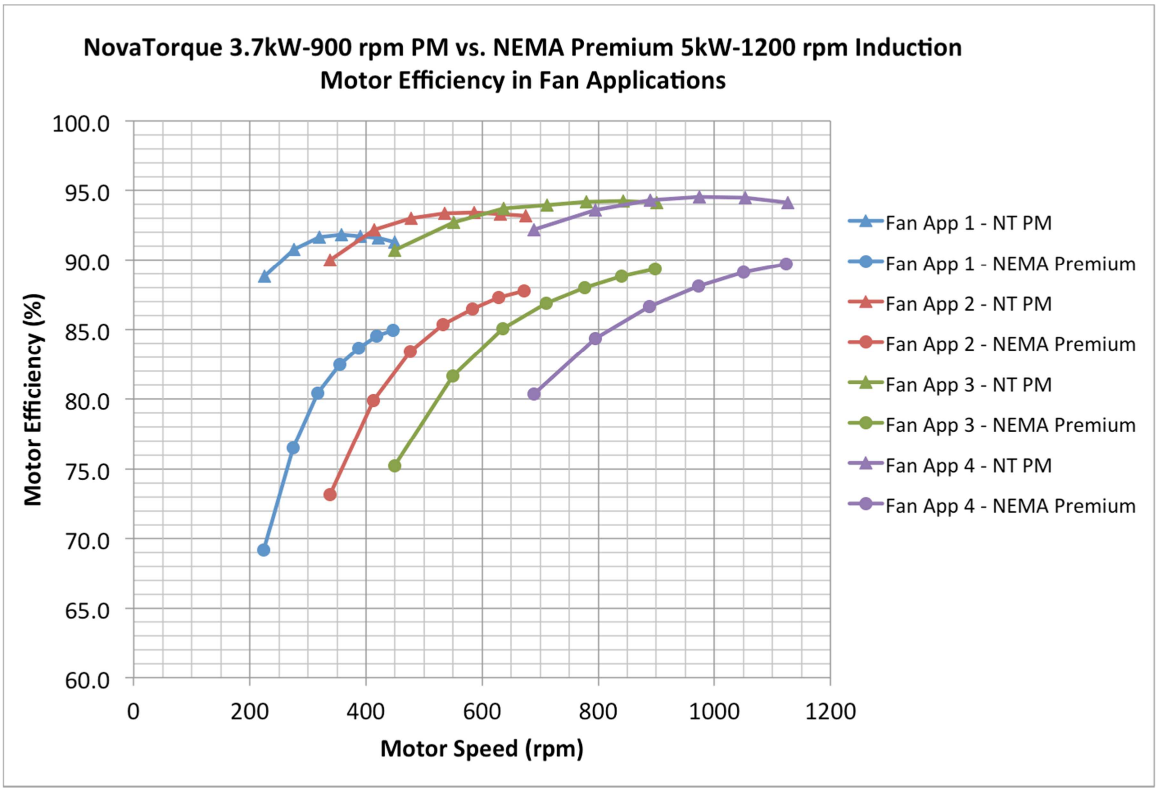


Figure 7. Measured Motor Efficiency for 3.7kW-900rpm NT PM and 5kW-1200 rpm NEMA Premium® Motors

Measurement Results – Motor Efficiency Graphs (cont.)

1.5kW(5hp) – 900 rpm Rated Motors

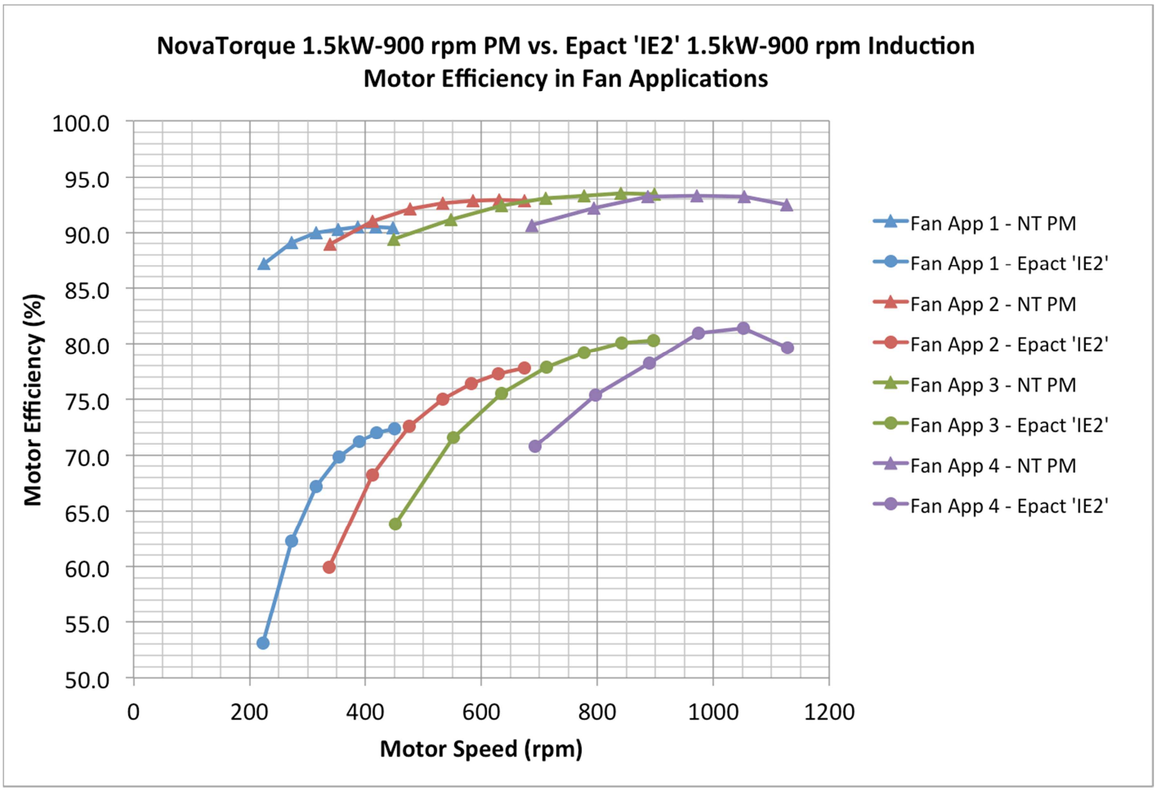


Figure 8. Measured Motor Efficiency for 1.5kW-900rpm NT PM and Epact Induction Motors

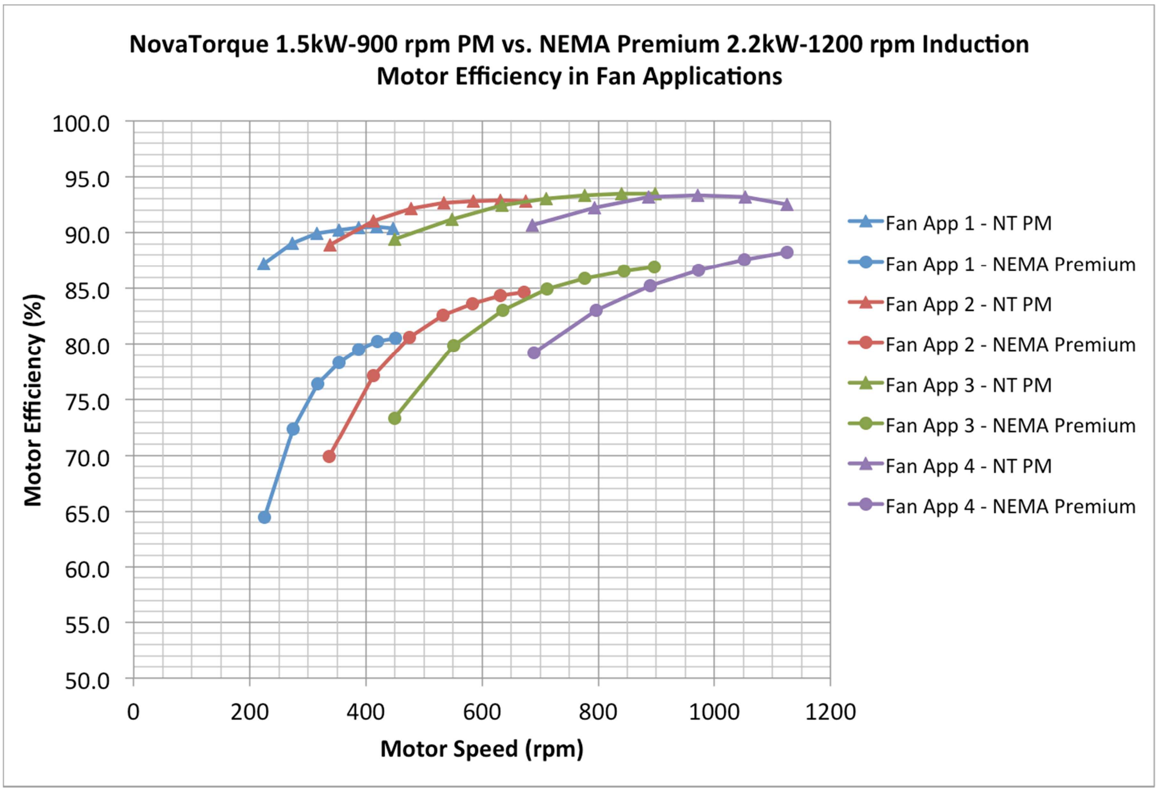


Figure 9. Measured Motor Efficiency for 1.5kW-900rpm NT PM and 2.2kW-1200rpm NEMA Premium® Motors

Measurement Results – Interpolation of Efficiency

Motor		Interpolation - Analytic		Interpolation - Numerical	
Type	Description	Q_{ISI}	Efficiency Deviation (Average Percent)	Q_{ISI}	Efficiency Deviation (Average Percent)
ACI 4-pole	7.5kW-1800rpm	0.011	0.080	0.006	0.046
ACI 4-pole	3.7kW-1800rpm	0.012	0.127	0.005	0.058
ACI 6-pole	5.0kW-1200rpm	0.006	0.074	0.004	0.058
ACI 6-pole	2.2kW-1200rpm	0.005	0.071	0.002	0.033
ACI 8-pole	3.7kW-900rpm	0.010	0.154	0.005	0.070
ACI 8-pole	1.5kW-900rpm	0.010	0.177	0.004	0.067
NT PM	7.5kW-1800rpm	0.062	0.352	0.015	0.086
NT PM	3.7kW-1800rpm	0.045	0.300	0.016	0.118
NT PM	3.7kW-900rpm	0.020	0.131	0.009	0.058
NT PM	1.5kW-900rpm	0.061	0.486	0.020	0.144

Table 11: Interpolation Metrics for Tested Motors

Definition of Terms:

1. ***Interpolation – Analytic***

The interpolation coefficients (A, B, … G) were calculated using the equations given in Section A.3 of IEC 60034-30-2 (Draft 2/1782 CD). Section A.3 provides an exact solution for the seven interpolation coefficients from seven simultaneous equations, where each equation is the interpolation formula given in Section A.2 applied to a normative operating point. The seven normative operating points are shown in Figure 3 (Table A.2 in the draft IEC 60034-30-2 standard). The interpolation formula is defined as:

$$\boldsymbol{P_L(f,T) = A + B \cdot f + C \cdot f^2 + D \cdot f \cdot T^2 + E \cdot f^2 \cdot T^2 + F \cdot T + G \cdot T^2}$$

where $P_L(f, T)$ is the relative motor loss at the specified relative speed (f) and relative torque (T). $P_L(f, T)$, f, and T are known values for each of the normative operating points; the interpolation coefficients (A, B, … G) are analytically determined.

The interpolation formula was then used to solve for $P_L(f, T)$ at the fan application test points, employing the calculated coefficients. Motor efficiency, $\eta(f, T)$, is then calculated as:

$$\eta(f,T) = \frac{f \cdot T}{f \cdot T + P_L(f,T)}$$

2. ***Interpolation – Numerical***

The interpolation coefficients (A, B, … G) were calculated using the CVX modeling system in MATLAB to minimize Q_{ISI} (See definition below). The measured points used were the fan application test points where f <= 1.0.

The interpolation formula was then used to solve for $P_L(f, T)$ at the fan application test points, employing the calculated coefficients. Motor efficiency is calculated from $P_L(f, T)$ as above.

3. $$Q_{ISI} = \sqrt{\frac{1}{29}\sum_f \sum_T \left(\frac{P_{L(f,T)}^{measured} - P_{L(f,T)}^{interpolated}}{P_{L(f,T)}^{measured}}\right)^2}$$

Q_{ISI}, or Interpolation Stability Index, is defined in IEC 60034-30-2 (Draft 2/1782 CD). Twenty-nine test points were used for the Q_{ISI} determination. Three of the fan test points in Fan Application 4 were at a speed above the motor rated speed and so were not included. Extrapolation to f > 1.0 is not possible per A.2 Note 3 in IEC 60034-30-2 (Draft 2/1782 CD). For this paper, extrapolation calculations were made for all test points, including the points where f > 1.0, however the extrapolation results for these points were not included in the determination of Q_{ISI} and Efficiency Deviation.

Measurement Results – Interpolation of Efficiency

Definition of Terms (cont.)

4. ***Efficiency Deviation***
Efficiency Deviation is the average absolute deviation of interpolated efficiency from measured efficiency for the twenty-nine test points where *f* <= 1.0. The units are percentage points of efficiency.

Example of Efficiency Interpolation

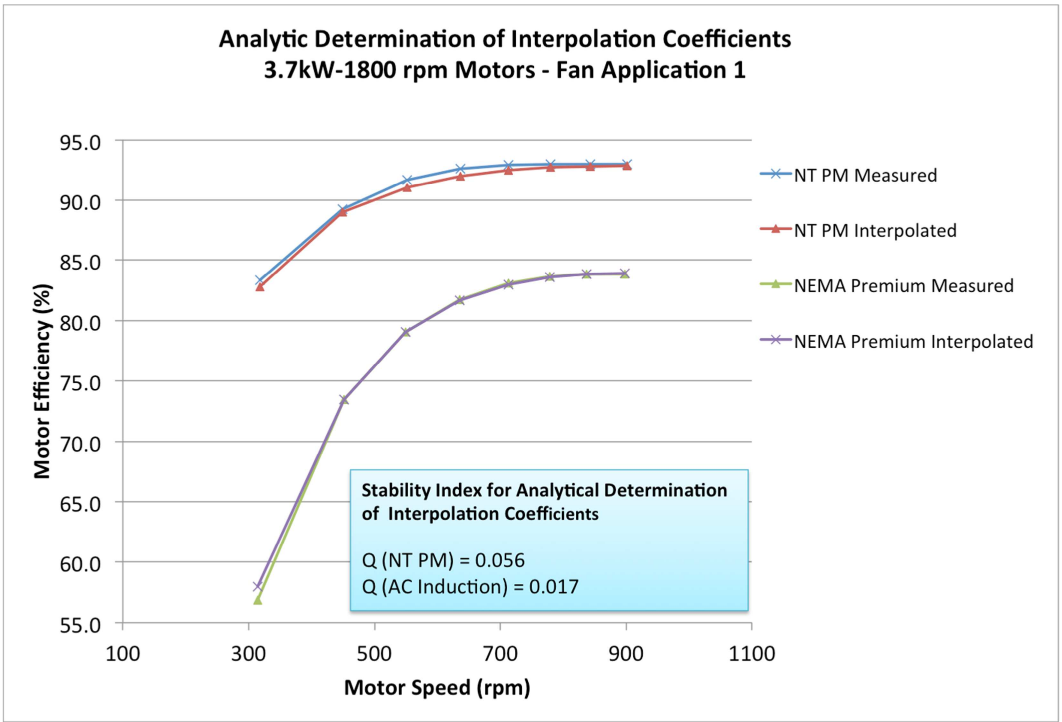


Figure 10. Analytic Determination of Interpolation Coefficients - Example

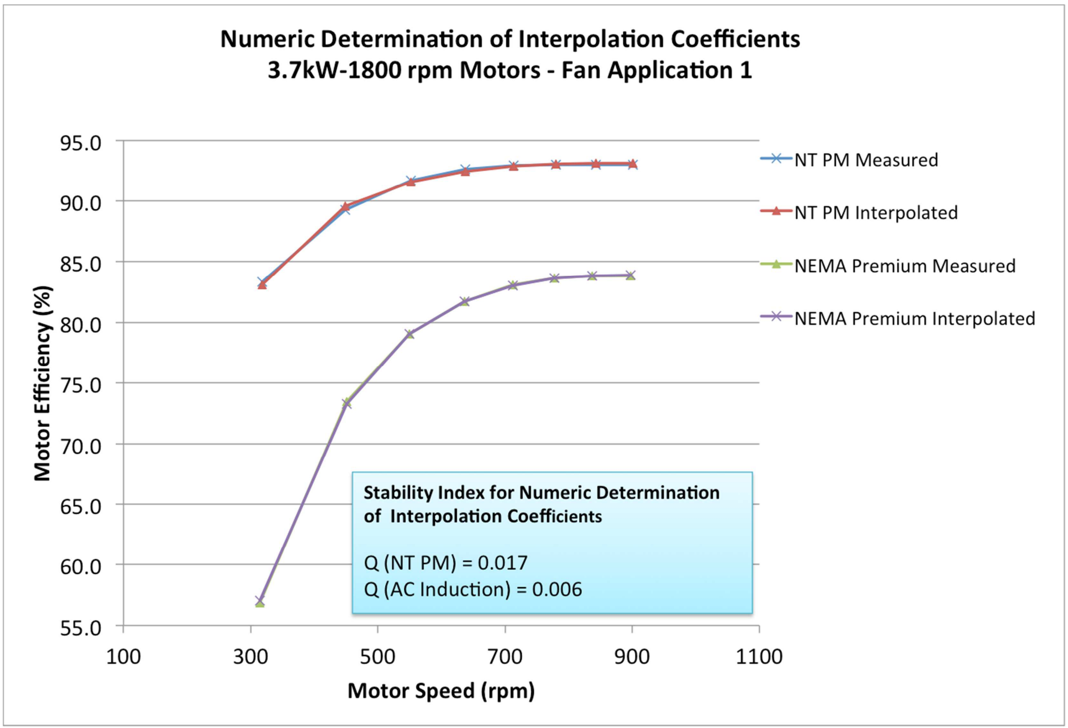


Figure 11. Numerical Determination of Interpolation Coefficients - Example

Discussion

Measured Motor Efficiency/Losses

The permanent magnet motors tested showed significantly higher efficiency (lower losses) at all fan application test points compared with their AC Induction motor counterparts. Table 12 provides a summary of the percent reduction of losses seen when operating a NovaTorque PM motor as compared with a NEMA Premium® or Epact-efficient AC Induction motor. The percent loss reduction is calculated as $(P_L(f, T)_1 - P_L(f, T)_2) / P_L(f, T)_1 * 100.0$ where $P_L(f, T)_1$ is the motor loss of the AC Induction motor under test, and $P_L(f, T)_2$ is the motor loss of the PM motor, both operated at speed f and torque T. Aggregating the test points of all fan applications, the minimum, maximum, and average values for percent reduction of motor losses are listed for each comparative motor test. In addition, the percent reduction in motor losses at rated output of the motor is also provided (Point 1 of Fan Application 3 is at rated motor output).

Output	Comparison	Reduction of Losses			
		Min	Max	Average	Rated Output
7.5kW-1800 rpm	PM to NEMA Premium ACI	30%	61%	46%	47%
3.7kW-1800 rpm	PM to NEMA Premium ACI	44%	73%	57%	52%
3.7kW-900 rpm	PM to Epact-Efficient ACI	68%	83%	73%	69%
	PM to NEMA Premium ACI (5kW-1200 rpm rated)	46%	77%	61%	48%
1.5kW-900 rpm	PM to Epact-Efficient ACI	69%	87%	75%	72%
	PM to NEMA Premium ACI (2.2kW-1200 rpm rated)	40%	79%	62%	54%

Table 12: Percent Reduction in Motor Losses Provided by PM Motor Compared to ACI Motor

Below rated motor speed, the percent reduction of losses seen with the PM motors generally increases as speed is reduced. The largest percent reduction of losses is seen at the slowest test speed in Fan Application 1. However, it should be kept in mind that total power reduction is a product of the percent loss reduction and the power output requirement.

Above rated speed (Points 1, 2, and 3 of Fan Application 4), the tested PM motors show an increasing level of loss reduction for most test cases. The exceptions are the comparison tests of 900-rpm rated PM motors with 6-pole, 1200-rpm NEMA Premium® AC Induction motors. While the PM motors still show a significant reduction of losses over the AC Induction motors at the highest speeds, the magnitude of the loss reduction does not increase with speed in the case of the 6-pole ACI motors. This is largely because the 6-pole motors, having a synchronous speed of 1200 rpm (60 Hz line), are not operating in the 'field-weakening' or constant-power region as is the case with the 8-pole, 900-rpm motors.

Interpolation of Motor Efficiency

An average of the interpolation metric results for AC Induction (ACI) and NovaTorque Permanent Magnet (NT PM) motors yields the following:

	Analytic Determination of Coefficients		Numerical Determination of Coefficients	
	Q_{ISI}	Efficiency Dev. (%)	Q_{ISI}	Efficiency Dev. (%)
ACI	0.009	0.114	0.004	0.055
NT PM	0.047	0.317	0.015	0.102

For AC Induction motors, the standard analytic determination of interpolation coefficients, as given in the equations of Section A.3 of IEC 60034-30-2 (Draft 2/1782/CD), enables the interpolation of motor efficiency with a Q_{ISI} (Interpolation Stability Index) of less than 0.01,

Discussion

Interpolation of Motor Efficiency (cont.)

and an average absolute efficiency deviation of slightly more than 0.1%. As evidenced by the graphical result shown in Figure 10, a set of interpolation points with a Q_{ISI} of 0.01 appears to constitute a very good match to measured results. While an even better match to measured AC Induction motor efficiency values was achievable by using a 29-point numerical determination of the interpolation coefficients, the analytic determination fulfills its intention of enabling accurate motor efficiency interpolation to arbitrary speed and torque points via a measurement of motor efficiency at the seven normative operating points given in Figure 3 (from Table A.2 of the draft IEC 60034-30-2 specification).

For NovaTorque Permanent Magnet motors, the average Q_{ISI} for efficiency interpolations using the analytically determined interpolation coefficients of 60034-30-2, Section A.3 was 0.047, with an average absolute efficiency deviation of more than 0.3%. The deviation between measured data and interpolated data using the analytic determination of coefficients was significantly higher than with AC Induction motors. Further testing and analysis is needed to determine the reason for the higher Q values on the PM motor interpolations.

The numerical determination of interpolation coefficients for the PM motors provided efficiency interpolations with an average Q_{ISI} of 0.015, and an average absolute efficiency deviation of about 0.1%. Figure 11 gives an example of efficiency interpolation using numerically derived coefficients.

The absence of a means to extrapolate efficiency in the region above rated speed ($f > 1.0$) is a significant limitation for use in fan applications where the practice of 'overspeeding' motors with variable speed drives is very common. The ability to extrapolate efficiency to operating points above rated motor speed would be a welcome addition to 60034-30-2.

Acknowledgments
The author wishes to thank Ken Allen for his MATLAB analysis and for his help in ensuring conformance to the CSA C838-13 test standard.

References

[1] CSA-C838-13: Energy efficiency test methods for three-phase variable frequency drive systems. March 2013

[2] IEC 60034-30-2 TS Ed. 1 (Draft 2/1782/CD) Rotating electrical machines - Part 30-2: Efficiency classes of variable speed AC motors.

[3] NEMA MG1-2014: Motors and Generators

[4] US Energy and Independence Security Act 2007, Section 313: Electric Motor Efficiency Standards

Policy 4

The Motor Systems Retirement Program (MSRP) Strategy to speed up replacement of old motor systems

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Abstract

Based on systematic research of industrial motor systems applications in Swiss industry (Easy, 2010-2014, [1], [4]), 56% of motors in use are older than their technical life expectancy as defined by de Almeida et al. (EC Lot 11, 2008, [2]). This means that the motor systems including their applications are old, inefficient, often oversized and less than 20% adapted to varying loads. A feasibility study VELANI[1] establishes a Swiss program to increase the renewal rate and provide systematic energy savings.

The replacement rate for industrial machines is not well known. Experience from systematic industry audits shows that only machine failure or changed and/or expanded production processes lead to renewal programs for machines. The MSRP program includes a focused approach to mid- and larger size industries, consuming between 500 MWh and up to 100'000 MWh electricity per year which is equivalent to between € 60'000 and up to € 12 millions of electricity costs per year. It is estimated that some 14'000 enterprises are in this range from the industrial and services sectors in Switzerland. The program provides audits with an efficiency plan without lengthy and costly analyses targeted at medium-sized factories. Large-sized industrial plants have to go through a systematic 4-step audit supported by adequate software tools.

The Motor Systems Retirement Program (MSRP) defines the renewal cycles, efficiency targets and the necessary policies for regular mandatory audits, MEPS and the necessary financial incentives. This approach aims at lowering the barrier for the systems' analysis before improvement (by: downsizing, replacing motor, application, transmission and introducing variable frequency drives, etc.) is possible.

The program is based on Swiss industry experience and will be tested in the new Topmotors program also in China.

1. Where is the problem?

Electric motors, turning a squirrel cage rotor within a stator by the principle of induction, are the workhorse of global industry. They are cheap, simple and reliably running for 100'000 hours or more, even much more so with a little grease once in a while. Their simple construction with steel laminations and copper wiring and their robust build in a mostly cast iron frame means they can be operated easily with the least amount of controls and maintenance almost by every unskilled janitor under normal ("General Purpose") or even under adverse conditions of hot and cold, dry and wet, under dust and in smoke, heavy or light duty, continuously or on/off, with some precautions also in explosive atmospheres, etc. Their problem is their longevity, their durability, their good aging without wrinkles while new technologies arise.

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[1] VELANI: Improvement of Electric Energy use in Industry, feasibility study for the Federal Office of Energy, Switzerland 2015

Old age is not a functional disadvantage with electric motors, but a technological problem. Since more than 10 years motor technology has started to climb in efficiency. Better understanding of their electromagnetic properties and the geometry of the magnetic flux, the more careful selection of electro steel and high grade copper, the precision manufacturing with fine slots and densely packed wiring, has made them run cooler and smoother. And many percentages more energy efficient than before.

More important though, are the widespread use of electronic controllers and the integration of electric motors into complete motor systems with variable frequency drives, high tech gears, and potentially super-efficient applications in pumps, fans, compressors, also in transport, industrial handling and process machines. Better design calculation methods and simulation tools are facilitating the installation of properly sized machines with well-matched components. Together with factory automation to make parallel machines work together smoothly and supporting each other in sharing load and torque, the modern motor system is a high-tech combination of electronic, electro-mechanical and mechanical engineering.

This makes the performance of older standalone and fixed speed machines look old, outdated, and wasteful, in need of retirement, redesign and replacement. The good thing is that old motors can be recycled almost 100%: today's prices for copper, aluminum and steel might give a larger recycling fee than what the motor has cost 10, 20 or even 40 plus years ago.

In the Swiss Topmotors program[2] 4142 machines were listed and analyzed. 56.4% were older than the 10-12-15-20 year expected technical operation based on their size (see Table 1, [2]). On average the machines were much older than that: the ones exceeding their expected age limit were actually double the age.

2. The misconception about motor repair and retrofit

Motors are electro-mechanical machines that age and wear. Their mechanical parts (mostly ball or roller bearings) wear off even when regularly maintained. The wear has mostly mechanical and today also electric sources from converters. Worn out bearings make a machine noisy, vibrating and run unevenly. This can be detected easily from the outside without instruments. The bearings can be exchanged well in mid-size and larger machines. After the bearing-change, the motor will be as performant as before. In smaller machines (below 5 kW) this change will be too costly because of the dismantling of the machine.

The electrical part, mainly the copper wiring in the stator, can be damaged by overheating from overload, insufficient and malfunctioning cooling from ventilation, bad insulation and short-cuts within the copper coils also from exterior mechanical damage. This usually results in a machine failure and stop. The motor has to be disconnected, taken apart, cleaned from the old wiring and insulation and rewired (usually by hand). This process is time consuming, very costly and is feasible for machines over 30 kW only and machines with very specific properties. The rewiring in most cases results in a motor running at the same or lower efficiency than before. In very rare cases, a rewind by hand can include more wiring than the original machine-wound stator. In most cases observed, the general rewinding practice was far from "State of the Art" as demanded by EASA guidelines now since 1999 (see [3]).

Also rotors can be damaged, mostly from mechanical wear (lateral pull by belts above the allowed force) that leads to the rotor touching the stator and thus damaging both the squirrel cage and the stator wiring. It is difficult to replace an old rotor because they are not standardized products. Although the motor frame follows an IEC or NEMA standard (shaft diameter and height, bore holes, etc.), the stator and its gap are not standard. You have to be lucky if an old rotor matching a damaged rotor, can be found. Still this rotor replacement does not yet mend the also damaged stator.

The retrofit of old motors has two possible ways: one is to install a new more performant rotor (e.g. copper rotor). The other is to feed the single speed motor with a frequency converter. In both cases cost and disadvantages have to be considered. The stator, friction and winding losses are not reduced by inserting a new rotor. The old motor's winding is usually not fit and insulated well enough to handle

[2] Topmotors: Implementation program for energy efficient motor systems in Switzerland, 2010-2015, Zurich Switzerland

voltage peaks from converters and over-speed. The cooling is not prepared to work at reduced speeds. In the majority of the cases, a full motor replacement will be more safe and cost effective.

In all of these cases, the cost and time for the repaired IE1 motor competes with a readily available new more efficient IE3 or IE4 motor, adapted in output size and speed, and possibly fixed with a converter to adapt to the required load. Also, the renewal of the motor gives a chance to reassess the actually required load for the application, to improve the driven pump, the fan, the compressor, etc. and to get rid of old transmissions and throttles. A renewal concept for machines older than 10 to 20 years is an investment in an industry with higher productivity and less interrupts from failure.

The repair industry has long recognized their chances to avoid becoming superfluous by starting to expand their scope from changing bearings and wires to analyze motor performance, to also downsize and upgrade machines and to improve entire systems.

3. Quantitative background

The motor world is divided in the industrialized world (USA, Canada, Europe, Japan, Australia, etc.) and the developing part (with the fast growing BRICS economies like Brazil, Russia, India, China, South Africa, and the slower growing economies in Asia, Latin America and Africa).

In the industrialized world, the average age of the rolling stock is estimated to be around 20 to 30 years. The efficiency level of the rolling stock is around the efficiency class IE1 (based on IEC 60034-30-1, 2014, in [9]); the sales are around IE2 (with the exception of the few countries with mandatory MEPS already at IE3). In the high income countries of the industrial world the growth rate of the Gross Domestic Product (GDP) between 2012 and 2017 is according to the Worldbank (Figure 1) nowadays slow (1% to 2% p.a.), thus the market for expansion of industrial capacity is relatively limited; the market focus is on maintenance and replacement of running machines in factories.

Figure 1 GDP development and projections (Source: Worldbank http://www.worldbank.org/en/publication/global-economic-prospects/data, 2015)

In the developing countries the growth rate of the GDP is considerably higher (4% to 6% p.a.) but irregularly distributed; the market focus is on new factories in expanding industries being built everywhere. The average age of the rolling stock is around 10 to 15 years. The efficiency level of the rolling stock is around IE0 (15% higher losses than IE1), the sales are around IE1.

For China, as an example of a developing economy with high growth rate, this has been modeled in the China Motor Model in 2005 (see Figure 2, [5]).The strata that can be found in existing rolling stock are based on an average life time of circa 20 years and on an annual growth rate of the motor market of 3%. It shows that in order to improve the efficiency of motor systems the rolling stock needs to be addressed as well as the new motor sales. A systematic renewal requires a program that will lower the "natural" average age of exchange of old motors.

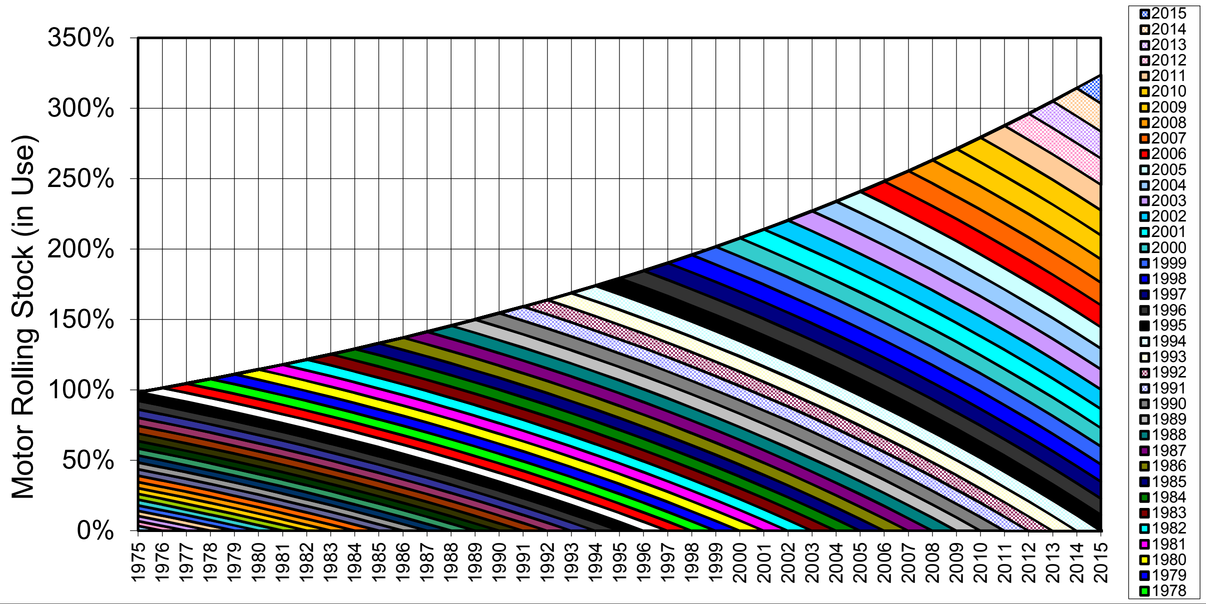

Figure 2 Age strata of motor stock with annual growth rate of 3% and 20 years average linear life time of operation (Source: China Motor Model 2005, in [5])

In normal factory analyses of rolling stock, reliable data on the age and the efficiency of motors can hardly be found. Rarely the rating plate show these data, even more rarely the technical specifications are still available in printed copies. For the sake of a rapid evaluation of the urgency for replacement one has to estimate the year of start of operation. Based on market data for the efficiency of motor sales (NEMA, CEMEP, etc.) and more recent market research data from IHS [6] the following approximation of efficiency by the respective year of the start of operation is used (see Figure 3).

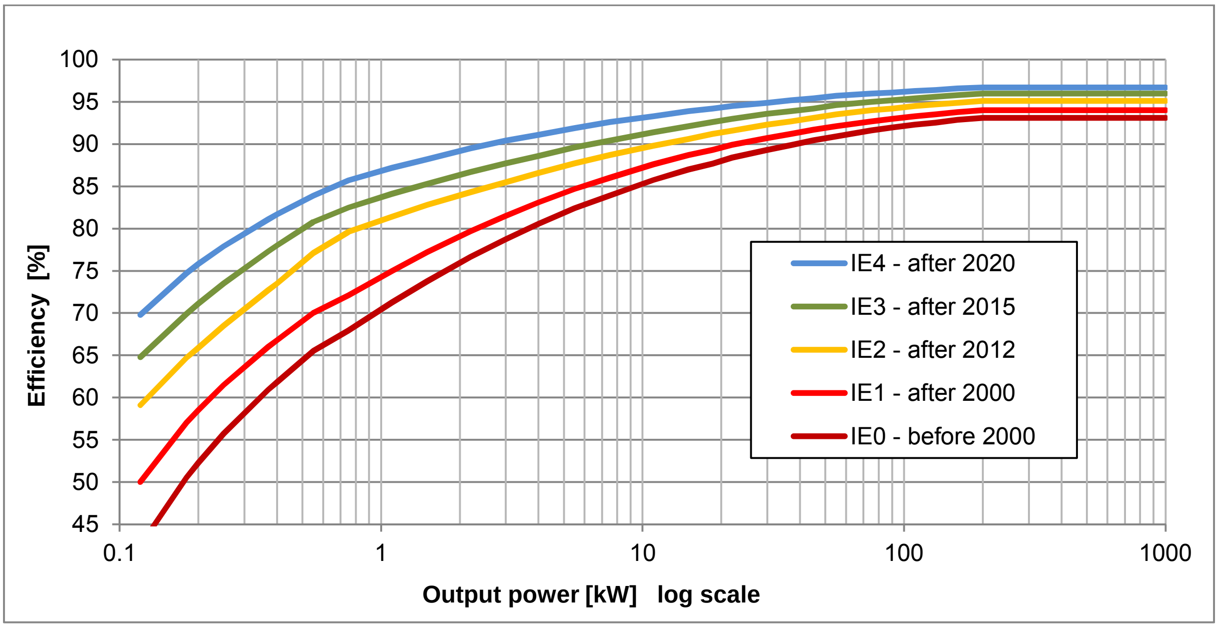

Figure 3 Motor efficiency by output power and year of entry into service (Source: S.A.F.E. 2014, based on IEC 60034-30-1, 2014)

Crucial for all industry programs is the distribution of the size of factories involved. Figure 4 shows the situation in Switzerland, based on data from 2007 and analysis in the context of new policy instruments in 2011. It shows that the group of classes above an annual electricity consumption of 0.5 GWh use 62% of electricity with only 3.9% of the factories. This is of course a favorable result indicating that a large deal of savings can be gained in an engineering driven effort including on-site analyses in this medium to large size range.

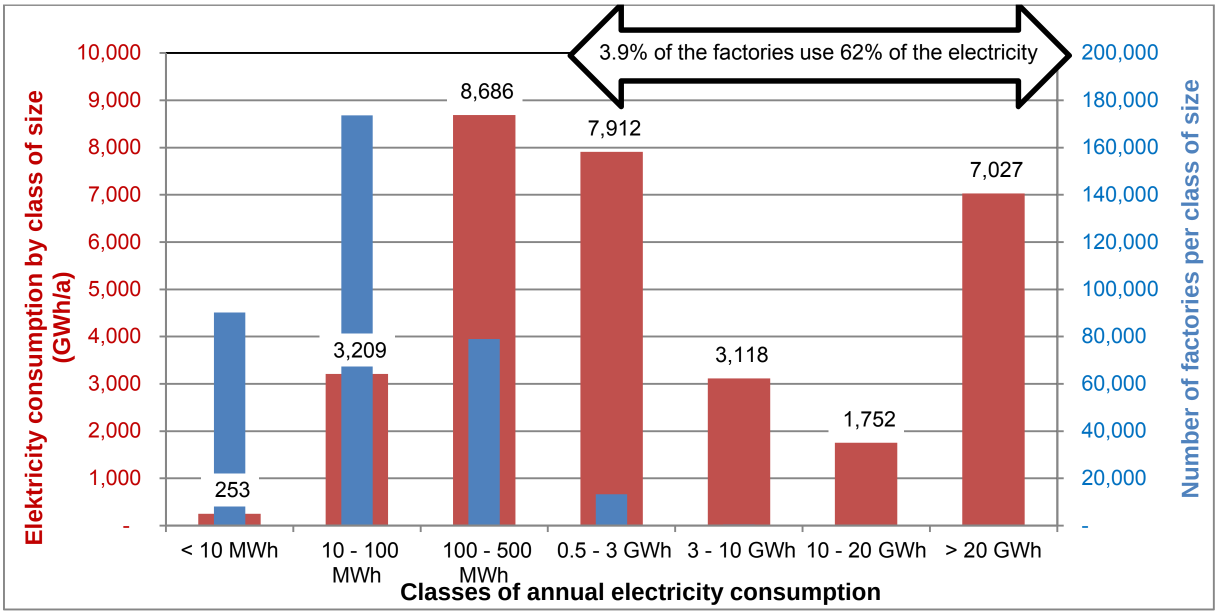

Figure 4 **Electricity consumption in industry and service sector by size (Source: S.A.F.E. 2014)**

The age structure of electric motor systems was analyzed on 4 122 motors in Switzerland (Easy 2010-2014, [1]). The results show that 56% of the motors are older than their technical life expectancy (see Table 1) which was defined based on de Almeida in [2] as:

Table 1 **Average operating life expectancy of electric motors (Source: de Almeida [2])**

Motor output size	Average technical operating life expectancy
< 1 kW	10 years
< 10 kW	12 years
< 100 kW	15 years
> 100 kW	20 years

The analysis of the 4 142 listed motors by 4 classes of motor output size is shown in Table 2. Important fields with a higher share of older systems than average for a retirement program are marked in green.

Table 2 **Analysis by classes 1 to 4 of motor output size (Source: Easy 2015 [1])**

Easy data	output power (kW)			number of motors	years too old		share too old	VFD	efficiency potential		
class	from	to	average		a	share	share	share	MWh/a	share	kWh/a motor
1	0.1	0.99	0.5	623	8.6	86%	80%	3.9%	134	17.7%	216
2	1	9.9	3.9	2'094	5.6	46%	64%	15.5%	1'304	6.7%	623
3	10	99	30	1'206	0.9	6%	43%	35.2%	2'499	3.1%	2'072
4	100	999	178	160	-3.1	-16%	39%	26.9%	1'627	2.2%	10'169
average	**0.015**	**4'050**	**21.2**	**4'142**	4.4	39%	60%	19.8%	6'290	3.2%	1'519

4. Policy instruments

A motor system retirement program MSRP has to be embedded in a complete energy efficiency policy framework to rejuvenate industry. It includes:

- Regular mandatory audits with standard protocols,
- Negotiated efficiency target setting for 5 to 10 years ahead,
- Annual monitoring programs,

- Financial incentive programs,
- Build-up of capacity for energy efficiency experts for industry,
- Training of factory in-house technical personnel.

The renewal of existing overaged rolling stock is a wide ranging transformation of industry. It will require considerable attention of policy leaders and investors. It will not be based on the economy of energy efficiency alone. It requires an integral understanding of lowering risk of energy supply disruption, dependency on imported and eventually limited energy resources, strategic development of manufacturing locations and potentials.

It also includes a new understanding of how industrial energy investments are taken. The approach solely based on short term economic benefits (expressed in the usual less than 3 years payback rule) does NOT solve the problem for mid and long term. It requires a well-balanced decision making procedure based on the three key elements: risk, value and cost (see C. Cooremans, 2013 in [8]).

The introduction of MEPS only influences sales of new machinery but does not necessarily stimulate the renewal, maybe even to the contrary. It can give the owner the (false) economic incentive to stay with his old rolling stock to avoid buying more expensive new equipment.

5. Financial incentives

Even with payback times below 3 years, industry economic culture is not ready for investment in energy efficiency. Financial incentives that pay at least for the analysis and the training of the in-house personnel open doors and create awareness (see Financial Incentive Program Easy, in: [1]). If strategic goals of a management converge with the proposed systematic Motor Systems Retirement Program and if environmental concerns are already part of the company profile the chances are good to start. Short payback times are usually not yet enough to convince the management to go through the effort of the necessary engineering analysis and the potential interruption of the production during replacement work. Both managers and technical staff shy away from the added risk of new machines with higher technology not operating smoothly from the beginning.

The financial program needs to reassure the management and confirm this:

- The new technology is proven and safe.
- The program team has the necessary knowledge and experience.
- No leaks of confidential information to the outside.
- The preparatory engineering and measurements are necessary to decide on the best and most cost effective replacement.
- The replacement period can be planned and the production interruption can be kept to a minimum.
- The cost-effectiveness can be calculated at the outset and monitored at the start of the new operation.
- A competitive tendering will render the best offer.
- Guarantees of performance, energy efficiency, service intervals and MBF (mean time between failures) can be negotiated early on.
- The red tape (bureaucratic administration) to get financial incentives is kept to a minimum.

In many cases as in Switzerland, the US and UK, etc., a number of financial incentive programs already coexist in a non-coordinated way. Central, provincial and local government, together with power utilities and other groups, run efficiency programs with different focus also for industry. Some programs focus on pilot & demonstration projects, others on research & development, while many give incentives for actual energy improvement of existing rolling stock or new machines. For industry, the effort to find a potential financial incentive is too high and the process too tiresome. A central industry information platform can be built.

6. How to start

Motor system size

All industries use electric motors in large numbers. Very young high-tech industries that have been built only in the last decade will not have the problem of old motors.

Certain manufacturing processes typically require large numbers of very small motors (around 1 W to 10 W for electronic equipment and motor cars; around 100 W to 500 W for robots, etc.), medium size motors (around 1 kW to 5 kW for machine tools, conveyors, etc.); most industries need medium range (5 kW to 100 kW) motors; only few specific industries need large (100 to 10'000 kW) motors for industrial processing in large furnaces, refineries, compressed gas pipelines, steel mills, coal mines, stone cracking, etc.

Motors over 500 kW are sometimes Medium or High Voltage and mostly custom made. Standard motors in Low Voltage (below 1000 V) lend themselves easier for replacement programs because they are catalogue products held in stock with short delivery times.

Factory size determines audit methods

The audit program has to be differentiated according to the size of the factories to be analyzed and improved. Larger companies have a higher chance of having their own in-house capacity and competence for energy efficiency improvements. Also, engineering costs with necessary on-site measurements and calculations are in large factories in a much better proportion to potential savings.

The analysis can be based on the Motor-Systems-Check[3] with a four step audit.

Quick MSC MotorSystemsCheck	*Select MSC* MotorSystemsCheck	*Full MSC* MotorSystemsCheck
Web based, interactive < 0.5 GWh/a < 60 k EUR/a	Selective on-site analysis > 0.5 GWh/a; <10 GWh/a > 60 k EUR/a; < 1'200 k EUR/a	Systematic on-site analysis > 10 GWh/a > 1.2 million EUR/a

Figure 5 Motor-Systems-Check: three variants according to size of factory

This distinction of the audit methodology (see Figure 5) into three classes of factory size is necessary to allow for costly engineering audits on site in relationship to the potential energy cost savings.

- The **Full MSC** is designed for factories with more than 10 GWh/a (1.2 million EUR) electricity consumption. On-site engineering support and training.
- The **Select MSC** for 0.5 to 10 GWh/a (60'000 to 1.2 million EUR/a): web-based analytical tool with engineering support on site (walk through audit), see Figure 6
- The **Quick MSC** is targeting companies with less than 0.5 GWh/a (below 60'000 EUR/a): fully web-based interactive dialogue with standard improvement check lists. Telephone hotline.

It can easily be understood that a bigger factory (Full MSC) using EUR 1.2 million electricity cost per year can well afford an in-depth 4 step audit over 2 years: This will need 3 expert engineers for audit and measurements that will cost around EUR 100'000 and propose an annual decrease of 2-3% of electricity cost over the next 10 years. This involves both external specialist engineers as well as trained in-house staff to implement the defined improvement measures. On the other side it is also understandable, that a small factory with EUR 60'000 electricity cost per year (Quick MSC) will not be able to afford for 2 engineers taking measurements on a number of machines and proposing improvements of 5 to 10% within the following 3 years. It will then rely much more on web-based interactive dialogues and standardized learning modules.

[3] The Motor-Systems-Check was introduced in 2010 by S.A.F.E, within the Topmotors program. It includes the software tools to facilitate the analysis.

Basic Company Data					
Company		Epsilon Ltd, Cast Iron Technology			
Address		Bahnhofstrasse 10, 4566 Wülflingen			
Contact		Peter Meier, technical manager			
Employees	Anzahl	821			
Operation	hours per year	4800			
		Energy consumption		Energy price	Energy cost
		original units	GWh/a	CHF/kWh	k CHF/a
Electricity	GWh/a	13	13	0.12	1'543
Distric heating	GWh/a	0			-
Heating Oil	t/a	487	6	0.05	292
Gas	m3/a	657	7	0.08	526
other		0			-
on-site					
Total	GWh/a		25		2'361

Equipment overview				Urgency				
Electric equipment	Number of units	Electric power (kW)	Electricity consumption (MWh/)	Average age (>20 a; >10 a)	Average size (>100 kW; >30 kW)	Hours of operation per year	Share (<20%; >10%)	Priority
Pumps	12	453	2'718	18	38	6'000	21%	2
Fans	22	324	1'361	12	15	4'200	11%	3
Compressors cold	8	1'200	3'600	22	150	3'000	28%	1
Compressors air	8	130	390	18	16	3'000	3%	
Transport goods	6	120	106	26	20	880	1%	3
Transport people	4	40	32	26	10	800	0%	3
Process machines	22	777	2'953	12	35	3'800	23%	3
UIP	4	50	430	8	13	8'600	3%	3
Light	444	12	53	12	0	4'400	0%	3
ICT	34	12	29	4	0	2'400	0%	
Trafo (3%)	2	4'500	1'183	23	68	8'760	9%	2
other	23	145	9	10	6	2'000	0%	
Total	589	3'263	12'862	15.9	5.5	3'942	100%	

Figure 6 Select MSC: web based analytical tool with engineering support on site (Source: Impact Energy, 2015)

Analytical steps

DECISION MAKER (see Figure 7):

With the motor list established for the majority of the machines in a factory, the first step is to determine the machines with the best potential cost effectiveness for improvements. S.A.F.E. uses the Decision Maker as part of the Intelligent Motor List (ILI+)[4] to do so. It allows securing the “20-80-rule”, that means to implement 80% of the potential savings by only working on 20% of the rolling stock. The selection criteria are age, operating hours per year, output size and use of variable frequency drives. It can also focus on applications: pumps, fans, compressors for cold and compressed air, mechanical conveyors, etc. The selected machines then undergo measurement tests and detailed assessment to be reported in the STR (Figure 8).

Consumption datas and potential of reduction by motor replacement

	[MWh/a]	[MWh/LC]	[EUR/a]	[EUR/LC]
Consumption effective	10'672	209'350	1'600'746	31'402'563
Consumption optimised	10'194	200'101	1'529'174	30'015'216
Potential of reduction	477	9'249	71'572	1'387'346

Potential of reduction according to criteria

Criteria		Default values	My values	Number of motors		Potential of reduction of energy		Potential of reduction of costs	
				absolute	in %	[kWh/a]	[kWh/LC]	[EUR/a]	[EUR/LC]
(1) Rate of realisation of the maximal saving potential in %		50	80	7	21%	398'069	7'961'355	59'710	1'194'203
(2) Age, older than x years		15	20	26	76%	454'224	8'843'372	68'134	1'326'506
(3) Operating hours per year > x Stunden		3000	1800	17	50%	464'787	9'104'496	69'718	1'365'674
(4) Dimension of motors > x kW		10	10	18	53%	468'018	9'154'437	70'203	1'373'166
(5) Motors without FC (frequency converter)		yes	yes	34	100%	477'148	9'248'973	71'572	1'387'346
(6) Application	Pump	yes	yes	12	35%	253'494	4'936'162	38'024	740'424
	Ventilator	yes	yes	6	18%	3'596	37'286	539	5'593
	Compressor air compr.	yes	yes	10	29%	216'770	4'241'533	32'516	636'230
	Compressor cold	yes	yes	4	12%	2'084	21'468	313	3'220
	Mechanical conveyor	yes	yes	2	6%	1'204	12'524	181	1'879
	Others	yes	yes	0	0%	0	0	0	0

Calculate

Display

Figure 7 Decision maker: tool to determine the most cost-effective improvements (Source: S.A.F.E., ILI+ 2014[4])

STANDARD TEST REPORT (see Figure 8)

[4] ILI+ Intelligent Motor List, software tool, download under www.topmotors.ch/download

The key element in the MSRP is a solid methodology to calculate in advance the expected energy savings and the payback.

This requires a tool to analyze the measured current energy use and some guidance in calculating the replacement energy use and cost. The Standard Test Report (STR)[5] was developed for this task. Generally, it is not easily possible to measure on site all components of a system with sufficient accuracy. This can only be done under laboratory conditions. But, it is possible to combine measurements, data from rating plates or technical documentation with observations during the starting and operating situation. Together with operating data (daily, weekly and yearly operating hours under specific loads) a fairly precise calculation can be made. It includes a detailed step by step analysis of the current load based on the efficiencies of the individual components involved.

First the data and estimates of the current situation in the actual state have to be understood and quantified. Once the result fits the measured overall electrical input power, the improved efficiencies of new components can be introduced in the calculation. With this the possible energy savings can be calculated fast. They can also be tested as to which component provides high or low savings at high or low cost.

A fast cost estimate requires experienced engineers or a lot of inquiries to individual manufacturers of components. Planning, dismantling and assembly as well as introductory time and costs for new control equipment need to be included in the cost-benefit-analysis.

	Energy consumption				
	(definition see right side)		unit	actual state old motor	target state new motor
application	1 reduction at fan		%		10%
application	2 output power at fan	$P_{mech\,3}$	kW	7.17	6.46
application	3 efficiency of fan	η_A	%	45%	65%
	4 power output transmission	P_{mech2}	kW	15.94	9.93
transmission	5 efficiency transmission belt	η_T	%	90%	96%
transmission	6 efficiency gear	η_G	%	100%	100%
	7 output power (motor)	P_{mech1}	kW	17.71	10.35
motor	8 nominal power (motor shaft)	P_{mech}	kW	55.0	15.0
motor	9 efficiency (100% load)	η_{nom}	%	90.5%	92.1%
motor	10 efficiency average load	η_{teil}	%	80.5%	92.0%
	11 average system load factor	LF	%	36%	69.0%
motor system	12 efficiency VFD	η_{FU}	%	100%	96%
motor system	13 reduction due to VFD		%		20%
motor system	14 total el. power	P_{el}	kWe	22.0	9.4
motor system	15 operating hours	t	h/a	3'000	3'000
motor system	16 mechanical work (output)	E_{mech}	kWh/a	59'730	31'035
motor system	17 el. energy (input)	E_{el}	kWh/a	66'000	28'111
motor system	18 costs el. energy		CHF/a	8'250	3'514

Economic feasibility			
payback (static)	years	2.0	
Cost efficiency*	cts./kWh	1.7	*investment costs per each kWh saved

Figure 8 STR: comparison of current and future energy use. (Source: S.A.F.E. Easy 2015, [1])

[5] STR, download under www.topmotors.ch/download

Replacement sequence

Any industrial renewal program involving process-based equipment needs to go through a systematic order of sequence. The technical staff and the management group have to be convinced of the necessary investment decisions and implementation plan. The time line for budgeting and for the appropriate slot of time to make changes in equipment that will halt part of productions have to be carefully planned.

The program starts with the clear notion that any improvement will pay its cost back within 3 years or less. The incentives needed are used mainly (or exclusively) to overcome the barriers of "not knowing where to start, what exactly to do", that means to pay for the necessary on-site analysis and the engineering of the development of the improvement package of measures.

The mid-term program is a joint venture between three major groups:

- the enterprise, meaning the factory owners, managers and operators,
- the national efficiency program leadership who sets national targets, allocates financial incentives and monitors developments and success,
- the energy improvement program managers who provide training, methodology, experience, resources, checks and inspiration.

Table 3 MSRP in an enterprise: step by step

1.	Inform management on a systematic performance review of old motors systems and get agreement for retirement plan
2.	Train technical staff for Motor-Systems-Check: savings potential analysis, intelligent motor list
3.	Start measurement campaign for high risk and old machines, train staff for STR in order to provide reliable payback and savings estimate
4.	Plan ahead for necessary budgeting periods
5.	Identify your motor systems (and their twins) ready for retirement
6.	Check necessary output size and potential motor systems improvement
7.	Build improvement package based on payback and life cycle cost
8.	Define priorities for implementation based on technical, operational and economical concerns
9.	Set best time of the year for replacement (service periods over summer or winter holidays)
10.	Estimate necessary cost and time for first implementation stage
11.	Get project budget allocated
12.	Prepare detailed specification documents for equipment to be improved including performance test requirements
13.	Tender with competitive suppliers, clarify service and maintenance cycles
14.	Start replacement program with one typical pilot machine per application: improve application with necessary maximum load and best operating point, resize, install IE3 or IE4 motor (according to IEC 60034-30-1, in [9]) plus VFD if needed, eliminate throttle, eliminate or improve transmission and gear. Integrate in factory automation system.
15.	Test performance of pilot machine and adjust controls.
16.	Implement replacement for all the systems in the same age group in defined steps, not disrupting parallel processes.
17.	Set up monitoring system for energy performance and report regularly to management on progress

7. Necessary ingredients for a motor system retirement program

The MSRP needs the following set of key ingredients that support each other:

Table 4 Ingredients for a national MSRP

A **financial incentive** to make the program rolling (see also recommendations in: [7]). It needs a sufficiently strong support of some 50% for the initial preparatory analysis of the motor system until the improvement measures are clearly defined, and a smaller incentive of some 20% for the actual investment for new machinery that generally pays back within the first 3 years required in industry.
A **mandatory regular audit program** similar to the European Energy Efficiency Directive [10] that is now put into law in Germany in 2015. It needs a specific audit methodology (based on ISO 50002) and a four year update cycle. Plus, it needs precise rules to stipulate to what degree and within which delays the identified energy efficiency findings have to be implemented.
A **training program** for both engineers working as motor system analysts and technical operators in factories who need to maintain their rolling stock, as well as upgrade, analyze and plan the necessary improvements. It is clearly focused on the retirement of old, inefficient, oversized and not yet load controlled motor systems.
Advanced **observation tools**: the on-site testing and analysis of the efficiency of motor systems is complex and very costly. It will be done only in a strong engineering effort as part of a systematic audit and condition monitoring for machines that have been already been identified for having superior efficiency potentials because of their age, size, operating hours, etc. But, it also needs a grid operated network of small sensors attached to machines to continuously monitor temperatures, operation hours, electric input power (and thus partial load) and potentially also output flow. They can deliver continuous data to systematically plan replacement before machines fail.
An **analytical method** like the Motor-Systems-Check[6] with the respective software tools to go from the quick analysis of the efficiency potential (SOTEA tool), to the intelligent motor listing with a decision maker included (ILI^+ tool) onto the Standard Test Report (STR tool) of measurements with a methodology for current and potentially improved energy use. For the integration of motors, VFD and application, also the Motor Systems Tool[7] can be used.

The MSRP has to be embedded also in an Industry Awareness program and a Monitoring & Verification program that secures the compliance both with the regular audits and the subsequent implementation.

8. Conclusions and recommendations: the way forward

It has been observed that there is a problem with overaged motor systems throughout global industry. To harvest potential energy savings a regular and systematic retirement program will need to be established. First in the old and saturated economies in the industrialized world where a larger fraction of machines are in service 20 years and more. It seems appropriate to say that the observations show that industry by itself will not amend it rapidly. Government targets and mandatory actions are needed to speed up and focus the retirement process for old, inefficient and oversized machines.

The misconception of motor repair, motor retrofit and upgrade is presented as bearing in most cases higher risks, producing less energy savings and proving lower cost-effectiveness. Old motors can be easily recycled, and also rapidly replaced by high performant and downsized motors and systems that are now readily available.

The benefit of an integral motor replacement program is considerable: In Figure 9 three IEA scenarios from [11] show how much energy can be saved by efficiency regulation. The "Least Life Cycle Cost"

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[6] Download tools for Motor-Systems-Check at www.topmotors.ch/Download/
[7] Motor Systems Tool: download at www.motorsystems.org/motor-systems-tool

(LLCC) Scenario tops the savings with 30%. The "Policy Scenario" takes effect in 2015 and will potentially affect 60% to 80% of the sales by 2025. This scenario will be leading to total electricity savings of 25% compared to the reference scenario by 2030. The underlying assumptions are that pumps and fans can be 40% more efficient, compressors 25% and mechanical process and transport machines 20% than in 2010.

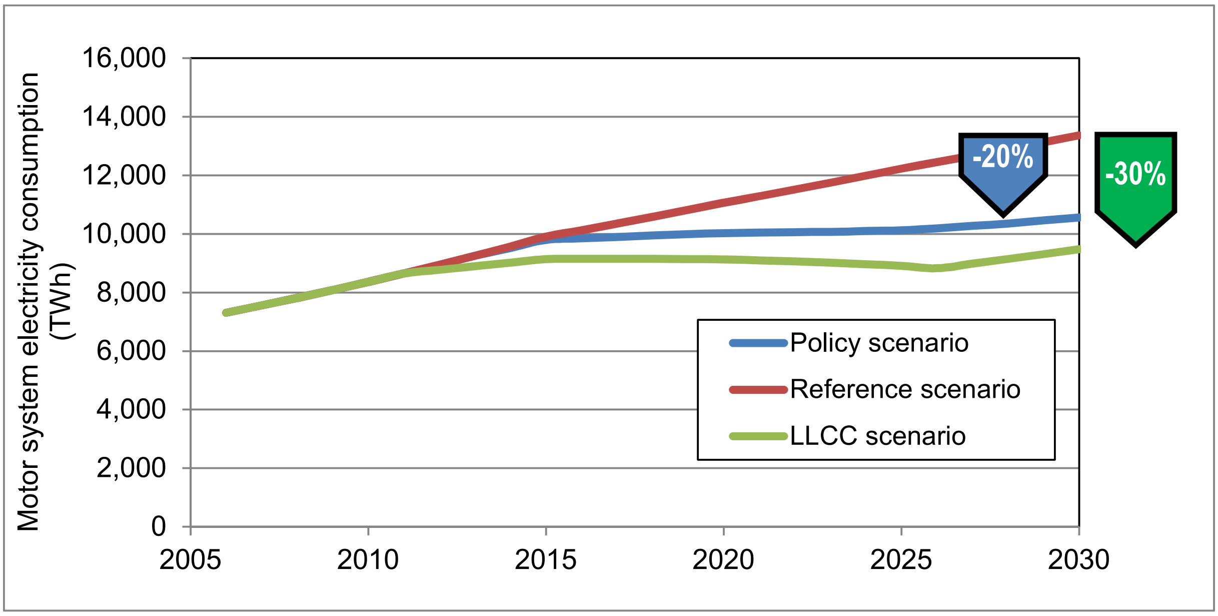

Figure 9 Energy efficiency development paths for motors systems (Source: Paul Waide and Conrad U. Brunner, IEA 2011, in: [11])

The challenge for a MSRP is to bring a bouquet of flowers together that includes the two key ingredients: the regular mandatory industry audit and the financial incentive focusing on system analysis and improvements. It is possible to envisage that a number of governments will embrace their role and secure their tasks in cooperation with motor manufacturers (and also pump, fan, compressor, etc.) and industrial users.

A comprehensive MSRP has yet to be tested. Every country, European, US, Asian, Latin American, etc., is invited to take part in this retirement program and to help make it a global success. All experiences will be shared.

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Consortium Based Energy Efficiency Research in Finland – Results and Benefits for Participating Companies

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Abstract

The programme on efficient energy use (EFEU) within the Finnish CLEEN consortium has been running for over three years. The programme is geared at providing methods, tools and technologies to enable a gradual increase in energy efficiency beyond what can be achieved by constant improvement and application of Best Available Technology (BAT).

The generic target of the EFEU research programme is to develop methods and tools to measure, model, analyse and optimise energy efficiency. The basic idea is to use a system level (top-down) approach in different scales instead of optimising individual system components.

The main focus areas for the third funding period (2014-2015) are Energy efficient fluid handling systems and Energy efficient regional energy systems. The focus areas have been selected to match the strengths of the current consortium and past learning from the first two funding periods (2011-2014). The planned EFEU research will provide a basis for developing future energy efficiency export concepts including products, control strategies and services, which are expected to be on the market in a time frame of five to ten years.

The research work is organized in four work packages (WP). The WP1 covers System energy efficiency analysis and optimisation. The WP2 focuses on Integrated energy efficient systems. The WP3 concentrates on the Regional energy efficiency solutions and services. The Assessment of medium and long term changes in business environment and Dissemination is carried out in WP4.

The consortium members have been selected by invitation to represent a strong combination of major industrial and supporting research organisations. Partners are specialized in the core expertise areas needed to fulfil the objectives of this programme. A shared budget together with shared competence creates an efficient way to run this kind of R&D programmes. The programme is also supported by the Finnish Funding Agency for Technology and Innovation, Tekes.

This paper presents the latest results of the programme. A foresight study – a joint activity by the whole consortium – has been started. Three future scenarios have been defined and the results will be published in spring 2015. A doctoral dissertation on energy-efficiency-based speed control of parallel-connected pumps was carried out. A method and software have been developed for multi-period optimization of regional heat supply systems, with suppliers, consumers and storage facilities. A small LNG supply chain has been optimized and an earlier one-dimensional formulation has been extended to two-dimensional cases.

Introduction

The well-being of people, industry and economy depends and has depended on safe, secure, sustainable and affordable energy. There is a strong and proven correlation between GDP and energy usage. Currently, the world energy and average power consumption is based on fossil fuels representing more than 80% of total energy use. The availability of fossil fuels, oil being the most significant one, is becoming scarcer than nowadays due to rapid growth of consumption. Simultaneously, the quality of the new energy sources decreases causing a declining trend of EROEI (Energy Return on Energy Invested). In order to handle the upcoming energy crisis, the EU Commission has declared a five step strategy. The first and the most important step in the strategy is to achieve an energy efficient Europe. The goal is to reach 20% savings in primary energy use by 2020. The main drivers behind the decision are: saving of non-renewable resources, threat of excessive climate change, competitiveness of the European industry, and reduction of energy independency due to decreasing availability of fossil fuels. The improvements in end-use energy efficiency have a positive effect on all above mentioned topics. The EFEU programme utilises a systematic approach to energy efficiency in its focus areas of industrial systems, energy chains and regional energy systems. The selected research approach requires multidisciplinary research co-operation. The selected research themes are extremely important to Finnish industries as well as the society.

The main objective of the EFEU programme is to provide methods, tools and technologies to enable a stepwise increase in energy efficiency beyond what can be achieved by constant improvement and application of BAT technologies, and ultimately to move economical and technical efficiency boundaries of process and energy systems through system integration, optimisation and technology development [1].

This paper presents some the results so far and benefits of these results for the participating companies. Because of the nature of the pre-commercial research activities it is quite difficult to estimate the final savings. These research results are used by R&D departments of participating companies and finally brought to markets after 5 to 10 years period. Instead this paper is linking the results to business plans of the participating companies.

Programme structure

The EFEU programme consists of four work packages: WP1: System energy efficiency analysis and optimization, WP2: Integrated energy efficient systems, WP3: Regional energy efficiency solutions and services, and WP4: Foresight and dissemination.

The focus areas of WP1 are: 1) energy efficiency analysis methods and 2) optimization of energy efficiency in complex systems.

WP2 focuses on the technology research on 1) the development of novel heat transfer and storage fluids, 2) fluid handling systems, and 3) assessing energy efficiency in upstream oil and gas production value chain.

WP3 concentrates on the research of regional energy efficiency solutions and service concepts. Energy efficient control strategies will be developed for ship energy systems and regional energy systems.

All partners of the research programme will participate in WP4, Foresight and Dissemination that consists of two themes. The first one focuses on assessing the significance and focus of energy efficiency with the help of different future world scenarios. This is used as a basis for analysis, where these future changes will affect industry, energy efficiency research, and society. In the WP4, the contributions of the actors outside the EFEU programme are utilized. Another task in the foresight part is to study the ongoing regulation and standardization work related to energy efficiency and energy efficiency products.
The second theme of WP4 is to disseminate the results of the programme. An important aspect of dissemination is to take care that the research results will be utilized in education at different levels. In this task, vocational training foundation AEL and Motiva, an affiliated Government agency that promotes efficient and sustainable use of energy and universities have an essential role.

The programme partners come from organisations, which represent high-level technical and scientific excellence in the area of energy efficiency technologies. The consortium consists of organizations listed in Table 1. In addition to the direct co-operation within the programme, the consortium members are connected to an extensive network of partners, suppliers, and international research institutes that participate in the work without direct membership in the programme..

The total budget for the research programme for the period 7.9.2011–31.12.2016 is approximately 12 million euros [1].

Table 1. Consortium partners

Number	Name
1	ABB Oy
2	Empower IM Oy
3	Fortum Oyj
4	Fortum Power and Heat Oy
5	Gasum Oy
6	Helen Oy
7	SKF Aktiebolaget
8	Sulzer Pumps Finland Oy
9	Valmet Technologies Oyj
10	Wellquip Oy
11	Wärtsilä Oyj
12	Aalto University
13	Lappeenranta University of Technology
14	Tampere University of Technology
15	VTT Technical Research Centre of Finland
16	Åbo Akademi University

Objectives

The current main focus areas for the EFEU programme are
- Energy efficient fluid handling systems
- Energy efficient regional energy systems.

The focus areas have been selected to match the strengths of the current consortium and past learning from the two first funding periods. The planned EFEU research will provide a basis for developing future energy efficiency export concepts including products, control strategies and services, which are expected to be on the market in a time frame of five to ten years.

Energy efficient control of regional energy systems is a new research area for the third funding period.

Table 2. Main focus areas for the third funding period.

	Energy efficient fluid handling systems	Energy efficient regional energy systems
Design	• Methods, tools and understanding to optimize and design life-cycle cost efficient pump, fan and mixer systems • Novel materials for heat transfer and storage fluids	• Understand the balance between energy, cost and CO2 efficiency in energy chains, optimise large regional energy systems • Strategic assessment of long-term scenarios for radical changes in energy supply systems
Control	• Energy efficient control strategies for different pump/blower/mixer systems and tasks	• Develop knowledge of the physical behaviour needed for controlling energy systems in energy efficient ways. • Develop control strategies that maximise energy efficiency at system level
Services	• Internet-based services allowing long-term monitoring and large-scale diagnostics of pump, fan and mixer systems	• Clarify future roles in energy business from regional points of view

In Table 2. the main focus areas of the EFEU program are presented. In Fluid systems we are designing an integrated pump-motor combination with intelligent control unit to demonstrate the earlier research work and utilize the results. Linking Internet of Things and service offering we can test not only technical solution but also new commercial approach. On Regional energy systems we have tested the method to unite local players together. After data collection these players meet and share ideas of possible co-operation in future. Practical examples have proofed that this approach is working and there is potential to boost the efficiency of the local energy systems.

Additionally, the methods and expertise developed during the first two funding periods will be applied in assessing energy efficiency of oil and gas production value chain. Future scenarios will be developed and implications on future energy efficiency businesses will be assessed [1].

The latest results

The result highlights of the latest period are [2]:

- Foresight study – a joint activity by the whole consortium – has been started. Three future scenarios have been defined and the results will be published in spring 2015.
- Journal article “Assessing energy efficiency of a small-scale biorefinery – A case study at the University of Limerick” written in collaboration between University of Limerick, Ireland and Aalto University.
- Conference article “Primary Exergy Efficiency- Effect of System Efficiency Environment to Benefits of Exergy Savings” presented at ECOS14 conference
- Journal article "The thermal analysis of a combined heat and power plant undergoing Clausius–Rankine cycle based on the theory of effective heat-absorbing and heat-emitting temperatures" published in Applied Thermal Engineering.

- Doctoral dissertation on energy-efficiency-based speed control of parallel-connected pumps.
- A method and software have been developed for multi-period optimization of regional heat supply systems, with suppliers, consumers and storage facilities. A small LNG supply chain has been optimized and an earlier one-dimensional formulation has been extended to two-dimensional cases.

These results will be presented by work packages in the following chapters.

WP1 System energy efficiency analysis and optimization results

One of the main results of WP1 in the recent period is the article “Primary Exergy Efficiency- Effect of System Efficiency Environment to Benefits of Exergy Savings” that was presented at ECOS14 conference [3]. In this work an advanced energy assessment method called Primary Exergy Analysis (PeXa) is explained. This method combines Primary Energy Efficiency (PEE) and Exergy Analysis (EXE). The objective of the method is that the whole energy chain needs not to be modelled, but yet the effect of an energy improvement can be analysed with respect to the whole energy chain. Also the losses of studied processes are assessed based on exergy values. The method is presented by a simple district heating system. PEE does not work well alone inside production processes especially because the factors are calculated only for products of interest. Inside a process also different products like semi-products typically exist and these products don’t have any factors available. Individually EXE could be used, but then there arises a need to analyse all the possible energy chains leading to the final products. This is typically very time-consuming and hence it is much easier to use product factors to model the surroundings. Additionally PeXa considers the system exergetic values of the products, not just the exergetic values of the products produced in the process being studied. For this reason the PeXa method provides an improved approach for energetic performance assessment. In the future the Pexa method will be developed further by providing energy factors that are based on exergy, not energy values. Additionally the method will be used to assess CO_2 emissions and non-energy products. The method will also be applied in more complex production chains and used as a performance indicator in multi-objective process optimization projects.

For Gasum Oy these results give an opportunity to compare different smaller-scale gas-based energy production systems. Such systems could utilize both natural gas and bio-gas components and contain peak-load and back-up systems. System –level impacts of these are important to be demonstrated clearly.

One interesting WP1 result is related to the optimization of a LNG distribution system. Small-scale supply chains of liquefied natural gas for ships have been selected as an example of an energy chain to be optimized. An early model of the supply chain along the Finnish coastline, combined with decisions and dimensioning of LNG terminals to be constructed and truck transports for LNG delivery points was developed [4], considering investment and operation costs. The model was used for a sensitivity analysis [4][5], where, e.g., the effect of a drop-out of some main consumers on the performance of the supply chain and the effect of the truck-based transportation costs were studied. In a continuation of the work, the model was extended to two-dimensional cases. Figure 1 illustrates the optimal solution for ship routing and truck transports, with two main LNG supply terminals (Inkoo and Tornio) and satellite terminals constructed at the optimal sites for supplying to consumers at the coast and farther off.

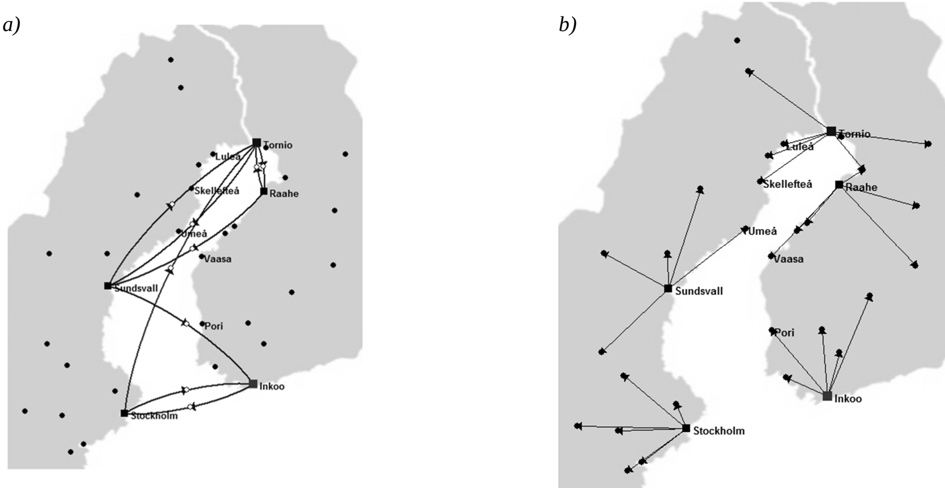

Figure 1. Connections for shipping LNG from supply ports to receiving ports and b) connections for LNG distribution from ports to consumers.

In order to evaluate the strategy on cases with more two-dimensional features, routing problems for an LNG supply chain from some main natural gas liquefaction plants to a number of power plants located on islands were considered, optimizing the routes, deliveries and ship sizes. This system has been evaluated under different LNG demand at the power plants, different LNG prices at the liquefaction plants, etc. Figure 2 provides an illustration of the solutions for two cases, where ships of a different size have been depicted by different colours. The optimizer has found Florida and Trinidad & Tobago to be suitable supply ports. In the first case (left panel) ships of one size are used to supply the island, applying load splitting at some ports, while in the second case three different ship sizes are optimal for the delivery, avoiding load splitting [2].

Figure 2. Optimal solution for an LNG supply problem to a set of power plants located on islands under two different sets of demand at the power plants located on the islands

For Wärtsilä Oyj these results help to modernize power plant installation base. In some cases LNG based fuel option might be an attractive solution to update coastal power plants using conventional fuel.

WP2 Integrated energy efficient systems results

Results presented in this paper focus on Energy efficient fluid handling systems. A journal paper on energy-efficiency-based speed control of reservoir pumping applications was accepted for publication in Springer Energy Efficiency Journal in July 2014 [6]. The feasibility of a proposed control scheme has also been tested in Heimosilta wastewater station in Lappeenranta during autumn 2013, and the test results were published in Vesitalous trade journal in March 2014[7]. Also a public presentation on these tests was given during the event Energiatehokkuuspäivät at LUT, Lappeenranta University of Technology, on 25-26 of March 2014 (http://www.lut.fi/energiatehokkuuspaivat). As its name implies, this event promotes methods to improve energy efficiency in pumping, fan and compressor applications. Pumping System Optimization Tool was also promoted in the SHOK Summit in Helsinki on 15th May 2014.

LUT organized the EPE'14 conference on August 2014 (http://www.epe2014.com/). EPE is the largest European Conference event related to power electronics and their applications. Tero Ahonen presented there his review paper on the most energy efficient and suitable electric motor type for realizing next generation pumping systems, which is one of the ongoing key targets in EFEU with Sulzer Pumps and ABB. Also a paper on energy-efficiency-based pump control for heating applications was published in EPE'14 [8]. With the method studied by Jussi Tamminen, energy consumption of heater systems having circulation pumps and thermostat-operated valves can be minimized without additional instrumentation in the system. ABB is studying the further usage of this method in their products.

Juha Viholainen successfully defended his doctoral thesis [9] on energy-efficiency-based speed control of parallel-connected pumps in March 2014. The thesis [10] and publications in it provide new information on systems level possibilities for improving pumping energy efficiency. As the research work has been done in co-operation with ABB, the results have direct application possibilities. There has also been near collaboration with TUT, Tampere University of Technology, researcher Matti Lindstedt about developing analytical approaches for driving parallel-connected pumping systems as energy efficiently as possible.

A new software tool for analysing pump and fan systems was built in LUT. Compared to Pumping System Optimization Tool (PSOT, Figure 3) for detailed analysis applications, the Excel-based Savings Calculator for Centrifugal Pumps SCCP is very easy to use and gives indication of existing energy saving potential with little requirements for background information. Besides having made this software publically available, Lauri Nygren also finished his bachelor thesis in September 2014 on this topic [10].

Figure 3. Screenshots of Pumping System Optimization Tool (left) and Savings Calculator for Centrifugal Pumps (right).

Pekka Pasanen's research area is in the efficiency development of low nq centrifugal pumps that Sulzer Pumps manufactures. Pasanen has recently studied the Computational Fluid Dynamics (CFD) calculation of whole volute-impeller construction instead of making this analysis for a small section. With this approach the efficiency of new 3D impeller structures could be determined more accurately before making actual model devices. The preliminary results are promising, because the obtained results are in the same class with the expected measurements. Therefore, actual impellers will be built and tested with the test setup that was built in Pasanen's master's thesis for Sulzer Pumps. If mechanically possible, these impellers/pumps may be driven in LUT laboratories with researchers Tero Ahonen and Lauri Nygren.

Matti Lindstedt has recently studied the energy efficiency and time-based speed control reservoir pumping applications. Lindstedt's journal paper submitted for review provides thorough theoretical results and mathematical control models for realizing energy efficient pumping systems [11].

WP2 activities are helping ABB, Sulzer and SKF to move from traditional product based pumping solutions to system based solutions and services. These results give theoretical guidelines for product integration. Results are tested with demo unit.

WP4 Foresight and dissemination results

The objectives of the WP4 are 1) to make long term assessments of how the business environment will change, and how it will affect the requirement of systems energy efficiency and energy efficiency services, 2) to publish and spread the results of the research work [2].

Work was started in a workshop (January 22nd, 2014) by sketching alternative future scenarios. During the workshop 12 alternative scenarios were created, five of these were studied in more detail, and three of these were proposed for a detailed study in next funding period. In the second workshop (October, 2014) one future skeleton was re-selected by industry due to changes in business environment during the past year.

Alternative futures in form of matrixes (scenario skeletons) were sketched out of twenty-six identified crucial and intriguing factors. These factors, which are key forces and driving forces, were first ranked by importance and uncertainty. Each matrix is based on two uncorrelated ranked factors, containing four alternative scenarios. Three out of the five matrixes were selected as a basis for a more detailed study, containing altogether ten alternative scenarios.

A major part of the contents was created in a foresight workshop arranged in January 2014. The participation of companies was vital to get relevant and good results out of this workshop. VTT facilitated the workshop.

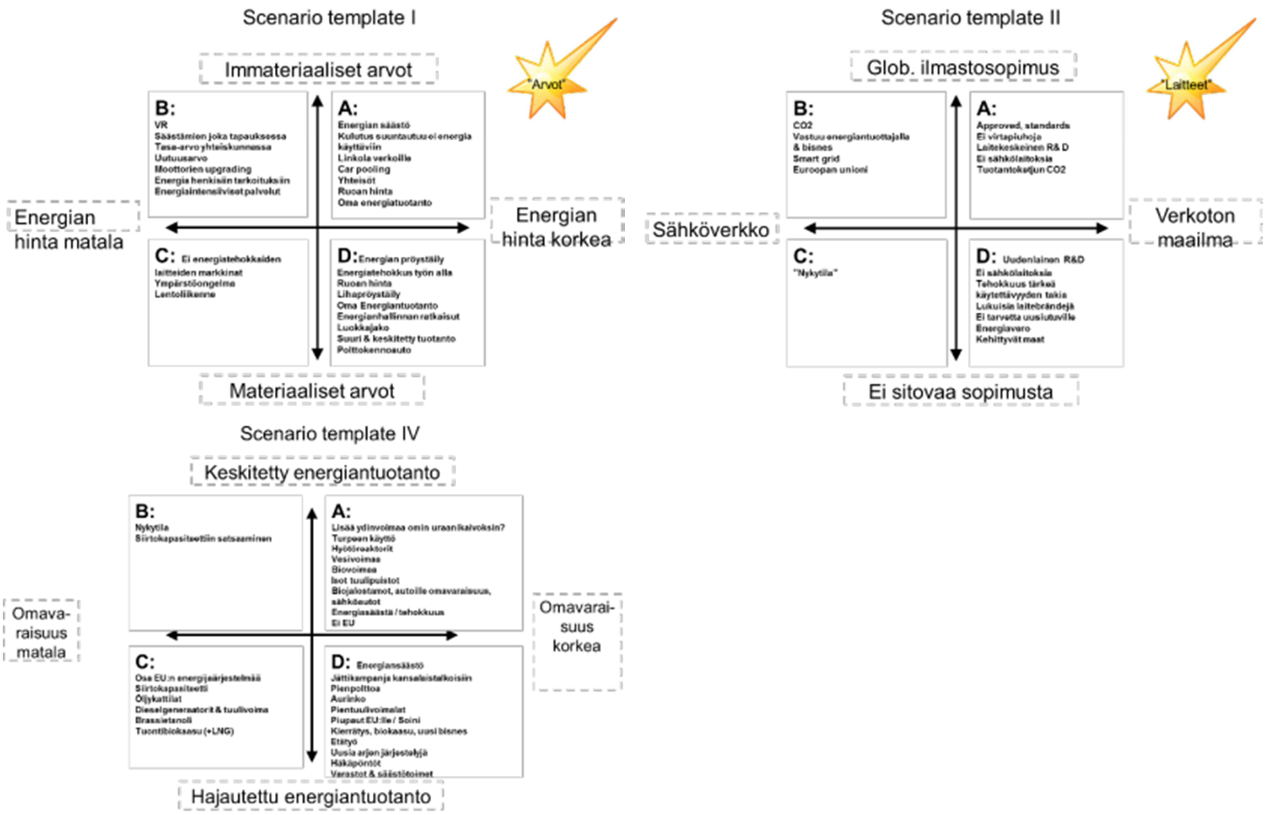

Figure 4. Scenario matrixes selected for further studies (in Finnish).

Scientific Advisory Board (SAB) review

The Scientific Advisory Board for the EFEU programme was formed in early 2014. SAB members are prof. Ernst Worrell from Utrecht University (NL), prof. Simon Harvey from Chalmers University (SE), prof. Truls Gundersen from NTNU (NO) and prof. Peter Karnøe from Aalborg University (DK).

The first SAB meeting was organised in September 2014 in Helsinki. The main feedback by the SAB was

- Strong emphasis on systems for achieving energy efficiency is a clear strength of the programme
- Academic participants are publishing in relevant international conferences and journals
- International collaboration is rather weak and the programme would benefit from more international collaboration and visibility
- Activities are conducted in relatively isolated silos. The programme must focus on identifying mechanisms to foster more exchange across WP boundaries

These points raised by the SAB were already addressed during the planning of the third funding period. Stronger integration between research topics and tasks was found as a prerequisite for developing system level energy efficient solutions and services. A systems approach in achieving energy efficiency will continue to be the key element in EFEU research. A plan for international collaboration has been made and progress will be systemically monitored. All the comments and suggestions have been discussed in Programme Steering Group (PSG) and action points have been made [2].

The next SAB meeting has been tentatively scheduled for late 2015 or early 2016.

Conclusions

The EFEU research programme is a multidisciplinary research programme, where each participating organization has energy efficiency as its common research theme. The strength of EFEU is in its approach – taking a scientific system level approach to energy efficiency and using energy intensive systems as research objects to test the hypotheses. The selected approach makes it possible to produce new, high quality scientific results of technological novelty that will lead into future products and services.

The results of the research will be utilized in all organizations participating the research programme. The companies will use the results to initiate future product and service development activities. Correspondingly, the universities and research organizations will use the results for the research and education purposes. The results will be also utilized in adult education by organizations such as AEL. The far-reaching design and dimensioning of energy efficient systems will provide long term benefits for the Finnish society.

The scientific results of the programme will be continuously evaluated by reviewers in scientific journals. Also, the number of doctoral dissertations indicates the scientific quality of the programme. The number of company product and service development projects indicates the quality and the significance of the results generated by the research programme [1].

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Green Deal – Results and lessons learned in 2 years of cooperation of industry and government in the Dutch Green Deal program on motor systems

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Contents

1. Abstract

The Green Deal Efficient Motor Systems is initiated by three parties: the Federation of suppliers of Electric Motors and Components (FEDA), the trade association of installation and electromechanical maintenance companies (Uneto-VNI) and the Dutch Ministry of Economic Affairs. Key objectives of the program are to encourage of a wider application of efficient electric motor systems in industry by exploring and communicate the potential of motor systems in example projects, and strengthening the competitiveness of the partners by developing innovative products and services on motor systems.

Main elements of the program are: 1) Define audit for efficiency improvements in motor systems; 2) Develop sound business cases on efficient motor systems, delivering concrete energy savings; 3) Knowledge transfer and communication to end users and the supply chain to create leverage in terms of working methods, capacities and energy savings.

The results in energy savings differ per project depending on the project targets, the partners' and end users' expertise and available capacity. At the lower end of the savings spectrum we find projects with the focus on applying premium motors. With these savings start at 4-5% up to 10% where older motors are replaced. On the other end of the spectrum some projects show savings of up to 40% as a result of improving a total motor system, including benefits like increased level of productivity.

The main challenges for the Green Deal partners, the government and the end users are to focus on efficient motor *systems*. All parties involved cooperate with one or more involved partners in the supply chain. But although some of the classical barriers have been removed in some cases, like knowledge and systems approach, others appear still in place. Up till now (end of 2014) some of them are directly linked to the commitment of the end users themselves; the internal 'competition' for the right capacities, i.e. in terms of mandate, knowledge, time and financing. The program runs from 2012 up to 2015.

2. Introduction

Electric motor systems use up to 69% of electricity in Dutch industry. Research and (international) projects show that system optimization and the state of art drive technology can reduce 20 - 30% energy use in various systems such as heating, cooling, production and processing systems. By upgrading these systems, the national electricity bill can be reduced by 5 to 8 percent. The low awareness of the best practice and state of art drive technology combining with obstacles in the Dutch marketplace hamper the end users to utilize the new market opportunity [1].

The possible cost and energy savings are hindered due to a number of reasons such as: the complexity of the issue, unfamiliarity with best practices and the Best Available Technology (BAT), the limited use of life cycle cost principles, the lack of funding and the heterogeneity of the supply chain. As a result, the maximum and long term energy and cost saving are not realized.

For the industrial users, optimized motor systems can generate directly additional cash flow due to a lower monthly or quarterly energy bill. This additional cash flow can be used for other projects in the company. This translate into a 1 on 1 enhance competitiveness. In addition, companies also demonstrate their environmental commitment by investing in more efficient motor system.

In 2005 the European Directive (2005/32/EC) came into force with requirements on the minimum efficiency of energy using products, including electric motors. This Directive, further explained in the Regulation EC 640/2009 dated July 22, 2009, offers an excellent opportunity to apply the effective system approach directly and optimize the motor systems. The Directive includes 3 steps, starting in 2011 up to 2017. In early 2014 an amendment was put into place with stricter limit values for different motor features.

Government and the Dutch motor systems industry have started the Green Deal Efficient Electric Motor Systems to accelerate the market penetration, in alignment with other initiatives like the transition within industry towards the energy management system standard ISO50001.

3. Green Deal as policy program for sustainable initiatives

The Dutch government recognises that in the development of sustainable initiatives, companies, civil society organizations and others face barriers. For example, if they want to run a project to generate energy or to reduce the water usage. There are several barriers or challenges. For instances, the laws and regulations can cause unnecessary delays. In other cases, it is hard to find a partner or funding for the project.

For those cases, the Dutch government initiated a program called "Green Deal" to offer the necessary resources. Figure 1 shows a simple diagram with the parties involved, i.e. the Submitter, the Government and the Green Deal Results.

The Netherlands want to move towards an economy where sustainability and financial growth go hand in hand. Environment focus cannot be undermined by the financial profit. Green Deal provides the short and long term solution to a more sustainable and profitable economy.

Figure 2 includes the participating parties for a specific Green Deal project called the Green Deal Efficient Motor Systems. This project is in a series of 150 different Green Deal projects. Hereafter the Green Deal Efficient Motor Systems is referred to as the *program* Green Deal Efficient Motor Systems.

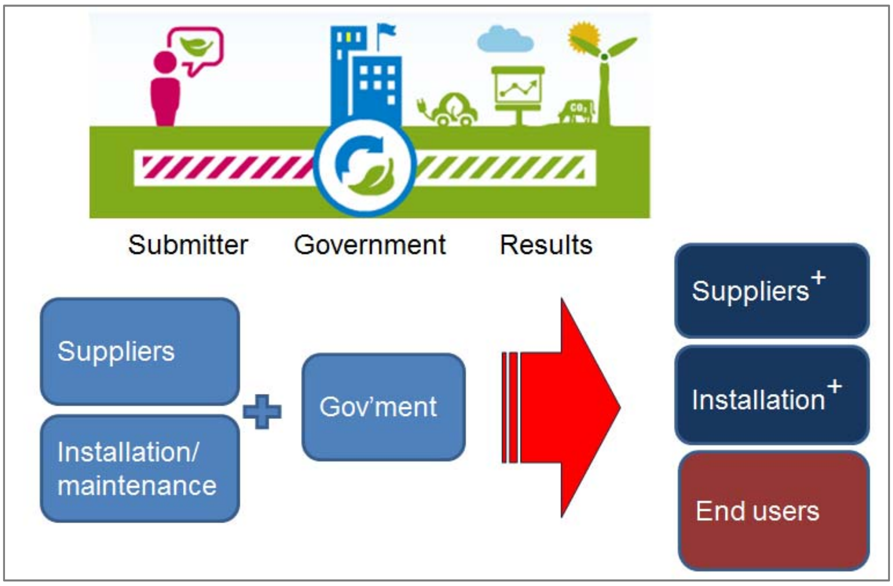

Figure 1: From Submitter with Government to Results

4. Green Deal Efficient Motor Systems

The initiators of this specific program Green Deal Efficient Motor Systems are the FEDA and the Uneto-VNI. FEDA is the Federation of suppliers of Electric Motors, Drives and Automation Engineering, and Uneto-VNI is the trade association of installation and electromechanical maintenance companies.

The two organizations want to encourage a wider application of efficient electric motor systems. They provide assistance to the end users to reduce their energy cost and strengthening their competitiveness by providing them innovative products and services. And aim at reducing or lowering (some of) the barriers that hinder the implementation of efficient motor systems.

Bottlenecks on the implementation of Efficient Motor systems

In the introduction several causes for the slow implementation of efficient motor systems were mentioned, like obstacles in the Dutch marketplace and a low awareness of best practice and technology in the supply chain and with end users. Many other aspects play a role in this situation as well, i.e. in the supply chain itself, and the way industrial organizations work with respect to analyzing and implementing energy efficiency measures.

(Inter) national studies, projects and practical experiences confirm the bottleneck associated with market players in the supply chain, such as the manufacturers / suppliers of electric systems, installers and maintenance providers, Original Equipment Manufacturers (OEM) and end-use industries (manufacturing).

Analysis of the market of electric motors supply and maintenance in the Netherlands, and the practices of the OEM and industrial end-users show that for a successful acceptance of efficient motor systems all market parties have to get involved [2].

Several main barriers that various parties in the supply chain are facing, are given below

- the focus on lowest investment cost; the OEM and the end user's main interest is to buy the motor at the lowest price possible
- the split in allocation of investment and operational cost with the end user. The employee that is responsible for buying the motor is usually not the one who holds the energy budget
- focus on motors only, instead of the entire motor system
- insufficient knowledge regarding the possibility of improving system efficiency [5, 6].

The energy costs associated with the motor's lifetime operation are estimated to be around 95% of the total cost, while initial purchase price and maintenance account for the remaining 5%.

Systems approach

The maximum savings potential of efficient motor systems can only be realized by following a systematic approach. This is a term which hints at systematic analyses of a motor system starting with the process or the drive-load.

Applying a state of the art efficient electric motor can bring efficiency improvements of 0,1% to 10% compared to the minimum standards in place. See the green dotted line on the electric motor in figure 2 below. By improving the 'core motor system' (the oval blue dotted line), the savings potential can be increased considerately. The control, the transmission and the components like pumps or compressors are a part of the analyses for an optimal motor system. Potential savings can be increased up to 20-30%. The best approach however in terms of efficiency improvements is at making an analyses of the complete motor system, i.e. including also the ducting and the process (conditions) itself, see the red outer dotted line in figure 2.

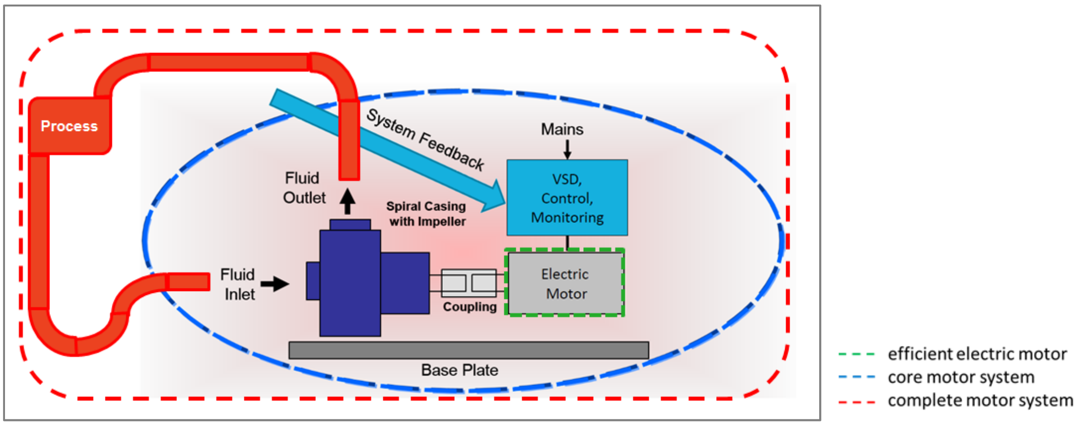

Figure 2: System borders electric motor systems

The Green Deal Efficient Motor Systems

Thirty one member companies from the FEDA and Uneto-VNI together with two main pump suppliers have joined the Green Deal as participating companies. The companies (logo's) are shown in figure 3. The government is involved via the Netherlands Enterprise Agency (NEA) as secretary of the project group and the Ministry of Economic Affairs in a steering committee. The program management is done by FEDA, Uneto-VNI and TPA.

The Green Deal motor systems program consists of three main elements. First is the cooperation between the partners on this specific subject and on the second main element, i.e. the development of a number of projects / business cases with end users. These projects are intended to show the benefits of efficient motor technology, and should give elaborated examples of the potentials in the different industrial sectors, industrial activities. Thirdly focus will be on communication to stake holders such as the suppliers and end users. By working together closely between partners and stake holders, knowledge can be exchanged and shared for further system improvements. The program duration is 2,5 to 3 years [3].

Figure 3: Partners Green Deal electric motor systems

Each separate project within the program has the following step plan: preparation, developing standard methods, following by execution of projects, analyses, financial feasibility study, possible solutions and knowledge transfer.

In cooperation with the partners of the Green Deal Efficient Motor Systems and some end-users of motor systems, a standard approach or working method has been developed for analysing and optimizing a specific motor system. The five basic steps are shown in figure 3. The definite format of the business case will be defined by the partners, with a number of objectives. Each project is customized based on the specific expertise and interest of the partners and the end-users, the available data and the desired scope of the project.

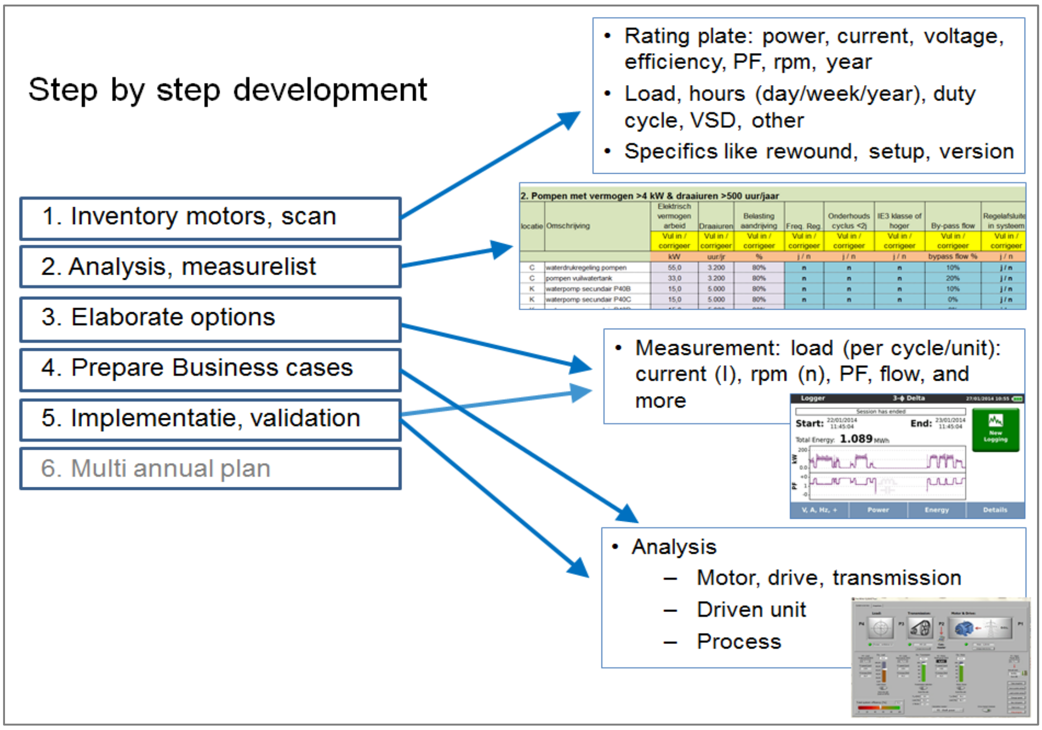

Figure 4: Step by step development of business case in Green Deal project

Several tools are available and used to calculate the efficiency of the motor systems, cost, and type of drive and control components. Via the participation of the Netherlands in 4E EMSA, the Electric Motor Systems Annex to the IEA 4E Implementing Agreement, the Motor Systems Tool became available for analysing and optimizing motor systems for all type of end users [4]. The tool is unique in its 'system approach' and is branded independently. See www.motorsystems.org for more information.

A more generic tool, the Quickscan EMS, has become available via NEA and can be used to get a first idea of the possible savings and benefits of a specific motor system.

Projects

At the moment the list of Green Deal efficient motor system projects has reached the number of 32. The projects are executed in different industrial sectors and companies. In figure 5, an overview is given for the number of projects per industry and the corresponding project description.

Industry sector	# projects	typification
Chemicals	4	Pumps, motors, VSD, system lay out, belts
Plastics	4	Improved motor system extruders, pump systems
Metals	4	Pump systems, fans, transmissions, process control
Food	10	Production systems, pumps, fans, conveyor systems, other
Water purification	3	Improved motor systems, process control, design
Other	7	Improved motor systems, process control, design
Total	32	

Figure 5: Green Deal projects per sector

Many companies realize that in order to gain a large efficiency increase, one should not only focus at the motor itself, but instead investigate the entire motor system as described in the section earlier. For instance, the project completed in the glass industry has reduced the total energy use of 39.6% by replacing not only the motor, but also the brake system where the energy is generated instead of being wasted in the new system. More projects are described in the next section in more detail.

5. Successful cases

In this section five different cases in various industries are described in more detail:

Case 1: Plastics Industry

A new motor system is implemented in a plastic manufacturing factory to improve the motor system efficiency and to reduce production cost. The improvement of this new motor system includes the replacement of a DC motor by an AC IE3 motor with a variable speed drive and the placement of the current conveyor belt by a gear wheel conveyor belt.

By implementing the new motor system, the manufacturer can save €17,390 per year. This includes also lower maintenance costs compared to the DC motor. This cost saving is achieved by implementing a more efficient motor with a variable speed drive and a new gear wheel conveyor belt, which run a relatively low number of operating hours of 3,000 per year. The total investment is € 42,500 which leads to a simple payback time of 2 years and 5 months.

Case 2: Silt processing factory

The silt processing factory processes 400,000 ton silt annually, which makes it the largest silt processor in the Netherlands. The energy use of the cooling tower was investigated. The energy saving made possible by upgrading the existing motor system.

The motor system is used to drive the water pump and the ventilator in the cooling tower. The water pump transports the water from the reservoir to the water tower. The ventilator sucks the air from the atmosphere to cool the flowing water in the tower.

The cooling system uses two water pumps, but only one water pump is used at the time. The other one is used as backup. Both pumps have the same annual operation hours. The amount of flow was controlled by a bypass. Measurements show that 12.4% of the total flow was being recycled through the bypass. By closing this bypass, the total amount of flow rate was reduced by 12.4%, hence less energy is required. For this a frequency converter has been implemented to control the pump's variable flow rate and power output. An additional frequency converter has been implemented for the ventilator as well. Depending on the flow rate of the water, the amount of air required to cool the water can be adjusted accordingly. The upgrade the pumps and the ventilator by frequency converters made the process and it's control more efficient leading to savings of 22% of the electricity use.

By upgrading the motor system with frequency converters, the amount of the energy used annually by the pumps and the ventilator is reduced by 426,000 kWh (22%) which is equivalent to a cost saving of € 27,710. The total investment is € 69,156. The breakeven point for the investment is after 2.5 year.

Case 3: Glass Industry

A glass manufacturer upgraded their conventional motor system by a state-of-the-art motor system. The motor system is used for the rotational movement of the mould where the final form of the glass is created. During the rotational movement, acceleration and deceleration of the mould take place. Before the upgrade, brakes are used to decelerate the mould where the kinetic energy is converted into heat. After the upgrade, during the deceleration, the kinetic energy is converted into electrical energy and transported back to the grid.

By upgrading the conventional motor system including the motors, variable speed drive and brake system, a total energy use is reduced by 39.6%, while the production rate is increased from 49 to 52 strokes per minute due to a more efficient and quicker deceleration method. In addition, no heat will be produced during the deceleration. As a result, no cooling system is required for the motor system. This reduces the number of components and the size of the system. The calculated break event point is less than 3 years.

Case 4: Food industry

A sugar food factory improves the efficiency of one of their production lines by improving a pump system. In one of their production processes, a set of three pumps was used to transport the fluid to the boilers where the product is being processed. Due to the increase of production in the recent years, all three pumps (3x 130 kW) had to be used simultaneously. The pumps are controlled by flow valves.

A new system is proposed with a set of two IE3 motors with new pumps, 200 kW each. A power output of 170 kW is required for the current production rate. One single new pump is sufficient to do the task, the other pump is used as a backup in case when the first pump is not functional. The new pumps are equipped with a variable speed drive, making a switch from flow control towards pressure control possible. This allows the pump to operate more efficiently in a large operating range. Finally, the factory worked also on a more efficient pipe network where aspects such as friction loss in the pipe and the number of corners were investigated and optimized. After implementing these latest upgrades, a total of 41 percent of energy reduction is realized compared to the old system.

Case5: Steel industry

A steel production plant uses high quality processes to produce hot-rolled, cold-rolled and coated steel. Over the past 25 years, the energy efficiency at the production site gets continuous attention leading to a 30% overall improvement. This particular project targets at the Brackish Water Pump Station (BWPS).

The BWPS delivers water to a basin of Blast Furnace 6&7. The station has three big pumps and one small pump. The required static head is 9,4 meter. The calculated dynamic head of the pipe is 3 meter. Under normal circumstances, only the small pump is in operation. Depending on the water level in the basin, the big pumps are switched on and off. The average flow rate required is 2900 m^3/h and the corresponding annually energy use of the BWPS is 2800 MWh.

The main cause for the efficiency loss is that both big and small pumps are not operating at their best efficiency point. In addition, the big pump delivers a total head of 26,2 meter whereas the required total head is only 12,4 meter. This over performing of the big pump leads to extra energy use which has no additional value to the system.

By installing a variable speed drive, it can reduce the total head of the big pumps to 12 meter and the flow rate from 2234 m^3 to 1000 m^3. It also reduces the average specific energy of the pumps from 99.2 kW/1000 m^3 to 40 kW/1000 m^3. This will result into a total energy saving of 30%. In addition, the maintenance cost for the new pump system will also be 50% lower, equaling 15k EUR per year.

6. Conclusions

Based on the project results available at this moment, the following provisional observations can be made:

- The Green Deal Efficient Motor Systems projects proof to deliver profitable and environmental friendly solutions for end users. Depending on the scope of the specific projects the savings amount from 10% working on the ‘motor level’ – replacing motors and upgrading transmissions -, up to 20% to 40% when applying a broader scope in the analysis and taking up all components of the motor driven unit, i.e. the application itself, the transmission, the motor and the actual load (process demand) itself. These results align with the expectations of the GD partners and with other research and projects [1-3].
- End user
    - The limited capacity of the end users to spend time and capacity on the subject of (energy) efficiency improvements. The responsible employees do not always have a clear mandate from the management to invest in analyses and project detailing. As a result many companies choose to start on a small basis, with one specific motor system.
    - To address and to exploit the full potential of efficient motor systems within these participating end users a prolonged and continuous effort is needed, something which has to be addressed and detailed further.

- There's a need for quick available information of possible savings and a need for tools, knowledge for a quick step-by-step analysis or assessment of potential improvements, benefits and profits.
- The lack of available data of the actual installed base, its performance, energy use, its specifics on a more detailed level.
- The practice with end users of handling operating motor systems as a low interest item, leads to corrective maintenance practices, and to non-optimal solutions when maintenance demands occur. Helping the end user with a transition towards preventive maintenance and a better understanding of total cost of ownership will lead to more interest in and implementation of efficient motor systems.

- Working on projects targeted at efficient motor systems, bring about opportunities for other benefits, 'multiple benefits', like improved productivity, product quality and lower production costs. However to assess these extra benefits demands extra capacity, data, which are not always easy to access, or available by the employees working on motor systems. Involvement of other disciplines within the end user would enable the approval of these potential benefits.
- For OEM an improved awareness of the potential of efficient motor system technology, and the identification of potential benefits for their customers (end users) can open up opportunities for product improvement. Whilst the 'group' of OEM is a large and heterogeneous group of companies, a combined approach by GD partners to involve the OEM is difficult and time intensive, but certainly worthwhile if not necessary.
- The cooperation between GD partners and end users proves to be a fruitful one. A clear definition of roles and responsibilities, and costs at the start of a project lead in most cases to a successful project.
- More focus is needed within the supply chain on system aspects, of the interactions between components, and opportunities for more integrated solutions. More partnerships could be useful for this.

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Glossary

EMSA = Electric motor systems annex (4E IEA)

FEDA = Federation of suppliers of Electric Motors, Drives and Automation Engineering

GD = Green Deal

OEM = original equipment manufacturer

Uneto-VNI = the trade association of installation and electromechanical maintenance companies

Industry Engagement and Challenges to Transforming the Market for Super-Efficient Motors: the SEAD Global Efficiency Medal

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Abstract

The Global Efficiency Medal competition, a cornerstone activity of the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative, is an awards program that encourages the production and sale of super-efficient products. SEAD is a voluntary multinational government collaboration of the Clean Energy Ministerial. This winner-takes-all competition recognizes energy-efficient products, guides purchasers towards energy-efficient product choices, and demonstrates the levels of energy efficiency achievable by commercially available technologies.

The third Global Efficiency Medal competition recognized super-efficient electric induction motors in two size categories and four regions around the world. The SEAD Global Efficiency Medal complements existing labeling programs and advances comparable and transparent international test procedures that support MEPS efforts. The SEAD award-winning motors are 1.5 - 6.4% more efficient than the average motor sold in each corresponding regional market. For induction motors, this is a huge improvement that represents significant potential energy savings.

This paper will focus on methods of engagement with the motor industry and the challenges inherent to a motors competition, where the supply chain is complicated by numerous split incentives and bulk purchasers having varying criteria for motor purchasing.

Throughout the course of the competition – from planning the awards through the ceremony – SEAD reached out to industry to fine-tune the award categories and rules and to gain a better understanding of the benefits such an award could play in the motors market. SEAD liaised closely with the IEA 4E Electric Motor Systems Annex (EMSA) at all stages to maximize collaboration among international organizations and outreach to relevant motors stakeholders. Outreach activities to raise the profile of the competition within the motor industry included email solicitation of input during rules development and personalized email and telephone outreach to solicit product nominations. After the competition closed, SEAD convened an in-person roundtable with motor manufacturers, organized an awards ceremony at the 2014 Motor Summit, and generated trade and general press releases.

SEAD experienced a number of challenges while running this competition, and has identified possible solutions to help inform potential future competitions. One technical challenge was the absence of an international test method for motors that require a variable frequency drive for operation. Without an ability to reliably assess the efficiency of these motors, they could not be included in the competition, presenting a barrier to nominations for a “new technology” category. One cultural challenge was the fact that most motor purchasers (such as OEMs) do not consider energy efficiency a key criterion, which lessens motor manufacturers’ desire to participate in an energy efficiency competition.

Introduction: the SEAD Global Efficiency Medal competition

The SEAD Initiative of the Clean Energy Ministerial is a voluntary international government collaboration that seeks to engage governments and the private sector to advance global market transformation for energy efficient equipment and appliances. The SEAD Global Efficiency Medal (GEM) competition is developed by the SEAD Awards Working Group, which is comprised of government representatives from Australia, Canada, India, Japan, Sweden, the United Kingdom and the United States, and administered by CLASP.

The SEAD GEM competition is a global and regional awards program that encourages the development, production and sale of super-efficient products. Specifically, this competition aims to accelerate efficiency gains in existing technologies and to promote the introduction of new technologies into the market by recognizing both commercially available and emerging technologies. Products are voluntarily nominated by manufacturers, and nominations are kept private by SEAD. The SEAD Global Efficiency Medals complement existing national and regional efficiency labelling programs and the competition process actively engages the manufacturing industry in the design of the award categories and rules. It fosters international collaboration amongst government agencies responsible for promoting and regulating product energy efficiency by encouraging the development of transparent international test procedures. As SEAD's most publicly visible activity, the awards program is a cornerstone of SEAD's market transformation strategy.

The SEAD Global Efficiency Medal competition encourages the production and sale of super-efficient equipment, appliances, and electronics by identifying the most efficient product in each category in four regions, as well as an overall global winner. The main objectives of the competition are to:

- Maximize energy savings;
- Increase market share of highly efficient products, moving the median of the market to efficient products while staying technology neutral;
- Spur innovation among manufacturers;
- Support test procedure harmonization activities, moving closer to being able to apply the test results of region A to region B;
- Build test lab capacity;
- Provide internationally comparable and transparent test results; and
- Complement and support S&L policies. [1]

When selecting products to be covered by the SEAD Awards, several factors are taken into account. Products should have significant energy savings potential; well-established and accepted test methods (to the extent possible); large energy efficiency potential between products, which enables products to be differentiated through energy efficiency; and potential to benefit the market – that is, the market for that product has high interest in an award and stakeholders are seeking to differentiate products.

The SEAD competition is a recognition award, not a financial award. SEAD builds awareness of the competition before announcing winning products and promotes the competition and the winning products. SEAD holds regional and international ceremonies to recognize the manufacturers of winning products, releases a press announcement about the winners, and works with partners to promote winning products.

Figure 1: SEAD Global Efficiency Medal logo

SEAD Global Efficiency Medal for Electric Induction Motors[1]

While the first two SEAD GEM competitions focused on consumer electronics, successfully identifying the world's most efficient TVs in 2012 and displays in 2013, the third SEAD GEM competition recognized super-efficient electric induction motors in two size categories and four regions around the world. Electric motor-driven systems (EMDS) account for 44%-46% of electricity end-use globally, and the operating costs of medium and large size motors over their lifetime can dwarf the initial purchase price. In North America alone, cost-effective efficiency technologies and practices can reduce the industrial motor-system electricity demand by 11%-18% (62 TWh to 104 TWh) and save US$3 billion to $5 billion a year. [2] SEAD liaised closely with the IEA 4E Electric Motor Systems Annex (EMSA) at all stages to maximize collaboration among international organizations and outreach to relevant motors stakeholders.

Award-winning Products

Nominated products were expected to be fairly similar in terms of energy efficiency. Therefore, to eliminate any testing variations between test laboratories, SEAD tested all nominated IEC motors (eligible for the international awards) in a single laboratory to determine international award-winners and to verify manufacturers' energy performance claims. Products were randomly sampled from manufacturers for testing. In addition, energy performance claims for the competition were calculated as the weighted average of measured efficiency at 25%, 50%, 75%, and full (100%) load conditions.

While most categories had GEM winners, several categories had either no nominations or no eligible products nominated. These included the two categories in Europe as well as the two IEC categories in North America. (North America did have GEM winners in the NEMA categories.)

The winning products for each region of the SEAD Global Efficiency Medal for electric motors are:

Australia:
- 4 kW: YZTE4-112M – Nanyang Explosion Protection Group Company Limited
- 11 kW: YZTE4-160M – Nanyang Explosion Protection Group Company Limited

Europe:
- 4 kW: No winner
- 11 kW: No winner

India:
- 3.7 kW: 1LA21134NA80 – Siemens Limited (India)
- 11 kW: 1LA21634NA80 – Siemens Limited (India)

North America:
- 5 hp: NSPE184T – Nanyang Explosion Protection Group Company Limited
- 15 hp: NSPE254T – Nanyang Explosion Protection Group Company Limited
- 3.7 kW: No winner
- 11 kW: No winner

The two products that won regional awards in Australia also won the international awards.

Winning Product Efficiency

The winning products in the commercially available electric motors categories were between 1.5 to 6.4 percent more efficient than the average motor sold in each corresponding regional market. For induction motors, this is a huge improvement that represents significant potential energy savings.

[1] More information is available at: http://superefficient.org/motorawards

Table 1 shows the average efficiencies of motors in each regional market[2], the efficiencies of the winning products, and the efficiency improvements that these winners have achieved over the average.

Table 1 also shows the average efficiency of motors in the market of each competition region. This table clearly shows that the average efficiency of 4kW and 11kW motors in the EU falls well below those in North America and Australia. It is likely that this stems from the less stringent minimum energy performance standards in Europe (IE2 levels) as compared with Australia (slightly above IE2 levels) and North America (IE3 levels).

Table 1: Comparison of average motor efficiencies and SEAD Global Efficiency Medal winner efficiencies

	Average efficiency		Efficiency of winners	
North America	5HP	15HP	Nanyang 5HP	Nanyang 15HP
	89.3%	92.2%	91.1%	93.6%
Improvement over average			**2.0%**	**1.5%**
Australia	4kW	11kW	Nanyang 4 kW	Nanyang 11 kW
	88.2%	90.8%	91.2%	93.5%
Improvement over average			**3.4%**	**3.0%**
India	3.7kW	11kW	Siemens 3.7 kW	Siemens 11 kW
	83.1%	87.6%	88.4%	91.5%
Improvement over average			**6.4%**	**4.4%**
EU	4kW	11kW		
	85.5%	89.1%		
Note: Average efficiency data is based on 2013 sales as determined by IHS Technology (NYSE: IHS) through market analysis.				

New Technology Motors

A number of manufacturers nominated motors for a proposed new technology category, but each of these required an electronic controller or variable frequency drive. The SEAD Global Efficiency Medal competition uses test methods that have international consensus. Table 2 shows the test methods that were indicated for this competition.

[2] The average motor efficiencies in each regional market in 2013 were analyzed through market analysis by IHS Technology (NYSE:IHS).

Table 2: Test methods indicated in the Official Rules for various categories of the SEAD Global Efficiency Medal competition for electric motors

Award Category	Test Method
IEC Induction Motor	IEC 60034-2-1:2007, Summation of Losses Method
NEMA Induction Motor	U.S. Department of Energy test procedure for Electric Motors and Small Electric Motors, as specified in 10 CFR part 431
New Technology Motor (< 75 kW)	IEC 60034-2-1:2007, Direct Test Method: Out/Input
New Technology Motor (< 100 HP)	IEEE Standard 112, Test Procedure for Polyphase Induction Motors and Generators, Efficiency Test Method A, Input-Output

For products that require an electronic controller, the test methods indicated for new technology motors can only determine the efficiency of the system (electronic controller or variable frequency drive plus motor); they cannot determine the efficiency of the motor alone. Therefore, in the absence of an internationally-accepted test method that could determine the efficiency of the motor within the system, these products were ultimately deemed ineligible for the competition. However, based on manufacturer claims, these products were 1.2 to 6.4 percent more efficient than requirements for the IE4 super-premium efficiency category.

With new technology motors using electronic controllers or variable frequency drives being the most efficient and the direction the market is trending, there is a clear need for a test procedure to compare controller and motor combinations across different regions.

Industry Engagement: Feedback on the GEM Competition for Motors

Throughout the course of the competition – from planning the awards through the ceremony – SEAD reached out to industry to fine-tune the award categories and rules and to gain a better understanding of the benefits such an award could play in the motors market. Outreach activities to raise the profile of the competition within the motor industry included email solicitation of input during rules development and personalized email and telephone outreach to solicit product nominations. After the competition closed, SEAD convened an in-person roundtable with motor manufacturers, organized an awards ceremony at the 2014 Motor Summit, and generated trade and general press releases.

Through engagement with industry, SEAD examined a number of improvements to a potential future round of a motor competition. These are discussed below.

Using More Precise Terminology for "New Technology" Category

SEAD used the term "new technology" for a category in the motors competition, as had also been used in the previous two competitions for televisions and displays. As discussed above, however, for products that require an electronic controller, the test methods indicated in the competition for new technology motors can only determine the efficiency of the system (electronic controller or variable frequency drive plus motor); they cannot determine the efficiency of the motor alone.

The use of the term "new technology" therefore misled a number of manufacturers to understand that motors using electronic controllers were included in the competition. Many manufacturers expressed excitement about participating in this category, and several manufacturers nominated products that required electronic controllers, before realizing that these motors did not qualify.

Instead, the category should have been clear about focusing on new technology line start motors, which are the motors that can be tested with existing, internationally-accepted test methods. The competition could then have subcategorized induction motors versus other technologies. It is important to also note that restricting the competition to line start motors is fairly limiting, as most new technology motors are controller or variable frequency driven technologies. In addition, these technologies can product huge energy savings.

Until there is an internationally-agreed test standard, however, it is difficult to establish rules for these motors for a global competition. As national, regional, and international test bodies are establishing methods for testing these products, it would be inappropriate for SEAD to attempt to step into this role. While SEAD would have liked to include variable speed motors, one objective of the GEM competitions is to support test procedure harmonization activities – and this would not be accomplished by adding to the test procedures being proliferated.

Shipment Requirements

The SEAD competition put in place shipment thresholds, shown in Figure 2, to ensure that winning products would have sufficient market share to impact energy savings. Nominated products were required to have plans to ship a certain number of units within a one year period starting between 3 June 2013 and 1 September 2014. These shipment thresholds also ensure that nominated products are not custom-made products or prohibitively expensive. Shipment thresholds were determined through market analysis and consultation with technical experts and industry representatives.

Figure 2: Minimum projected annual shipment of motors

Minimum Shipments (units)	IEC Induction Motor		NEMA Induction Motor	
	3.7 kW - 4 kW	11 kW	5 HP	15 HP
Australia	1400	500		
Europe	1400	500		
India	1400	500		
North America	420	150	980	350

Some manufacturers indicated that the shipment thresholds were a barrier to entry. For newly commercialized products in the complex motors supply chain, manufacturers may sell very low quantities of new, super-efficient products until purchasers and end-users are better educated about the benefits of these products. In this case, commercialized super-efficient products may not be sold in quantities sufficient to meet the shipment thresholds set for the competition.

Awarding Individual Products versus Product Families

Because motors are needed in a variety of sizes depending on the application, motor manufacturers advertise a family of motors that use the same technology within a range of sizes. Manufacturers note that motors in a family are made to identical specifications along the efficiency curve.

To meet policy requirements in some countries, such as the US and Australia, manufacturers must provide a number of samples to represent the product line. If these samples meet verification testing, the whole product family is assumed to meet the requirements. For other economies, such as Europe, each size product must be tested independently to ensure that it meets policy requirements.

Since the Global Efficiency Medal competition encompasses economies with both of these approaches, this competition awarded only the nominated motor, rather than the whole product family to which that motor belongs. This approach maintains the validity of the competition in all of the participating regions. However, it also restricts the ability of manufacturers of winning motors to advertise that their product won this international competition – because the manufacturers advertise product lines. SEAD is doing additional research into this issue in advance of any potential future competition for motors.

Market Education for More Efficient Motors

SEAD heard from manufacturers that the majority of motors manufactured are not at high efficiency levels of IE4, IE3, or even IE2. There is a need to better educate the market in order to change that paradigm. Manufacturers spend significant resources on education because it sells equipment, and if education can lead purchasers or end-users to demand motors at a higher efficiency class, then this could reduce energy consumption dramatically.

Market Education for Motor Systems

Motor manufacturers noted that the IE classification system has very effectively been propagated through the market, and purchasers and users all know and understand this system. However, because there are no internationally-accepted test methods for motors that require electronic controllers, there is also no IE classification for these motors.

Therefore, in order to transform the market for energy-efficient motors with controllers, manufacturers identified market education as a major need. Without an energy label that purchasers and users recognize, manufacturers must try to convince each purchaser and end-user of why this technology is super-efficient and therefore suited to their needs.

Through dialogue with manufacturers, SEAD heard that it would be helpful to have a comparison between the package efficiencies of VSD + motor systems and IE-labeled motors run with a drive. This would provide a comparison of VSD + motor systems with recognized efficiency classes. Although new test methods are under development that may ultimately take this systems approach, this comparison is not possible currently.

In addition, there were instances mentioned of motors controlled by a drive being labeled as IE4 or IE5, even though this is impossible given the current international test procedures, to use the IE-labels as a marketing tool. This indicates a need for more enforcement of motor labeling worldwide.

Challenges to Transforming the Motors Market

Complexity of the Supply Chain: Making Energy Efficiency a Criterion in Motor Purchases

Most motor purchasers (i.e., machine builders and OEMs) do not consider energy efficiency a key criterion in the motor purchases – it is generally in their interest to buy the lowest cost motor because they will not be paying the energy costs of running the motor. Energy efficiency is often a third or fourth order consideration, and is a byproduct of process improvement. This lessens motor manufacturers' desire to participate in an energy efficiency competition. In addition, even educated end users might have to redesign their machines to accommodate a larger motor + drive package, which would lead to greater initial expense and potential delays in replacing the system.

Some manufacturers indicated that for their sales team, the critical information is return on investment (ROI) – if energy savings in one to two years make up for extra capital costs for an energy-efficient motor, then that has value to the end user. However, others indicated that while ROI is important, it is not sufficient because manufacturers sell to OEMs rather than to end users.

In addition, manufacturers reported that some OEMs are willing to pay more for energy efficient motors if that leads them to be able to create a less expensive machine overall. Therefore, it is now valuable for OEMs to understand their options for overall reductions in energy consumption. In some cases, it may be less expensive for OEMs to pay considerably more for a super-efficient motor if they then can avoid redesigning a whole machine.

There is a clear need to incentivize machine builders and OEMs to purchase more efficient motors in the absence of an inherent motivation for them to do so. In some cases, manufacturers reported that OEMs are beginning to be impacted by customer demand when large companies look at their buildings in aggregate and request more efficient motors. This suggests that aggregating end-users might be one way to incentivize OEMs to purchase more efficient motors.

Complexity of Motor Companies

There are many different priorities among departments and interests within motor companies themselves. Those who decide whether companies will take part in an energy efficiency competition, for instance, may be part of a marketing department that wants to put forward an image of sustainability. Those employees who design new products, however, are likely to have a number of competing priorities and engineering challenges, only one of which is the efficiency of new products.

Complexity of End Users

The variety of end users of motors and motor systems is enormous, and therefore end users as a group are very difficult to target. To change the mindset of end users wanting the least expensive motor in the market, even though energy efficiency would save them money in the long run, there is a need to educate this large group about the benefits of improved efficiency motors.

Need for Regulations

The most effective way to transform the market for super-efficient motors is through regulations. Presently, prices are high for IE4 motors because there is low demand and they are therefore produced in low quantities. If manufacturers knew that regulations would demand even higher efficiency motors, they would take steps to produce more IE4 motors in a cost-competitive way. Ultimately, given the complexity of the motors market and supply chain, regulation drives efficiency.

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Fluid Systems 2

Pump efficiency regulations and labeling in the USA

Greg Towsley

Abstract

Currently no energy conservation standards for commercial and industrial pumps exist in the United States of America (USA). However, the Department of Energy (DOE) of the USA has had the authority to issue energy conservation standards, test procedures and labeling requirements for commercial and industrial pumps since the Energy Policy and Conservation Act (EPCA) of 1975 (Public Law 94-163). In June 2011, the rulemaking process to establish standards, procedures and labeling requirements for commercial and industrial pumps began. It is expected that by the end of 2015, DOE will have published a Final Rule for efficiency standards and a pump test procedure.

This paper will discuss actions and industry standards that provide the basis supporting requirements of regulatory efficiency and test procedure rules for commercial and industrial pumps in the USA. The paper will also analyze potential effects on the USA market. In addition, a bridge to a USA initiative for industry collaboration developing voluntary measures that accelerate high performance extended pump product adoption in the market will be explained.

Introduction

The overall regulatory landscape related to pumps in the United States of America (USA) is limited. Those regulations that do exist primarily deal with personal safety. For those types of regulations, third party organizations exist to develop safety standards for pumps related to the integration of pumps with electrical motors, or with the pump materials that may come in contact with liquids for human consumption. These organizations also provide the associated testing and certification that provides the public with likely safer equipment and peace of mind. Example of the organizations include Underwriters Laboratories Inc. (“UL”), Intertek Group plc, and NSF International.

Standards related to the design and construction of pumps are developed by the primary trade association of manufacturers of pumps in North America, Hydraulic Institute (HI). Specific end use markets or applications may also develop design and construction standards that provide for specific needs for that market. Pumps used in the petroleum industry are designed to the American Petroleum Institute standard API-610. Pumps used in chemical process plants are typically designed to ANSI/ASME B73 standards. Fire pumps will be designed to meet National Fire Protection Association NFPA 20. While these design standards exist, no national regulations exist that require pump buyers to require pumps designed to those standards. The market is somewhat self-regulating in requiring pumps of those design standards, as buyers are involved in the development of the standards.

Building codes provide a method of regulating the selection, application and control of pumps into buildings, primarily for commercial use. The building codes will reference other existing safety standards or how the pumps are applied to a pumping system. It is up to the local jurisdiction to insure that the codes and standards are being complied with during building construction.

For many USA government funded infrastructure projects, a requirement of “Buy American” can be incorporated into the project. If an American-made pump product cannot be found for the service, and waiver can be obtained for non-domestic manufactured projects. In the state of Pennsylvania, there is a strict requirement in their Steel Products Procurement Act that any products, or pumps in this case, that are to be purchased and installed in state or state-funded projects, must have a certain percentage of raw materials that came from Pennsylvania steel mills and foundries.

Pump Efficiency Regulations

As of the writing of this publication, no energy conservation standards for commercial and industrial pumps exist in the USA. However, Title III of the Energy Policy and Conservation Act (EPCA) of 1975 (Public Law 94-163), as amended (42 U.S.C. 6291 et seq.) [1], established an energy conservation program for certain commercial and industrial equipment. This program, as set forth in Part C of Title III of EPCA, includes pumps as covered equipment and authorizes DOE to issue standards, test procedures and labeling requirements for them (42 U.S.C. 6311(1)(A)). More specifically, the law states that the DOE has the authority to regulate energy conservation standards and test procedures for covered industrial equipment which includes "electric motors and pumps" [2].

On 13 June 2011, the Office of Energy Efficiency and Renewable Energy, within the DOE, published a notice in the Federal Register, requested information regarding product markets, energy use, test procedures, and designs for energy efficiency for commercial and industrial pumps. This request for information from the DOE officially began the process for the energy conservation standards and test procedure rulemakings.

Department of Energy Rulemaking Process Overview

During the process of setting standards, EPCA requires the DOE to consider seven factors during their analysis in an attempt to insure that the standards are achievable and economically defensible [3].

1. Economic impact on consumers and manufacturers
2. Lifetime operating cost savings compared to increased equipment cost
3. Total projected energy savings
4. Impact on utility or performance
5. Impact of any lessening of competition
6. Need for national energy conservation
7. Other factors the Secretary considers relevant

To meet the requirements of EPCA, the DOE will complete various types of analysis that correspond to the factors. The analyses include screening of design options, engineering, life-cycle costs, and impact on the manufacturers, energy savings, consumer economics, emissions, and employment.

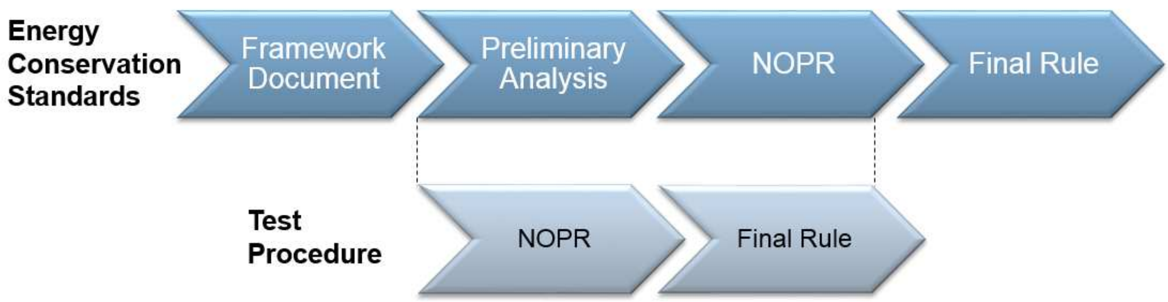

Figure 1 Standards and Test Procedure Process Overview

The rulemaking process consists of two parallel processes: Energy Conservation Standards and Test Procedure. While these two processes are separate, the timing of them, and their inherent activities, are integral. The Test Procedure process may take up to 1.5 years within the total approximate 3 year process of the Energy Conservation Standard.

Initial Preliminary Rulemaking Timeline

In February 2013, the DOE communicated that the planned pump rulemaking schedule would be as shown in Figure 2 below.

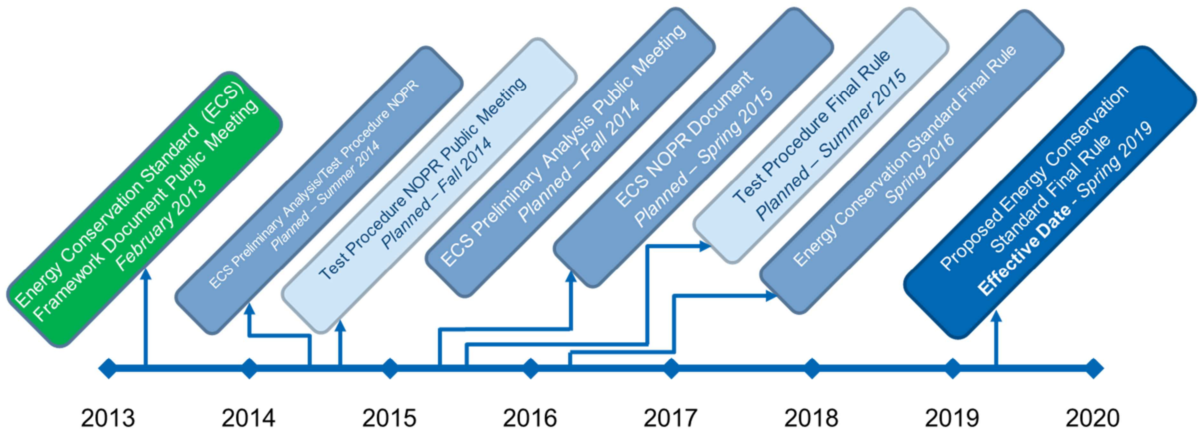

Figure 2 The Initial Planned Pumps Rulemaking Schedule

Framework Document

The first step in DOE's standards development process is issuing a Framework Document. The purpose of the Framework Document is to communicate to all interested stakeholders the process and analyses that the DOE will use to develop new energy conservation standards for pumps. It is intended to be the initial starting point of discussions and to communicate the DOE's initial understanding of the market and potential path forward for the standards and test procedure. The DOE announced in the Federal Register that the Framework Document was available on 1 February 1 2013 [4]. The DOE held a public meeting on 20 February 2013 in Washington, DC to provide further information about the process and to take questions from industry stakeholders. Among other information, they had advised that all documents and public communications could be found in the future at a summary document location on a government web site [5].

In the instance of the pumps rulemaking, the Framework Document provided information on the scope of coverage DOE is considering for the initial standard, communicate their understanding of equipment definitions, discuss the various metrics used to describe pump efficiency, and communicate test procedure methods that the DOE found that could be used to measure pump efficiency. The desire of the DOE with the Framework Document is to engage stakeholders in the process early and to get comments on their approach and potential issues.

Preliminary Analysis

From the feedback that the DOE receives from the Framework Document and subsequent investigative meetings that are held with stakeholders of the process, a technical support document is created that provides a preliminary analysis by the DOE that includes analysis on:

- An engineering analysis on potential design options that could increase pump efficiency
- Profitability of the products within the value chain of the pump products (markups)
- Energy consumption of pump products in scope
- Consumer life-cycle cost (LCC) and payback period for product changes and energy savings
- Unit shipment for products in scope
- Impacts on national energy savings, consumer net present value, and the manufacturers
- Discussion of comments received in response to the Framework Document

A public meeting would be held after the technical support document for the Preliminary Analysis is made available. The DOE encourages interested stakeholders to provide further comments to the Preliminary Analysis.

Notice of Proposed Rule (NOPR)

After a period of time to review the comments received from the public and stakeholders on the technical support document of the Preliminary Analysis, the DOE modifies assumptions used in the process, adjusts the proposed standard accordingly, and revises the various analyses conducted. The DOE will then provide a notice in the Federal Register about the availability of a Proposed Rule, and will have an accompanying public meeting. The Proposed Rule will include the scope of the products covered and the standard levels. As with the Framework Document and the technical support document for the Preliminary Analysis, the DOE encourages additional comment and feedback from stakeholders of an efficiency standard on pumps.

Final Rule

Based on the comments and feedback received from the stakeholders from the Proposed Rule in the process' previous step, the DOE will consider all written and verbal (from public meetings) input. That input will be used in preparing the Final Rule by revising all analyses on impacts, determining the efficiency levels standards that will be adopted, and establishing a date for compliance for standards adoption. Upon development of the Final Rule, the availability will be communicated in the Federal Register.

It must be noted that the typical DOE rulemaking process includes a concurrent activity of announcing a proposed testing procedure prior to releasing the technical support document for the Preliminary Analysis, and releasing the Final Rule for the test procedure before the notice of Proposed Rule.

Appliance Standards and Rulemaking Federal Advisory Committee

The Appliance Standards and Rulemaking Federal Advisory Committee (ASRAC) was established by the Appliance and Equipment Standards Program within the DOE [6]. The intent of the Committee, consisting of interested stakeholders to the equipment being considered for energy efficiency standards, is to negotiate recommendations to be incorporated into a Final Rule. The negotiating stakeholders meet to attempt to reach consensus recommendation through discussions about information about the equipment to be regulated and to gather data to be used in analysis. The recommendations obtained through consensus by a subcommittee and the primary Committee are forwarded to the DOE with the desire for the recommendations to be included into the Final Rule. It is the expectation of DOE that recommendations from ASRAC will be more acceptable to the entire stakeholder population of the equipment to be regulated and that the efficiency standards will be implemented at earlier dates than under the typical rulemaking process.

On 23 July 2013, as communicated in the Federal Register, ASRAC provided a notice on the intent to establish a working group to negotiate recommendations for energy conservation standards for pumps [7]. As announced on 12 November 2013 [8], the membership of the working group was established and later, a series of meetings to develop recommendations were identified. The working group consisted of representation from the DOE and the primary ASRAC committee, as well as representatives from pump manufacturing sector, electric motor manufacturing sector, energy efficiency advocacy, utility sector, and the pump end user sector.

During multiple sets of meetings held from December 2013 through June 2014, the working group met to discuss and negotiate recommendations for the Final Rule. During the entire period of meetings, the DOE provided information on recommended metrics and analysis based on data provided to them from stakeholders within the industry.

The outcome of multiple meetings of the working group through June 2014 was a term sheet of recommendations that were forwarded to ASRAC [9]. These recommendations were later approved by the full ASRAC committee and forwarded to DOE, with the hope of being incorporated into the Final Rule.

The recommendations established by consensus of the work group are summarized as follows:

1. Covered product definition
    - ‘Pump’ is a device that moves liquids (which may include entrained gases, free solids, and totally dissolved solids) by physical or mechanical action and includes a bare pump and, if included by the manufacturer, the mechanical equipment, driver, and controls.
2. The components of a ‘pump’ will be defined as below:
    - ‘Bare pump’ is a ‘pump’ excluding mechanical equipment, driver, and controls.
    - ‘Mechanical equipment’ is any component that transfers energy from the driver to the bare pump.
    - ’Driver’ is the machine providing mechanical input to drive the bare pump directly or through the mechanical equipment, and may include an electric motor, internal combustion engine, or gas/steam turbine.
    - ‘Controls’ means any device that can be used to control the driver.
3. For this first initial DOE energy conservation standard for pumps, it is recommended that the metric will not cover non-electric drivers. The test procedure will specify that the bare pump rating calculations for the energy conservation standard also apply to pumps with non-electric drivers.
4. The ASRAC working group recommended that the scope of this initial rulemaking should include the following pump types (DOE designation/Hydraulic Institute designation). It should be noted that these pump types are the same as was covered in the initial European Commission regulations for energy efficient pumps.
    - End suction frame mounted/own bearings (ESFM/OH0, OH1)
    - End suction close coupled (ESCC/OH7)
    - Inline (IL/OH3, OH4, OH5)
    - Radial split (multistage) vertical (RS-V/VS8)
    - Vertical turbine submersible (VT-S/VS0)
5. Ensuing standard development activities
    - Circulators (CP1, CP2, and CP3 as defined by Hydraulic Institute) should not be included in the initial rulemaking. Recommendations for energy conservations standards for circulators should be developed through an additional informal negotiation between manufacturers, efficiency advocates, and other stakeholders. March or April 2015 was targeted for the stakeholders to present a joint proposal to the DOE. An ASRAC negotiating working group would began following the presentation of the proposal to DOE. A date of September 2015 was targeted for a Notice of Proposed Rule for an energy conservation standard for circulators.
    - A separate rulemaking on dedicated-purpose pool pumps should begin by the end of calendar year 2014.
6. The ASRAC working group recommended that specific types of pumps be excluded in this initial rulemaking.
    - Positive displacement pumps
    - Axial/mixed flow pumps
    - Horizontal split case, double suction pumps
    - Multistage axially split pumps
    - Multistage radial split-horizontal pumps
    - Multistage radial split vertical immersible pumps
    - Vertical turbine (non-submersible) pumps
7. The ASRAC working group intended that the initial rulemaking be for pumps in clean water applications. As the DOE cannot regulate applications, only covered products, additional pumps that are designed for specific applications were recommended to be excluded from the initial rulemaking.
    - Wastewater, sump, slurry, solids handling
    - API-610 pumps
    - ASME/ISO chemical pumps
    - Fire pumps that are compliant with NFPA 20 and UL listed or FM approved
    - Self-priming pumps
    - Prime-assisted pumps

- Nuclear pumps that comply with ASME Boiler and Pressure Vessel Code Section III or 10 CFR 50
- “Navy” pumps that are MIL Specification Compliant (MIL-P-17639, MIL-P-17881, MIL-P-17840, MIL- P-18682, MIL-P-18472)
- “Sanitary” or “hygienic” pumps that are typically used in food processing and pharmaceutical applications. Certifications for hygienic or sanitary products include, but are not limited to 3-A Sanitary Standards, EHEDG (European Hygienic Equipment Design Group) recommendations, or QHD (Qualified Hygienic Design)

8. It was recommended that this rulemaking will be limited to pumps with the following characteristics:
    - Driver size of 1-200 horsepower (0.75-150 kW), based on the shaft power at the best efficiency point (BEP) for the full impeller diameter
    - Capacity rating of 25 gallons per minute (5.7 cubic meters per hour) and greater, based on the flow at BEP for the full impeller diameter
    - Total pump head of 459 feet (140 meters) maximum at BEP for the full impeller diameter)
    - Design temperature range from -10 to 120 degrees C
    - Pumps designed for nominal 3600 or 1800 rpm driver speeds
    - 6-inch or smaller bowl diameter for vertical turbine submersible pumps

    Additional requirements recommend that the pump certified rating for a given model should be based on testing at full impeller diameter. Pump models that otherwise meet all the above characteristics will not be excluded on the basis of having a trimmed impeller. Full impeller means the largest impeller diameter offered for sale for a given model.
9. The pump test procedure is recommended to be based in accordance with HI Standard 40.6 for determining bare pump performance.
10. The metric for assessing compliance with the standard should be the Pump Energy Index (PEI), which is constructed based on values for a given pump model’s Pump Energy Rating (PER). A PEI could be developed for a pump applied with constant speed, PEI_{CL}, and a pump applied with a variable speed, PEI_{VL}. The PEI is found by the ratio of the PER_{CL} and PER_{VL} of a particular pump model and its rating at the full impeller diameter, to the PER_{CL} for a minimally compliant pump (PER_{STD}) with the same hydraulic load, as shown in Table 1.

    The Pump Energy Rating (PER) CL and VL used in the PEI is an equally weighted average electric input power to the ‘pump’ measured or calculated at the driver input or, when present, controls input, over a specified load profile:

Table 1 Summary of Proposed Metrics [10]

Pump Energy Index	Constant Load Pump Energy Index (PEI_{CL}) (uncontrolled)	Variable Load Pump Energy Index (PEI_{VL}) (with motor and controls)
Ratio	$PEI_{CL} = \left[\frac{PER_{CL}}{PER_{STD}}\right]$ [1]	$PEI_{VL} = \left[\frac{PER_{VL}}{PER_{STD}}\right]$ [2]
Pump Energy Rating (PER)	$PER_{CL} = \sum_i \omega_i (P^{in}{}_i)$ [3]	$PER_{VL} = \sum_i \omega_i (P^{in}{}_i)$ [4]
PER Load Profile	i = 75%, 100%, 110% of BEP flow at nominal speed for uncontrolled pumps	i, for VL = 25%, 50%, 75%, and 100% of BEP flow at nominal speed for pumps sold with motors and controls
PER_{STD}	PER_{CL} for Minimally Compliant Pump of the same equipment class serving the same hydraulic load	
Applicable Pump Configurations	Pumps sold without continuous or non-continuous controls	Pumps sold with continuous or non-continuous controls
Where: • ω_i = weight at each load point i • $P^{in}{}_i$ = power input to the “pump” at the driver, inclusive of the controls if present, (hp) • i = Percentage of flow at the BEP of the pump		

Note: All formulas have been developed for typical units used in the USA at 60 Hz. Conversion to metric units and 50 Hz is not being considered.

For the equations shown in Table 1 above, PER_{STD} can be expanded as:

$$PER_{STD} = \omega_{75\%}\left(\frac{P_{Hydro,75\%}}{0.95\times\eta_{pump,STD}} + L_{75\%}\right) + \omega_{100\%}\left(\frac{P_{Hydro,100\%}}{\eta_{pump,STD}} + L_{100\%}\right) + \omega_{110\%}\left(\frac{P_{Hydro,110\%}}{0.985\times\eta_{pump,STD}} + L_{110\%}\right) \quad [5]$$

And

$$\eta_{pump,STD} = -0.85 \times ln(Q_{100\%})^2 - 0.38 \times ln(Ns) \times ln(Q_{100\%}) - 11.48 \times ln(Ns)^2 + 17.80 \times ln(Q_{100\%}) + 179.80 \times ln(Ns) - (C + 555.6) \quad [6]$$

Where:

- Ns = the specific speed at 60 Hz,
- Q = the flow rate of the pump at BEP in GPM,
- C = constant which is set based on the speed of rotation of the pump, and the pump equipment class

$\eta_{pump,\,STD}$ is a similar formula utilized in the EuP regulations for energy conservation standards for pumps in the European Union.

Expanding on Equation [1]:

$$PEI_{CL} = \left[\frac{\frac{1}{3}\times\left(P^{in}{}_{75\%}+L_{75\%}\right)+\frac{1}{3}\times\left(P^{in}{}_{100\%}+L_{100\%}\right)+\frac{1}{3}\times\left(P^{in}{}_{110\%}+L_{110\%}\right)}{PER_{STD}}\right] \quad [7]$$

Expanding on Equation [2]:

$$PEI_{VL} = \left[\frac{\frac{1}{4}\times\left(P^{in}{}_{25\%}+L_{25\%}\right)+\frac{1}{4}\times\left(P^{in}{}_{50\%}+L_{50\%}\right)+\frac{1}{4}\times\left(P^{in}{}_{75\%}+L_{75\%}\right)+\frac{1}{4}\times\left(P^{in}{}_{100\%}+L_{100\%}\right)}{PER_{STD}}\right] \quad [8]$$

P^{in}_i are the values of the tested input electrical power to the pump (speed x torque) or driver (motor or control) at each load point i.

It must be noted that the proposed PER_{CL} and PER_{VL} calculations require assumptions for part load motor performance. Analysis by the DOE developed a conservative equation to provide fractional motor losses at each load point i (L_i) that are calculated as the rated full load motor losses (L_{rated}) multiplied by the part-load loss factor (y_i), which is calculated as a cubic polynomial of the load fraction on the motor (x_i) that is used in the PEI calculations [11]. At the time of publication of this paper that equation with its coefficients is:

$$L_i = L_{rated} \times \left(-0.4508 \times \left(\frac{P_i}{MotorSize}\right)^3 + 1.2399 \times \left(\frac{P_i}{MotorSize}\right)^2 + (-0.4301) \times \left(\frac{P_i}{MotorSize}\right) + 0.6410\right) \quad [9]$$

Where:

- L_i = the fractional load loss of the motor at load point i (hp);
- L_{rated} = the rated full load motor losses as determined in accordance with the DOE test procedure for motors at 10 CFR 431 subpart B (hp);
- y_i = the part-load loss factor;
- x_i = the load fraction for the motor at each load point i;

- P_i = the shaft input power to the bare shaft pump (hp);
- MotorSize = the nominal rated output power of the motor (hp); and
- i = Percentage of flow at the best efficiency point (BEP) of the pump.

11. It was recommended that the energy conservation standards will set the index at PEI 25 for pumps designated by the DOE as ESCC, ESFM, IL, and VT-S pumps in both 1800 and 3600 rpm speeds. This index has been calculated through DOE analysis to remove approximately 25% of the least efficient pumps sold in the USA market. For pumps designated by the DOE as RS-V, the PEI and energy conservation standards should be set to harmonize with the European Union No 547/2012 MEI 40 level, with the intent that no models known to pass the EU standard would fail the US standard. By consensus agreement of the working group, it was recommended that the compliance date to the energy conservation standards for all equipment classes will be four (4) years from the publication of the Final Rule.
12. A basic labeling configuration was recommended by the ASRAC working group. The pumps should include the information below on the pump nameplate for the configuration in which they were sold.

Table 2 Recommended Labelling Information by Sold Configuration

Bare Pump	Bare Pump + Motor	Bare Pump + Motor + Controls
PEI_{CL} Model number Impeller diameter for each unit	PEI_{CL} Model number Impeller diameter for each unit	PEI_{VL} Model number Impeller diameter for each unit

13. To support the DOE's certification and compliance activities, it was recommended that specific data determined from the required test procedures be included in a DOE-maintained database. It was agreed by consensus that the follow information be included in that database for each certified pump.
    - Manufacturer name
    - Model number(s)
    - Equipment class
    - PEI_{CL} or PEI_{VL} as applicable
    - BEP flow rate and head
    - Rated speed
    - Number of stages tested
    - Full impeller diameter (in.)
    - Whether the PEI_{CL} or PEI_{VL} is calculated or tested
    - Input power to the pump at each load point *i* (P^{ini})
14. Certification for the pump types that the DOE has designated as RS-V and VT-S pumps should be based on testing the same number of stages as has been included in the EU pump efficiency regulations. If a pump model is not available with that specific number of stages in the given scope, the model would be tested and certified with the next closest number of stages offered for sale by the manufacturer. If only fewer than the required number of stages are available, the testing and certification should be with the highest number of stages offered for sale to the market for that pump model. If only more than the required number of stages are available, the testing and certification should with the least number of stages offered for sale to the market for that pump model.
    - RS-V: 3 stages
    - VT-S: 9 stages

Example of the Effect of High Efficiency Motors and Control Technology on the PEI

The PEI methodology to reduce the energy consumption of pumps has been developed to provide manufacturers various opportunities for solutions to the market. Simply improving the hydraulic performance of the pump itself can provide an acceptable PEI that would allow the pump to be sold in the USA. The addition of a more efficient motor, with or without controls, can improve the PEI of a bare pump, allowing it to be sold into the market only with those components.

Table 3 provides examples of outcomes to a bare pump with less than adequate performance. Alternative to the calculation, similar or improved outcomes could be expected from testing the pump with a motor different than the regulated minimum efficient allowed by federal regulations or with controls.

Table 3 Examples of Calculated PEI for Various Configurations

ESCC, 1800 rpm	**Bare Pump, Baseline**	**Bare Pump, Improved Hydraulics**	**Bare Pump, Baseline + High Eff. Motor**	**Bare Pump, Base Line + Motor + Controls**
Q, gpm	1845	1845	1845	1845
H, feet	70	70	70	70
Pump Efficiency	79	**83**	79	79
Pump input power (hp)	41.32	**35.28**	41.32	41.32
Motor Efficiency, Minimum	94.50	94.50	**96.80**	94.50
$PEI_{CL/VL}$	1.02	0.99	0.99	0.46
PASS/FAIL	FAIL	PASS	PASS	PASS

Status of USA DOE Rulemaking for Commercial and Industrial Pumps

Test Procedure NOPR

On 13 March 2015, the Department of Energy issued a pre-publication NOPR and announcement of a public meeting regarding test procedures for commercial and industrial pumps [12]. The public hearing on the NOPR was held 29 April 2015 in Washington, DC.

This proposed rule will establish definitions and a test procedure that will be used for pumps, inclusive of motors and controls if applicable, and energy conservation standards that will be established. The DOE concurs with ASRAC that the HI Standard 40.6-2014 shall be the basis of their test procedure with minor modifications related to excluding specific reference found in HI 40.6, sampling and data collection, additional requirements for test consistency and repeatability, normalization of pump shaft input power at the specified flow rates, and equipment used to measure “wire-to-water” power consumption of a pump tested with a motor and variable speed drive. They also agree with the use of a Pump Energy Index (PEI) metric included in the ASRAC recommendations. The test procedure proposed by the DOE includes methods for determining the PEI for pumps sold with or without motors and controls, by use of physical testing or calculation methods. The proposed rule for the test procedure also includes a sampling plan that would follow their minimum requirements of two units of a specific model.

The public comment period for the test procedure was closed on 15 June 2015.

Energy Conservations Standards for Pumps NOPR

On 17 March 2015, the Department of Energy issued a pre-publication NOPR and announcement of a public meeting regarding energy conservation standards for commercial and industrial pumps [13]. The public hearing on the NOPR was held 29 April 2015 in Washington, DC in conjunction with the public hearing on the test procedure NOPR.

As with the information provided with the test procedure NOPR, the proposed standards in the NOPR for the energy conservation standards for pumps have incorporated the consensus recommendations of ASRAC. The proposed rule is in full correlation with the test procedure NOPR. The PEI proposed in the NOPR correlates to values for ESCC, ESFM, IL, and VTS pumps that would not allow those pumps with efficiencies in the lowest 25th percentile to be sold in the United States. The PEI for the RSV pumps would be set a values to harmonize with the standards recently set for the same style pumps in the European Union [14].

In the analysis completed by the DOE, it was found that the proposed standards provided a simple payback period of less than half the estimated average lifetime of the pumps for all of the pumps types within the scope of the NOPR [15]. The DOE also conducted various analyses on the benefits for the United States. They estimate that the energy savings from the standards over a 30 year period beginning with a full year of compliance would be 0.28 quadrillion Btu, which is approximately one percent of the base case energy use of the pumps within scope of the NOPR. The environmental benefits through 2030 amount to a cumulative CO_2 reduction of 2.5 Mt, which is equivalent to the annual electricity used by 360,000 homes in the United States.

The DOE also concluded that the standards proposed in the NOPR, based on technology that is currently commercially available, is the maximum energy efficiency improvement for pumps the would provide significant energy savings and would be economically justified.

A public comment period on the proposed Test Procedure and Proposed Rule was closed on 1 June 2015. After closing of the public comment period, it is expected that the DOE will take an additional 6-8 months to review and consider all of the comments and feedback, and, based on the comments and feedback, revise all analyses on impacts, determine the final efficiency levels standards that will be adopted, and establish a date for compliance for standards adoption. The final action is targeted to be the end of December 2015.

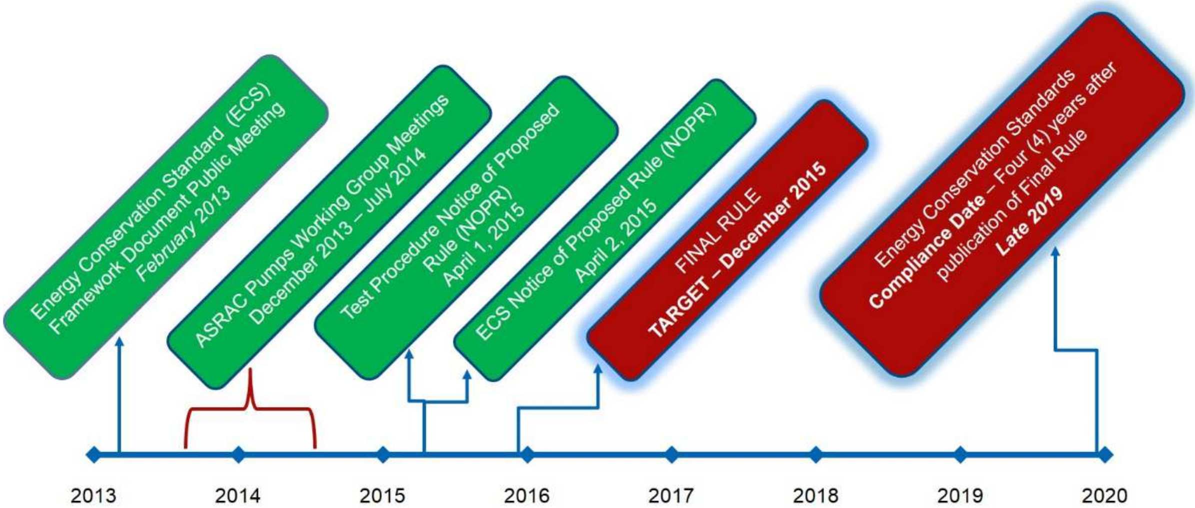

Figure 3 Updated Pumps Rulemaking Schedule

Voluntary labeling

Electric utilities in the USA provide nearly $1 billion in demand management incentives that help reduce energy consumption [16]. As pumps have been identified as a top candidate minimum energy-efficiency standards, coordinating the implementation of an informative and useful energy label will support demand management programs that encourage the purchase high efficiency pumps [17]. Industry experience has shown that an informative energy efficiency label will stimulate manufacturers to remove lower efficiency products and to expand efforts to develop more efficient solutions for the market.

Currently in the USA, there are no energy labeling requirements for commercial and industrial pumps. California and the Environmental Protection Agency (EPA) have established a labeling scheme for residential swimming pool pumps. With the establishment of energy conservation standards for pumps by the DOE, a simplistic categorical label, as described previously, will communicate how efficient the pump is compared to similar models.

In July 2013, The American Council for an Energy-Efficiency Economy (ACEEE) invited the trade associations, and their members, of the pump industry (Hydraulic Institute, HI), the fan industry (Air Movement and Control Association, AMCA), and the compressor industry (Compressed Air and Gas Institute, CAGI), and organizations from the utility sector that administer energy efficiency programs, to an introductory meeting to propose a collaboration to develop labeling schema for equipment driven by electric motors, inclusive of the motors and applicable controls.

The intent of the collaboration is to develop "extended motor product" labels for each type of motor-driven equipment that can be used in utility programs, such as with prescriptive rebate programs or custom programs [18]. An "extended motor product" is considered the electric motor plus the driven equipment, such as pump, fan or compressor, and other controlling equipment, such as a variable speed drive, as depicted in Figure 4. The concept of the "extended motor product" was developed by EUROPUMP, the European Association of Pump Manufacturers. It is planned that the "extended motor product" will also become incorporated into the energy conservation legislation for pump in the Energy Related Products (ErP) Directive. The definition of an extended motor product for pumps used in the collaboration conforms to the recommendations of ASRAC and the proposed rules of the DOE.

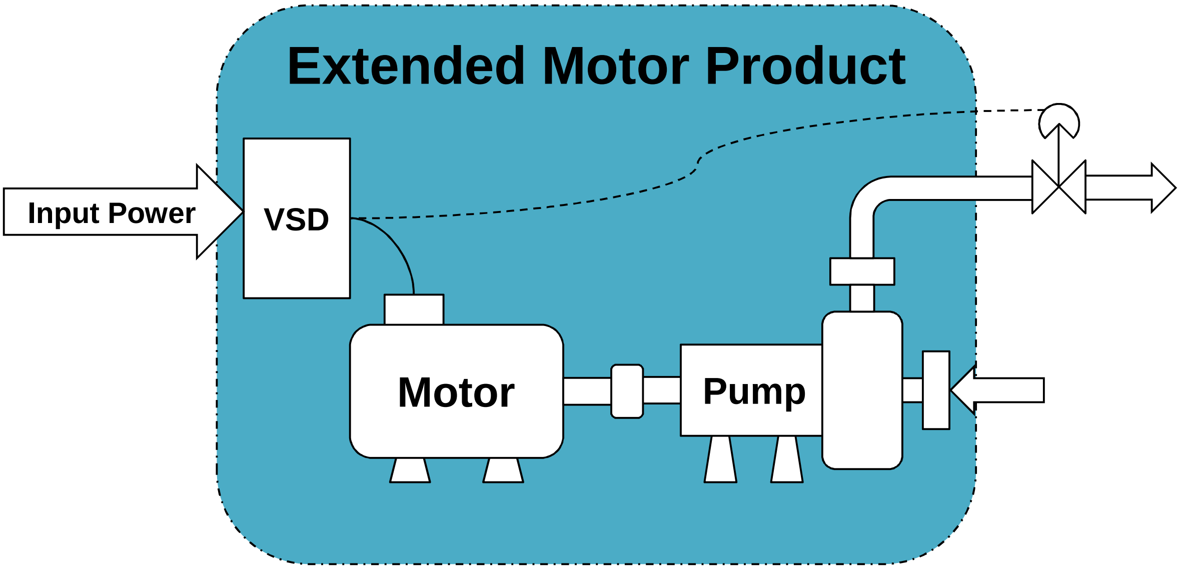

Figure 4 - Example of an extended motor product for a pump

ACEEE designated the collaborative effort as the Extended Motor Product Label Initiative (EMPLI). Within EMPLI, three working groups were created for pump, fans and compressors. The membership of the pump working group consisted of a representative of HI, representative of major pump manufacturers (of whom some were also part of ASRAC), and partners from the utility and energy efficiency interests, include the California investor owned utilities, Bonneville Power Administration and National Grid. The objective of the pump working group is for HI to develop a voluntary extended product label that will meet the requirements of the energy efficiency programs that provide incentives to the market to purchase the most efficiency extended motor product available for their application.

The EMPLI pump working group meets in person or via teleconferences to develop the label. Since initial meetings at the end of 2013, the pump working group determined that utilizing the DOE proposed metric and test procedure would be the basis of the extended motor product label standard. In addition, the initial focus would be on those pumps that are also within the scope of the proposed regulations from the DOE. Upon development of the label, the members from organizations that have efficiency programs would conduct field studies and analyze the results of energy savings on the concept. Adjustments would be made to the label standard and program, and, eventually, a minimal launch would be initiated.

In addition to regular label development meetings, parallel communication and development activities have taken place. The DOE was informed by the EMPLI stakeholders of the activities of the working groups. Reaction from the DOE was positive, as the pump working group label development is expected to utilize their regulations and will support the transformation of the market towards increased energy efficiency.

In addition, HI established a technical committee whose purpose is to develop and maintain a voluntary label program to support the energy efficiency incentive programs. Their deliverable included developing a program guide, policies and procedures for the program, marketing concepts and tools, and an educational awareness plan for the program. The target for completion of the guide is targeted for Q1 2016.

Summary

While the United States may be considered lagging to other global regions for regulations on efficiency conservation standards for industrial equipment, activities related to commercial and industrial pumps are moving forward, and at a substantial pace. Energy conservation standards and test procedures for the most commonly used pumps in the USA is targeted for completion by the end of 2015, with a effective date of four years later.

In addition, a collaborative effort through EMPLI is developing a voluntary labelling program that will allow the utility sector to establish incentives to more rapidly transform the market to purchasing and operating more efficient pumps and motors.

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Fan System Assessment Tool Software (FSAT), proposed version 2.0

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Abstract

The Fan System Assessment Tool (FSAT) software, version 1.0 was released by the U.S. DOE in 2004 as a tool to assess the efficiency of industrial fan systems and determine possible savings, relative to the fan doing a job in the most efficient manner possible. After 10 years of experience with the FSAT, the U.S. DOE's Senior Fan System Trainers, and the United Nations Industrial Development Organization's lead national- and international Fan System Optimization Experts, agree that there are technical aspects of the software that can be improved. These proposed technical upgrades include: a) providing for the ability to override the FSAT peak achievable efficiency for cases when the peak efficiency is limited by existing conditions, b) providing system analysis in Imperial and Metric units of measure, c) enhancing software filters for improved fan recommendations, d) improving user experience with a new interface and offering more languages, and e) increasing functionality through the development of new tools, such as fan- and system curve graphing calculators. The purpose of this paper is to document changes to the software, and describe the new features of version 2.0, pending possible release in 2015.

Fan System Assessment Tool Software - FSAT

FSAT software was released by U.S. Department of Energy in 2004. Written by Don Casada, the FSAT software was modeled after his PSAT software, and was presented as part of a software suite meant to address energy efficiency opportunities in motor driven systems, including fans, pumps, and compressors. Readers familiar with the 1990s version of PSAT may recognize the similarities of FSAT from *figure 1*. The software is developed within the software development framework of the *LabVIEW Executable Modules*, and *LabVIEW* is the compiler for the software. The software includes product efficiency source data, provided by the Air Movement and Control Association International (AMCA) members.

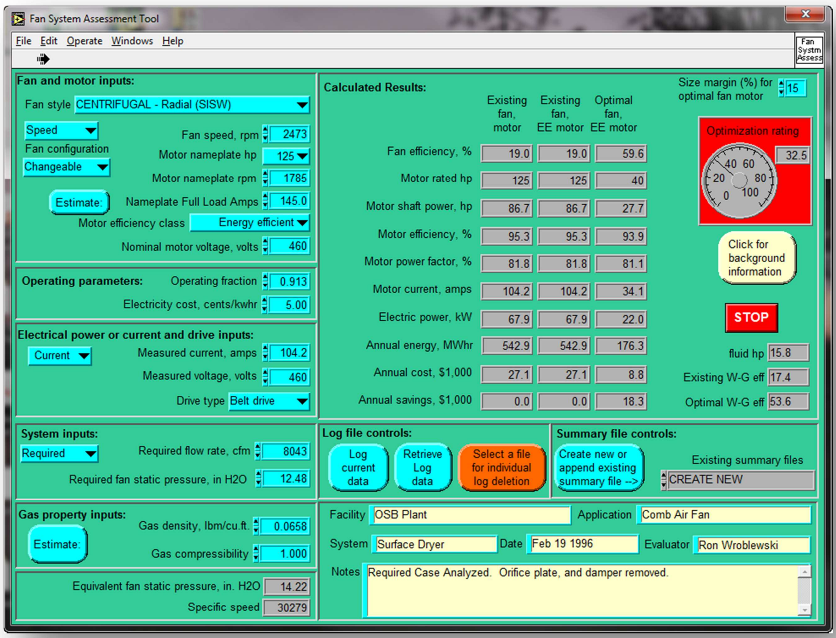

Figure 1 – FSAT home screen, Imperial

FSAT requires only a handful of inputs, as seen on the left side of the home screen, *figure 1*. Key input parameters include nameplate information on the fan and motor, the cost of electricity, running hours (operating fraction) plus power, flow and pressure. With these basic inputs, a user knowledgeable in fan application engineering can use FSAT to estimate fan system efficiency, or fan efficiency.

Calculated output values are organized into three columns on the screen's top-right. The left column shows calculated values for the existing (baseline) condition. The middle column shows equipping the present fan with an Energy Efficient (EE) motor. The output in the right column is relative to the "fan-configuration" switch: If the switch is set to "changeable", the column shows a *best-case scenario* of using the optimal fan with an energy efficient motor. This *best-case scenario* is based on using the most efficient fan design on the market, and then tuning the design to achieve its Best Efficiency Point (BEP), at the exact flow and pressure specified by the user. If the “fan configuration” switch is set to “fixed”, FSAT compares the baseline to the fan efficiency specified in the “efficiency vs. specific speed” calculations and graph.

Data management options are available in the lower-right corner. By using these buttons, the user can save or retrieve data, collect description information about the fan systems being analyzed, and generate reports across several FSAT analyses by assembling and exporting the summaries to Microsoft Excel.

A very useful and helpful feature in the background of FSAT is the look up table for motor performance data. By use of an engineering analysis trick, the software can use motor performance data to estimate the motor’s power factor. With an estimated power factor, an estimate of actual motor power (kW) can be made using field collected amps and volts. This feature is useful when the plant electrician does not have access to a portable power meter.

The software also includes a full psychrometric calculator based on the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) method. This calculator estimates gas density, which is a major factor in the fan system engineering analysis.

The engineering basis of the FSAT software is an equation referred to as the Fan Power Law (*equation* A_i *&* A_m).

$$H = \frac{Q * P * K_p}{6345 * Eff}$$

Where:

H=Shaft Power (absorbed) in Brake horse power
Q=Flow in cfm
P=Fan static Pressure in Inches Water Gauge
K_p=Compressibility factor
Eff=Fan Static efficiency in decimal form

Equation A_i
Imperial units version of the Fan Power Law[1]

$$H = \frac{Q * P * K_p}{Eff}$$

Where:

H=Shaft Power (absorbed) in Watts
Q=Flow in m^3/s
P=Fan static Pressure in Pascals
K_p=Compressibility factor
Eff=Fan Static efficiency in decimal form

Equation A_m
Metric units version of the Fan Power Law

The Fan Power Law’s compressibility factor is calculated by FSAT as shown in *equation B*. For low pressure fans, the compressibility factor is usually equal to 1 (or very close to 1); when the fan is developing significant amounts of pressure, there is some compression of the air, i.e., there are fewer cfm (m^3/s) coming out of the outlet, then there were going into the inlet.

[1] Although a Metric version of FSAT was developed, only the Imperial unit version is available to the public.

$$K_p = \left(\frac{In(1+x)}{x}\right) * \left(\frac{z}{In(1+z)}\right)$$

Where:

$$x = \frac{P_{ft}}{P_{ta1}}$$

$$z = \left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{6354 * P_{shaft}}{Q * P_{tal1}}\right)$$

K_p = Compressibility
P_{ft} = Fan total Pressure (Inches Water Gauge)
P_{ta1} = Fan total Pressure at fan inlet (Inches Water Gauge)
ϒ = Specific heat ratio (dimensionless)
P_{shaft} = Shaft Input Power (Brake Horsepower)
Q = Volumetric flow rate (CFM)
6354 = Conversion constant

Equation B_i – Imperial units version of the compressibility factor calculation

Where:

$$x = \frac{P_{ft}}{P_{ta1}}$$

$$z = \left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{1000 * P_{shaft}}{Q * P_{tal1}}\right)$$

K_p = Compressibility
P_{ft} = Fan total Pressure (Pascal)
P_{ta1} = Fan total Pressure at fan inlet (Pascal)
ϒ = Specific heat ratio (dimensionless)
P_{shaft} = Shaft power (kW)
Q = Volumetric flow rate (m^3/s)

Equation B_m – Metric units version of the compressibility factor calculation

The Fan Power Law is used in several different algebraic forms depending on what variable is being solved for. *Equation A* returns the power when inputs of flow, pressure and efficiency are provided, and this form is used to calculate fan performance values in the *best-case scenario*, (right hand column of FSAT output table). If we re-arrange the Fan Power Law to *equation C*, then we can solve for the efficiency of the base case (left hand column of FSAT output table).

$$Eff = \frac{Q * P * K_p}{H * 6345}$$

Where:
Eff = Fan Static efficiency in decimal form
Q = Flow (cfm)
P = Fan static Pressure (Inches Water Gauge)
K_p = Compressibility factor
H = Shaft Power (absorbed) (Brake horse power)

Equation C_i – Imperial units version of the re-

$$Eff = \frac{Q * P * K_p}{H}$$

Where:
Eff = Fan Static efficiency in decimal form
Q = Flow (m^3/s)
P = Fan static Pressure (Pascal)
K_p = Compressibility factor
H = Shaft Power (absorbed) (Watts)

Equation C_m – Metric units version of the re-arranged Fan Power law

arranged Fan Power law

Refining FSAT - Specific Speed Calculations

The software is based on and includes data received from AMCA members concerning the efficiency of their catalog products. Similar types of fan products already on the market were matched by specific speed, and this determined the *efficiency vs. specific speed* distribution. Specific speed is an artificially constructed indicator that is commonly used in the fan industry when looking at distributions of fans. FSAT uses the *equation D* to calculate a fan's specific speed.

$$N_{se} = \frac{N * Q^{0.5}}{P^{0.75} * K_p^{0.25}}$$

Where:
N_{se} = Fan speed, in RPM
Q = Flow in cfm or m^3/s
P = Fan static Pressure in Inches Water Gauge or Pascal
K_p = Compressibility factor

Equation D – Specific speed calculation

One way to think of the fan specific speed is as a general indication of the balance between the amounts of work the fan is putting into developing flow versus pressure. More exactly, it is a numerical representation of the shape of the impeller. Fans with a high specific speed will be moving a lot of flow at a very low pressure (like a propeller window fan), while fans with a low specific speed will be developing a lot of pressure but relatively little flow (such as a vacuum cleaner).

The catalog *efficiency vs. specific speed* information from all the AMCA manufacturers was overlaid on a graph, and the analysts sketched a new curve that represented the best available *efficiency vs. specific speed*. Of course there were many other steps done on the data before it could even be expressed in this distilled form. An example for an airfoil fan is provided in *figure 2*.

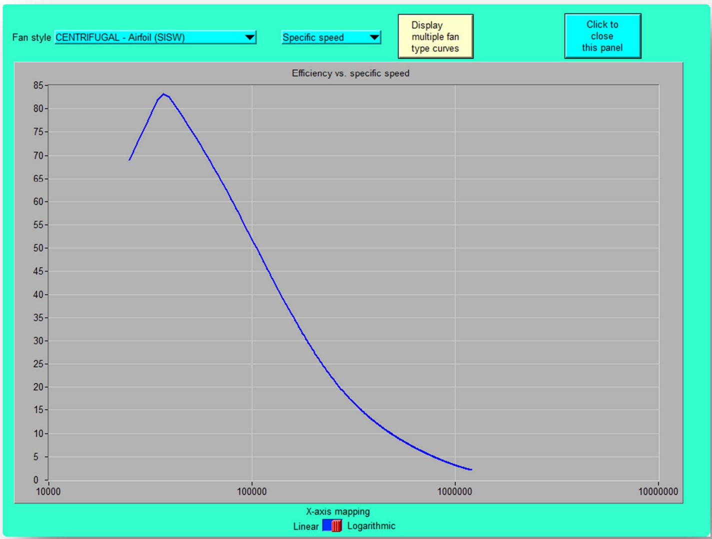

Figure 2 – Efficiency vs. specific speed (log scale) for airfoil fan – from FSAT

In examining *figure 2*, we observe that the airfoil fan achieves its peak efficiency of 83% at a specific speed of 37 000 (Note Log Scale – also, Imperial units were used to calculate these values of Fan specific speed). Furthermore, one may observe that at specific speeds higher or lower than 37 000, the peak achievable efficiency is less than 83%. The home screen of FSAT contains a switch labeled “fan configuration”. If this switch is set to “changeable” then FSAT uses the peak efficiency value from the curve, 83% in this case. If the “fan configuration” is set to “fixed”, then FSAT refers to the *efficiency vs. specific speed* curve data to look up the efficiency at that particular specific speed. So for example, if FSAT has calculated the specific speed to be 55 000, then FSAT would compare the baseline fan to an airfoil fan with an efficiency of 72%. This is a departure from the peak efficiency of 83% at a specific speed of 37 000.

In some cases, the fan designer (and by extension then also the fan user) has some control over the specific speed. If we examine the equation for specific speed (*equation D*) we see that in addition to the flow and pressure, the equation also contains the actual rotational speed of the fan. So for our given flow and pressure, if we want to get a replacement airfoil fan that is 83% efficient, then we will have to adjust the specific speed down to 37 000. The only way to do this is to find a fan that can meet our flow and pressure requirements, while turning at 67% (37000/55000) of the speed of our existing, baseline fan. Here in lays a potential problem – to deliver the same flow and pressure while turning at 67% of the original fan speed, the new fan will need to be larger; but there is often no space for a larger fan in industrial facilities! The fan laws would allow us to estimate the relative size of the new fan, using another fan property called the specific size, but this is not a feature in the present iteration of FSAT.

In *figure 3*, we see the *efficiency vs. specific speed* for three fan types from FSAT mapped out. In examining *figure 3*, we find that the different types of fans each have their own specific speed where the peak efficiency may be achieved.

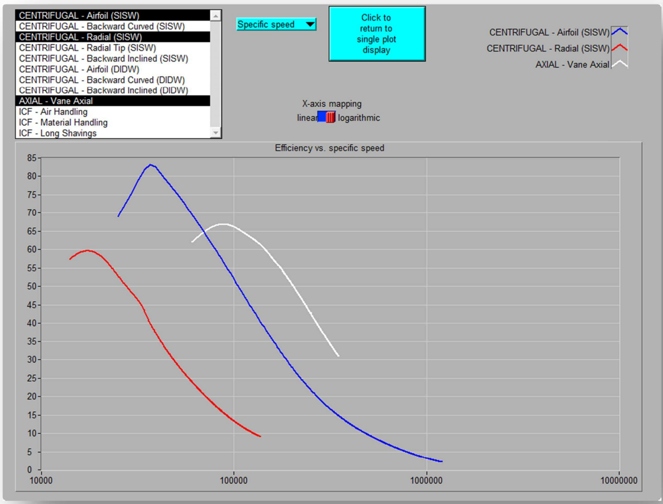

Figure 3 – Efficiency vs. specific speed for three types of fans: radial, airfoil SISW, vane axial

From *figure 3*, we see that the airfoil fan, with its top achievable efficiency of 83.2%, is the “most efficient” fan in the FSAT software database, but if the specific speed is higher than 80 000 then the vane axial fan is more efficient. At specific speeds below 25 000 the radial fan is more efficient than the airfoil.

FSAT specific speed range limits and peaks	Specific speed		Optimal efficiency	
	Lower limit	Upper Limit	Efficiency	Specific Speed
CENTRIFUGAL - Airfoil (SISW)	25,000	1,200,100	83.2	37,000
CENTRIFUGAL - Backward Curved (SISW)	27,900	102,000	81.1	36,000
CENTRIFUGAL - Radial (SISW)	14,000	135,800	59.6	17,000
CENTRIFUGAL - Radial Tip (SISW)	19,400	213,400	76.4	31,000
CENTRIFUGAL - Backward Inclined (SISW)	32,100	150,100	79.9	40,000
CENTRIFUGAL - Airfoil (DIDW)	39,000	1,800,000	82.4	50,000
CENTRIFUGAL - Backward Curved (DIDW)	38,000	270,800	76.4	48,000
CENTRIFUGAL - Backward Inclined (DIDW)	46,000	622,500	74.8	49,000
AXIAL - Vane Axial	60,375	348,620	66.9	88,000
ICF - Air Handling	15,100	67,600	70.8	16,000
ICF - Material Handling	10,100	65,600	68.5	17,000
ICF - Long Shavings	12,400	180,500	65.2	16,000

Figure 4 – Fan efficiencies from FSAT, and associated specific speeds

In Figure 4, we see the peak efficiencies for each style of fan included in FSAT, along with the upper and lower limits of the specific speed values valid for that style of fan. The lower and upper limits of specific speed for each fan style need to be reviewed and adjusted by the Senior FSAT Trainers. Some feel that present range is much too broad for the styles of fans. As an example, at very high flow rates and low pressures (low Specific speed) if a user tried selecting an airfoil fan for this duty, the fan would be much larger and much more expensive than an axial fan selected for the same conditions of flow and pressure.

Refining FSAT - Platform

When FSAT was released in 2004, many older Microsoft Windows computers were still running Windows 98, newer PCs had Windows XP, and a handful were running Windows Me.

Installing FSAT on computers running Windows 7 and Windows 8 presents special challenges, because at some point Windows interpreted LabVIEW's log and summary files for FSAT as locked and hidden. Every end user seminar has one or more participants who are unable to access the log or summary files, and it seems that every seminar has one or more participants that cannot successfully install FSAT on their computer – that is, one or two *in addition* to those without administrative rights on their laptop.

Refining FSAT – User Interface and Tools

In addition to refining the calculations, output, and platform, FSAT version 2 provides an opportunity to update the user interface and tools to accommodate the way the software is presently being used by the U.S. DOE's Senior Fan Trainers and UNIDO's FSO Experts. These opportunities include:

- Dual units – Metric / Imperial
- Readily support multiple languages
- Side-by –side comparison of 2 scenarios
- User over-ride of peak achievable efficiency
- Estimate relative size of new fan.
- Fan curve tools
- Power & efficiency curve tool
- System curve tool
- System pressure loss tool
- VFD/motor losses tool

Dual Units – Metric / Imperial

Having the ability to analyze in metric units will be quite useful for FSAT users outside North America.

Readily support multiple languages

Version 2 should easily manage a table of text strings so that other language versions (Russian, Malay, Vietnamese, etc.) could be quickly customized.

System Pressure Loss tool

There are many different sources of pressure losses in fan systems. Some of them are avoidable, some are not. Itemizing the losses (breaking down the losses into discrete pieces) can increase understanding of the fan system. Itemizing the losses also allows for a more ready comparison between different cases and different fans. In *figure 5*, we see a screen capture of the input table for the system pressure loss tool. In this example the user is able to increase the size of the air intake (thus reducing the intake loss), they are able to open the control damper (thus reducing the baghouse loss), and they are able to reduce the flow meter pressure loss. Also, the flow volume has been reduced by fixing leaks in the flexible connections and duct works. Giving the user the ability to consider all the different losses in the system adds structure to the analysis and encourages the user to think critically about losses in each line item. This approach can also guide the user in decisions about upgrading specific components in the fan system such as improving the size of the air intake louver, for example.

			As-Is System	Proposed System	Change
Flow Requirements					
	Flow Requirement ACFM	ACFM	40,000	38,000	2000
Pressure requirements					
	Inlet loss	in. w.g.	1.0	0.5	0.5
	Inlet ductwork loss	in. w.g.	0.5	0.5	
	System Damper loss	in. w.g.	4.0	0.1	3.9
	Air treatment loss	in. w.g.	10.0	8.2	1.8
	Flow measurement loss	in. w.g.	3.0	0.2	2.8
	Inlet damper loss	in. w.g.			
	Process requirements (Suction side)	in. w.g.	4.0	4.0	
	Inlet system effect equivalent loss	in. w.g.	0.4	0.4	
	Fan Suction Pressure	in. w.g.	-22.9	-13.9	-9
	Fan Outlet Pressure	in. w.g.	1.5	1.5	
	Fan outlet system effect equivalent loss	in. w.g.	0.5	0.5	
	Outlet Damper loss	in. w.g.			
	Air Treatment loss	in. w.g.			
	System Damper loss	in. w.g.			
	Process Requirements (discharge side)	in. w.g.	1.0	1.0	

Figure 5 – Proposed FSAT v.2, Input screens for system pressure loss tool

Side-by –side comparison of 2 scenarios

Whether the user desires to compare the existing with the proposed, or compare two options for a new system, it is very useful to be able to compare two scenarios side-by-side. In *figure 6*, we see a summary of the results of reducing pressure losses and flow leakage, but rather than upgrade to a new fan, we are using the existing fan with a VFD, so we have taken a small reduction on fan efficiency compared to the base case, rather than assuming a new 80% efficient fan.

Calculated power parameters		As-Is System	Proposed System	Savings for 1 fans
Electrical power	kW	185.0	133.0	52.0
Motor Power	bhp	235.6	169.4	66.2
Motor Loading	%	79%	85%	
Annual Electrical energy	kWh/yr	1,480,000	1,064,000	416,000
Annual operating cost	$/yr	$74,000	$53,200	$20,800
Fan system benchmark parameters				
Fluid Power	fluid hp	148.7	93.2	
Fan Power	bhp	235.6	169.4	
Fan Flow (from above)	acfm	40,000	40,000	
Fan Pressure rise (outlet - inlet)	in. w.g.	24.4	15.4	
Velocity pressure correction	in. w.g.	0.3	0.3	
Fan Static	in. w.g.	24.1	15.1	
Compressibility factor	-	0.9800	0.9800	
Motor efficiency	%	95.0%	95.0%	
Drive efficiency	%	100.0%	100.0%	
Fan efficiency	%	63.1%	55.0%	
Control efficiency	%	83.4%	99.3%	
Installation efficiency	%	96.3%	96.3%	
System efficiency	%	48.1%	50.0%	

Figure 6 – Proposed output screen layout for FSAT v.2, Calculated Power and Fan System Benchmarks

User over-ride of peak achievable efficiency

FSAT has good analytical tools built in to make sure the efficiency is achievable, but in some cases, it does not have the flexibility to accommodate the situation. In these cases, the user should be able to over-ride the efficiency of the fan for the optimal case. An example common scenario would be a fan that has more pressure capacity than needed at the desired flow rate. Perhaps formerly there was a damper there, taking the pressure loss. When we open the damper, we have removed the obstruction, which is very good, but we have also changed the balance between the work put into pressure versus the work put into flow. We shift to a new operating point on the fan curve, and the specific speed shifts to a new value. It is quite likely that the operating point will shift away from the BEP, so we might degrade our fan efficiency by between 5% and 20% (possibly more in extreme cases). So if we know we cannot achieve the 83% that FSAT thinks should be achieved by an airfoil fan, we want to enter the actual efficiency value from our performance test.

Estimate relative size of new fan.

When the user selects a “changeable fan configuration”, then some compatibility checks concerning the relative size and speed of the suggested optimal fan should be presented.

VFD Losses Estimating tool.

Work has been done by DOE and others to estimate the efficiency of the motor and drive at part load. This can easily be incorporated into FSAT version 2. FSAT already takes into account the variations in motor performance over the range of possible loading, so it would not be difficult to estimate part load efficiency of motor-drive combinations using information previously published by the US DOE in the motor systems tip sheet #11 "Adjustable Speed Drive Part Load Efficiency" publication.

Fan curve tools

The fan curve is a critical tool for understanding the response of the fan in a given system. Unfortunately, when a fan curve is available, often times it is based on a slightly different speed or gas density than current process conditions. A simple graphing tool could accept 10 data points and fit a fan curve to them, manipulate the curve according to the fan laws, and draw the new fan curve based on present operating conditions of speed and density. As shown in Figure 6, the fan curve can be re-drawn to represent current conditions as well as proposed strategies.

Power & efficiency curve tool

The power curve is also a critical tool for understanding the power draw response of the fan in a given system. Unfortunately, and for the same reason as the fan curve problem already discussed, when a power curve is available it often is based on a slightly different speed or gas density than current process conditions. A simple graphing tool could accept 10 data points and fit a power curve to them, manipulate the curve according to the fan laws, and draw a new power curve based on present operating conditions of speed and density. The calculator could also show the fan efficiency at various operating points so the user can compare their point of operation versus the BEP, to help highlight if there is any inefficiency in the selection. Very few manufacturers of fans provide efficiency information on their fan curve plots, so this would be a very useful feature.

System Curve tool

In addition to the fan curve and power curve, the other critical piece of the puzzle is the system curve. Overlapping the system and fan curves can often reveal a great deal of information about the present set-up, and suggest possible optimization strategies. The fan curve and system curve together comprise a map of where we are (baseline) versus where we want to be (the optimized state). For instance, one of the two system curves in figure 6 might represent present operation, while the other depicts the proposed system after the optimization project.

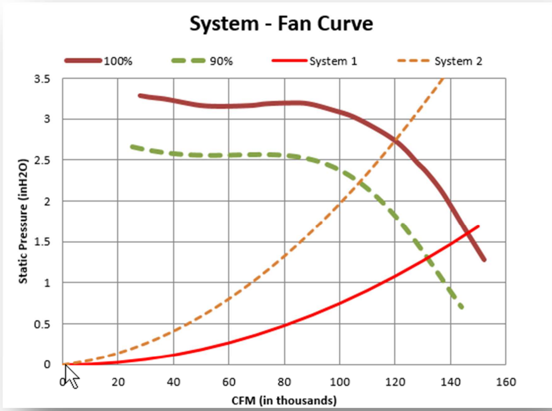

Figure 7 – Proposed output screen layout for FSAT v.2 – Fan and System Curve Tool, with comparison of multiple curves

Conclusions

UNIDO has a strong interest in a publically available, multi-lingual, metric version of FSAT for their Industrial Energy Efficiency projects, and the U.S. DOE has been meeting and discussing the future of this and other tools. However, the future of FSAT, version 2, remains unknown, particularly regarding its possible funding. As of the date of this paper being submitted for publication (July 2015) funding has not been secured for development of version 2.

One potential source of funding may be a subscription-based professional version supported by user fees, with a stripped-down version available for free. Another suggested means of support would be to require organizations, which sponsor FSAT trainings, to purchase a license for each training course attendee.

Any technical changes to the FSAT software need to be agreed upon by a software development oversight committee, comprised of the FSAT Senior Trainers for DOE and UNIDO prior to making changes.

If after reading this paper you have ideas or suggestions for features you think would be useful in version 2 of FSAT, or if you have ideas for potential sources of funding to support the development of version 2, please email the author – ron@productiveenergy.com.

Automatic determination of pumping system energy efficiency with EFEU software tools

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Abstract

Efficient Energy Use (EFEU) program has been founded in 2011 to assess industry-level problems in energy efficiency in Finland. The current focus is in improving fluid handling systems with systems-level approach to their design, selection and control. This paper focuses on developed software tools that allow the correct selection of fluid handling system components and control scheme based on the actual process needs throughout the typical operating cycle.

Since several existing pumping and fan systems are operating in different conditions than for which they have been originally selected, their replacement with more efficient and more suitable ones is one of the steps to more energy efficient fluid handling systems. However, one of the practical problems with existing selection programs is their focus on single device (pump, motor, frequency converter) at a time and the device selection only based on few known operating points (i.e., typical and maximum flow rates). Pumping System Optimization Tool (PSOT) was developed to solve these issues, and it allows the selection of the most energy efficient fluid handling system based on the given process needs for the flow rate and head. Matlab-based PSOT is especially usable for detailed energy audits and comparisons when device replacements are carried out in existing systems.

For throttle-controlled fluid handling systems, information on the available energy saving potential with variable-speed operation is often sufficient basis to start a more detailed analysis of system energy efficiency. Since PSOT is too detailed for this kind of preliminary analysis, Savings Calculator for Centrifugal Pumps (SCCP) was developed. It is an Excel-based software and able to estimate the fluid handling system operation accurately with a small number of input parameters and with given process needs for the flow rate. Based on other similar programs, SCCP uses more accurate models for the electric motor and frequency converter efficiency. Also the use possibility of available process data is an addition compared to other existing programs.

As these programs have a bit different calculation approach, this paper evaluates their differences and usability with actual case studies. Both programs are studied by evaluating the energy efficiency of a laboratory pumping system and of an industrial pumping system in a Finnish paper mill. According to comparison to the laboratory tests, both tools seem to give indicative results about the system energy consumption. However, it should be noted that real industrial pumping systems are often quite complex, so tools by themselves are not usually sufficient for design of entire system, but they are meant to assist in evaluation of achievable improvements in the system energy efficiency.

Introduction

Centrifugal pumps are one of the major energy consuming end-use devices in industrial and municipal sectors all over the world. For example, according to [1] pumping systems account for over one-fifth of the motor electricity consumption in the industrial sector in European Union. Recent studies have shown that there is still plenty of unrealized saving potential in the energy consumption of industrial pumping systems. The energy efficiency could be often significantly improved by using correctly chosen and sized devices, and by applying variable-speed operation instead of inefficient traditional flow control methods. Since lifetime of a pumping system is usually considered to be from 15 to 20 years, energy and operation costs often cover the major share of the life-cycle costs, even though the purchase and installation costs of devices are dominating at the beginning [2]. Therefore the investments that improve pumping system efficiency are not only viable from the energy saving aspect, but also often financially profitable. Two different software tools made to evaluate the possibilities in improvement of pumping system energy efficiency are discussed in this paper.

First tool introduced in this paper is the Matlab-based Pumping System Optimization Tool (PSOT), which optimizes the energy conversion efficiency of the pumping system by choosing the best combination of devices (pump, motor and frequency converter) on the basis of the given load profile. Similar tools, such as US DOE's Pumping System Assessment Tool, have been existed for a long time, but PSOT has several advantages compared to them. Unlike many traditional component selection tools, which usually concentrate only in single device at a time and use only few operation points in selection, PSOT takes into consideration the combined energy efficiency of all system components and uses all given process operation points in the optimization, making optimization process faster and easier. If static head and friction coefficient of a system are known, PSOT can also take into account the change of the flow control method from current one to the variable-speed control. The main window of PSOT is shown in Fig. 1.

Fig. 1. Pumping System Optimization Tool's main window.

Another tool introduced in this paper is the Excel-based Savings Calculator for Centrifugal Pumps (SCCP), which is used to assess the savings available by the change of the flow control method. SCCP calculates the achievable savings, when the pumping system components remain the same, but existing throttle control is substituted by variable-speed control. With variable-speed operation, unnecessary production of pressure can be avoided, so the same flow rate can be produced with less power than with throttle control. Because of its simplicity and small number of input parameters, SCCP is an easy tool to start with when assessing the possible improvements in energy efficiency of a pumping system. The detailed calculation results page of SCCP is shown in Fig. 2.

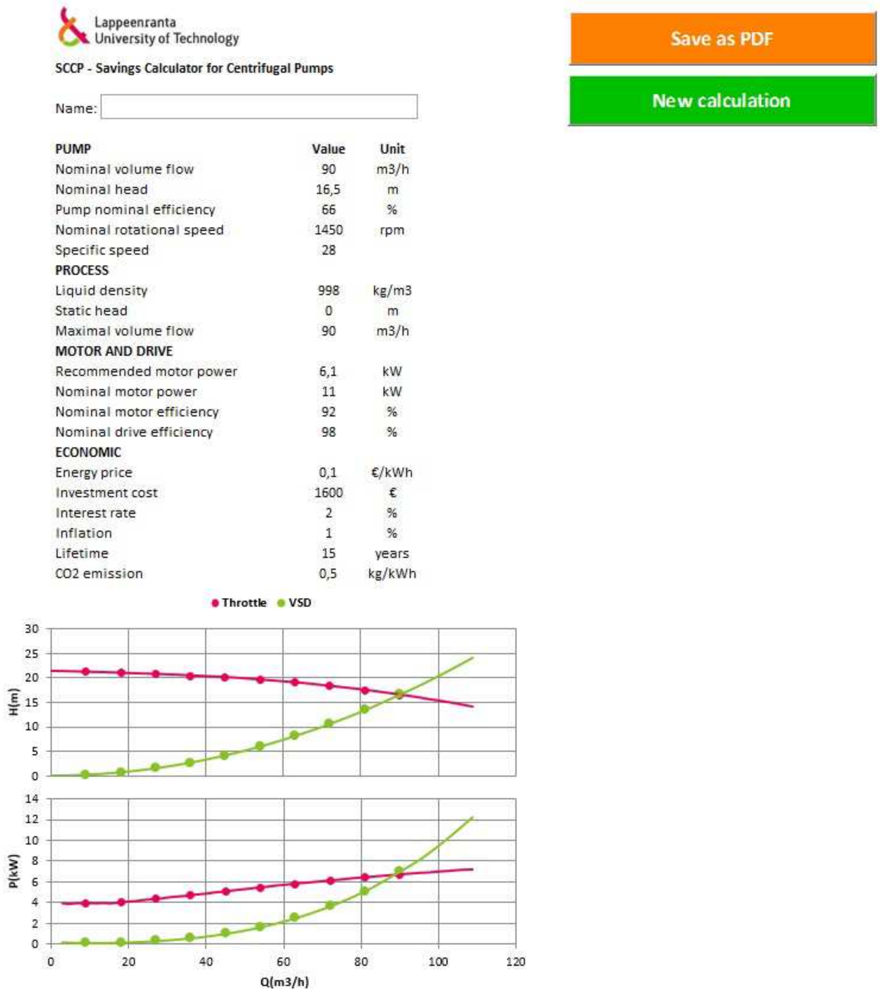


Fig. 2. Part of SCCP's detailed calculation results window.

SCCP and PSOT are partially based on the same modeling principles of the pumping system devices, but they also differ significantly on some parts. In this paper, the general principles of the pumping system modeling in both software tools are introduced and their usability is evaluated with laboratory tests and industrial scale case study.

Pumping System Optimization Tool

Unlike traditional component selection tools, which concentrate only in one component of a pumping system at a time, Pumping System Optimization Tool selects the best combination of pump, motor and frequency converter for the given process. With this kind of approach, the entire selection of the pumping system setup can be done by only one software and the total energy conversion efficiency of the process can be optimized. PSOT also calculates the lifecycle costs for the optimized system and shows how it is distributed in investment, operating and maintenance costs.

Pumping System Optimization Tool does the optimization in four individual parts as shown in Fig. 3: 1) the pump, 2) the motor, 3) the frequency converter and 4) the calculation of life-cycle costs (LCC). PSOT has database for each system component type (pump, motor and frequency converter), which are based on information given by manufacturer. This can improve PSOT's accuracy, since performance characteristics of particular device can be applied. User can also add own devices to the database, if it is not readily found from it. The best components are then selected on the basis of these databases. The optimization starts from selection of the most energy efficient pump *p* on the basis of the given load time profile. The best motor *m* can be then selected on the basis of required shaft power from the pump in each operation point. A suitable frequency converter *c* is then selected to meet the motor's requirements. When the optimized pumping system setup is found, the energy consumption and LCC with the given load time profile can be calculated. The calculation principles applied in PSOT are described in the following sections.

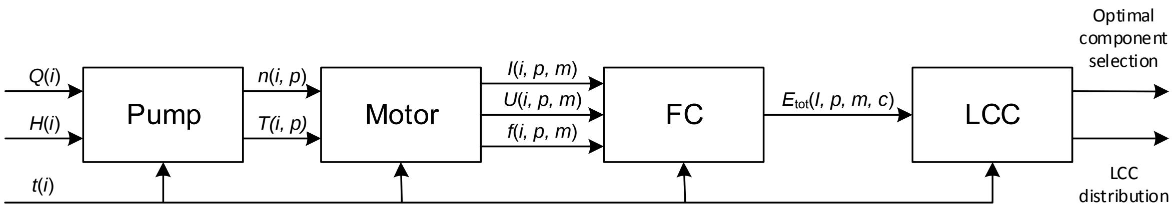


Fig. 3. Simplified block diagram of Pumping System Optimization Tool. The index *i* denotes the *i*th operation point of the given process. The system components are subscribed as follows; *p* is the *p*th pump, *m* is the *m*th motor and *c* is the *c*th frequency converter in the database.

Pump

The first pumping system component to be selected is a pump, which is selected on the basis of given hydraulic operation points. Operation points are given by pairs of flow rate *Q* and head *H* as a function of time. PSOT chooses the best pump for the given load profile from the pump database, which in practice contains digitized pump characteristic curves as text files. Characteristic curves describe the pump head *H* and power *P* as a function of flow rate *Q* and they are given for the nominal rotational speed of the pump. The pump selection is based on calculating the energy consumption of all options and by choosing the best alternative of them for the given application. To be able to describe all operation points, curves are converted to cover the operation points outside the curve by the well-known affinity laws described by equations

$$Q = \left(\frac{n}{n_0}\right) Q_0, \tag{1}$$

$$H = \left(\frac{n}{n_0}\right)^2 H_0, \tag{2}$$

$$P = \left(\frac{n}{n_0}\right)^3 P_0, \tag{3}$$

where *n* is rotational speed and the subscript 0 denotes the initial value. The required rotational speed *n* and power *P* in given operation points can be then calculated on the basis of these affinity laws, by applying the *QP*-curve-based estimation method described in [3]. The required torque *T* from the motor is then calculated by the equation

$$T = \frac{P}{2\pi \frac{n}{60}}. \tag{4}$$

PSOT also provides an option to input static head H_{st} and friction coefficient *k*. If these system parameters are given, PSOT can take into consideration the change of the flow control method from the one applied in the given process to the variable-speed drive, in which the required flow rate is produced with minimum pressure allowed by the system. With this kind of flow control scheme, all operation points are located in the system curve, which is described by the equation

$$H_{sys} = H_{st} + kQ^2, \tag{5}$$

where H_{sys} is the system head. The given process head values are then substituted by the system head values. It should be noted that this is optional and should be used only, if it is possible to substitute the current control method with variable-speed control.

The energy consumption of a pump as well as the total energy consumption of the system can be then calculated on the basis of given load time profile by the equation

$$E = \sum_{i=1}^{l} P_i t_i, \quad (6)$$

where E is energy consumption and t is a time used in each operation point. Subscript i denotes the individual operation points and l is the total number of given operation points. The pump with the smallest energy consumption is then selected.

Motor

In motor selection part, the most suitable induction motor for the pump is selected from the similar database as applied to the pump selection. The database includes efficiency maps for the motors, which are created by approximating the equivalent circuit of an induction motor on the basis of motor catalogue information [4]. The efficiency maps are created for both optimal and constant flux control scheme, but without considering the losses caused by non-sinusoidal supply voltage from the frequency converter. These provide indicative information of the flux optimization effect in energy consumption. The efficiency is then determined from the efficiency map on the basis of rotational speed and torque. An example of approximated induction motor efficiency map is shown in Fig. 4.

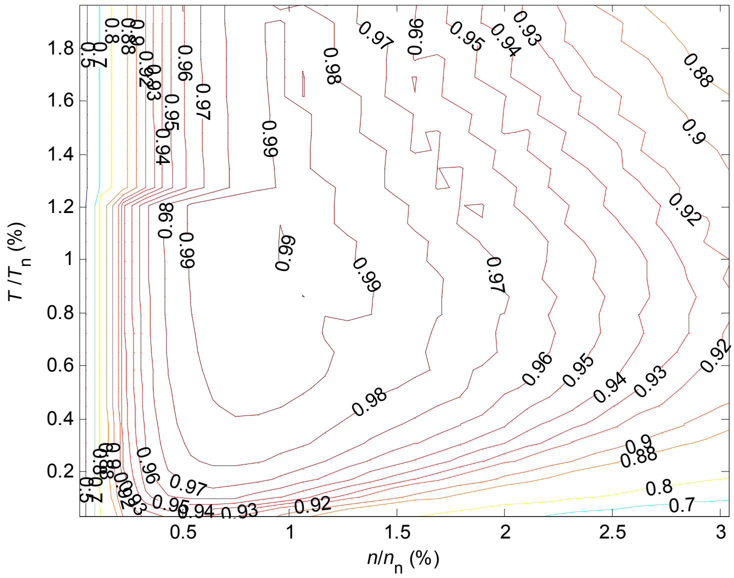


Fig. 4. An example of approximated induction motor efficiency map applied in PSOT with a nominal rotational speed of 1482 rpm and a nominal power of 37 kW. Rotational speed, torque and efficiency in the map are relative to the nominal values.

Frequency converter

The most suitable frequency converter for the given application is selected on the basis of easily available catalogue information. Conventional methods to approximate the frequency converter efficiency may be therefore too complex to use, because they usually require parameters that are difficult to produce from data provided by manufacturers. Instead of using a pre-generated efficiency maps like in the motor section, the power losses P_l in frequency converter are approximated by the equation presented in [5]:

$$P_l = \left(0.35 + 0.1\frac{f}{f_n} + 0.55\frac{T}{T_n}\right) * P_{ln}, \quad (7)$$

where f is frequency and subscript n denotes the nominal value. Only a rough approximation of frequency converter losses can be attained by using this equation, but while the efficiencies of frequency converters are usually very high, this approximation should be accurate enough to calculate the energy consumption with sufficient accuracy. Frequency converter efficiency can be then defined in each operation point on the basis of the calculated losses.

Life-cycle cost calculation

Life-cycle costs of the optimized pumping system setup are calculated on the basis of the given economic information and calculated energy consumption with the given load profile. The lifecycle costs is distributed in investment, operation and maintenance costs. In operating and maintenance costs, the inflation and interest rate are taken into account by calculating their net present values (NPV).

Savings Calculator for Centrifugal pumps

SCCP is a software tool for a quick analysis of the viability of change of flow control method from throttling to variable-speed operation. Even though variable-speed operation in a pumping system is already quite an old invention, throttle control is still used very widely, even if the energy efficiency of a pumping system could be often remarkably improved by using a variable-speed control. Therefore the main purpose of SCCP is to reliably show that in most cases significant energy and financial savings could be achieved, by relatively small investment in variable-speed drive. SCCP is not only of its kind, but there already exists many similar tools, for example ABB PumpSave and Vacon Save. Compared to them, SCCP requires less input information and has different calculation approach in modelling of pumping system devices. In addition, SCCP also provides an option to input the flow profile of the process with time stamped flow and save detailed PDF report.

SCCP is quite simple tool and requires only a small amount of input information from the user, so it can be easily used even by an uninitiated person, which makes it a good tool for marketing purposes. Due to small amount of input parameters, the accuracy of the tool can significantly vary depending on a case, and therefore it should be used mainly to show the benefits of variable-speed control with reasonable accuracy. Only nameplate information of a pumping system components and process information are required. On the basis of the given information, SCCP calculates achievable energy and financial savings in the system, and also some usable economic quantities. Like in PSOT, the modelling of the pumping system is divided in four different parts: 1) the pump, 2) the motor, 3) the frequency converter and 4) the energy consumption and economics. The simplified block diagram of calculation steps is shown in Fig. 5.

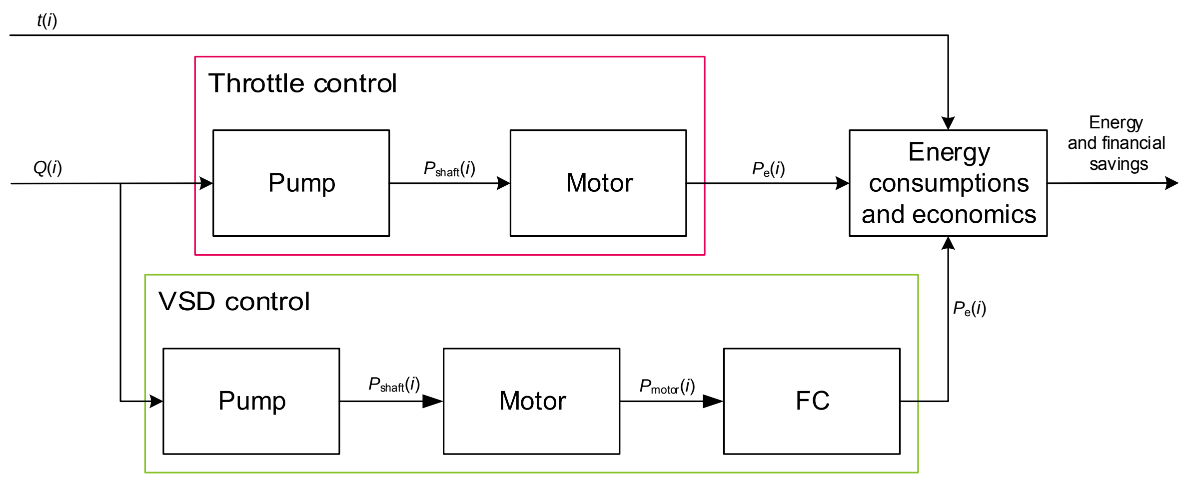


Fig. 5. Simplified block diagram of SCCP. The index *i* denotes the *i*th operation point of the given process.

As Fig. 5 illustrates, SCCP has two calculation branches since it compares two different flow control methods. The models for pumping system devices are different in both branches for some devices. The modelling principles of each devices with both control methods are introduced in next sections.

Pump

The calculation of the saved energy on the basis of the given operation points begins on evaluation of the pump characteristic curves. In contrast to PSOT, SCCP does not apply any kind of database of pump characteristic curves, but it estimates the curves on the basis of given nameplate information. The characteristic curves for pump head and efficiency are created on the basis of pump specific speed n_q, which is a dimensionless quantity that is used to describe the centrifugal pump characteristics regardless of pump size. Specific speed can be defined on the basis of the pump nominal values by the equation

$$n_{\mathrm{q}} = n_{\mathrm{n}} \frac{\sqrt{Q_{\mathrm{n}}}}{{H_{\mathrm{n}}}^{3/4}}, \tag{8}$$

where subscript n denotes the nominal value. The pump characteristic curves can be then estimated on the basis of calculated specific speed. In SCCP, head and efficiency curves are interpolated from the digitized curves relative to pump nominal values, originally published in [6]. These digitized curves are shown in Fig. 6.

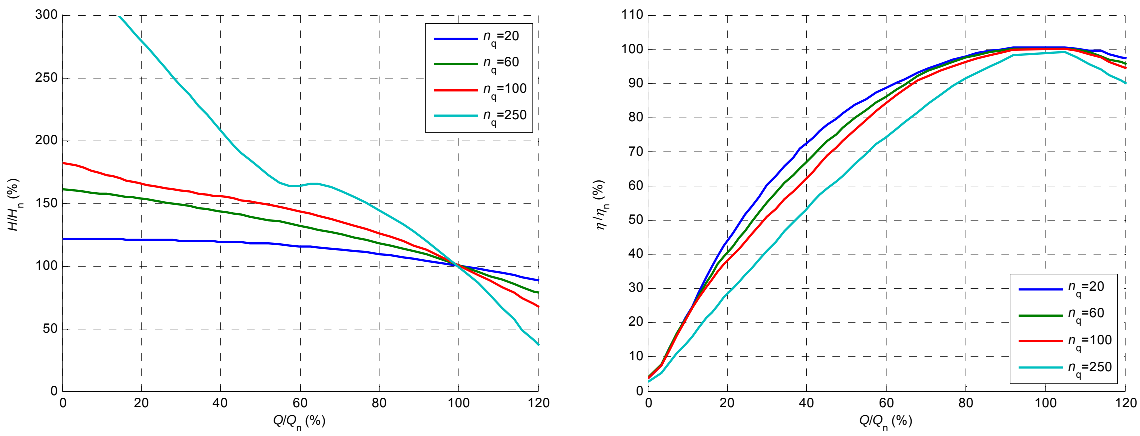


Fig. 6. Relative pump head and efficiency curves used in estimation in SCCP.

While a throttle controlled system can be modelled on the basis of these pump characteristic curves, the modelling of the variable-speed controlled system requires a little more complex approach. With variable-speed operated system, the desired flow rate is assumed to be produced with as small amount of pressure as possible. The minimum amount of head can be described by the system curve, which is defined by (5).

Since a rotational speed is not constant in variable-speed operated system, also the pump efficiency requires a different calculation approach than with throttle controlled system. First, the required rotational speeds in desired operation points are calculated on the basis of second degree polynomial fitting created from the interpolated pump head curve. The rotational speed can be calculated on the basis of this fitting, which is described by the equation

$$H = AQ^2 + BQ\left(\frac{n}{n_{\mathrm{o}}}\right) + C\left(\frac{n}{n_{\mathrm{o}}}\right)^2. \tag{9}$$

To solve the required rotational speed in certain operation point, the fitting is converted by varying the rotational speed so that the fitted curve intersects the system head curve defined by equation (5) at the operation point's flow rate value, in other words when $H = H_{\mathrm{sys}}$.

When rotational speed is known, the pump efficiency can be calculated. There exists multiple different models to approximate the efficiency of a variable-speed operated pump, but in SCCP, the equation given in [7] is used:

$$\eta_{\mathrm{pump}} = 1 - \left(1 - \eta_{\mathrm{n,pump}}\right)\left(\frac{n_{\mathrm{n}}}{n}\right)^{0.1}, \tag{10}$$

where η is the efficiency and n denotes the nominal value. With both control methods, a required shaft power P_{shaft} in given operation points can be then calculated by the equation

$$P_{\mathrm{shaft}} = \frac{\rho Q H g}{\eta_{\mathrm{pump}}}, \tag{11}$$

where ρ is the liquid density and g is the acceleration due to gravity (~9.81 m/s^2). Now when the rotational speed and shaft power in each operation point are known, the required torque can be calculated by the equation (4).

Motor

The motor efficiency in SCCP is estimated by the same kind of motor efficiency map than in PSOT. While PSOT applies the comprehensive database for motor efficiency maps, SCCP uses only one map for the simplicity. The used efficiency map in SCCP is for ABB M4BP 225SMA 4-pole 37 kW motor, which was chosen to describe the average induction motor driving a pump on the basis of [8].

Frequency converter

Frequency converter is modeled in SCCP with similar equation than in PSOT. Only difference from the equation (7) is that the relative frequency is substituted by relative rotational speed. This substitution is valid, when the slip of an induction motor is assumed to remain constant. Even if slip varies, it shouldn't have significant effect on the power consumption. When motor and FC efficiencies are known, required electric power for the system can be calculated. In the calculation of energy consumption of throttle controlled system, frequency converter efficiency is ignored.

Energy consumption and economics

On the basis of given load profile and calculated electric power consumptions, the annual energy consumptions with both throttle and variable-speed controlled systems can be calculated by the equation (6). When the economic conditions are provided by the user, also the net present value of the achievable savings and some economic quantities, such as payback period and internal rate of return can be calculated.

In calculation of the annual energy consumption, the given load profile is assumed to be repeated for an entire year. The annual consumptions are calculated separately on both of the control methods. On the basis of the given economic conditions, annual and lifetime financial savings can also be calculated. The lifetime savings are given in net present value of savings, which can be calculated by the equation

$$S_{\mathrm{lifetime}} = \sum_{k=1}^{l}\left(\frac{S_{\mathrm{annual}}}{(1+i)^k}\right) - C_{\mathrm{investment}}, \tag{12}$$

where S denotes the savings, i is the interest rate, l is the lifetime of the pumping system and C is the costs. Another good way to evaluate a profitability of an investment is calculating internal rate of return (IRR), which is the discount rate that makes the net present value of all savings achieved from investment equal to zero. In other words, IRR can be considered as the attainable rate of return of investment, but without concerning the environmental factors such as inflation and interest rate. IRR has to be solved by iterating it from the equation

$$\sum_{k=1}^{l}\left(\frac{S_{\mathrm{annual}}}{(1+\mathrm{IRR})^k}\right) - C_{\mathrm{investment}} = 0. \tag{13}$$

As a result of reduced energy consumption, also the level of emissions produced in energy generation is decreased. Therefore SCCP also gives the achievable reduction in CO_2 emissions by the change of flow control method.

Case studies

Both software tools are tested by evaluating the energy saving potential in two different cases. In the first case, accuracy of software tools is studied in both throttle and VSD controlled cases through laboratory tests. In the second case, PSOT is tested by assessing the savings available by optimizing the pumping system setup in a Finnish paper mill.

Laboratory measurements

The accuracy of both software tools is evaluated by comparing them to the laboratory measurements done in LUT pump laboratory. The main purpose of laboratory tests was to ensure the accuracy of software tools in calculation of energy consumptions in throttle and variable-speed controlled closed and open loop systems. The laboratory setup consists of Sulzer APP22-80 centrifugal pump with 255 mm open impeller, ABB M3BP160M4 11 kW induction motor and ABB ACS880 frequency converter. The piping of the laboratory system includes multiple sensors for pressure, flow rate and temperature. In addition, the pump shaft is equipped with torque and rotational speed sensors and the consumed electric power is also measured.

The measurements were carried out by using the so called Heating-Ventilating-and-Air-Conditioning (HVAC) load time profile, which is used as a standardized load time profile in calculation of Energy Efficiency Index (EEI) for circulators or closed loop variable flow systems, and it has already been established in EN-Standardization and EU-Regulation for circulators [9]. The standardized load time profile is shown in Tab. 1.

Tab. 1. The standardized load time profile for closed loop variable flow systems used in laboratory measurements.

Operation point	Flow rate [%]	Time [%]
L_1	100	6
L_2	75	15
L_3	50	35
L_4	25	44

As can be seen in Tab. 1, the load time profile has a high emphasis on part-load operation points. It is also designed for closed loop applications, so it might not describe very well usual industrial applications. It is still used due to standardization and to provide wider operation range for better assessment of accuracy of tools, since modeling of the system is often more difficult at part-load operation.

The standardized load time profile test runs are executed for closed and open loop systems, with both throttle and variable-speed controls. Static head H_{st} in closed loop system is zero and in open loop system 5.8 meters. In throttle controlled measurements, flow rate is regulated only by throttling a valve, while pump is run at the constant rotational speed of 1450 rpm. In calculation of EEI, in which the standardized load time profile is applied, the variable-speed operation is assumed to be executed with standardized pressure control curve [9]. To execute this kind of pressure control curve, the system needs to be controlled by both throttle and variable-speed drive. However, PSOT and SCCP are assuming that the desired flow rate is produced with the minimal amount of pressure by using only variable-speed drive, so the standardized pressure control curve cannot be applied in the evaluation of the accuracies of software tools. For this reason, in variable-speed controlled measurements the pump is controlled only by adjusting rotational speed of the motor, while remaining the same valve position.

To evaluate the accuracy of SCCP and PSOT, the results of the laboratory measurements are compared to the results calculated by the software tools. PSOT requires flow rate and head as a function of time from the throttle controlled measurements as an input. In calculation of energy consumption of variable-speed controlled systems, also static head H_{st} and friction coefficient k are given. The pump, motor and frequency converter used in laboratory setup are selected from the component databases of PSOT to be used as the only possible options in optimization. While SCCP does not have any kind of databases for system components like PSOT, the nameplate information of pumping system devices shown in Tab. 2 is required as an input.

Tab. 2. Nameplate and system information of the laboratory setup used as input for SCCP

Pumping system information	
Nominal flow rate	90 m^3/h
Nominal head	16.5 m
Pump efficiency	66 %
Liquid density	998 kg/m^3
Static head	0 m and 5.8 m
Rotational speed	1450 rpm
Nominal motor power	11 kW
Nominal motor efficiency	92 %
Nominal drive efficiency	98 %

To make the results given by SCCP and PSOT comparable to the laboratory measurements, the annual energy consumption of the laboratory setup has to be calculated. This is done by assuming the pump is driven with same load profile 8760 hours in year. The measured and calculated annual energy consumptions and achievable energy savings are shown in Fig. 7.

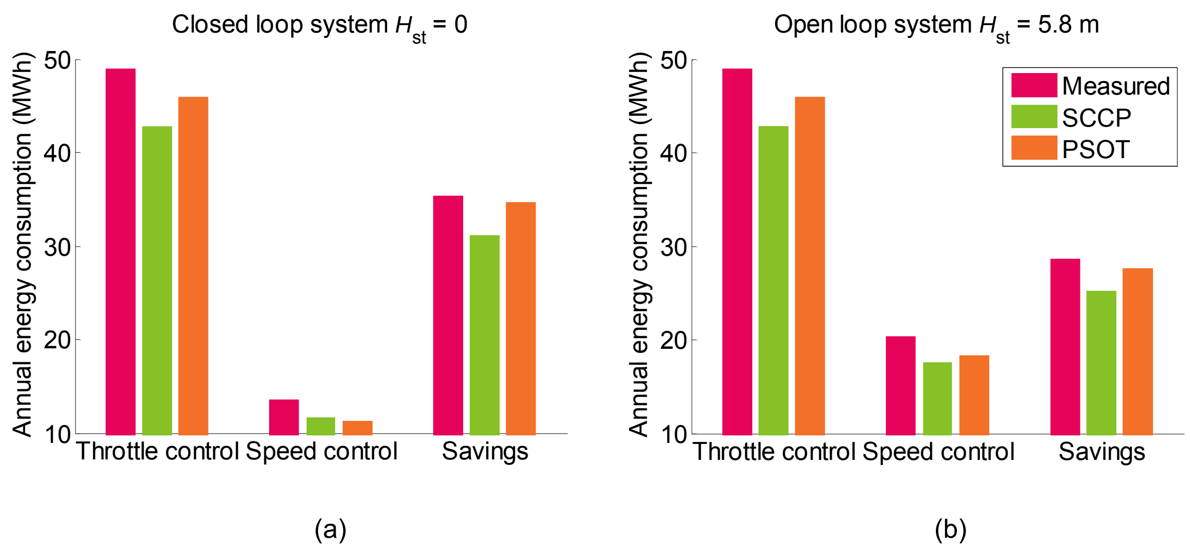


Fig. 7. Measured and calculated annual electric energy consumptions and energy savings in closed loop system (a) and in open loop (H_{st} = 5.8 m) system (b).

As Fig. 7 illustrates, the actual measured electric energy consumptions are higher than estimates of SCCP and PSOT in both throttle and speed controlled closed and open loop cases. Energy consumption with throttle control is basically same in both open and closed loop systems, since static head has no effect on the head produced by pump. There SCCP and PSOT estimates of annual electric energy consumption are 12.7 % and 6.4 % lower, respectively, than measured consumption in throttle controlled laboratory system. The achievable energy savings by variable-speed control in closed loop system are illustrated in Fig. 7 (a). There SCCP gives 14.5 % lower and PSOT 17.1 % lower electric energy consumption compared to the measured variable speed controlled system electric energy consumption. In open loop system, static head increases the energy consumption of variable speed controlled system as shown in Fig. 7 (b), due to increased head in part-load operation. There estimates of SCCP and PSOT are 13.8 % and 10.4 % lower, respectively, than measured electric energy consumption.

As the estimated energy consumptions are remarkably lower than measured ones, the actual achievable savings will be even greater than predicted by SCCP and PSOT. This means that the installing of a frequency converter would be even more profitable than can be expected according to software tools. One reason for difference in the results may be the fact that in laboratory setup the induction motor is run by frequency converter also in throttle controlled system, in which frequency converter normally wouldn't exist. The use of frequency converter in throttle controlled system causes some additional power losses. However, according to measurements, the frequency converter efficiency in entire range of flow rates is about 98 % on average, so the additional energy consumption in throttle controlled system cannot be totally explained by it. Frequency converter can also decrease motor efficiency due to non-sinusoidal supply voltage.

SCCP approximates the relative savings of 72.9 % for closed loop system and 58.9 % for open loop system, when using throttle control is substituted by variable-speed control. Correspondingly PSOT gives 75.5 % savings for closed loop system and 60.2 % for open loop system. When calculating the actual savings from the measured values, the result is 72.3 % for closed loop system and 58.4 % for open loop system. The very high savings are mainly caused by profile's high emphasis on part-load operation.

The accuracy of pump modelling in SCCP has been already studied in [10] and the modelled pump characteristic curves corresponded to the measured and manufacturer's curves quite well despite the small number of input parameters. In order to get more information about the calculation accuracy of SCCP, the measurements presented in this paper were also used to study the accuracy of SCCP's estimates for electric power consumption and efficiencies of all pumping system components in presented measured systems. Measured and estimated electric power consumptions as a function of flow rate are shown in Fig. 8.

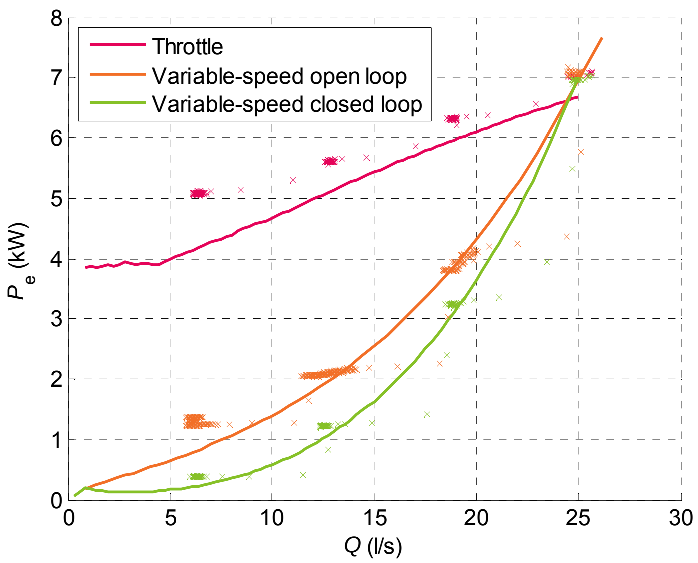
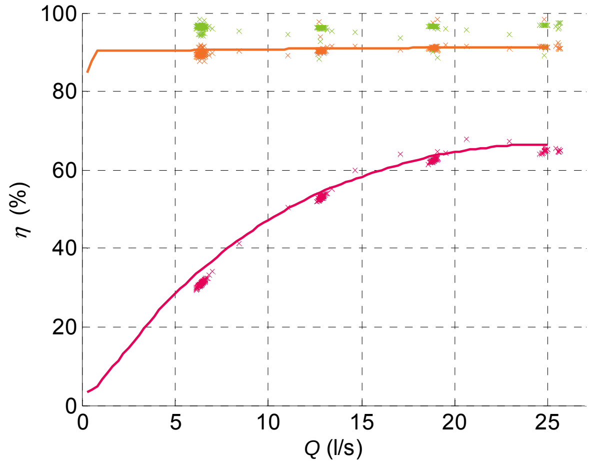
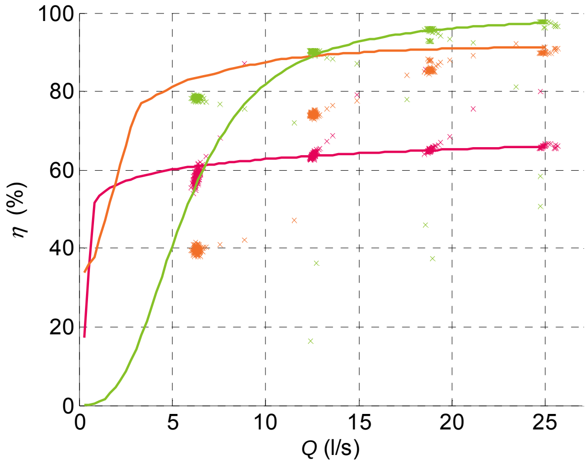


Fig. 8. Measured and SCCP's estimations of electric power consumption as a function of flow rate. Measured values are illustrated by individual points and SCCP estimates are illustrated by lines.

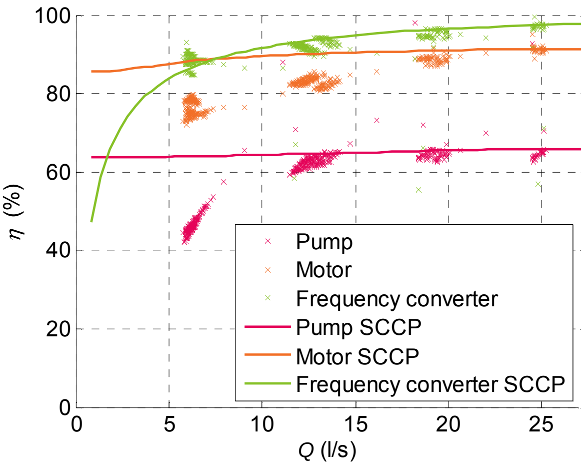
As can be seen in Fig. 8, SCCP estimates electric power consumption estimates are quite accurate for variable-speed operated systems, but have significant error with throttle controlled system, which may be caused by same the reasons mentioned for deviations between electric energy consumption measurements and estimates. To investigate the effect of accuracy of efficiency models for different devices, the measured and calculated efficiency values as a function of flow rate are compared in Fig. 9.



(a)



(b)



(c)

Fig. 9. Measured and SCCP's estimations of efficiencies for pumping system devices in throttle controlled system (a), variable-speed controlled closed loop system (b) and variable-speed controlled open loop (H_{st} = 5.8 m) system (c).

As can be seen from Fig. 9 (a), efficiency models in throttle controlled system are very accurate according to the laboratory measurements. Since the laboratory setup is driven by frequency converter, also measured frequency converter efficiency is shown in the figure, even though it does not usually exist in throttle controlled system. Efficiencies of devices in variable-speed controlled closed loop system are illustrated in Fig. 9 (b). As can be seen, efficiency model for pump is nearly perfectly accurate, but with motor and VSD efficiency estimates there is much more deviation from the measured values. VSD efficiency model seems to be accurate, when flow rate is greater than 50% of the nominal value, but with lower flow rates the estimate for efficiency is too low. Motor efficiency model gives too optimistic values in the full range of flow rates. However, in variable-speed controlled open loop system, the accuracy of pump efficiency decreases especially with low flow rates, while motor and frequency converter efficiency estimates improve significantly compared to the closed loop case, as shown in Fig. 9 (c).

Finnish paper mill

The usability of PSOT in actual industrial scale case was tested by evaluating the energy savings potential in a Finnish paper mill, on the basis of data gathered from the process over a 100 days with a 5 minute sampling interval. The pumping system at the paper mill includes Sulzer APP54-400 centrifugal pump with 990 rpm nominal speed and an open impeller, ABB 400 kW 991 rpm induction motor and ABB ACS800 frequency converter with 521 A nominal current. The pumped mass is a 1.5% density pulp suspension, so the pump has to have an open impeller, which has been taken into account in the pump selection. ABB Low Voltage Process Performance motors in IE2 efficiency class were only motors used in motor selection part, because the currently installed motor has the same efficiency classification. The average power consumption of the system during the measurements is approximately 226 kW and the total energy consumption during 2400 hour period is approximately 540 MWh. The system is controlled by both throttle and variable-speed drive to remain the constant pressure, so pure variable-speed control cannot be applied in this process. For this reason, SCCP is also not suitable for evaluation of energy savings in this case.

PSOT proposes for the optimal setup for the given application Sulzer APP62-400 pump with 745 rpm nominal speed and ABB 315 kW 743 rpm induction motor. The already installed ABB ACS800 frequency converter was identified to be the most suitable one for the process. According to PSOT, by using the optimized component setup, the power consumption would be reduced by almost 20 % to 186 kW and energy consumption would be 445 MWh with the given load profile. The annual energy savings with assumed 7000 h annual operating time would be 280 MWh, which corresponds to 28 000 € savings with energy price of 100 €/MWh. With assumed 5 % interest rate and 3 % inflation, the lifetime savings in 10 years would be even 300 000 €. This would mean reasonable payback period from two to three years for new pump and motor. More detailed information about the case is available in [4].

Conclusion

Pumping applications are one of the most energy consuming systems in both industry and municipal sectors all over the world. Since the major share of the life cycle costs of pumping system comes often from the energy consumption, the selection of the pumping system components and flow control method is essential from the energy and financial saving aspects. Two software tools to evaluate the possible improvements in energy efficiency of pumping systems, Pumping System Optimization Tool (PSOT) and Savings Calculator for Centrifugal Pumps (SCCP), were introduced in this paper.

There exists several selection tools for pumping system components, which are used to select the best device for the process. One problem with the existing selection tools is that they usually concentrate in a single device at a time and use only few operation points of the process in calculation. In contrast to them, Matlab-based PSOT selects the most optimal combination of all pumping system components (pump, motor and frequency converter) and takes into consideration all given operation points. With this kind of approach, the entire pumping system setup can be optimized at one time. Another tool introduced in this paper is SCCP, which takes into consideration only the flow control method of the pumping system. Significant share of pumping systems is still nowadays controlled by inefficient throttle control, even if it would be often financially viable to replace it by more energy efficient variable-speed control. SCCP is a simple Excel-based tool to evaluate the achievable energy and financial savings, when the throttle control is substituted by the variable-speed control. The modelling principles of both software tools and their differences are introduced in this paper.

The accuracy and usability of both software tools was explored in this paper through two case studies. In first case study, the accuracy of software tools was evaluated by comparing their calculations of energy consumptions to the laboratory measurements, in both throttle and variable-speed controlled case. The accuracies of efficiency models for different devices in SCCP were also evaluated through the laboratory tests. According to the measurements, both PSOT and SCCP give indicative results about the profitability of the replacement of throttle control with variable-speed control, with the achievable savings of over 70 %. The usability of PSOT was also studied through industrial scale case. PSOT proposed optimized pumping system setup for a Finnish paper mill that would reduce the average consumption by almost 20 %. These cases confirm that there is still need to develop this kind of tools to achieve improvements in energy efficiency of pumping systems. Already existing tools can provide indicative information about the profitability of replacements of devices or change of the control method in pumping systems, and therefore encourage to make investments to achieve better energy efficiency.

Acknowledgement

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Improving Simulated Ship Energy Efficiency using Variable-Speed Circulator Pumps

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Abstract

Improving ship energy efficiency aims at reducing both operation cost and environment-damaging emissions. Gains in efficiency are produced by modifying ship components and improving their control at the system level. A ship energy flow simulator has previously been developed to analyse and optimise ship energy flows and dynamic energy balance in modern cruise and cargo vessels. The simulator includes mechanical, electrical, and thermal energy domains.

In this paper, the ship energy flow simulator is used to investigate potential energy savings in the steam system of a modern cruise ship. The focus is on achievable saving potential by changing the number and type of circulator pumps used to harvest heat from the engine exhaust gas. In the current ship design, single fixed-speed pump circulates water through two exhaust gas boilers. The pump runs at full power when one or both engines are running.

This paper investigates using 3 alternative pump configurations: the same number of pumps operating at variable speeds, twice as many pumps operating at fixed speed, and twice as many pumps operating at variable speeds. The different pump configurations are simulated by using exhaust gas data from a commercial cruise ship. Simulation results show that the alternative configurations increase the net power recovered from the exhaust gas. It is estimated that the improvements could save between $20000 and $100000 per year of operation.

Introduction

Improving the energy efficiency of ships is becoming more and more important due to high fuel prices and international pressure to reduce fossil fuel emissions. In addition to optimizing the energy efficiency of individual components separately, an important system-level approach treats ship energy systems as a whole and investigates energy savings from changing the system architecture, re-dimensioning individual components, and changing the system operation. The Ship Energy Flow Simulator [1, 2] was created to study and develop efficient machinery configurations and ways to operate the machinery.

In this paper, the energy flow simulator is used to study the effects of modifying the steam system of a modern cruise ship. The steam system gathers thermal energy from several sources to convert water into steam, and distributes the steam to thermal energy consumers. Using modern technology, designers should be able to identify inefficiencies in this system, and propose methods to reduce its energy expenditure while maintaining the required level of performance. Reducing the energy consumption saves fuel, which lowers cost and emissions.

The next section gives more details about the ship energy flow simulator in general, and the steam system in particular. The section also describes the current configuration of the exhaust gas boiler circulator pumps, and proposes several alternative configurations. Mathematical models of fixed and variable-speed pumps used in the simulation experiment are then given. Finally, the experiment is described, and the obtained results are presented and discussed.

Ship Energy Flow Simulator

A modern cruise ship is an extremely complex system with a variety of functions and processes, most of which can be grouped into one (or more) of the categories shown in Figure 1. For example, the ship's power plant is nominally in the “power generation” category, but it also involves the electrical system (e.g. propulsion motors), water system (engine cooling), and steam system (fuel heating). In a similar way, many of the main components of the ship involve complex interactions between the different systems. These interactions are modelled in MATLAB and Simulink/Simscape, allowing simulation of multidomain physical systems. All main energy processes are represented, albeit at a simplified, system level. Two new Simscape domains, ***ThermalFluid*** and ***Steam***, have been created to fill gaps in the functionality of existing, commercially available Simscape libraries [3]. An attempt has been made to model the ship in sufficient detail to give good fidelity to the real system, but not so much detail that the model becomes too computationally expensive. The model attempts to be both accurate and practical. The model has been partially validated against a real-world case ship using data recorded during real operations [2]. The recorded data will be used as the basis for the simulations in this paper.

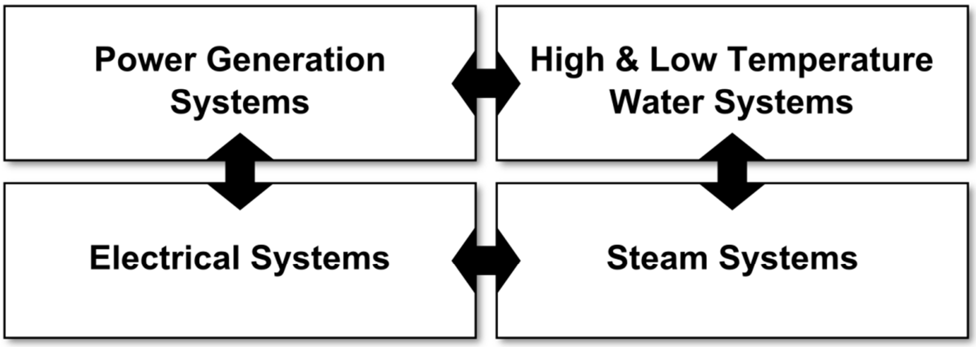

Figure 1. Main energy systems of cruise ship

Steam System

Figure 2 shows a basic overview of the ship's steam system. The steam drum contains a mixture of steam and water that is maintained at 800 kPa pressure. Steam from the steam drum is sent to steam consumers, where it is used for functions such as fuel heating, cabin heating, and distillation into clean water for drinking, showering, laundry, etc. The energy needed to create steam is provided by two main sources: exhaust gas boilers and oil fired boilers.

The exhaust gas boilers improve the total power plant efficiency by recovering exhaust heat from the ship diesel engines. Saturated water is pumped from the steam drum through the boilers, where it is heated by the exhaust gas, and returns as a saturated steam/water mixture. If the exhaust heat recovery is insufficient, the oil fired boilers are used to add more thermal power to the water in the steam drum. The boilers work together to produce the amount of steam required by the steam consumers.

For simplicity, several components of the model were left out of Figure 2, such as the steam dump condenser, hot well, and feedwater pump. Also for simplicity, Figure 2 only shows one of the 4 generators (ship power plants) and exhaust gas boilers that are on the actual ship.

This paper focuses on the pump that circulates water through the exhaust gas boiler. The current configuration of the pumps is shown in Figure 3a with the exclusion of the variable frequency drives. Each exhaust gas boiler is heated by its own diesel engine. One pump supplies water to two exhaust gas boilers. As a result, the pump must be switched on whenever one or both engines are running. Currently, the pump drive speed is fixed, so the pump works at full speed even when one of the two engines is running. The pump has been designed to satisfy the water flow specification for two engines running at full power, which is rarely the operating condition. It is hypothesized that a different pump configuration that accounts for varying demand in circulation mass flow could yield improvements in system efficiency.

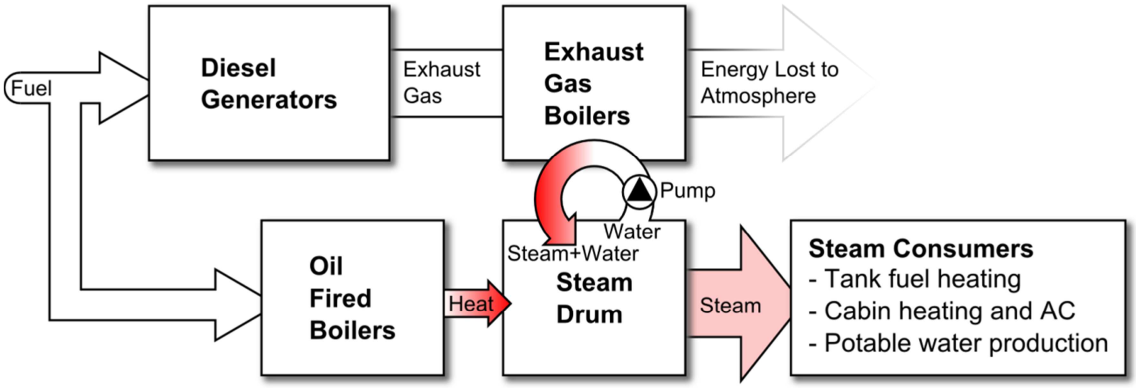

Figure 2. Simplified representation of the steam system

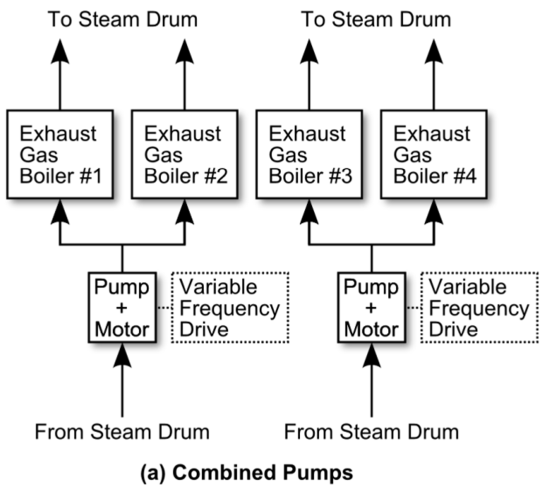

Figure 3. Different configurations for pumps supplying the exhaust gas boilers

Three alternative configurations are shown in Figure 3. In Figure 3a, variable frequency drives (shown in dotted boxes) are added to the pumps to allow their variable-speed operation. These pumps can provide just the required mass flow of circulating water. In Figure 3b, the number of pumps is doubled so that each exhaust gas boiler has its own pump. Also in Figure 3b, variable frequency drives are connected to the pumps to allow their speed adjustment.

These alternative configurations allow increasingly better control over the flow of water through each of the exhaust gas boilers. It is hoped that the improved control can yield improved efficiency. The four pump configurations will be called:

1. Combined Fixed Speed (i.e. current pump configuration shown in Figure 3a)
2. Combined Variable Speed (configuration of Figure 3a with variable frequency drives)
3. Separate Fixed Speed (shown in Figure 3b)
4. Separate Variable Speed (shown in Figure 3b with variable frequency drives)

Pump Modelling

For this study, the pumps are designed based on common approximations. Pumps are generally chosen based on the maximum power they are expected to produce in operation, which is computed as a function of maximum flowrate and pressure head. Then, the power at different flowrate values can be computed using the standard "affinity laws."

For the case ship, the flowrate and pressure of the circulator pump are 60 m^3/h (= 0.0167 m^3/s) and 4.5 kPa of added pressure (= 51.14 m head for saturated water at 8 bar_a), respectively. In the alternative configurations, pumps that supply water to just one exhaust gas boiler can be smaller, and only need a maximum flow rate of 30 m^3/ h (= 0.0083 m^3/s). By knowing the required flowrate and pressure, we can calculate the maximum pump power [4, 5]:

$$P_{max} = \dot{V}H\rho g \tag{1}$$

where $\dot{V}$ is the required flowrate, H is the pump head, ρ is density of the fluid, and g is gravitational acceleration. This yields an idealistic power value that does not account for inefficiencies in real-world pumps, motors, and variable-frequency drives. Corrections for these inefficiencies are included in Table 1. We have chosen commonly used values for the pump and motor efficiency η_{pump} and η_{motor}. Note that the maximum power of the variable-speed pumps must be slightly larger than the fixed-speed pumps because of the extra η_{VFD} factor.

Table 1. Design of pumps based on required power

Combined Fixed Speed	**Combined Variable Speed**
$P_{max} = \dot{V}H\rho g\left(\frac{1}{\eta_{pump}}\right)\left(\frac{1}{\eta_{motor}}\right)$ $P_{max} = (0.0167)(51.14)(897)(9.81)\left(\frac{1}{0.7}\right)\left(\frac{1}{0.9}\right)$ $P_{max} = 11.93\ \mathrm{kW}$	$P_{max} = \dot{V}H\rho g\left(\frac{1}{\eta_{pump}}\right)\left(\frac{1}{\eta_{motor}}\right)\left(\frac{1}{\eta_{VFD}}\right)$ $P_{max} = (0.0167)(51.14)(897)(9.81)\left(\frac{1}{0.7}\right)\left(\frac{1}{0.9}\right)\left(\frac{1}{0.95^*}\right)$ $P_{max} = 12.56\ \mathrm{kW}$
Separate Fixed Speed	**Separate Variable Speed**
$P_{max} = \dot{V}H\rho g\left(\frac{1}{\eta_{pump}}\right)\left(\frac{1}{\eta_{motor}}\right)$ $P_{max} = (0.0083)(51.14)(897)(9.81)\left(\frac{1}{0.7}\right)\left(\frac{1}{0.9}\right)$ $P_{max} = 5.93\ \mathrm{kW}$	$P_{max} = \dot{V}H\rho g\left(\frac{1}{\eta_{pump}}\right)\left(\frac{1}{\eta_{motor}}\right)\left(\frac{1}{\eta_{VFD}}\right)$ $P_{max} = (0.0083)(51.14)(897)(9.81)\left(\frac{1}{0.7}\right)\left(\frac{1}{0.9}\right)\left(\frac{1}{0.95^*}\right)$ $P_{max} = 6.24\ \mathrm{kW}$

*Estimates for η_{VFD} range from 0.92 [6] to 0.97 [7], so an intermediate value was chosen

The units in Table 1 are m^3/s, m, kg/m^3, m/s^2, and W/W for $\dot{V}$, H, ρ, g, and η, respectively. The relative power of fixed and variable speed pumps can be compared using the so-called "affinity laws." These laws state that flow is proportional to shaft rotational speed, pressure or head is proportional to shaft speed squared, and power is proportional to shaft speed cubed. In equation form:

$$\frac{\dot{m}}{\dot{m}_{ref}} = \left(\frac{N}{N_{ref}}\right) \tag{2}$$

$$\frac{H}{H_{ref}} = \left(\frac{N}{N_{ref}}\right)^2 \tag{3}$$

$$\frac{P}{P_{ref}} = \left(\frac{N}{N_{ref}}\right)^3 \tag{4}$$

where N is rotational speed, $\dot{m}$ is mass flow, H is head, and P is power. The reference rotational speed is chosen to be the maximum rotational speed of the pump. The affinity laws are a useful approximation that can be used in this case because the steam/water mixture flows in a closed loop.

Simulation

The relative efficiency of the different pump configurations is compared using a simulation. Figure 4 shows exhaust gas temperature profiles of the ship's 4 exhaust gas boilers over the course of 1 week. The dotted line shows the temperature of exhaust gas entering the boiler, and the solid line shows the temperature of gas leaving the boiler.

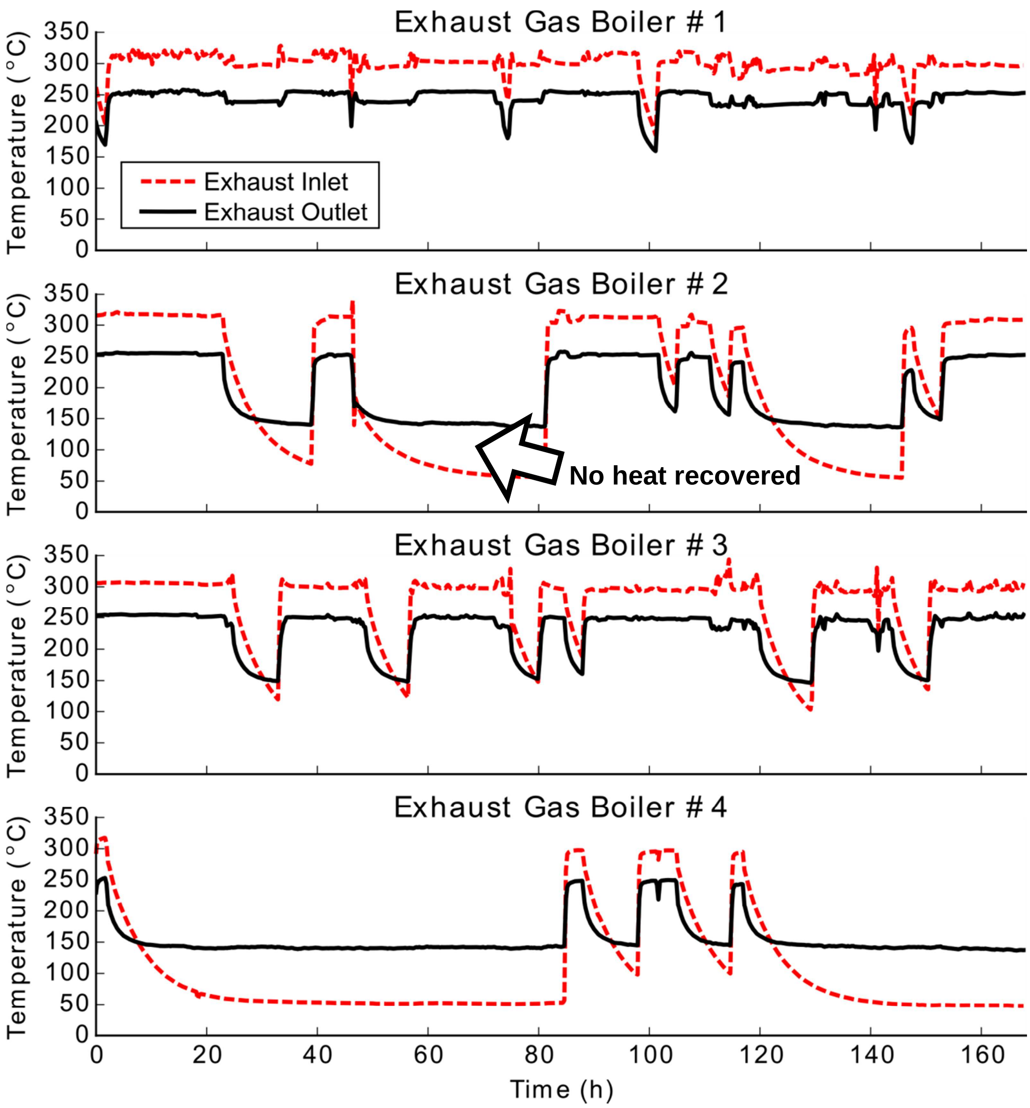

Figure 4. Temperature profiles of exhaust gas into and out of exhaust gas boilers

Calculating the amount of energy transferred to the exhaust gas boilers requires both the temperature change and mass flow of the exhaust gas. Data for the exhaust gas mass flow is estimated from a lookup table of mass flow vs. engine load given in the manufacturer's engine project guide. The exhaust gas mass flow is generally high when the inlet temperature in Figure 4 is high, and low when the inlet temperature is low. The maximum mass flow is around 30 kg/s when the engine is running, and a small nominal value of 1 kg/s is used as a minimum mass flow when the engine is off. The amount of heat transferred from the exhaust gas and the circulating fluid is calculated as:

$$Q = \dot{m} C_p (T_{in} - T_{out}) \tag{5}$$

where $\dot{m}$ is mass flow of the exhaust gas, C_p is the heat capacity (approximated as 1.085 kJ/(kg·K)), T_{in} is temperature of the exhaust gas entering the exhaust gas boiler, and T_{out} is temperature of the exhaust gas leaving the exhaust gas boiler. Note that whenever T_{in} is less than T_{out}, as indicated in the profile of Exhaust Gas Boiler #2, heat is lost from the circulating water back to the gas. Avoiding circulating water during these times is one of the ways that using individual boiler pumps is expected to improve the system efficiency.

The temperature profiles in Figure 4 are used to control the pumps. Note that these temperature measurements would be available on most commercial cruise ships, making it possible to implement one of the pump configurations proposed in this paper. Control laws for each pump configuration are shown in Table 2.

Table 2. Pump control laws

Combined Fixed Speed

Run at $\begin{cases} P = P_{max} & \text{if } ([T_{in}]_{boiler\ \#i} > 150\ ^\circ C) \text{ or } ([T_{in}]_{boiler\ \#i+1} > 150\ ^\circ C), \text{ with } i = 1 \text{ or } 3 \\ P = 0 & \text{otherwise} \end{cases}$

Combined Variable Speed

Calculate minimum required flowrate based on inlet and outlet temperatures of exhaust gas in both supplied boilers. The minimum water flow required to carry the heat is:

$$\dot{m}_{water} = \left[\frac{\dot{m}_{gas} C_p (T_{in} - T_{out})}{\Delta h}\right]_{boiler\ \#i} + \left[\frac{\dot{m}_{gas} C_p (T_{in} - T_{out})}{\Delta h}\right]_{boiler\ \#i+1} \quad \text{with } i = 1 \text{ or } 3$$

where Δh is the change in enthalpy of the circulating fluid, estimated to be 1326.5 kJ/kg. This assumes that the fluid transitions from saturated water to saturated steam, both at 8 bar_a.

The pump is run at a minimum of 50% and a maximum of 100% speed. That is, if the $\dot{m}_{water}$ calculated above is less than 50% of $\dot{m}_{max}$, then it is set to $\dot{m}_{max}/2$. Likewise, if $\dot{m}_{water}$ is greater than $\dot{m}_{max}$, then it is set to $\dot{m}_{max}$. Then, the affinity laws are used to calculate power required to produce this mass flow:

$$P = P_{max}\left(\frac{N}{N_{max}}\right)^3 = \left(\frac{\dot{m}_{water}}{\dot{m}_{max}}\right)^3$$

Separate Fixed Speed

Run at $\begin{cases} P = P_{max} & \text{if } [T_{in}]_{boiler\ \#i} > 150\ ^\circ C, \text{ with } i = 1, 2, 3, \text{or } 4 \\ P = 0 & \text{otherwise} \end{cases}$

Separate Variable Speed

Calculate minimum required flowrate based on inlet and outlet temperatures of exhaust gas in both supplied boilers. The minimum water flow required to carry the heat is:

$$\dot{m}_{water} = \left[\frac{\dot{m}_{gas} C_p (T_{in} - T_{out})}{\Delta h}\right]_{boiler\ \#i} \quad \text{with } i = 1, 2, 3, \text{or } 4$$

where Δh is the change in enthalpy of the circulating fluid, estimated to be 1326.5 kJ/kg. This assumes that the fluid transitions from saturated water to saturated steam, both at 8 bar_a.

The pump is run at a minimum of 50% and a maximum of 100% speed. That is, if the $\dot{m}_{water}$ calculated above is less than 50% of $\dot{m}_{max}$, then it is set to $\dot{m}_{max}/2$. Likewise, if $\dot{m}_{water}$ is greater than $\dot{m}_{max}$, then it is set to $\dot{m}_{max}$. Then, the affinity laws are used to calculate power required to produce this mass flow:

$$P = P_{max}\left(\frac{N}{N_{max}}\right)^3 = \left(\frac{\dot{m}_{water}}{\dot{m}_{max}}\right)^3$$

Results

Over the 7 days of recorded data, Table 3 shows average electrical power consumed by the pump, average recovered heat power from the exhaust gas, and net recovered power, which is calculated as $P_{net} = P_{recovered} - P_{pump}$. These numbers are averaged together over all four exhaust gas boilers.

Table 3 also gives an estimate for the yearly fuel cost that would be saved by each pump configuration, compared to the original configuration. The savings were estimated by comparing the net power recovered using the alternative pump configurations to the original configuration, computing the approximate amount of fuel needed by the diesel engines to produce this power, and extrapolating to one year of ship use. The following assumptions were used in calculation:

- The ship runs 24 hours per day, 300 days per year
- Efficiency of the diesel generators is 40%
- Energy content of heavy fuel oil (HFO) is 41.8 MJ/L
- Density of heavy fuel oil is 1.01 kg/L

Table 3. Average power for full duration of the recorded data (one week)

	Consumed by Pump (kW)	**Recovered Heat (kW)**	**Net Recovered Power (kW)**	**Yearly Fuel Savings (t)**
Combined Pump				
Fixed Speed	24.7	3241.2	3216.5	N/A
Variable Speed	3.3	3241.2	3238.0	33.0
Separate Pumps				
Fixed Speed	17.5	3329.0	3311.5	145.7
Variable Speed	2.3	3329.0	3326.7	169.1

The simulation results indicate that the alternative pump configurations could improve the exhaust gas boiler system's net recovered power. Assuming a cost of 600 USD/t for heavy fuel oil, the yearly fuel cost savings are predicted to be $19773, $87419, and $101438 for the three alternative configurations. A few main effects are clear from Table 3:

1. Changing fixed-speed pumps to variable-speed pumps decreased the pump power consumption but did not increase the recovered heat. This is because the variable speed pumps could run at a lower percentage of their maximum power, to match the flow requirements of the exhaust gas. The affinity laws predict that power decreases quickly as flowrate is decreased.

2. Increasing the number of pumps increases the recovered heat and also slightly decreased the pump power consumption, for both fixed and variable speed configurations. Recovered heat is increased partly because water was not circulated when temperatures in the boiler were low. Less heat was lost by using variable-speed pumps. This may be particularly significant for ships operating short distances.

One must be careful not to over-estimate energy savings, which is especially true when switching from fixed-speed to variable-speed pumps [5, 8]. Further analyses with less-favorable assumptions could be performed to determine the sensitivity of the predicted benefits.

Conclusions

A simulation analysis using recorded data from a case ship showed the possible benefit of changing the configuration of pumps that circulates water through the exhaust gas boilers of a cruise ship. Improvements in net power recovered from the exhaust gas were produced by making the current pumps variable speed, and by increasing the number of pumps to match the number of boilers. The monetary benefits of these alternatives could be used to justify changes to the hardware of the case ship. Ultimately, the decision of whether or not to change the pump configuration would depend on component cost, installation cost, and likely maintenance costs, relative to the expected savings over time. The authors suggest an exhaust-temperature-based control law for variable speed pump drives.

Acknowledgements

This work was carried out in the Efficient Energy Use (EFEU) research program coordinated by CLEEN Ltd. with funding from the Finnish Funding Agency for Technology and Innovation, Tekes. It is also part of the Ship Energy Efficiency Technologies (SET) project. The first author was supported by an ERCIM "Alain Bensoussan" Fellowship, in cooperation with VTT Technical Research Centre of Finland.

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Motors 6

EOMT - Electromagnetic Oscillating Motor Technology

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Abstract

System energy efficiency is an important subject for engineer's which affects human decisions and behavior and has a direct impact in energy resources, economy, and social activity and environment issues. Efficient energy conversion in motor driven systems must be seen as a global performance optimization, from energy cost of motor manufacture to the mechanical benefit that the motor provides to the load in exchange of the supplied energy.

Electric motors are devices to convert electricity into mechanical motion, most of them are rotary, but linear types also exist. A linear motor is essentially an electric rotary motor that has been "unrolled" so that instead of producing a torque (rotation), it produces a linear force along its length by setting up a traveling electromagnetic field.

In this case, a new electric motor paradigm is defined, having better operation efficiency and manufacture simplicity for certain applications. The EOMT - Electromagnetic Oscillating Motor Technology describes an electric energy conversion device that transforms electricity into an oscillating motion, where electromagnetic fields are used as the driving source of mechanical oscillation. This device or oscillating motor is a linear motor "rolled-back" into a spherical shaped segment so that it produces a combined double torque in the rotor (through oscillation) by setting up a traveling electromagnetic field.

Power electronics provides easy control over complex spherical traveling electromagnetic fields, improving power transmission and efficient conversion of electricity to a geared, friction free and backlash free mechanical oscillation. Then a spherical bellow, working as an angular coupling device, converts efficiently the mechanical oscillation motion into torque on the output shaft.

A compact ring-shaped prototype exemplifies the practicability of oscillating motor technology as being simple, inexpensive and effective. Analysis of pros-cons, efficiency and costs are illustrated by prototype observation. The concept of mechanical modulation and demodulation is presented. This technology could lead to embedded oscillating motor products and new machine designs having gearing drive train integrated in the motor.

Keywords

EOMT, oscillating motor, mechanical modulation, mechanical demodulation, spherical traveling electromagnetic field, spherical bellow coupling, nutate gear, nutating

Introduction

Electric motor technologies are one of the major technology areas of investigation and investments nowadays. The main reason has to do with energy costs implying a direct impact in industry manufacturing, transport, home and office appliances. Electric motors are one of the largest energy consumer devices and bring great market advantages when well optimized in fields like industry, transportation and home and office appliances. Higher electric motor efficiency normally means better products and higher benefits for clients. The "green electricity" and promotion of affordable renewable electricity year after year leads to reduction of oil consumption and CO2 emissions being replaced by electrical systems that have higher revenue, better efficiency and control with lower weight, lower volume, being compact and having lower maintenance and manufacturing complexity. The EOMT intends to continue this concept of motor efficiency having a broader approach, where the energy conversion efficiency is optimized for the mechanical system that is being actuated using a new direct drive concept. The EOMT uses a mechanical modulation and demodulation concept that integrates an electromagnetic motor with a speed reduction gear to drive high torque loads.

There is a permanent demand for simpler mechanical solutions, looking for the reduction of mechanical components complexity and dimensions and the increase of mechanic systems efficiency. This technology describes a new electromagnetic mechanical motor concept that can be applied to many complex systems simplifying them and increasing their efficiency. The mechanical principle consists in the conversion of distributed forces, produced by a source of oscillation through electromagnetic means, making use of permanent magnets and/or electromagnetic coils with rotating magnetic fields and acting over an oscillating annular body, into the rotation of a shaft having high torque and low rotational speed. The device, due to its mechanical working principle, has zero backlash and very low friction losses. The motor allows the design of new mechanical machines having slim and small annular shafts and bodies.

This technology aims to replace the use of conventional motors having high speed reduction gears connected between the load and the motor with a single EOMT device. The electromagnetic oscillating motor technology integrates the electric motor with a high efficiency speed reducer avoiding power losses of other types of speed reducers. Because of annular body format, low volume and high electromagnetic flux area can be obtained with high calorific energy dissipation. The EOMT motor device is foreseen to be capable of high load starts and with a control means, can be used as servo mechanism actuators. This device can be applied in machines that need small or larger electric motors that demand high torque output. It can also work as an electromagnetic generator with adequate control means.

The paper present here is the result of eiraSYS work as a continuation of the development started in the project funded by PRIME - Incentives Program for the Modernization of the Economy Inserted in the Incentive Scheme for the Use of Industrial Property in Portugal. PRIME SIUPI 40/01371 project was granted as a result of the Portuguese National Patent Application Pub. No 103437 – “Dispositivo Mecânico de Conversão de Energia”, 17 February 2006. Later translated and filled as patent PCT Pub. No.: WO/2007/094693 - “Mechanical device for energy conversion”, 23 August 2007. João Caeiro Antunes is patent applicant and inventor and responsible for the PRIME SIUPI project, also founder and CEO of eiraSYS company in 2008 and responsible for the development and research of EOMT.

The EOMT motor is based on a mechanical working principle described by patent PCT Pub. No.: WO/2007/094693 [1], capable to deliver high torque rotation to an output shaft while oscillating an internal gear that is driven by electromagnetic fields or other source of oscillation. To fully understand EOMT it is necessary to explain first the “Mechanical device for energy conversion” working principle. But if you don’t want to go into great detail and don’t care with patent description and mechanical operation, than jump to the Oscillating Motor Concept chapter.

Working Principle

General Working Principle based on patent “Mechanical device for energy conversion”

As described in the patent PCT Pub. No.: WO/2007/094693 - “Mechanical device for energy conversion”, the generic working principle describes the interaction between three annular bodies (1, 3, 6), that convert forces produced by an oscillation source (11) over a second annular body (3) making it oscillate, into a torque of the same body around its own axis (Z_2). This torque is produced by the tangential component of the reaction forces (R_{1t}, R_{3t}) exerted by the first annular body (1) and by the optional third annular body (6) over the oscillating second annular body (3) due to the non slipping contact between peripheral regions (2, 4, 5, 7) of the annular bodies (1, 3, 6). The rotation of the second annular body (3) is then transferred to a shaft (9) through an angular coupling device (10).

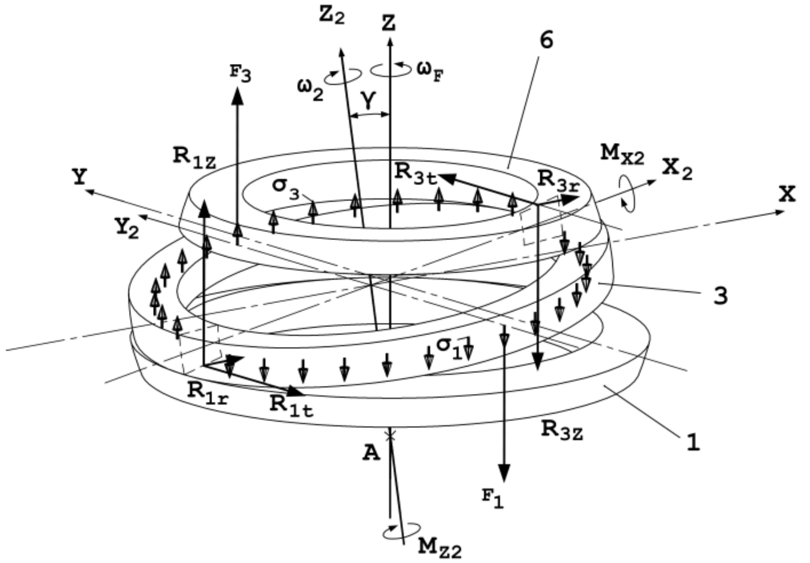

Figure 1. Mechanical modulator – perspective view

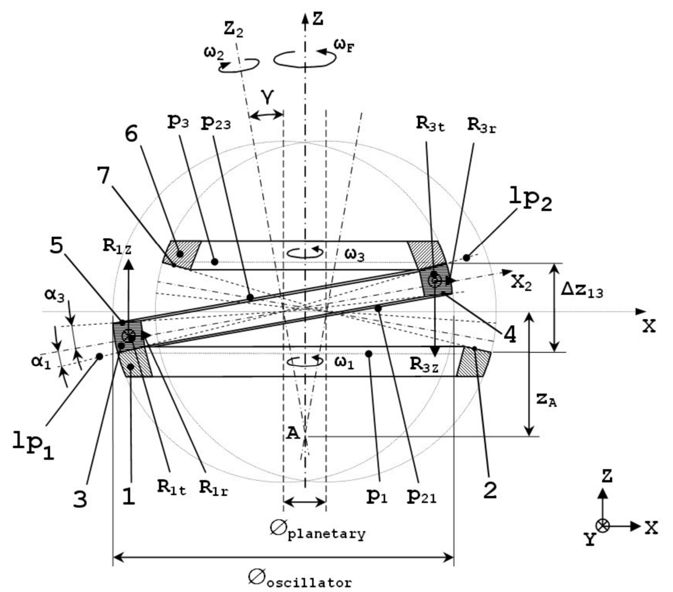

Figure 2. Mechanical modulator – front view

As it can be seen from figures 1 and 2, a perspective and a front view of three annular bodies 1, 3 and 6 are represented in the XYZ Cartesian system describing geometric relations and forces actuating in the second annular body 3 that oscillates. The arrangement of annular bodies 1 and 6 allow a stable equilibrium of the actuating forces over the oscillating second annular body 3.

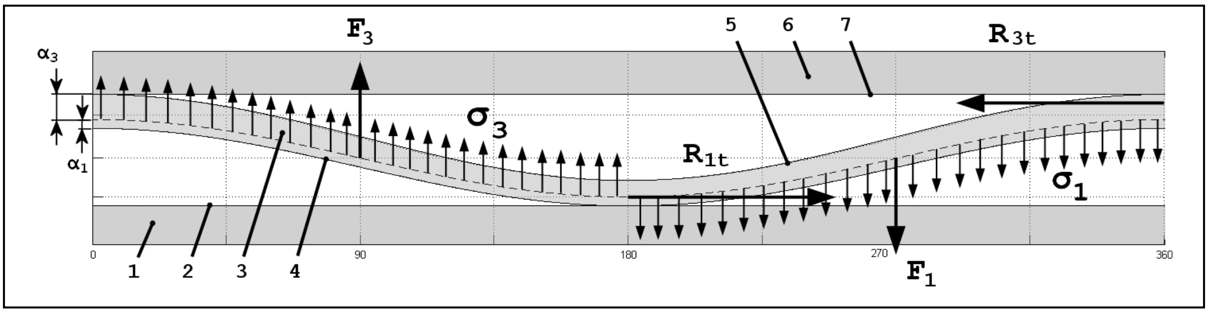

Figure 3. Annular bodies 1, 3 and 6 in a planar diagram with actuating forces

The figure 3 represents the same three annular bodies 1, 3 and 6 in a planar diagram of a toroidal surface resulting from the revolution of the circumference of figure 2 around Z axis, the distributed forces σ_1 and σ_3 actuating over the oscillating second annular body 3 and the tangential reaction forces R_{1t} e R_{3t}. The first annular body 1 makes contact with an oscillating second annular body 3 without slipping, over the primitive line l_{p1} in the position of a reaction force with radial R_{1r}, tangential R_{1t} and vertical R_{1Z} components acting on second oscillating annular body 3. The second oscillating annular body 3 contacts the third annular body 6 without slipping, over the primitive line l_{p2} in the position of a reaction force acting on second oscillating annular body 3 with radial R_{3r}, tangential R_{3t} and vertical R_{3Z} components. The angular speed rotation of the bodies 1, 3 and 6 are represented by ω_1 around Z axis, ω_2 around Z_2 axis, and ω_3 around Z axis respectively. The forces F_1 and F_3 are the sum of distributed forces σ_1 and σ_3 respectively, applied to the second oscillating body 3, producing a torsion force around its own X_2 axis. The distributed forces σ_1 and σ_3 are produced by a source of oscillation that make the second body 3 oscillate with angular velocity ω_F around the vertical Z axis. The referential with axis X_2, Y_2, and Z_2 rotate around Z axis coherently to the distributed forces σ_1 and σ_3.

The forces R_{1r} and R_{3r} are radial components that guide the oscillating annular body 2 in the planetary motion when $Ø_{planetary}$ is not null. For $Ø_{planetary}$ null there is no planetary motion and forces R_{1r} and R_{3r} are null.

The forces R_{1t} and R_{3t} are the tangential components due to the non slipping reaction of the first annular body 1 and the third annular body 6 respectively and are responsible for the output torque in the oscillating annular body 3 around Z_2 axis. The non slipping reaction between annular bodies can be obtained in different ways depending from the considered embodiment. The presented embodiments use gearing teeth's to avoid slipping. This invention pretends that other forms of non slipping be considered, such as the utilization of drag between contact surfaces, use of specific lubricants that provide more drag, use of belts or chains between the annular bodies, the use of electromagnetic forces, intermolecular forces or a combination of several.

The forces (shown in Figure 2) R_{1Z} and R_{3Z} are vertical reaction components and contribute indirectly to avoid slipping between annular bodies 1 and 6 and the second annular body 3. These forces are directly proportional to the drag and function of the drag coefficient between surfaces and directly proportional to gearing pressure in the case of embodiments that have gear teeth.

The second oscillating annular body 3 with diameter $\Phi_{oscillator}$ has peripheral regions making angles α_1 and α_3 with X_2 axis, defining the primitive lines l_{p1} and l_{p2} and where the angles are inside the interval [-90º, 90º].

The oscillating annular body 3 has an oscillating and precession motion around point A (also in Figure 2) and rotation around Z_2 axis. The motion is a compound movement with three components, it oscillates inside a sphere with diameter $\Phi_{oscillator}$ that has a vertical axis Z_2 making an inclination angle γ with Z axis. The oscillating annular body 3 rotates also around itself in Z_2 axis and the sphere has simultaneously a planetary movement with diameter $\Phi_{planetary}$ around Z axis. The composition of the movements results in a torus surface revolution where all three bodies 1, 2 and 3 are circumscribed.

Point A is the intersection point between Z_2 axis and Z axis and has distance z_A from XY plane. Point A is the fixed point vertex where the oscillating annular body 3 moves. This point is also the rotation center point of a cardan, double cardan or bellow to transfer the rotation of annular body 3 into a rotating shaft around Z axis.

The distance Δ_{z13} is a Z axis measure between annular bodies 1 and 6 in the intersection of the primitive line l_{p1} and l_{p3} and the sphere of diameter $\Phi_{oscillator}$.

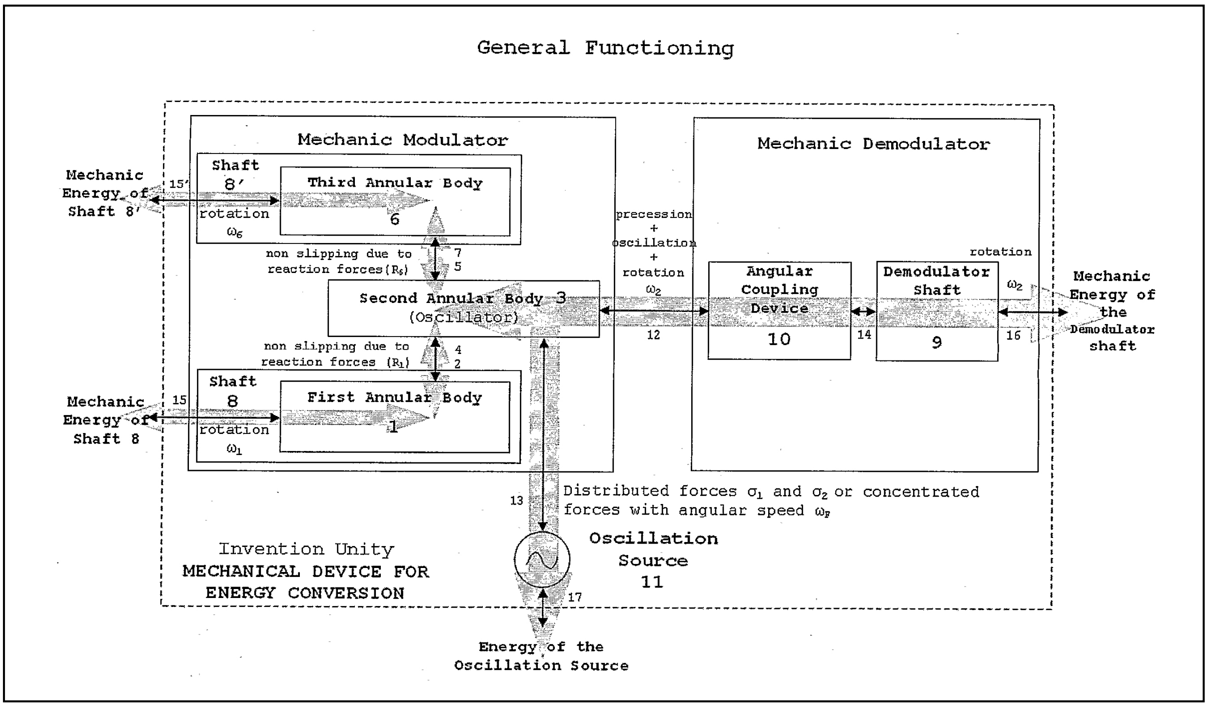

Figure 4. Block diagram for the general working principle

The figure 4 represents a block diagram with the working principle of the device where the same three annular bodies 1, 3 and 6 of figures 1, 2 and 3 are represented in block form. The blocks communicate between themselves through bidirectional arrows representing mechanical or other link means where energy exchanges exist. The set of the three annular bodies 1, 3 and 6 is called Mechanic Modulator where the bodies contact between them without slipping in peripheral regions 2 and 4 in annular bodies 1 and 3; and peripheral surface regions 5 and 7 for annular bodies 6 and 3; due to reaction forces R_{1t} and R_{3t}.

The Mechanic Modulator modulates the rotation of the second annular body 3 with annular bodies 1 and 6 because there is no slipping between bodies and because the oscillating and precession motion of annular body 3 is forced by the distributed forces σ_1 and σ_3, oscillating with angular velocity ω_F produced by connecting mean 13 to the Oscillation Source, being this one connected to exterior through connection means 17. The Mechanic Modulator is compound by Shaft 8 having at least the first annular body 1 and the Shaft 8' having at least the third annular body 6 and that transmit the rotation to exterior with connection means 15 and 15' with angular speeds ω_1 and ω_6 respectively swapping Mechanical Energy of Shaft 8 and Mechanical Energy of Shaft 8' with the exterior. The Mechanic Modulator transmits the motion of the second annular body 3, with oscillation, precession and rotation ω_2 to the block called Mechanic Demodulator through connection means 12 to the angular coupling device 10.

The block Mechanic Demodulator filters the oscillating and precession motion from the Mechanic Modulator through the angular coupling device 10 to the shaft of the demodulator 9 through connection means 14, transmitting only the rotation ω_2 of the second annular body 3. The angular coupling device 10 can be a simple cardan, a double cardan, a flexible bellow, an elastic coupling, a gearing coupling, blades coupling, drum coupling, elastic shafts subject to flexion or another similar device. The rotation of the demodulator shaft 9 is then transmitted to exterior with connection means 16, being available the exchange of Mechanic Energy of Demodulator Shaft with the exterior.

Working Principle of EOMT based on the Patent "Mechanical device for energy conversion"

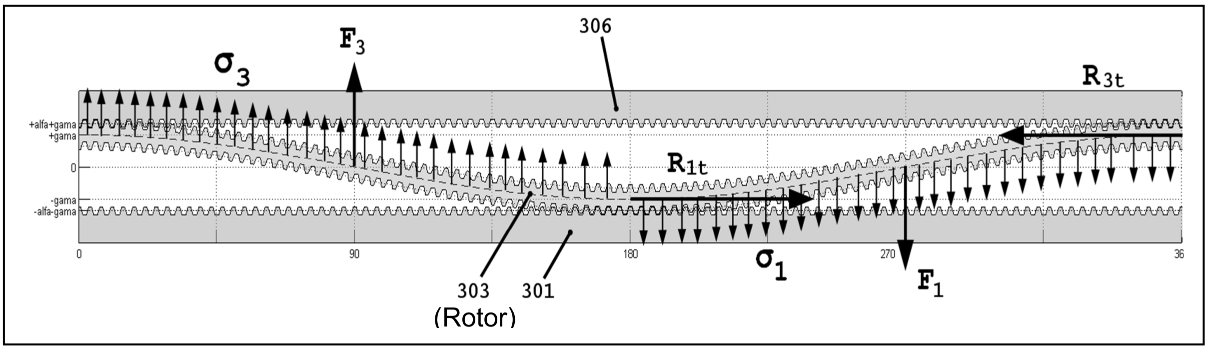

Figure 5. Planar diagram with teeth's profile for the electromagnetic motor application

The EOMT follows the particular case described in PCT Pub. No.: WO/2007/094693 - "Mechanical device for energy conversion" as a possible application of an electromagnetic motor-generator where bodies (1 and 6) are symmetric, where the oscillation of the oscillating annular body is controlled by electromagnetic means, where contact surfaces of bodies 1, 3 and 6 have teeth's, with body 3 having one teeth more than bodies 1 and 3, having the oscillating annular body 3 permanent magnets and the other annular bodies and/or enclosure have electromagnetic coils for magnetic induction. The figure 5 represents a planar diagram of the simplified actuating forces for this particular case.

The EOMT application described in the patent defines several design options for the motor. The stator is coincident with annular bodies 1 and 6 of Figure 1, or annular bodies 301 and 306 of Figure 5 having gearing teeth and where the Oscillation Source (11, from Figure 4) is obtained from distributed coils to generate a magnetic induction to the rotor. The rotor corresponds to annular body 3 (Figure 1), and annular body 303 (Figure 5) with gearing teeth. The rotor not only rotates but also oscillates around a central point A (Figure 1).

The rotor of the Oscillating Motor may be implemented with any traditional rotor technology and may benefit from most recent technological developments. This article exemplifies the implementation of a permanent magnet rotor (PM) motor having neodymium magnets distributed around the second annular body (3, from Figure 4) named as the Oscillator.

Other motor technologies may be converted to the EOMT such as the interior permanent magnet motor (IPM), the AC induction motor (ACIM), the switched reluctance motor (SRM) or the synchronous reluctance motor (SynRM).

Oscillating Motor Concept

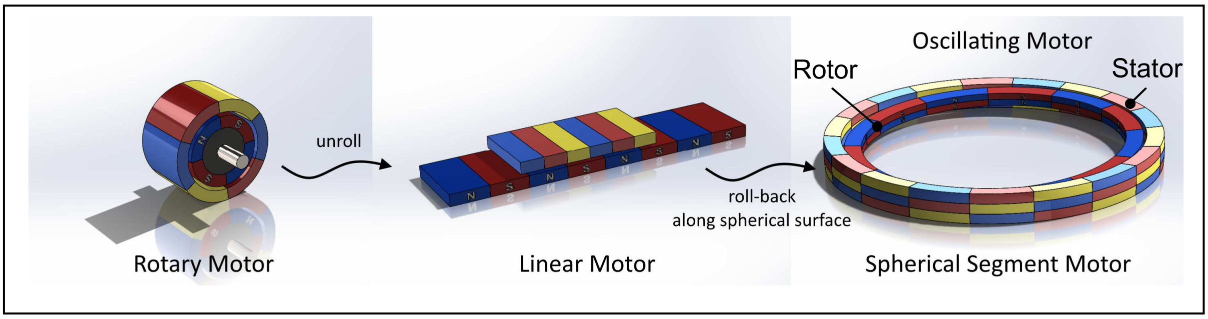

Figure 6. A rotary motor is unrolled to a linear motor and rolled-back into a spherical segment motor, named also as oscillating motor

Traditional motors are classified in two big groups, the rotary motors and the linear motors. Both of them are devices that convert electricity into mechanical motion. There are other devices that play similar roles, like for example electro mechanic actuators, valves or other devices that have mechanical motion based on electromagnetic fields. Tradition shows that it's easier to isolate and control motion into one single axis. Motion may be rotational in the case of rotary motors or simply linear in the case of linear motors, electro mechanic actuators or valves. But nothing prevents the motion to have more degrees of freedom. The control of the electromagnetic behavior increases in complexity, but with suitable hardware and software almost any configuration may be accomplished. This is the case of the Electromagnetic Oscillating Motor Technology (EOMT) or Oscillating Motor (OM), where three rotational axis of freedom are combined in a Rotor (Figures 6). The Rotor oscillates and rotates (relative to patent, Figure 5, annular body 303).

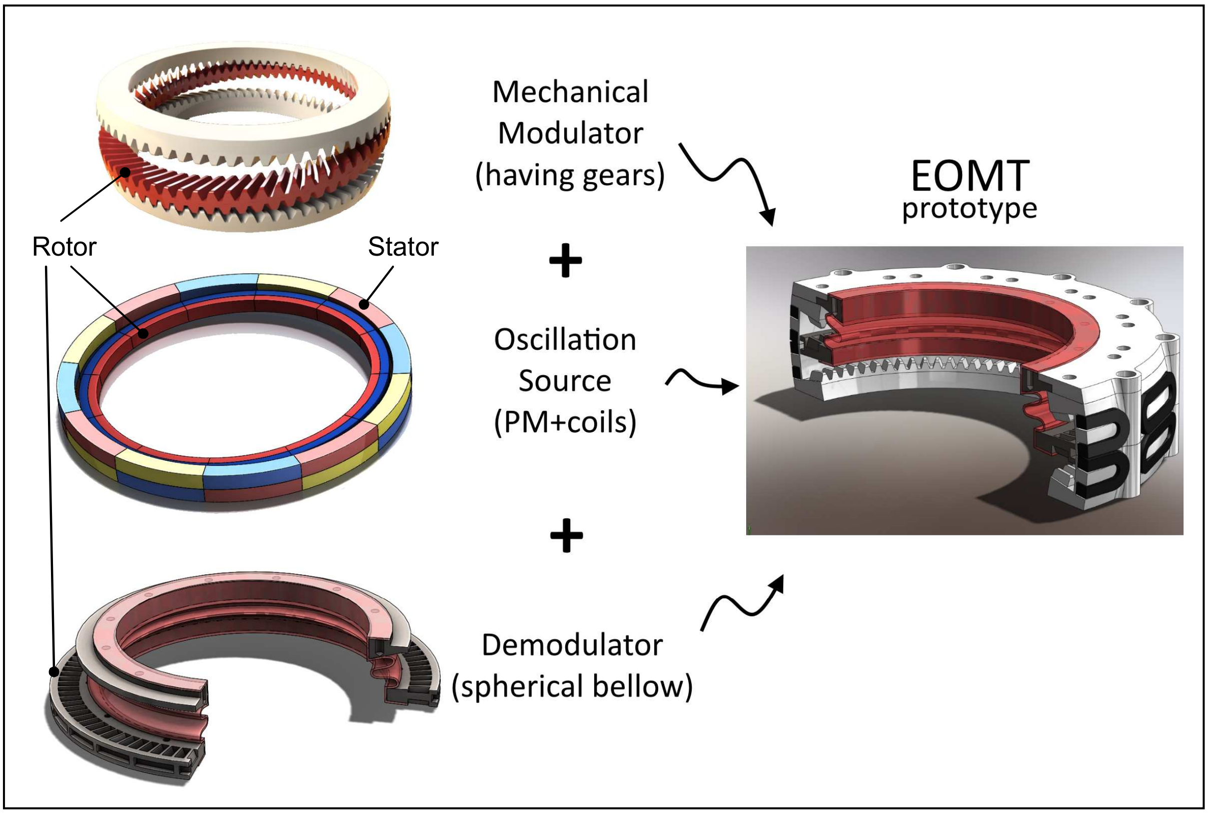

Figure 7. Main components of the oscillating motor

The mechanical motion of the Rotor is constrained by the gearing teeth's of the Mechanical Modulator (Figure 7) and it depends mainly of the motor geometry. Due to the gearing teeth coupling (relative to patent, Figure 2, surfaces 5, 7 and 4, 2), in fact, only one complex degree of freedom is obtained.

The motion in the Rotor is produced by the Stator (Figure 7) by means of the Oscillation Source. In this case the Rotor has radial permanent magnets and the Stator 24 controlled coils. As all other electric motors, the travelling electromagnetic fields are designed to maximize flux-carrying area over the surface between the stator and the rotor. In rotary motors this surface is a cylinder surface, for linear motors it's a plane, but in this case the surface is a spherical segment between the upper and lower annular bodies of the Modulator (relative to patent, Figure 4 and 5, annular bodies 1 and 301; 6 and 306). In rotary motors fields are optimized to maximize rotor torque tangentially to the cylinder surface, in linear motors field is optimized to maximize force in the direction of motion, in OM the field should be optimized to produce a combined double torque in the Rotor (relative to patent, the oscillating annular body, Figure 4 and 5, body 3 and 303), tangentially to the spherical surface with main direction of the axis of the motor (relative to patent, Z axis of Figure 2). The electromagnetic distributed forces can highly be optimized to maximize efficiency and control of the Rotor. The spherical segment surface is mapped into a planar diagram as shown in Figure 5 to study the electromagnetic behavior. All techniques used to increase efficiency in traditional motors can be translated to this type of motor, but this time applied and mapped to a spherical segment shaped motor. Permanent magnet motors (PM), interior permanent magnet (IPM), AC induction motors (ACIM), switched reluctance motors (SRM), synchronous reluctance motors (SynRM) or stepper motors can all be converted to an Oscillating Motor of the same type. Traditional technology that is used to optimize standard motors can also be used to optimize the OM, but now inducing a mechanical oscillating motion of the Rotor.

Finally a spherical bellow coupling is used to transform the complex motion of the rotor into a simple rotating motion on the output shaft and drive the load. This is described in the patent and Working Principle as the Mechanical Demodulator.

Adding all three components, Mechanical Modulator, Oscillation Source and Mechanical Demodulator, results in the EOMT, or Oscillating Motor (Figure 7).

EOMT Prototype

A simplified EOMT motor prototype was manufactured for demonstration purposes and to be an example of what is possible and practicable to achieve. There were no constrains about load requirements and efficiency. Power source was defined based in standard computer ATX power supplies, where the following voltages and maximum currents where available, 5VDC-24A and 12VDC-8A, both having short circuit protection. The big constrain was in fact the limited resources and time available to build more elaborated functional models of the motor. Approved SIUPI project was limited to FDM prototyping and CNC metal prototyping was also indispensable. The main objective of the project was to check that the electric oscillating motor could work without any load.

The EOMT prototype was developed according to the Portuguese Patent Pub. No.: PT105915 - “Motor eléctrico trifásico com nutação e oscilação e seu processo de fabrico por manufatura aditiva” [2]. Most parts where manufactured using FDM additive manufacturing technology from Stratasys 3D printers and drawn using SolidWorks as the main iterative CAD design software.

The prototype is a permanent magnet oscillating motor and has a gear ratio reduction of 95:1. Rotor has 95 teeth and the modulator 94 teeth.

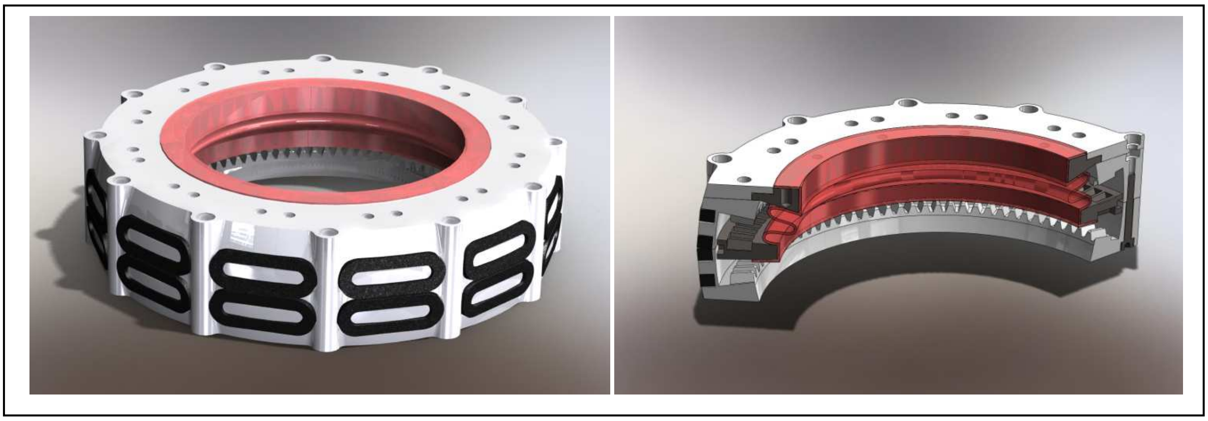

Figure 8. EOMT PM prototype, CAD renders

The figure 8 shows the prototype render obtained directly from SolidWorks. In red we can clearly see the spherical coupling demodulator that connects the oscillating rotor to an output shaft. This shaft has no bearing support as an option to avoid costs, and slides directly over the body of the motor. In black we can see the positioning and geometry of the coils.

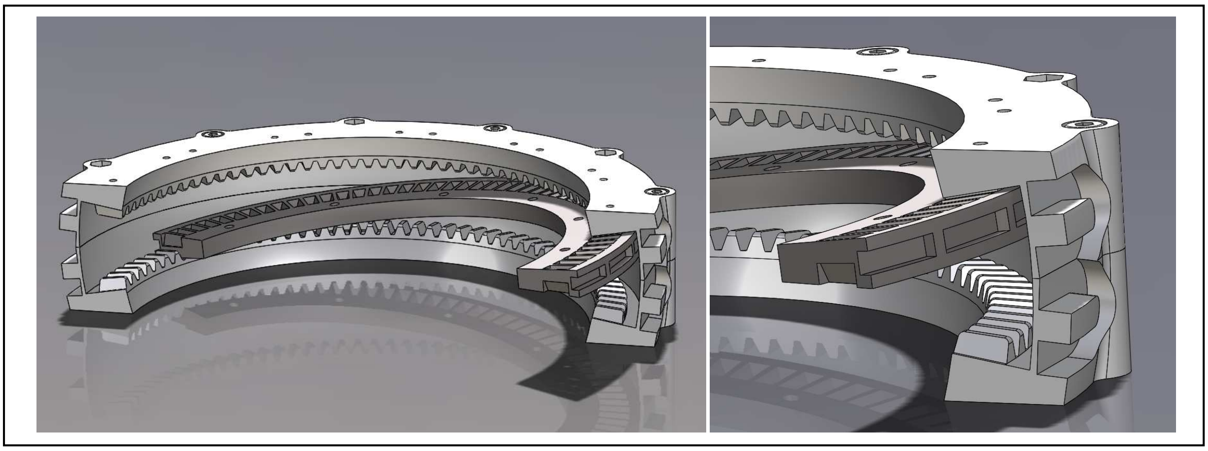

Figure 9. EOMT permanent magnet grooves and coil grooves

The figure 9 shows the grooves where the twenty six neodymium magnets with size of 20x4x3mm are glued to the rotor. It shows also the grooves for the twenty four 12V coils. No electromagnetic study!

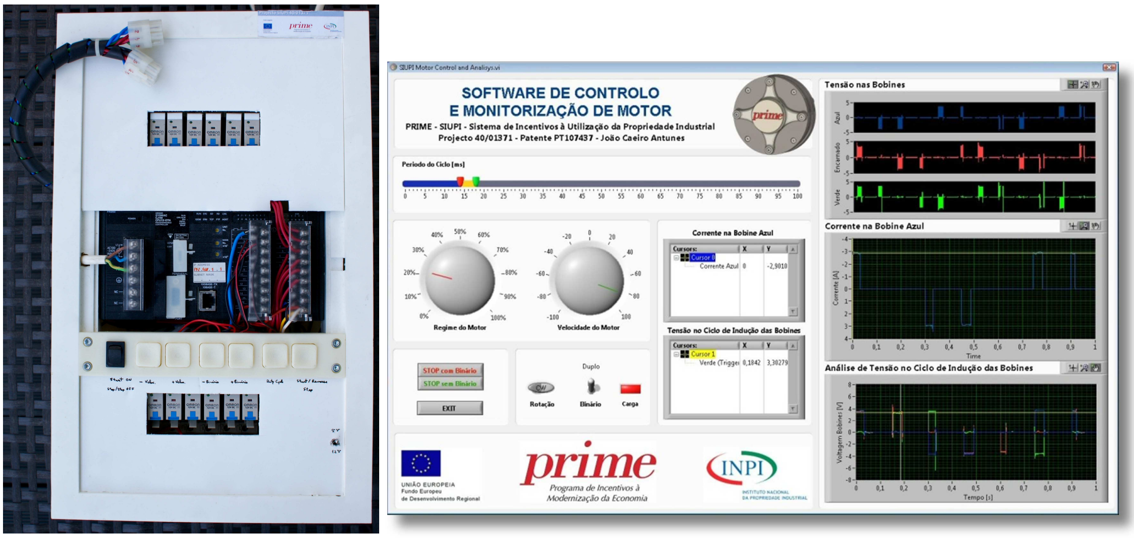

Figure 10. Control hardware and software

Figure 10 shows the controller of the motor which is based on OMRON PLC, having a six step sequencer with electromechanical 12V relays. Several step modes, speed control and duty cycle control are adjustable and configurable on the fly as well as the output voltage (5V or 12V). The OMRON PLC is controllable through a LabView application, also capable of acquiring current and voltage data to be analyzed with a NI-DAQ module.

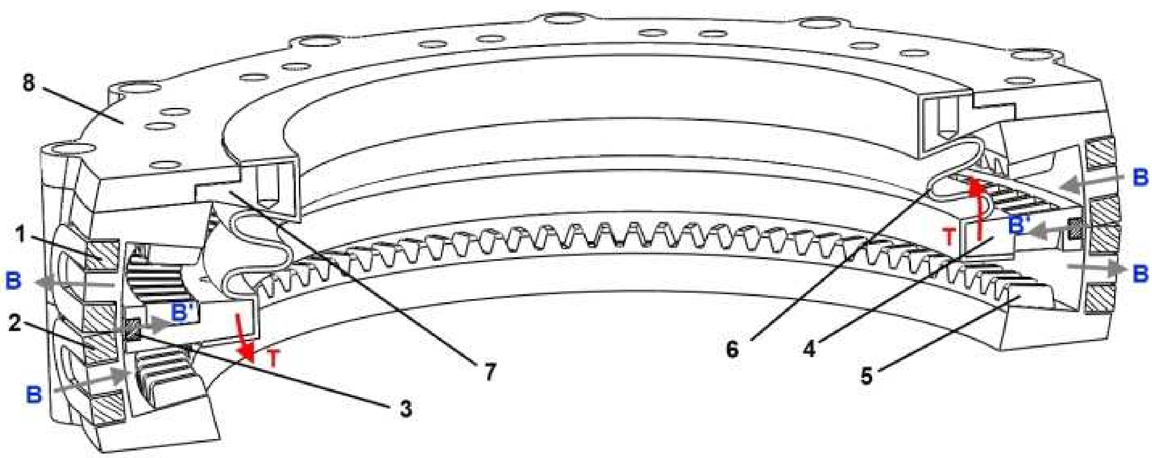

Figure 11. EOMT prototype and patent description

Patent description and operation principle

The figure 11 discloses an electric motor having a travelling electromagnetic field moving along a spherical segment and working as a step motor. The motor transforms electrical energy with the aid of coils (1 and 2) placed around the device, the oscillating motion oscillating toothed wheel (4) by electromagnetic fields (B), moving on the surface of a spherical segment, producing a torque (T) on the wobble gear (4) as reaction to the magnetic field (B'). One or more permanent magnets (3) arranged on the spherical surface, create the radial magnetic field (B'). The oscillating gear (4) engages in upper and lower sprockets (5) containing both one tooth's less, with friction-free and zero clearance. A spherical bellow (6) works as an angular coupling to transmit and efficiently convert mechanical oscillation in torque on the output shaft (7). The spherical bellow (6) may be manufactured in conjunction with the toothed wheel (4) and the output shaft (7) forming a single piece but containing distinct materials. Preferably the toothed wheel (4) and (5) are made of plastic or nylon. The support means (8) allows the rotation of the output shaft (7), optionally with bearings, and may be integrated with the toothed wheel (5) in a single piece.

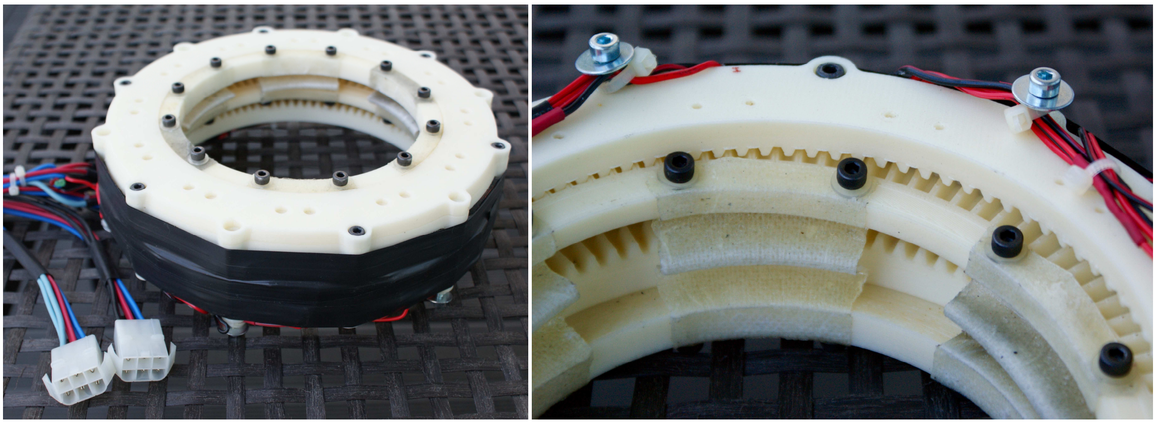

Figure 12. EOMT working prototype

The resulting prototype reached the objectives, Figure 12, which were to prove its correct operation under no load. However it shows several problems related to construction defects, with irregular gearing teeth's, abnormal spherical bellow construction and behavior since it was manufactured in small sections, low quality materials and inefficient specifications. The operating temperature was uncontrolled and above the limit of the ABS material. Missing bearing supports for the output shaft since the necessary slim bearings were quite expensive. The detail of the gearing teeth is irregular because FDM technology can only print a limited resolution. Anyway its objective was only to be a proof of concept showing that it is capable to work and rotate.

Work in Progress

More work is in progress to evaluate the operation and behavior of different types of Oscillating Motors. This is the case of the three-phase permanent magnet brushless motor.

Oscillating Three-phase Permanent Magnet brushless motor

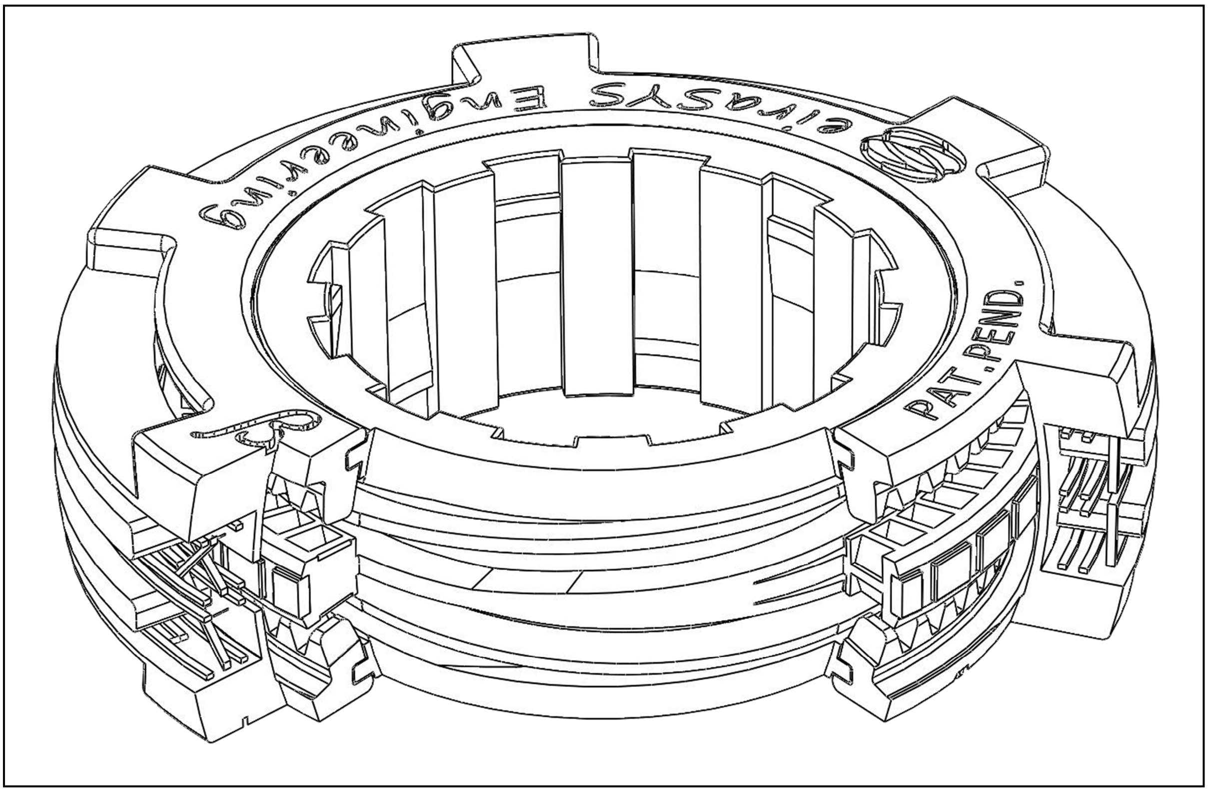

Figure 13. EOMT three-phase brushless motor

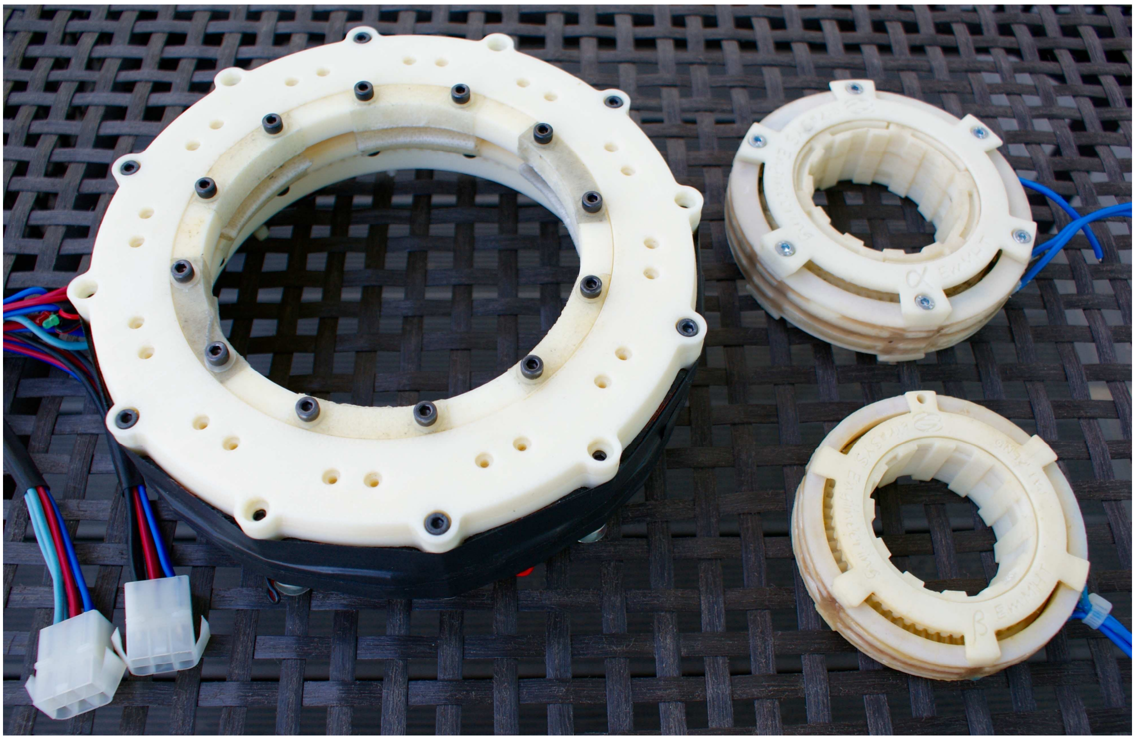

Figure 14. EOMT PM Stepper prototype (left) and EOMT three-phase PM motors (right)

The Portuguese Patent Pub. No.: PT105915 - "Motor elétrico trifásico com nutação e oscilação e seu processo de fabrico por manufatura aditiva" further describes a three-phase brushless permanent magnet motor manufactured with additive technology, as seen on Figures 13 and 14, where several improvements on magnets and coils design are being studied and optimized to improve efficiency.

The additive manufacture technology being used here is SLA, SLS and FDM, bringing gains to gearing detail but loosing in durability. Neither additive technology materials can withstand operating temperatures. Next step is to build a fully functional model with CNC subtractive manufacture technology based on most recent studies of SolidWorks CAD integration with ElectroMagneticWorks (EMS simulations of Dassaults Systemes) where rotor lamination and poles can be optimized.

Improvements are not limited to the motor itself but also to the control hardware. Use of fast solid state semiconductor switching relays will allow increasing the frequency of the variable frequency drive (VFD) making possible higher speed rotations of the motor. The control hardware and software may include PID control with angle sensors or current control means to build a servo drive system.

EOMT efficiency and operation

In traditional radial motors, efficiency improves with increased size, from [3].

"When considering what constitutes a high efficiency motor, the power rating and speed of the motor must be taken into account. Motor efficiency generally increases with larger physical sized motors and higher power levels."

"Efficiency improves as radial motors get larger, because motor torque increases directly with motor volume, while losses increase at a lower total rate. While iron losses scale directly with motor volume, conduction losses proportionally decrease with larger motor sizes. This is the result of the increased area having more flux carrying capability. High flux means that for the same operating voltage, fewer turns of conductor are needed to achieve the same output torque. Given that the larger size has also increased the area available for conductors, fewer turns of heavier wire can be used, which reduces the motor resistance in two ways."

EOMT technology is designed to have large motor diameters with hollow shafts which will benefit the overall efficiency. At the same time the total volume will be smaller than conventional motors because of the hollow shaft. Iron losses may decrease because their volume can be higher when located in the periphery of the motor. This results in increased area having more flux carrying capability. Heavier wire can also be used on the stator to decrease the total motor resistance since its diameter is larger. Conductor volume will increase comparatively and there will also be more surface area for heat dissipation.

“For an axial motor, the output torque increases faster than the motor volume increases, so the iron losses are proportionally smaller as motor size increases. In addition, axial motors also experience reduced conduction losses proportionally as motor size increases. This gives the axial motor design an even better increase in efficiency with increased motor size.”

As a result, the EOMT technology efficiency will benefit a lot from larger diameter motors, giving result to extremely high torque motors based on the rotor leverage effect and having high electric motor efficiency.

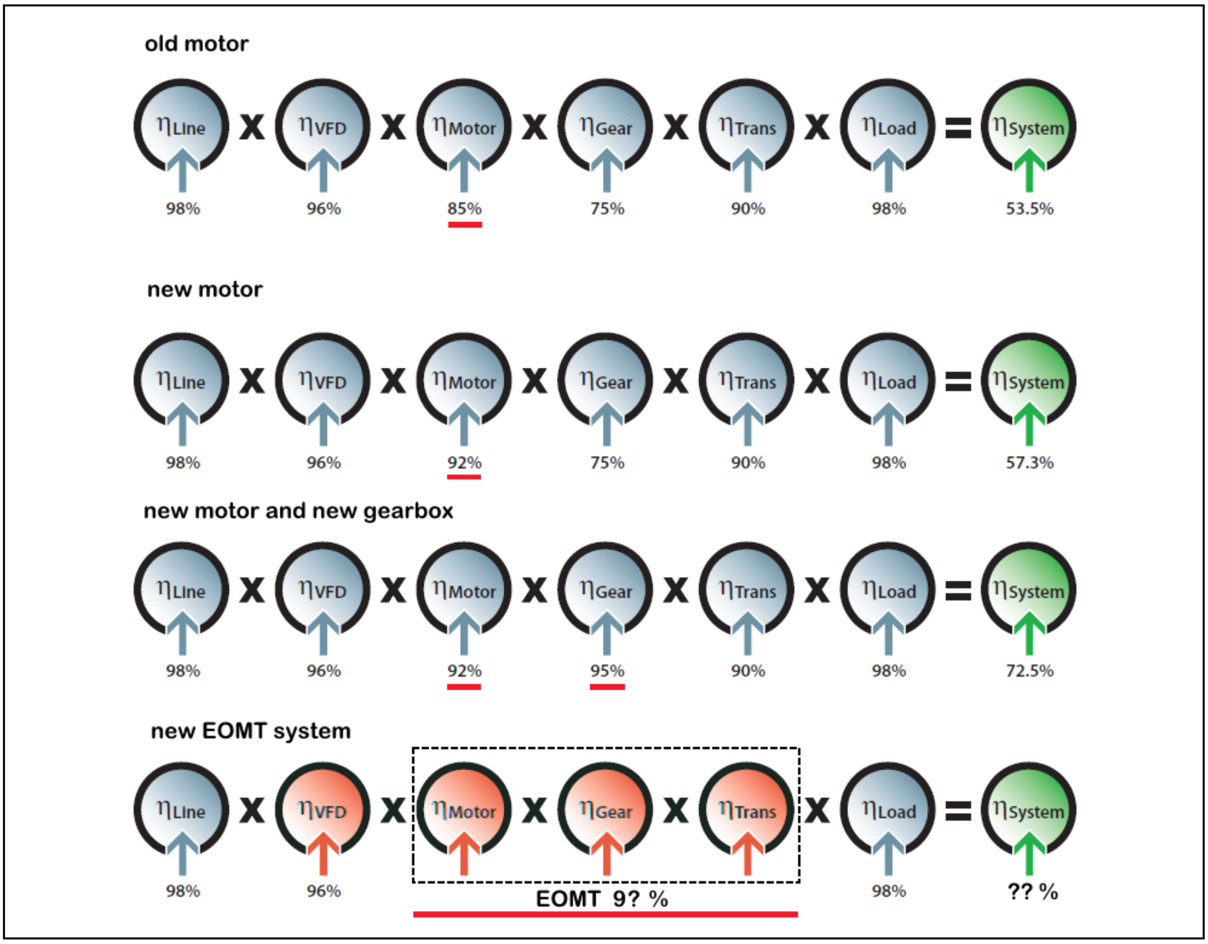

Figure 15. EOMT efficiency in overall system

Motor replacements are quite often decided when energy consumption begins to be a problem. Saving money with energy cost reduction by replacing the old motor by a new one with higher efficiency may not be the solution to your problem. The savings obtained from the increase in efficiency of the new motor may not be enough to outweigh the cost of the new motor (Figure 15). Other parts of your drive train may be much less efficient, causing higher than necessary energy consumption from the new motor. The new motor may not be well suited to saving energy in your type of application, e.g. high-cycling applications. While efficient motors are important, it's critical to evaluate your entire drive train for energy efficiency. Remember that energy efficient motors are just a single part of the efficiency equation [4].

EOMT technology is not supposed to be compared as an efficiency improvement to other motors but to a motor and gear drive system. It cannot replace a single motor. It must be seen as a possible improvement to an entire drive train, where the overall system efficiency of a type of application can be optimized.

A motor is only one component in the drive train. Each component in a system will inherently have some inefficiency, and these energy losses multiply together to provide and overall system efficiency. Just one component with poor energy usage will quickly drag down the rest of the system, from [4].

The EOMT technology will reduce the number of components of a system, significantly the speed reduction gears used between the motor and the load where the efficiency is considerably lower. The transmission efficiency can also be optimized if a direct drive connection is possible to achieve (Figure 15). Systems that use EOMT need to rethink gearboxes. All the system must be reengineered to achieve an optimized performance because EOMT is not supposed to provide a direct replacement of older motors. The technology affects many parts of the efficiency equation.

The variable frequency drive (VFD) may be designed to fit the complexity increase in motion and behavior of the oscillating annular body, but values of efficiency will look similar because electronic power control devices are the same.

Size and shape of EOMT motors are completely different from traditional ones, having an annular slim body that may result in the redesign of new products.

An important consideration to EOMT is that it can produce vibration and noise of the motor. One solution for that problem is to operate the motor at higher frequencies so that it works outside audible frequencies and also solving problems with material resonance. Other way to solve the problem is to improve the gearing system and use helical gears to reduce noise. Another more complex and expensive solution is to build a symmetric mirrored motor so that the oscillating body inertia motion can be cancelled.

Applications

EOMT motors can be developed to be widely used in many applications with special focus on high torque and low speed direct drives. Also in machines that need high efficiency in energy consumption. Products that need large diameter hollow shafts or that can be redesigned to benefit from it. A hollow shaft may have less material, less weight and a better force distribution, meaning that comparatively to traditional shafts, for the same loads, the materials will suffer less normal and shear stress. This means that the same application can be manufactured with lower tensile strength materials but having the same loads.

Examples that need compact motors, lightweight applications, embedded motor applications or servo drives may find EOMT as a solution, such as aerospace applications, robots joints, machine tools, drones, toys, hands and feet prosthesis.

Most recommended applications will be toward the drive of high torque loads and high accuracy mechanical positioning. Examples of possible applications can be found on astronomy, antennas, solar panels, microscopy, metrology, micro motion, nanotechnology, molecular machines and nanomotors.

On an opposite direction, the EOMT technology may be useful for big machines that need extreme high torque and highly efficient requisites. In theory, the oscillating motor can have a very large hollow shaft diameter with several meters and have extremely small angles of oscillation, resulting in big gear ratio reductions and extreme high torque rotation. In this case the oscillator frequency will be much higher to obtain the desirable output speed. Oscillating motors with this type of features could in theory be applied to redesigned applications such as mining trucks, mining excavators, oil machinery, tunneling excavators, electric marine solutions such as pod electric propulsion or electric Voith Schneider propellers, building construction machinery, cranes and pumps.

Conclusion

The Electromagnetic Oscillating Motor Technology (EOMT) is taking its first steps in the world of engineering. The theory and working principles of the technology are now public through this paper so that next steps can be taken to make a depth study, develop and improve the technology turning it useful to humans, having a positive direct impact in energy resources, economy, and social activity and environment issues.

The EOMT motor prototype manufactured with additive FDM technology is proven to work, but it has several engineering problems and construction defects to be solved. Due to limited resources investment and available time no more work has been done so far. Information disclosed here is the most up to date state of the art. An engineer research team is being organized to follow up this work so that better results can be obtained from EOMT prototypes, maybe achieving in the near future a competitive consumer product adapted to industry needs or market demand.

There are limitations for this type of technology and the type of applications where it can be used. Motors have lower speed, higher torque, significant efficiency differences, different manufacture costs and also different control means. In this work none of them where quantified and measured making difficult the comparison with other technologies. Assumptions that overall efficiencies are higher than alternative systems are obtained from theoretical deductions and must be proven after developing the EOMT technology and making physical prototypes that can be tested, measured and compared. Any expectations about maximum speeds, available torques, maximum energy consumptions or any other attempt to define quantitatively ranges for a running EOMT motor are just speculation for now. More prototype variations need to be build, tested and measured. There are many unknown variables that affect the behavior of those systems. Future long term work will be the creation of a good information database about the EOMT motors allowing confident choices for this technology.

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Impact of Voltage Unbalance on the Energy Performance of Three-phase Single Cage Induction Motors

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ABSTRACT

In electric supply systems of industry and other entities, it is very common to find problems of power quality. Among these problems, unbalanced voltage is very common. In this paper, is presented the study of the effects of unbalanced voltages on the energy performance of three-phase induction motors. The main contribution of this investigation is the analyses of the influence of positive sequence voltage on line currents, losses, efficiency and power factor of motor, under different voltage unbalanced conditions. A three-phase induction motor of 3 HP was used in the study. As results, the paper suggests that the positive sequence voltage must be considered together with the Voltage Unbalance Factor VUF to evaluate the energy performance of the induction motor.

1. INTRODUCTION

The electric motors - driven systems (EMDS) are the single largest electrical end-use, the report of the International Energy Agency [1]-[2] estimated that EMDS account approximately 46% of all global electricity consumption and the 68% of demand electricity in the industrial sector, see Figure 1. Among the electric motors, the three-phase induction motors are the most used in industrial and commercial systems, because of their ruggedness, simplicity and relatively low cost. Therefore, efficiency of induction motors operation is important goals to improve the industry energy efficiency and to reduce both the energy consumption as well as the production costs. The IEC standard [3] shows that induction motors in the power range from 0.75 kW to 70 kW represent a particularly attractive opportunity for electricity savings.

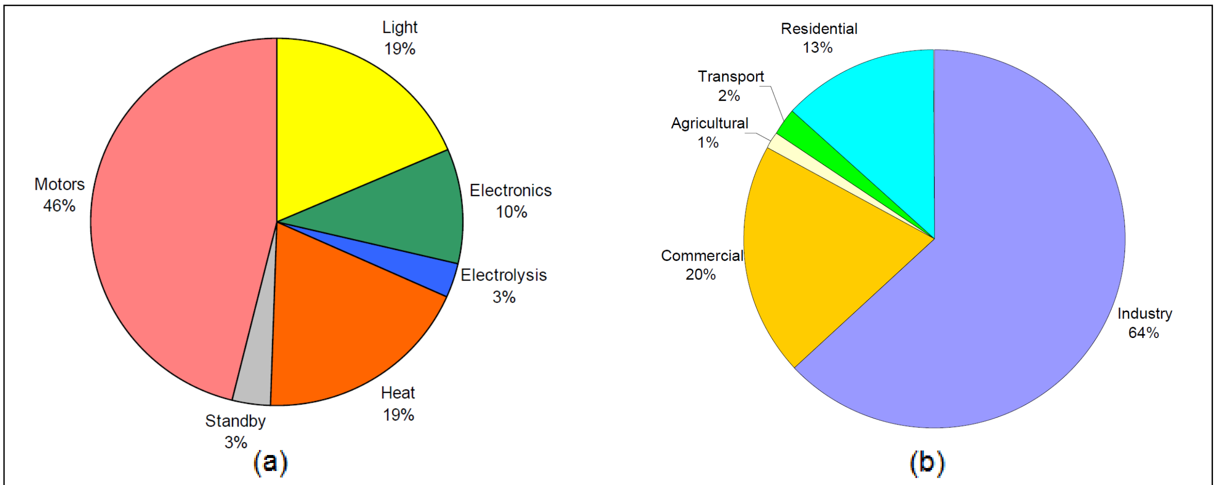

Figure 1. (a) Estimated share of global electricity demand by end-use [1]. (b) EMDS energy use by sector [2].

Unbalanced voltage is one of the most frequent disturbances in electrical systems. The major cause of voltage unbalance in power systems is the uneven distribution of single-phase loads. The American National Standards Institute's report [4] pointed out that 98% of utilities customers have less than 3% unbalance, while 66% have less than 1%, see Fig.2.

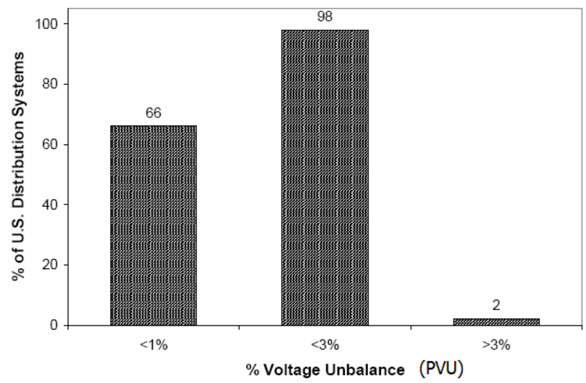

Figure 2. Approximate "percent voltage unbalance" (PVU) in the U.S.A. Distribution System [3].

When an induction motor is operating under voltage unbalance conditions, the motor phase currents will vary from each other and it will produce alternating magnetic fields of different magnitude in each phase. Therefore in the motor air gap there will be two rotating fields, one in the direction of the motor rotation (positive sequence) and another in the opposite direction to the rotation of the motor (negative sequence) [5]. Then when the motor operates under unbalance voltage conditions and a given load is introduced, the phase currents and the temperature rise will be much greater than when it operates with balanced voltages and the same load, which affects the motor performance. The effect of unbalanced voltages on the motor has been studied by several researchers, who state that the main effects on the motor are: unbalanced currents, higher temperature rise in the motor, higher losses, reduction in efficiency, speed reduction, reduction of the rated power and torque, pulsation torques, etc. [6] - [23]. These studies are generally focused on the effects caused by the negative sequence voltage. Recently, other authors have proposed to consider both the positive and negative sequence voltage in the analysis of the induction motor operating under voltage unbalance condition [24]-[25].

In this paper, using the method of symmetrical components, a qualitative and quantitative analysis of the effects of unbalanced voltages on the power flow, the current, losses, efficiency and power factor is presented. The analysis considers the effect of the positive and negative sequence voltage components. In addition, it presents practical recommendations to get the best motor performance under voltage unbalance conditions.

2. Model Equations and Energy Diagram under Voltage Unbalance Condition

A. Model Equations and Energy Diagram

In a steady state the induction motor operating under voltage unbalance condition can be represented by the equivalent circuit of Figure 3. The circuit shows the effect of current displacement due to the frequency of the negative sequence current [24].

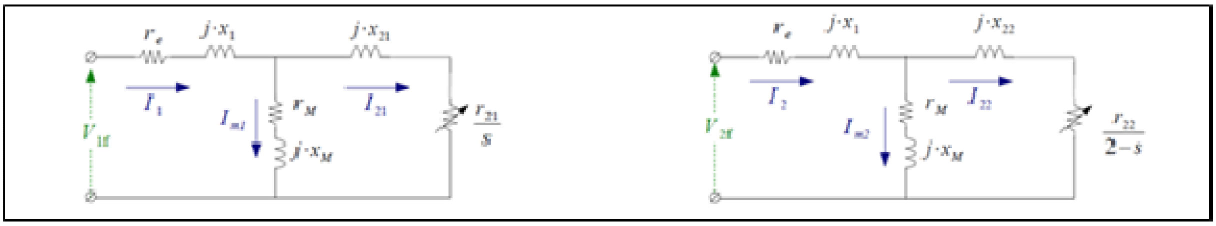

Figure 3. Positive and negative sequence circuits which show the current displacement effect caused by negative sequence frequency.

The active power P_{in} that the machine consumes has two components: active power consumed by the positive sequence P_1 and active power consumed by the negative sequence P_2. Then: $P_{in} = P_1 + P_2$. The motor output power is P_{out} and it is composed by the sum of the output power values provided by each sequence. Using the positive sequence circuit the following is obtained:

$$P_{Perd\_1} = 3 \cdot r_e \cdot I_1^2 + 3 \cdot r_M \cdot I_{m1}^2 + 3 \cdot r_{21} \cdot I_{21}^2 \quad (1)$$

The mechanical power converted by the positive sequence is:

$$P_{mec\_1} = 3 \cdot r_{21} \cdot \left(\frac{1-s}{s} \right) \cdot I_{21}^2 \quad (2)$$

And the mechanical output power, P_{eje_1}, will be equal to the converted mechanical power minus the friction and ventilation losses:

$$P_{eje\_1} = 3 \cdot r_{21} \cdot \left(\frac{1-s}{s} \right) \cdot I_{21}^2 - P_{fv} \quad (3)$$

From the negative sequence circuit the following is obtained:

$$P_{Perd\_2} = 3 \cdot r_e \cdot I_2^2 + 3 \cdot r_M \cdot I_{m2}^2 + 3 \cdot r_{22} \cdot I_{22}^2 \quad (4)$$

The mechanical power converted by the negative sequence is:

$$P_{mec\_2} = 3 \cdot r_{22} \cdot \left(\frac{s-1}{2-s} \right) \cdot I_{22}^2 \quad (5)$$

Therefore, the motor output power, $P_{out,}$ is:

$$P_{out} = 3 \cdot r_{21} \cdot \frac{(1-s)}{s} \cdot I_{21}^2 + 3 \cdot r_{22} \cdot \left(\frac{s-1}{2-s} \right) \cdot I_{22}^2 - P_{fv} \quad (6)$$

When the motor is in the operating zone, the slip varies between 0.01 and 0.05, then, from Equation (6), the mechanical power generated by the negative sequence field P_{mec2} will be negative. This can be interpreted as the power expending by overcoming the torque produced by the magnetic flux of negative sequence. This power is dissipated in the rotor copper losses of the negative sequence circuit.

From power flow in the negative sequence circuit, it can be shown that:

$$3 \cdot \frac{r_{22}}{(2-s)} \cdot I_{22}^2 - 3 \cdot \left(\frac{s-1}{2-s} \right) \cdot r_{22} \cdot I_{22}^2 = 3 \cdot r_{22} \cdot I_{22}^2 \quad (7)$$

Equation (7) shows that the power dissipated as losses in the negative sequence rotor resistance has two sources: the air gap power of the negative sequence source $P_{entreh2}$ and mechanical power which is expended in overcoming the torque produced by the negative sequence magnetic field. Both powers are dissipated in P_{Cu22} as losses. Also as for a given voltage unbalance the negative sequence current is almost constant in the motor operating zone, then the negative sequence losses will also be constant.

If Equation (6) is applied to the operation zone of the motor, slip values between 0.01 and 0.05, we get:

$$P_{out} = 3 \cdot r_{21} \cdot \left(\frac{1-s}{s} \right) \cdot I_{21}^2 - \frac{3}{2} \cdot r_{22} \cdot I_{22}^2 - P_{fv} \quad (8)$$

Equation (8) shows that the voltage unbalance has an effect on the reduction of the motor shaft power. It is also noted that this reduction effect is independent of the motor slip, so it will be more noticeable if the motor operates at less than the rated power. Total losses in the motor are:

$$P_{Perd\_Tot} = 3 \cdot (r_e I_1^2 + r_M I_{m1}^2 + r_{21} \cdot I_{21}^2 + r_e I_2^2 + r_M \cdot I_{m2}^2 + r_{22} \cdot I_{22}^2) + P_{fv} \quad (9)$$

Then in voltage unbalance conditions, the motor total losses will be higher compared to the balance operation. And therefore the efficiency will be lower. And motor efficiency is:

$$\eta = \frac{P_{out}}{P_1 + P_2} = \frac{P_{out}}{P_{out} + P_{Perd\_Tot}} \qquad (10)$$

In order to do the calculations, first the positive and negative sequence line voltages are calculated using Equation (11):

$$\begin{bmatrix} 0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \qquad (11)$$

Then, using the positive and negative sequence phase voltages, the positive and negative sequence currents are calculated. Finally, the line currents are calculated using the transformation of symmetrical components:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}\begin{bmatrix} 0 \\ I_1 \\ I_2 \end{bmatrix} \qquad (12)$$

B. Parameters and Data of the Motor

A 3HP motor was used for the analysis. The tests and parameters were calculated following the method proposed by Quispe [24]. The motor data are: induction three-phase motor, Standard NEMA, 3 HP, 220V, 8.4 A, 60 Hz, 1740 RPM, Frame 225, Design B.

The parameters of the equivalent circuit of the motor, calculated from tests are:

r_e =0.78Ω, r_m =1.573Ω, r_{21} =0.599Ω, r_{22} =1.054Ω, x_1 =0.951Ω, x_M =26.447Ω, x_{21} =1.509Ω, x_{22} =1.473Ω, $P_{fV\ (mech\ losses)}$=9.76 W

3. EFFECTS OF UNBALANCED VOLTAGE ON THE ENERGY PERFORMANCE OF THREE-PHASE INDUCTION MOTORS

A. Effects on the Line Currents

The line currents are calculated from the line voltages using Equation (11), (12) y (13).
The current unbalance is given by the Complex Current Unbalance Factor CCUF. According Oliveira [13], it is:

$$CCUF = \frac{I_2}{I_1} = \left(\frac{V_{2f}}{V_{1f}}\right)\left(\frac{Z_1}{Z_2}\right) = CVUF\left(\frac{Z_1}{Z_2}\right) \qquad (13)$$

Thus:

$$CCUF = \left(VUF \times \left|\frac{Z_1}{Z_2}\right|\right)\angle\theta_{I2} - \theta_{I1} \qquad (14)$$

From which we obtain:

$$CCUF = CUF\angle\theta_{I2} - \theta_{I1} \qquad (15)$$

From Equation (14), the Current Unbalance Factor CUF can be expressed as:

$$CUF = \left|\frac{I_2}{I_1}\right| = \left|\frac{V_2}{V_1}\cdot\frac{Z_1}{Z_2}\right| = VUF\cdot\left|\frac{Z_1}{Z_2}\right| \qquad (16)$$

Equation (14) shows that the Complex Current Unbalance Factor CCUF, depend of CVUF and of the sequence impedances. Equation (16), relates the magnitudes of the equation (14). From Equation (15), the relationship between the positive and negative sequence current is:

$$I_2 = I_1\cdot CUF\angle\theta_{I2}-\theta_{I1} \qquad (17)$$

From Equations (12) and (17) we can deduce the next equations for the line currents:

$$I_a = I_1 + I_2 = I_1\left(1+CUF\cdot\angle\theta_{I2}-\theta_{I1}\right) \quad (18)$$

$$I_b = a^2\cdot I_1 + a\cdot I_2 = I_1\left(1\angle 240° + 1\angle 120°\cdot CUF\angle\theta_{I2}-\theta_{I1}\right) \quad (19)$$

$$I_c = a\cdot I_1 + a^2\cdot I_2 = I_1(1\angle 120° + 1\angle 240°\cdot CUF\cdot\angle\theta_{I2}-\theta_{I1}) \quad (20)$$

Equations (18) to (20) show that the line currents dependent of CCUF. Applying the law of cosines to these equations and considering equation (17), we find the magnitude of the line currents based on the angle between the positive and negative sequence currents, thus:

$$|I_a| = \left|\frac{V_1}{Z_1}\right|\cdot\sqrt{1+2\cdot VUF\cdot\left|\frac{Z_1}{Z_2}\right|\cdot\cos\left(\theta_{I2}-\theta_{I1}\right)+VUF^2\cdot\left|\frac{Z_1}{Z_2}\right|^2} \quad (21)$$

$$|I_b| = \left|\frac{V_1}{Z_1}\right|\cdot\sqrt{1+2\cdot VUF\cdot\left|\frac{Z_1}{Z_2}\right|\cos\left(\theta_{I2}-\theta_{I1}-120°\right)+VUF^2\cdot\left|\frac{Z_1}{Z_2}\right|^2} \quad (22)$$

$$|I_c| = \left|\frac{V_1}{Z_1}\right|\cdot\sqrt{1+2\cdot VUF\cdot\left|\frac{Z_1}{Z_2}\right|\cos\left(\theta_{I2}-\theta_{I1}-240°\right)+VUF^2\cdot\left|\frac{Z_1}{Z_2}\right|^2} \quad (23)$$

From equations (21) to (23), it is observed that the currents depend on the magnitude of V_1, VUF and the sequence impedances. The maximum value of the current in phase 'a' occurs when the positive and negative sequence current are in phase, thus $\left(\theta_{I2}-\theta_{I1}\right)=0$. It is also noted that the line current will be different in each phase and thus, different warming to occur at each phase.

The current in each phase will have a maximum value. That same maximum value will be reached by the other phases after 120 °:

$$I_{a\max} = |I_1|\cdot\left(1+CUF\right) = \left|\frac{V_1}{Z_1}\right|\cdot\left(1+VUF\cdot\left|\frac{Z_1}{Z_2}\right|\right) \quad (24)$$

Equation (24) permits to determine the maximum load that reached the phase current for a VUF and V_1 given and a speed operation fixed. The voltage angle for which the maximum value of the current is reached in a phase occurs when: $(\theta_{I2}-\theta_{I1})=0$, i. e. whether:

$$\left(\theta_2-\theta_1\right) = \left(\theta_{Z2}-\theta_{Z1}\right) \quad (25)$$

B. Effect of the Motor Load on the Current Unbalance

From the Equations (21) to (23) it implies that is important to analyze the variation of the impedance with the slip. Equation (16) also shows that the current unbalance factor CUF can be expressed as:

$$CUF = \left|\frac{I_2}{I_1}\right| = \left|\frac{V_{2f}}{V_{1f}} \cdot \frac{Z_1}{Z_2}\right| = VUF \cdot \left|\frac{Z_1}{Z_2}\right|$$

Hence for a given unbalance, being V_1 and V_2 fixed, the values of I_1 and I_2 depend on the variation of the impedance with the load. Because the impedances are function of the slip, it is important to evaluate how the impedance varies as a function of this.

If the impedance Z_1 is evaluated since the starting motor (s=1) until the no-load condition (s ≈ 0.001). It is noted that the term, r_{21}/s vary from r_{21} until 1000 times r_{21}. Therefore the value of Z_1 is strongly dependent of the slip and its value increased from the start to the point of no-load. If the impedance Z_2 is evaluated, since the starting motor (s=1) until the vacuum condition (s≈0,001). It is noted that the term, r_{22}/s varies from r_{22} until $r_{22}/2$. Therefore, the value of Z_2 varies very little with the slip and his value will decrease slightly from the start to the point of no-load.

To quantitatively analyze the variation of the impedance, were used the 3 HP induction motors. Figure 4 shows the variation of the impedances of positive and negative sequence according to the slip, for the 3HP induction motor.

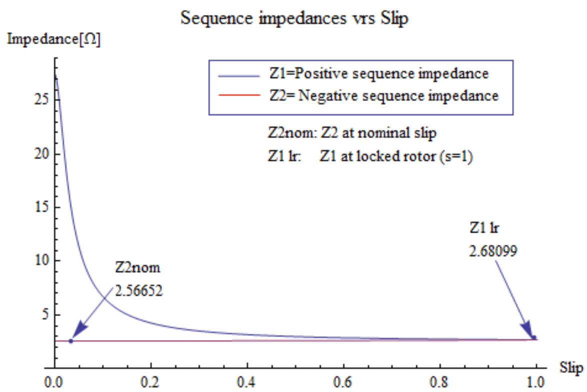

Figure 4. Variation of the sequence impedances with the slip. Comparison of the negative sequence impedance in nominal slip with the locked rotor impedance: motor 220 V, 3 HP.

Figure 4 shows that the positive sequence impedance Z_1 strongly dependent on the slip, taking the highest value in no-load and its lowest value in blocked rotor. And the most variation of the Z_1 occurs at low slip, ie in the operating zone of motor. The Figure 4 also shows that the negative sequence impedance Z_2, practically no depend of the slip and for practical purposes can be regarded as constant. It also shows that the value of Z_2, is slightly higher in the starter, as expected.

Another interesting fact shown in Figure 4, the negative sequence impedance $Z_{2\ Nom}$ at nominal slip, has a value very close to the impedance of the positive sequence Z_1 at the point of locked rotor, $Z_{1\ lr}$. This phenomenon is explained by the effect of the displacement of the negative sequence current, which causes the resistance of negative sequence of the rotor is greater than the resistance of the positive sequence, [19], [20], [24], [25]. Therefore, the following equation is valid:

$$Z_{2Nom} = Z_{1lr} \qquad (26)$$

Additionally, because the slip in the operation zone varies from 0 to 0.05, and it is much lower than 2, then it is possible to make the following approximation:

$$\left(R_1 + \frac{R_{22}}{2-s}\right) \approx R_1 + \frac{R_{22}}{2}$$

Therefore, it can be considered that in the motor operating zone, the negative sequence impedance Z_2 not depends on the slip. Which is verified in Figure 5, for the 3 HP motor, where the variation of the impedances Z_1 and Z_2 shown in the motor operation zone.

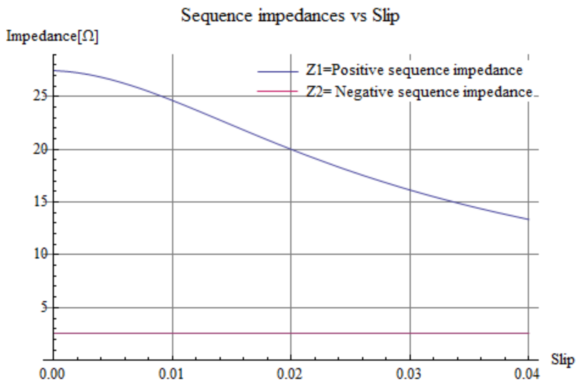

Figure 5 Variation of the positive and negative sequence impedances with the slip in the motor operation zone: motor 220V, 3 HP.

The Equation (16) establishes that the Current Unbalance Factor CUF is equal to the Voltage Unbalance Factor VUF multiplied by the ratio of impedances. As seen above, in the motor operation zone $/Z_2/$ is kept constant while $/Z_1/$ increases when the load is reduced. Consequently the result will be that the CUF increases sharply with decreasing of motor load. The Figure 6 shows the variation of CUF% with motor slip for 3 HP induction motor.

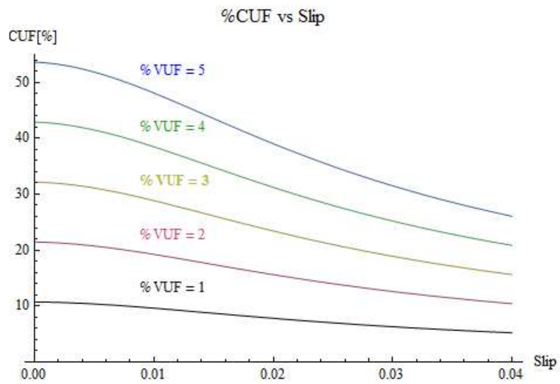

Figure 6 Variation of the Current Unbalance Factor CUF% for 3 HP motor 220V , 60 Hz.

Table I, shows how the relationship $/(Z_1 /Z_2)/$ varies for the three typical motor speeds: no-load, rated and locked rotor. It is evident that in no-load the value of the current unbalance is 7-11 times the voltage unbalance.

Table I. Ratio of the values of the sequence impedance for several operation point of the motor.

Motor	**NEMA, 3 HP**		
Operation point	**No load**	**Rated Load**	**Locked Rotor**
Error! Objects cannot be created from editing field codes.	10.4	5.66	0.99

C. Effect on the Motor Losses

In voltage unbalance conditions, the losses are increased, since the component of the negative sequence voltage generates a magnetic field in the opposite direction to the rotation of the motor, creating negative effects on its operation. The effect of voltage unbalance on induction motor losses are important for its effect on the efficiency and economic and energy consumption [26] - [28].
From the Equation (1) and (4), the iron loss can be expressed according to the voltage unbalance:

$$P_{Fe} = 3 \cdot R_M \cdot \left(\left| \frac{V_{1f}}{Z_M} \right|^2 + \left| \frac{V_{2f}}{Z_M} \right|^2 \right) = 3 \cdot R_M \cdot \left| \frac{V_{1f}}{Z_M} \right|^2 \left(1 + VUF^2\right) \quad (27)$$

The Equation (27) shows that the iron losses depend on the square of the magnitude of the component of positive sequence voltage and the square of voltage unbalance factor VUF. Because VUF squared is much smaller than unity, these losses are mainly caused by the positive sequence component.

Analyzing the copper losses, the Equation (27) shows that losses due to the positive sequence voltage dependent on the magnitude of V_1 and the motor load. While losses caused by negative sequence voltage are practically constant with the motor load. This is because the negative sequence current for a given voltage unbalance, not dependent on the motor load. Therefore, the losses of the negative sequence circuit remain constant independent of the motor load. These losses are mainly defined by the magnitude of the negative sequence voltage $/V_2/$. This makes the effect of voltage unbalance is more noticeable when the engine is under load. On the other hand the voltage unbalance has little influence on the friction and windage losses.

Thus it can be concluded that under unbalanced conditions, is added to the motor loss independently of the load, additional losses in the iron and mechanical, and these are the losses caused by the negative sequence current. The method of symmetrical components shows that the braking torque produced by the negative sequence rotating field; decreases the torque of positive sequence and the joule loss increases mainly in the rotor resistance.

D. Effect on the Efficiency and the Power Factor

The efficiency and power factor are important components that determine the energy consumption of the induction motor. The apparent power absorbed by the motor voltage unbalance condition is:

$$S_{ent} = 3 \cdot V_{1f} \cdot I_1^* + 3 \cdot V_{2f} \cdot I_2^* = 3 \cdot \frac{\left|V_{1f}\right|^2}{Z_1^*} + 3 \cdot \frac{\left|V_{2f}\right|^2}{Z_2^*} = P_{ent} + jQ_{ent} \quad (28)$$

Where:

$$P_{ent} = \mathrm{Re}[S_{ent}] \qquad Q_{ent} = \mathrm{Im}[S_{ent}] \quad (29)$$

In (28) shows that the apparent power input S_{ent} in unbalanced conditions, has two components, and depends on the magnitude of the sequence voltage and the sequence impedances. The positive sequence component changes with the motor load while the negative sequence component is kept approximately constant, since the impedance will not change with the load.
Therefore, the efficiency and power factor are expressed as:

$$\eta = \frac{P_{eje}}{\mathrm{Re}[S_{ent}]} \quad (30)$$

$$FP = \frac{\mathrm{Re}[S_{ent}]}{\left|S_{ent}\right|} \quad (31)$$

In (30) and (31) show that the efficiency and power factor dependent of voltage unbalance factor (VUF), the magnitude of the positive sequence (V_1) and the load of the motor, so the positive sequence voltage should be one more variable in the analysis of the efficiency and power factor.

If the positive sequence voltage is greater than the nominal, for a given VUF, increase the iron losses in the motor. Therefore, if the motor is made of a magnetic flux density close proximity to the saturation zone, may be considerably increased iron losses.

The Figure 7 shows the evolution of the efficiency in function of the voltage unbalance and the positive sequence voltage. For three values of V_1 (0.95Vn, Vn and 1.05Vn) and different values VUF and a fixed angle CVUF. It shows that the efficiency decreases with increasing voltage unbalance, but efficiency increases when the positive sequence voltage increases. Then for a given voltage unbalance, efficiency will be greater if the positive sequence voltage is greater.

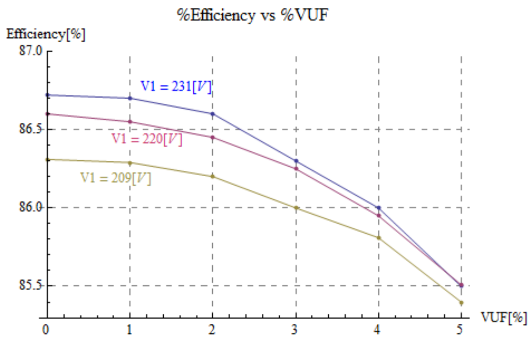

Figure 7. Variation of the efficiency with V_1 (positive sequence voltage unbalance) and VUF. Motor 220 V, 3 HP, NEMA.

The Figure 8 shows that the power factor decreases with increasing unbalance, and that the power factor increases with decreasing positive sequence voltage.

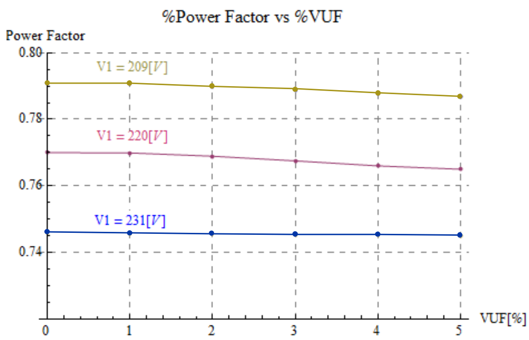

Figure 8. Variation of Power Factor with the V_1 (positive sequence voltage unbalance) and VUF.

4. CONCLUSIONS

In this paper, is presented the study of the effects of unbalanced voltages on the energy performance of three-phase induction motors, the main conclusions are:

Under voltage unbalance conditions, the unbalance of the motor line currents depends on: the VUF; the angle of the Complex Voltage Unbalance Factor (CVUF); the positive sequence impedance of the equivalent circuit and the motor speed.

If the negative sequence voltage is fixed the magnitude of the negative sequence current is practically independent of the motor load. Thus the copper losses caused by the negative sequence current depend mainly on the magnitude of the negative sequence voltage and not the engine load.

If the magnitudes of the positive and negative sequence voltage are fixed (VUF fixed), the negative sequence current is independent of the motor load. But the magnitude of the positive sequence current is dependent on the motor load. Then the current unbalance is strongly dependent on the motor load. It has been verified analytically and experimentally that CUF (current unbalance factor) varies between 4 to 11 times the VUF.

Under unbalance condition, the losses caused by the negative sequence voltage are fixed and are independent of the motor load, these losses are added to the other motor losses and thus the motor efficiency is reduced. These losses are located mainly in the rotor copper losses.

The motor efficiency decreases with increasing voltage unbalance, but this increases when the positive sequence voltage increases. Then for a given voltage unbalance, efficiency will be greater if the positive sequence voltage is greater.

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Magnet-free motor technology for fixed speed applications reaching “IE5” efficiency level

Ari Tammi, Pietro Savio Termini, Tero Känsäkangas

ABB IEC low voltage motors

Abstract

The ever increasing demand for higher energy efficiency is driving motor manufacturers, end users and OEMs to seek solutions to reduce energy consumption. This paper presents the efficiency potential of magnet-free synchronous reluctance motor technology with line-start capability, namely *direct-on-line SynRM* (DOLSynRM) and compares characteristics between different motor technologies. Practical considerations when replacing an induction motor with a DOLSynRM motor are also discussed.

Introduction

In the past energy efficiency was only seen as a means of reducing the energy bill. Nowadays different regulations set maximum energy consumption values not only for motors but also for entire machines such as fans. Now OEMs also have to find ways to improve energy efficiency. Often there are two ways to choose from: redesign the machine or choose a motor with higher efficiency. This paper presents a new alternative when it comes to a high efficiency motors.

New technology synchronous motors, such as permanent magnet motors or synchronous reluctance motors, offer a novel way to increase motor efficiency. The basic principle is that, in contrast to induction motor technology, these motors do not have any rotor losses. The possibility to extend synchronous motor technologies to line-start operation is a topic that, in the past as in the present, has fascinated the industry world due to the clear potential for performance and energy saving. While demand for higher efficiency levels has increased, traditional induction motors have demonstrated limited advances that, because of unavoidable rotor losses due to the intrinsic working principle of this technology, are progressively leading to increased motor size or to the use of more expensive electromagnetic materials.

Line-start permanent magnet motors, already present in the market, have been thought of as a potential solution. However these motors inherit the typical drawbacks that are common to all PM motors: cost, sustainability issues and maintainability.

Addressing the challenges related to PM motors, magnet-free synchronous reluctance motors (SynRM) have already been demonstrated to be a good alternative in variable speed applications. Extending these advantages to line-start operation can clearly constitute an interesting technological turning point towards new, simple, environmentally friendly, compact, reliable and high efficiency motors.

DOLSynRM technology

While the DOLSynRM motor looks identical to a traditional induction motor (IM) on the outside, the working principle is very different. 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.

One type of DOLSynRM motor has traditionally been used in specific applications such as in the textile industry. However in that case the only goal was to create a motor with synchronous speed, and neither efficiency nor other electrical characteristics were important. These motors could be considered as modified induction motors [3]. This paper focuses on modern and advanced use of DOLSynRM technology where high efficiency is the main goal. With these motors the design basis is a pure SynRM motor with an added cage to enable direct-on-line starting.

Induction motors have dominated the market for so long that all applications and the surrounding infrastructure are designed on the basis of induction motor characteristics. New technology motors often have slightly different characteristics, which is a good point to understand when considering new technology motor alternatives. The most important differences between induction and DOLSynRM motors are the nominal speed and starting characteristics. The difference in speed is easy to understand as the induction motor is an asynchronous motor with slip, while the DOLSynRM is a synchronous motor without slip. The effect of the speed difference is presented at the end of this paper. The difference in starting characteristics, by contrast, deserves more attention, as illustrated in the following sections.

Induction motor characteristics

Induction motor technology relies on the motor rotational speed being asynchronous against the network frequency. This rotational speed difference, known as slip, between the motor and network increases as the load of the motor increases. The speed difference induces current in the rotor cage. This induced current causes the bulk of the rotor losses, decreasing induction motor efficiency. Starting an induction motor is straightforward. When the motor is energized the slip is very high, resulting in high torque that starts the motor. A motor torque curve is shown in figure 1.

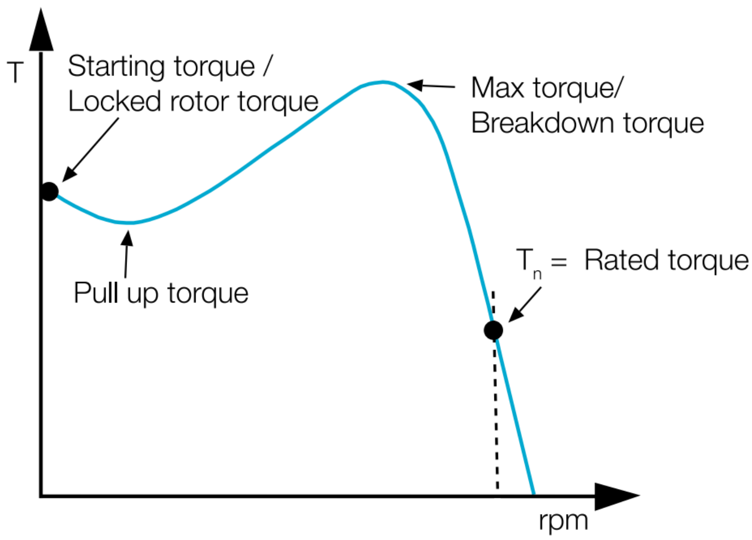

Figure 1. Traditional IM torque curve [1].

DOLSynRM motor characteristics

In theory pure synchronous reluctance motors do not have starting torque at all. This is because the rotor’s inertia prevents the motor from jumping to fully synchronous speed instantly when the motor is energized. In one way or another a synchronous motor has to be helped to start. This can be done by an external device or by adding a cage to the rotor construction. Even though a synchronous motor is rather more laborious to get started, it still possesses interesting features compared to a traditional induction motor. As explained earlier, an IM always has a certain slip which then creates current in the rotor cage. The current in the cage produces losses, which affects the motor's efficiency. A synchronous reluctance motor, as the name implies, runs at synchronous speed with the network frequency resulting in zero slip. This means that in principle there are no currents causing extra losses in the rotor, resulting in a more efficient motor [2].

Understanding DOLSynRM motor starting characteristics

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 [4].

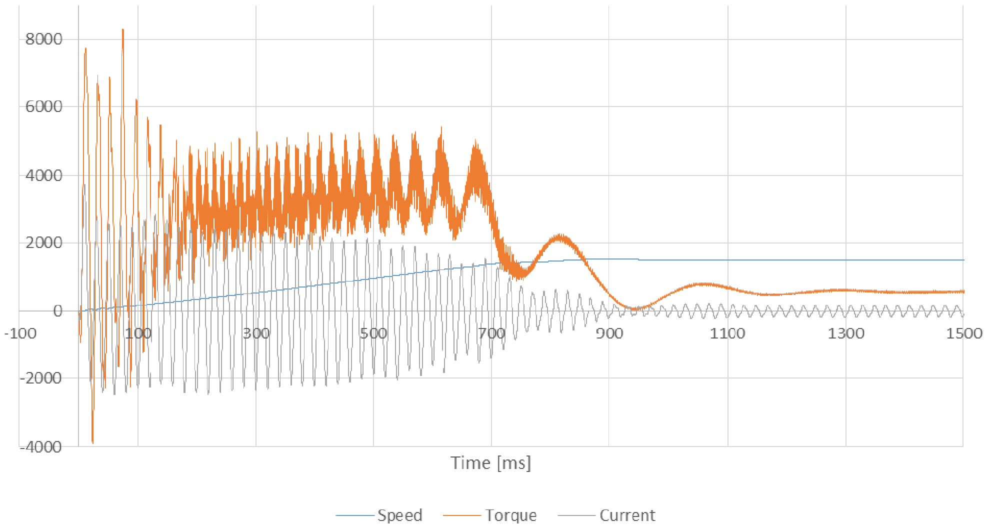

Figure 2. Simulated DOLSynRM start-up with speed, torque and current

DOLSynRM motor start

As discussed in the previous section, the DOLSynRM motor start is more sensitive to load inertia than with an induction motor. This can be understood by looking at the conceptual DOLSynRM torque curve in figure 3. In the DOLSynRM torque curve there is a noticeable dip just before the synchronous speed. When load inertia is not exceptionally high the DOLSynRM motor jumps over the torque dip practically without noticing and synchronizes. However if the motor's acceleration rate is very low due to high external inertia, the motor may not be able to pass the dip. In this case the motor would remain in the oscillation phase. This behavior is also typical for line-start permanent magnet motors. In this phase the motor would draw a high current and would be stopped by common protection devices. This problem can be avoided by knowing the load inertia in advance. The starting capability can be checked in advance when the load characteristics are known. Most pumps, fans, compressors etc. can be started without problems.

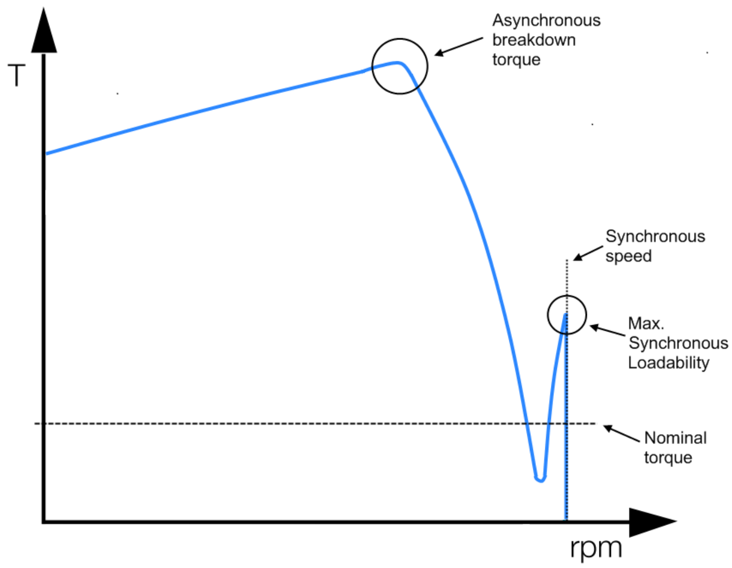

Figure 3. Conceptual DOLSynRM torque curve.

DOLSynRM loadability under steady-state synchronous operation

Finally there is the issue of loadability and stability of the motor when synchronous speed has been reached. Figure 3 shows that a DOLSynRM can handle similar short-time overload peaks as an induction motor without losing synchronization. However if synchronization is lost the motor drops back to the oscillation phase. Due to the torque dip in this phase it is likely that the motor will not synchronize again without stopping. In the oscillation phase the motor would draw high current and the protection devices would stop it. The reason for the overload should be eliminated, after which the motor could be started again. This process is very similar with induction motors, with the exception that if the load peak is very short the induction motor could recover without stopping. This is an area where more research is needed for improved understanding of DOLSynRM behavior.

In general it is clear that more scientific studies are required into direct-on-line synchronous reluctance motors to understand and explain various phenomena relating to DOLSynRM technology. In steady-state operation DOLSynRM has already proved its efficiency potential [5 – 6].

Design principles, case studies and prototypes

The main targets of ABB DOLSynRM design are to provide high levels of efficiency at steady state and to secure reliable starting under given load conditions. While the first objective leads to the maximization of the rotor's anisotropy, as in pure SynRM, the second requires a proper strategy for the installation of the rotor cage, in order to enable the starting capability without interfering with the synchronous performance and ensuring that possible current limits are respected.

This section provides some real examples of DOLSynRM designs in order to demonstrate in a concrete way the capabilities of this technology. In each case, the motor design started with detailed finite element analyses, with the aim of acquiring knowledge and optimizing the "starting vs. performance" trade-off. Dedicated investigations have therefore been performed to evaluate the distribution of losses within the stator and rotor, and predict the evolution of the motor's speed, torque and current during starting. After the design phase, the prototypes listed in table 1 were manufactured and tested.

Table 1. DOLSynRM prototypes.

P [kW]	Frame Size	Number of Poles	Efficiency Class
1.5	90	4	IE4
1.1	90	4	IE5
15	160	4	IE4
90	280	4	IE4

Note: IE5 efficiency class is here based on the IE4 limits specified by IEC 600034-30-1, with a further 20% decrease of losses.

The prototypes in frame size 90, in particular, are intended to underline the potential of the technology in small size motors, where the limits of induction technology are well known. The other prototypes illustrate the possibility to extend DOLSynRM to bigger frame sizes.

IE4 1.5 kW DOLSynRM

The first prototype is an IE4 1.5 kW 4-pole DOLSynRM, derived from a traditional 4-pole SynRM design in IEC frame size 90.

Table 2. IE4 DOLSynRM 1.5 kW, measured performance at motor nominal point in steady-state conditions.

P [kW]	Frame size	f [Hz]	Speed [rpm]	U [V]	I [A]	Eta [%]	PF
1.5	90	50	1500	400	3.84	88.2	0.64

Test results confirmed that the design meets the requirements for the IE4 efficiency class. Moreover, the test showed winding temperature rises consistently below 30 K, hence enabling the use of thermal categorization even lower than Class B, which is generally available on the market.

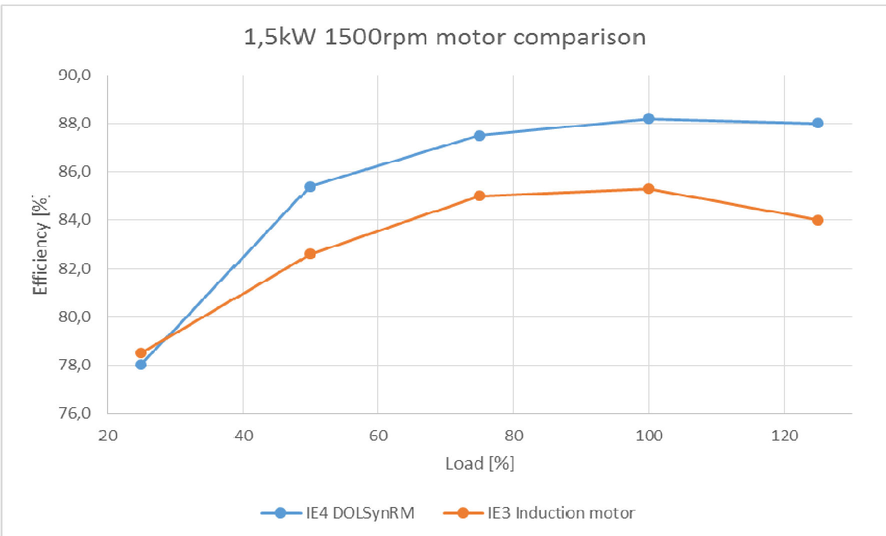

Figure 4. 1.5 kW IE4 DOLSynRM vs. IE3 induction motor efficiency performance.

In addition to efficiency performance this prototype was used to investigate starting characteristics. Starting current and locked-rotor torque were measured. The following table lists these values, adding the figure of the pull-out torque in steady-state synchronous operation, which gives an indication of how much the motor can be overloaded at nominal speed before losing synchronization.

Table 3. Measured starting current, locked-rotor torque and pull-out torque

I_S / I_N	T_L / T_N	T_M / T_N
7.5	3.1	3.1

Note: Starting current (I_s) and locked-rotor torque (T_L) describe the capability of the motor to start when loaded, whereas pull-out torque (T_M) indicates the robustness of the synchronization once nominal speed is stably reached.

Starting capability with different loads was also analyzed. Speed oscillation during starting was predicted by finite element analysis. Tests were performed with different loads until the motor failed to synchronize. It should be noticed though that even 150% load was started successfully. Figure 5 also shows how the motor remains in the oscillation phase around 1050 rpm if the start is not successful.

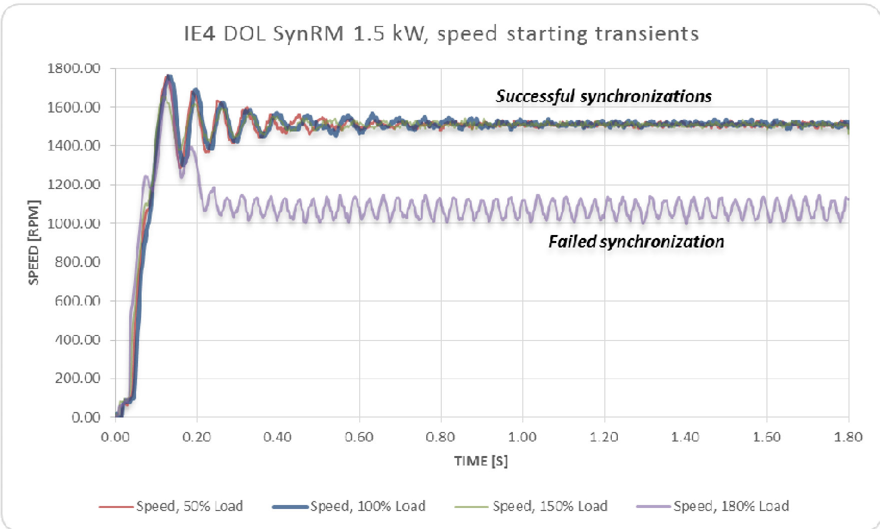

Figure 5. Starting transients under successive increasing loads. The motor begins to fail when loaded with 180% of the nominal torque: the speed then begins oscillating around values lower than synchronous.

IE5 1.1 kW DOLSynRM

This prototype clearly demonstrates the efficiency potential of DOLSynRM technology and shows the way towards a long-lasting solution with new levels of efficiency and sustainability.

Table 4. IE5 DOLSynRM 1.1 kW, measured performance at motor nominal point in steady-state conditions.

P [kW]	Frame size	f [Hz]	Speed [rpm]	U [V]	I [A]	Eta [%]	PF
1.1	90	50	1500	400	2.82	90.0%	0.63

Measurements at partial loads are also presented, together with an interesting analysis on how the losses are distributed within the motor. Compared to an induction motor, the significant reduction in rotor losses is quickly noticeable.

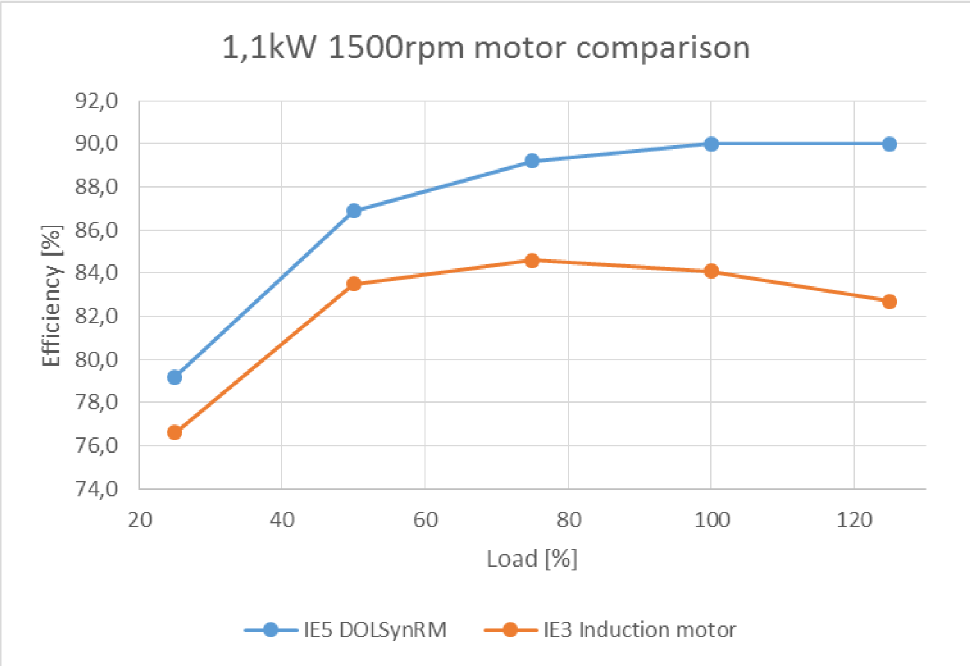

Figure 6. 1.1kW IE5 DOLSynRM vs. IE3 induction motor efficiency performance.

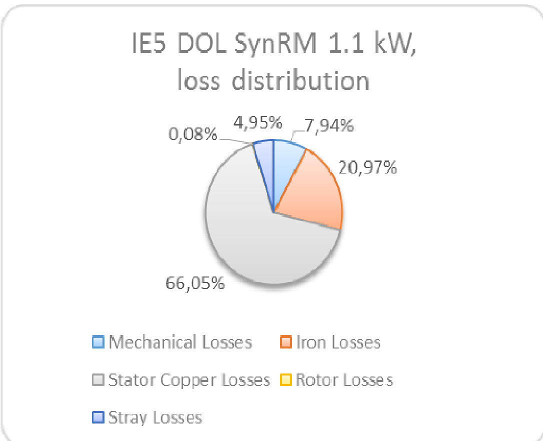

Figure 7. IE5 DOLSynRM 1.1 kW, loss distribution.

DOLSynRM power range

DOLSynRM technology has also been tested at different power levels, namely 15 kW and 90 kW in CENELEC frame sizes 160 and 280. In each of these cases, clear proof of the suitability of the technology has been obtained, with designs that meet IE4 efficiency class requirements.

Comparison between DOLSynRM and traditional IM

Direct comparisons between traditional induction and DOLSynRM motors (or, in general, line-start synchronous motors), can lead to ambiguities which derive from the intrinsically different working principles behind the technologies. In fact, relating starting capabilities to traditional parameters derived from the speed torque curve, as typically considered with regard to asynchronous motors, can bring about misleading interpretations of motor capabilities.

Line-start synchronous machines are designed to work only at synchronous speed and exhibit asynchronous slips only during the start-up phase. Direct comparisons should be limited to parameters like starting current and locked-rotor torque. With regard to steady-state operation, DOLSynRM motors should be dimensioned so that the motor's maximum torque at synchronous speed exceeds the typical torque peaks of the application.

Table 5 presents typical values for locked-rotor torque and starting current of DOLSynRM compared to what is commonly available on the market for induction motors, using similar quantities and qualities of rotor and stator materials:

Table 5. DOLSynRM vs. Induction Motors, typical ranges of DOLSynRM and induction motor starting current and locked-rotor torque.

	T_L [pu]	I_S [pu]
DOLSynRM	3.1 – 4.4	6.6 – 8.5
IM	1.8 - 3.8	5.5 – 8.5

Practical considerations when replacing an induction motor with a DOLSynRM motor

Synchronous speed vs. induction motor speed

From the application point of view the most important difference is motor nominal speed. Synchronous motors do not have slip, which means that they run faster than induction motors. Obviously this is not a problem if the load machine (pump, fan, etc.) is optimized to produce the same output at higher speed.

It is also possible to replace induction motors with synchronous motors in existing applications, but in these cases the following should be considered. Higher speed means increased flow or other "production" but also increased shaft power. This impacts both motor selection and energy consumption. Table 6 indicates how much shaft power typically increases when replacing an induction motor with a synchronous motor without making any changes to the load machine.

Table 6. Shaft power increase due to synchronous speed vs. typical IE3 induction motor nominal speed.

Power kW	IE3 induction motor rpm	Speed increase to 1500 rpm	Efficiency difference IE4 – IE3	Shaft power increase due to speed increase	
				Pump/fan	Constant torque
1.5	1440	4.2%	2.9%	13%	4.2%
15	1474	1.8%	1.8%	5%	1.8%
90	1487	0.9%	0.9%	3%	0.9%

In the table it can be seen that shaft power, which is directly linked to energy consumption and flow, increases more than motor efficiency. The effect is most significant in quadratic torque applications such as pumps and fans.

When does this matter? It matters in applications where the increased flow cannot be utilized and is wasted. This happens in continuous duty applications, for example, where extra capacity is regulated by a valve.

When is it not a problem? It is not a problem in applications where the system includes a reservoir and the motor is controlled with a start/stop function. Examples of such applications are industrial compressed air systems or a pump feeding water into a reservoir.

In some cases the increased shaft power may even impact the dimensioning of the motor.

Starting characteristics

As discussed in the section on technology, DOLSynRM starting capability should be evaluated case by case. Both the load torque and load inertia should be known in order to evaluate whether successful starting can be performed. Especially very high load inertia can cause problems in starting. However the clear majority of applications have low enough inertia for successful starting.

Different pole numbers?

So far studies have focused on 4-pole motors. Further studies are needed in order to understand how this technology could be utilized with other pole numbers and nominal speeds.

Power factor

DOLSynRM motors typically have slightly lower power factor than induction motors. This means that motor current is a little higher than with induction motors, even if the efficiency is higher. For the user this is generally not a problem as today most factories and other facilities commonly have separate reactive power compensation units.

Service

DOLSynRM and induction motor service procedures are identical. As there are no permanent magnets in DOLSynRM motors they can be disassembled and assembled just like any induction motor. The motor windings are similar and the materials are identical. Both motor types can be tested with a direct-on-line supply after repair work.

Frequency converter operation

Frequency converter operation has not been studied for this paper. It may be possible to run DOLSynRM motors in scalar control but the control performance is unknown. Pure SynRM motors with verified control performance and measured motor-drive package efficiency are recommended for variable speed applications.

Conclusions

Tested DOLSynRM prototypes demonstrated efficiency performance up to IE5 level. The fact that DOLSynRM was able to reach IE5 efficiency with the same frame size as IE2 or IE3 induction motor means that this technology has potential to offer a cost effective way to reach high efficiency.

Differences between DOLSynRM and induction motors have been presented, with particular attention to starting capability. Results indicate that, when difference in nominal speeds is considered, DOLSynRM can be a good alternative to induction motors especially in applications where load inertia or starting requirements are not particularly demanding.

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Policy 5

NEMA and IECEE GMEE “Global Motor Energy Efficiency” Program

Dan Delaney
Regal

Introduction

Electric motor driven systems account for approximately 45% of all global electricity consumption [1]. Over the past twenty years the motor industry has made significant efforts 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) and national energy efficiency regulations. There are many national and/or regional global motor energy efficiency regulations currently in place [2] with many more in development. Table 1 below provides a list of a few of the national and regional Motor MEPS programs operating around the world today.

Efficiency Levels	Efficiency Classes IEC 60034-30-1	Testing Standard	Country MEPS (Minimum Energy Performance Standard)	Country MEPS Regulation
Premium Efficiency	IE3	Low Uncertainty IEC 60034-2-1, IEEE 112B or CSA C390	USA (0.75-375kW)	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
High Efficiency	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

Table 1 – Global MEPS Programs

One of the major MEPS obstacles for motor manufacturers is navigating the various rules and regulations at the national and regional levels. While many of these regulations have similar registration processes, each one varies from the next. Below are important considerations in the typical motor energy efficiency regulation process.

- Motor Efficiency Test Standard
- Product Definition (Scope of Regulated Motors)
- Test Laboratory Qualification
- Registration and Certification
  - Minimum number of test samples
  - Labeling or Product Marking
  - MEPS (Minimum Energy Performance Standard)

In 2010 NEMA attempted to address this lack of enforcement issue with the development and subsequent release of the NEMA Premium License program [3]. This voluntary motor efficiency program provides a certification program based upon the US DOE (Department of Energy) 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 this 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 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 [5]. The IECEE 50 plus global member countries, per Figure 1 below, was a key factor in this decision.

Figure 1 - IECEE Member Countries

Working Groups 5 (Strategy-GMEE) and 6 (Technical-GMEE) were formed under the IECEE Policy and Strategy Committee (PSC). With WG5 focused on the planning and marketing of the program while WG6 is concentrated on the technical and certification details of the program. The next step was to recruit a global team of motor manufacturers, NCB's and other interested participants. Figure 2 provides the list of current team members.

Organization/Affiliation	Attendee	Working Group
IEC-IECEE-Switzerland	Mr. Kerry McNamana	IECEE Secretariat
Regal Beloit Corporation	Mr. Dan Delaney	WG5/6 Convernor
IEC-Germany	Prof. Martin Doppelbauer	WG6
IECEE-Australia	Mr. Ron Collis	IECEE Chairman
IEC-Sweden	Mr. Thomas Korssel	WG5
IECEE-CSA International-Canada	Mr. Shawn Paulsen	WG5
Panasonic Corporation-Japan	Mr. Toshi Kajiya	WG5
IECEE-UL -USA	Mr. Steven Margis	WG5
MOTOR SYSTEMS - Switzerland	Mr. Conrad Brunner	WG5
NEMA-USA	Mr. William Hoyt	WG5
NIDEC MOTOR CORPORATION-USA	Mr. Rob Boteler	WG5
Australia	Mr. Andrew Baghurst	WG6
Brazil	Mr. Paulo Quintaes	WG6
Canada	Mr. Pierre Angers	WG6
IECEE-CSA International-Canada	Mr. Jean-Pierre Boivin	WG6
SAUDI ARABIA MOTOR INDUSTRY	Mr. Thani Alanazi	WG6
IECEE-KTL –Korea	Mr. Byung-Guk Kang	WG5
SIEMENS (USA)-Germany	Mr. Bill Finley	WG6
Underwriters Laboratory PDE	Mr. Kirk Anderson	WG6
4E / EMSA	Ms. Rita Werle	WG5
General Electric (USA)	Mr. P.C. Shivalingam	WG6
VDE (Germany)	Mr. Ulrich Pfau.	WG6
ABB (Finland)	Mr. Jukka Hannuksela	WG6

Figure 2 – IECEE PSC WG2D Members

The IECEE is a multilateral certification system based on International Standards prepared by the International Electrotechnical Commission(IEC) per Figure 3 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, whilst 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.

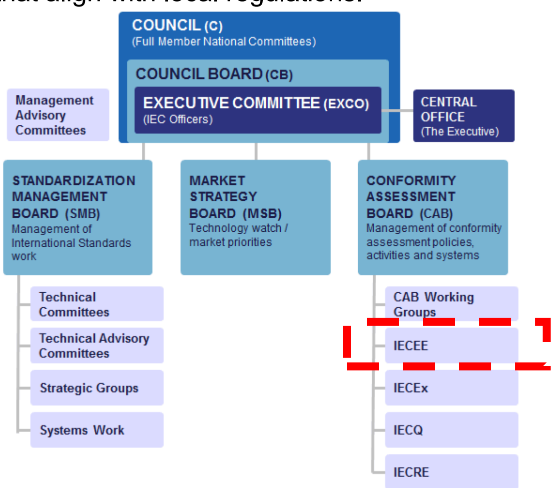

Figure 3 – IEC Organization

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, 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: How does the GMEE program work?
A: A manufacturer applies to a participating National Certification Bodies(NCB) operating in the IECEE CB Scheme (NCB) 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.

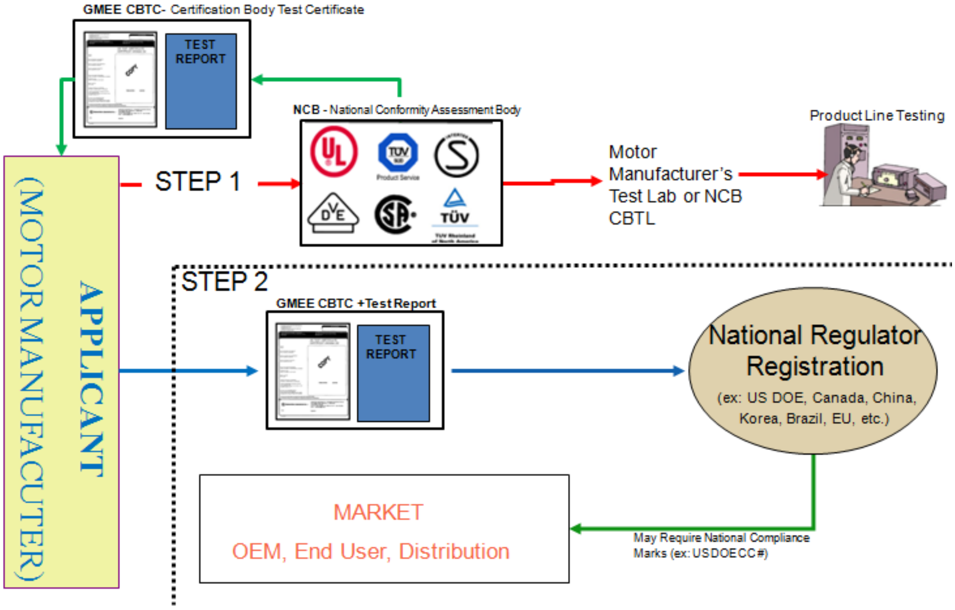

Figure 2 - GMEE Process Flow

Q: How can I apply for the GMEE Program?
A: A manufacturer begins this process by applying to any National Certification Body for the GMEE program which can be found on the IECEE website [5].

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: 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: 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.

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Topmotors China: Improving Motor System Efficiency with Motor-Systems-Check in Zhenjiang

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Abstract

Electric motor systems consume 64% of China's total electricity. From June 2010 to May 2014, China has subsidized 33 GW of installed capacity of high efficient electric motors with 1.4 billion RMB in total. However, only replacing motors cannot improve system efficiency effectively. In 2013, China launched a three-year national Electric Motor Energy Efficiency Improvement Plan, aiming to deploy high efficient motors, eliminate inefficient motors and improve motor system efficiency.

In July 2014, the Topmotors China Zhenjiang Pilot Project was launched by Renergy Technology Consulting Beijing LLC (Top10 China), Impact Energy Inc. (Impact Energy) and Zhenjiang municipal government. It develops a "Second Generation" bottom-up training program for industry in order to introduce motor-systems-efficiency know-how and capacity for the factory staff. The goal is to empower the factories to improve systematically the energy efficiency of their rotating machines. A systematic methodology "Motor-Systems-Check" was introduced and trained in 19 pilot factories whose annual electricity consumption is higher than 20 GWh in Zhenjiang city in China.

In this paper, the barriers for energy efficiency improvements for Motor Systems in China are identified by factory survey. The Motor-Systems-Check methodology was introduced and implemented in three selected pilot factories, which have high electric energy savings potential and have shown the willingness to implement motor system projects. A motor system energy efficiency improvement plan on the Zhenjiang municipal level was developed, including the motor system audit with the Motor-Systems-Check, subsidy for advanced measurement instruments, a train-the-trainers program, as well as "Reward & Penalize" policies. Lessons learned from this pilot program in Zhenjiang are summarized.

Background

The stock of electric motor in China reached 2.1 TW in installed capacity in 2013. Electric motors consumed about 3,400 TWh electricity which accounted for 64% of the total electricity consumption in China. In the industrial sectors, electric motors consumed 2,900 TWh electricity which accounted for around 75% of industrial electricity consumption [1]. The Ministry of Industry and Information Technology of China (MIIT) launched a national program named “Electric motor energy efficiency improvement plan (2013-2015)” in 2013. This program stated that the average energy efficiency of electric motors in China is 3 to 5 percent lower than international advanced technology, and the average energy efficiency of electric motor system is 10 to 20 percent lower than advanced motor systems. 1 percent improvement of motor efficiency can save 26 TWh in industrial sectors. This plan set the goal of 3 to 5 percent general motor system efficiency improvement. The following actions were proposed: promote the deployment of high efficient electric motors; phase out the inefficient old electric motors; improve total motor systems efficiency; promote high efficient retrofitted motors; and promote research and development of high efficient motor technologies. Several programs have also been implemented with this general plan, including:

- National and corresponding local subsidy programs [2] for high efficient electric motors and affiliating driven equipment including pumps, ventilators and air compressors. From June 2010 to May 2014, the national program has subsidized 33 GW installed capacity of high efficient motors with 1.4 billion RMB in total [3]. The subsidy scheme applied on three kinds of motors is as below,

Table 1 China national subsidy program criteria

Motor type	Rated power (RP, kW)	Subsidy (RMB/kW)	
		Tier 1	Tier 2
Low-voltage three-phase asynchronous motor	0.55≤RP≤22	40	35
	22<RP≤315	20	15
High-voltage motor	355≤RP≤25000	12	12
Permanent magnet motor	0.55≤RP≤22	60	60
	22<RP≤315	40	40

- Phase out of inefficient old electric motors, which are classified as the J, Y, Y2 and Y3[1] series motors whose efficiency is lower than IE1. Three inefficient motor product lists are published [4]. Factories which are using listed products have to replace the listed motors to new motors with at least IE2 efficiency level.

Current policies focus on replacing old electric motors; but only replacing motors cannot improve system efficiency effectively. Huge electric energy savings potentials are not explored.

[1] China motor model naming standard: GB/T 10405-2009, Type design for electrical machine for automatic control system

Introduction of Topmotors Zhenjiang pilot project

Top10 China started to introduce the Topmotors methodology and EASY [5] incentive programs to MIIT from 2012. The Topmotors methodology adopts a system improvement approach to explore the full energy savings potential from electric motors, transmission, driven equipment and system integration. It promotes four standardized steps and corresponding tools to help factories to gain full savings potential of motor systems in a sustained approach. The EASY program (shown in figure 1) highlighted the subsidy for the knowledge and know-how spreading, which supports each steps in different proportion of cost. This is based on the experience that factories have little incentive to test and evaluate their rolling stock and the necessary engineering cost; they are only ready to invest in hardware like motor replacement. For a profound analysis of the best improvement plan of a motor system, the test of the existing system and the evaluation of the best improvement is a necessary prerequisite for a successful implementation.

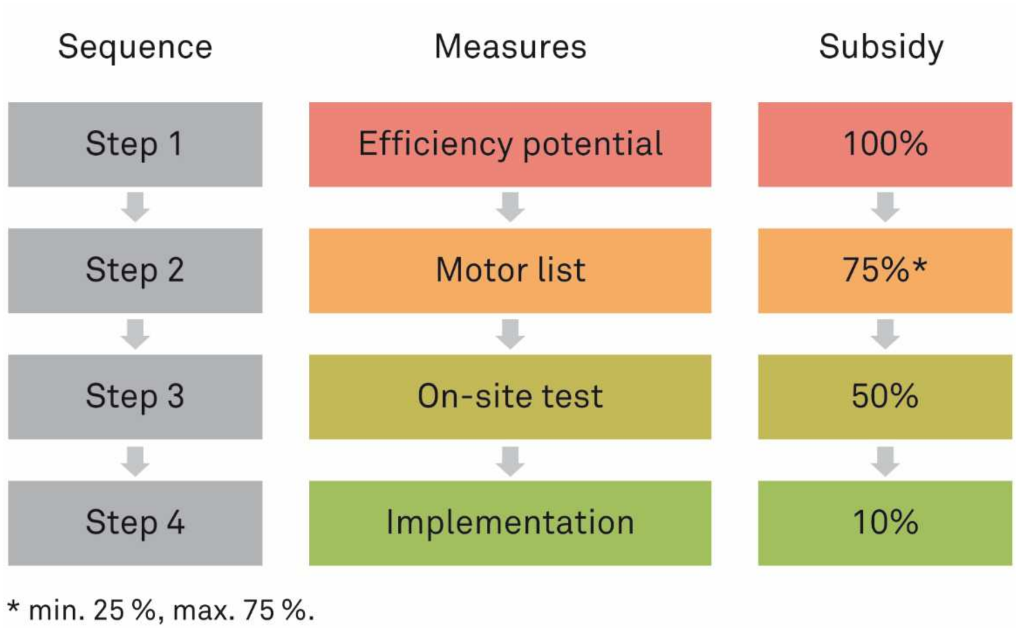

Figure 1 EASY method: four steps and respective subsidy

Topmotors methodology and EASY program fit the actions set in the national motor efficiency improvement plan. It is advised by policy makers to start a pilot project to demonstrate the effectiveness. Top10 China initiated a pilot project in Zhenjiang Economic and Technological Development Zone (ZETDZ). In July 2014, this pilot project was launched by Top10 China, Impact Energy and the Zhenjiang municipal government. It aims at developing and demonstrating a “Second Generation” bottom-up training program for industries in order to introduce motor-systems-efficiency know how and to build capacity for factory staff.

This project conducted the following activities:

- Pilot factory selection, including efficiency assessment of each factory's energy savings potential, survey and selection.
- Pilot factory training, including training of technical staff for motor system efficiency know-how, on-site testing and application of the Topmotors tools.

- Pilot motor system improvement plan development, including on-site motor system testing and development of an implementation plan.
- Implementation of pilot factory energy savings project, (voluntary).

This project is financed by ZETDZ and Top10 China. The subsidy for equipment replacement as well as for awarding energy savings after the implementation is not included.

Project activity 1: Pilot factory selection

There are more than 100 factories in ZETDZ. 3 pilot factories were selected for this pilot project to conduct the following project activities. The pilot factories should have energy savings potential and interests to be involved in project activities. Both a survey and a factory visit were conducted to select the pilot factories. Most of the factories from ZETDZ were invited to take part in the project launch event in July 2014. The survey was conducted with a questionnaire during the event to determine the interests of the factories. A factory list with the 2012 annual electricity consumption was also provided to the project team by the local government. 13 factories located in ZETDZ were chosen to do the first round of the motor system energy efficiency potential assessment. 6 more factories out of ZETDZ were chosen to conduct the second round of the efficiency potential assessment.

After two rounds of efficiency potential assessment and factory visits, the project team established an overview of the electric motor energy consumption, motor efficiency and improvement potential. They also gained an impression about the capacity of the management and the technical knowledge of the factory staff.

SOTEA (Software Tool für effiziente Antriebe" – software tool for efficient motor systems) [5] is a tool for the assessment of the energy savings potential developed by Topmotors Switzerland. The motor age is one of the most important parameters to assess the eventual payback of the energy savings potential. As most of the visited factories were built within the last 15 years, SOTEA was not applied directly to calculate the energy savings potential. The project team developed a new questionnaire for assessing the energy savings potential. It includes the general questions about the electricity consumption, numbers of installed electric motors by size and type, electricity price and application of variable frequency drives (VFD), etc. The questionnaire was sent to the factories two weeks in advance. At least two staff – one energy manager and one motor engineer were asked to take part in the meeting. After the meeting, the project team made a one-hour walk through on-site visit to get a general impression of the facilities and its energy savings potential.

A standard assessment program was followed to collect data and related information by questionnaire, discussion and on-site visiting.
The 19 factories have the following general profile:

- Industries include: chemical, iron and steel, cement, paper and pulp, new energy (solar), mining and construction material. Chemical factories have the biggest share of all factories.
- Ownership includes: state-owned, foreign and private enterprises.

The average establishment year of the factories is around 2001, because ZETDZ was setup in the late 1990s. This means, the average age of electric motors is less than 15 years, although some motors are listed in types for phase-out categories.

The surveyed factories consume a significant amount of electricity. The highest annual electricity consumption of one single factory reached 1.8 TWh and the average electricity consumption reached 57 GWh. The 19 factories consumed in total 4.77 TWh in 2012 which accounted for 31.2% of total industrial electricity consumption in Zhenjiang city.

Electric motors are the main driven equipment of all factories. Except one chemical factory whose electricity is mainly consumed by an electrolysis process and one new energy factory whose electricity is mainly used for electric heating processes, electric motors use around 85% of the total factory electricity consumption. The biggest consumption share of motors in a factory was, as stated by energy manager, 99% of the factory electricity, mainly used for pumps, fans and air compressors.

Table 2 Summary of factory survey

	Unit	**Average**	**Sum**	**Min**	**Max**	**Data available factory number***
Establishment year		2001		1963	2011	12
Annual turnover	M RMB/a	2559	29559	200	14000	11
Staff number		743	9461	108	1500	12
Annual electricity consumption	GWh/a	240	4769	26	1823	19
Annual electricity cost	M RMB/a	335	6683	20	3850	19
Grid electricity price	RMB/kWh	0.71		0.32	0.80	19
Own electricity generation	GWh/a	57.0	1140.3	0.0	700.8	19
Average electricity price	RMB/kWh	0.68		0.40	0.80	19
Motor electricity consumption	GWh/a	298.4	5668.8	8.8	1650.0	18
Installed motor output power	MW	134.5	1745.1	1.0	1069.4	12
Annual motor operation hours	h/a	5624		2250	8760	18
Number of motors		1845	27668	20	12075	14
Number of S&M motors (< 50 kW)		1656	24835	15	10500	14
Number of big		189	2831	5	1575	14

motors (>= 50 kW)						
Average power of S&M motors	kW	26.9		7.7	60.0	7
Average power of big motors	kW	1104		106	6000	10
Rate of VFD application	%	3.47		0.05	24.44	12
Loading factor		0.825		0.6	0.95	4

* Not all the factories can provide full and precise data. This data availability number can imply the level of factories' energy management.

In Zhenjiang, the industrial electricity price from the grid is different in peak, flat and valley hours during the day. Peak, flat and valley time has the same duration which is 8 hours every day. The peak time electricity price is 1.112 RMB/kWh, the flat time electricity price is 0.667 RMB/kWh and the valley time electricity price is 0.322 RMB/kWh [6]. The average electricity price for a 24*7 production factory is about 0.70 ~ 0.75 RMB/kWh. Some non 24*7 production factories produce in valley hours to reduce energy cost.

Few factories build their own power generation facility from coal or recycled energy. The electricity cost from their own power generation is much lower than the grid electricity price. In one factory, its own power generation capacity can cover its full production needs. Own generated power covers peak and flat hours, and grid electricity is applied in valley hours. So the average price of this factory is lower than 0.5 RMB/kWh. The low energy price is lowering the interest of energy savings in this factory.

Each factory which was able to count the number of installed motors has more than 1,800 motors on average. The highest number of motors in one single factory was more than 12,000. Small and medium motors, whose output power is below 50 kW, takes around 90% share of the total number of motors, while big motors took around 10% of all. Factories often focus on the 10% large motors regarding operation hours, maintenance and sometimes energy saving. However, most factories cannot give detailed data of the energy consumption of small and big motors.

Although VFDs have been proved its effectiveness in saving energy, the penetration rate of VFDs is still very low. The average equipped application rate is below 4%. During on-site visiting, it was found that a lot of installed VFDs are not properly used and maintained. Some VFDs have no frequency adjustment regulation and frequency is adjusted manually by operation engineers. In some extreme cases, regulation sensors are out of function and VFDs are operated at 50 Hz all the time. Valves and dampers are still the most common ways to adjust pressure and flow.

The availability of load factor data is quite poor as most engineers of all factories have no idea of the correlation between load factor and motor efficiency. In daily operation and maintenance, engineers check the current from ampere meters from the motor electric box to ensure the operation current is below the rated current for safety. Most of them did not use power meters to test the motor load factor. Some factories have documents about motor operation and maintenance. It records the current motor values and often shows that a lot of motors are running at low load factor.

For transmission, V-belts are widely used, especially in fan systems.

Findings and problems from factory survey

After the data collection and in-depth discussion with the managers and engineers from factories, a lot of factory-specific and common problems have been identified.

- Factories have no systematic and long-term planning in motor system energy savings. The internal motivation of energy saving is still quite low. There are some implemented energy savings projects. However, those are isolated projects identified by external energy service companies, which explored only a small proportion of the total energy savings potential.
- The internal motivation of conducting energy savings projects is low mainly due to the following two reasons: running risks and lacking of incentives. In all factories, it was frequently stated: ensuring production is the first priority. Nobody would like to put production at risk. On the other side, the incentives for doing energy savings projects are not enough. The managers or engineers who promote energy savings projects do not get enough financial incentives for their projects. It is common for the design capacity of the motor system to be oversized for normal production. Most maintenance engineers know this fact, but they have no idea about how much it is oversized and how to find the proper system outputs. Keeping the existing design is the most common choice. In factories, the phasing out of old inefficient motor is just to replace it by a new, more efficient motor with the same output power size. Because the new motor has the same dimensions and frame size like the old one, it is a one to one replacement without any risk for the process. Due to the use of a more efficient motor, "theoretical" energy savings were tapped.
- Factories lack electric motor systems energy savings knowledge and experience: factories have a lot of experienced experts in producing their products, but they have limited managing and engineering capacity in energy savings of electric motor system. Senior management has only low awareness of the energy savings potential of the motor systems. Middle management has no ideas in how to manage motor system energy savings projects, how to convince the higher management to invest in motor system energy savings projects and also low awareness of the size of the motor systems energy savings potential. Engineers lack the required knowledge and experience, they receive only little or no management support for motor systems energy savings projects. Because of the internal absence of expertise and knowledge external energy service companies have to provide energy savings plans. Internal experts who can run and support such programs are missing which often leads to a failure of the projects. Unsuccessful projects reduced confidence and credibility on both sides.
- Many factories have high expectation in high and new technologies to solve all the problems once for all. The most frequent question asked by factory managers is what new technology or equipment you can provide from the pilot project. This question might imply

that factories have strong faith in machines. However, a lot of cases from factories have proven that only new technology and machines without systematic thinking and integration and proper operation cannot save energy.

- Factories also have high expectations in energy service companies to solve the major problems. There are more than 3400 registered energy service companies in China[2], but most of them are small and medium enterprises, which means that they have limited technology fields and capacity. And energy performance contracting dominates energy savings projects in China, which implies that energy service companies naturally prefer big power motors. Under the same energy savings rate and to reach the same total energy savings, by installing VFDs for example, the cost of engineering and work on one 500 kW big motor is much lower than ten 50 kW motors. So, the first question from energy service company manager was how many big motors the factory has. Energy service companies have low interests in small and medium motors. However, small and medium motors are widely deployed in factories and consume a significant share of electricity. Considering business, energy service companies have no knowledge and no obligation and interest to teach the factories how to save energy after a project.

- The energy service market is not well developed and regulated. China's energy service market grew fast in recent years, but this is also an underdeveloped market. Factories and energy service companies have a lot of problems in project consulting, implementation, inspection, auditing and contracting. The credibility and reputation of both sides are not good enough. Some factories frankly stated that they do not trust energy service companies. Even the project team was not welcomed by some factories.

- Electric motor systems are separately managed by different departments in factories. And coordination between equipment maintenance and product operation is quite poor. Normally, the equipment maintenance and production operation are independent departments. The first priority of the maintenance equipment is to ensure all the equipment can perform its function safely. The operation department decides how much liquid and air flow is needed for the production. The implementation of energy savings potential relies on scientific and proper operation, but the maintenance department has no right to ask the operation department to change the existing routines. And, the operation department has only low motivation to make changes, which might increase the risk of failure in production. A lot of cases were observed that new equipment is under poor operation and runs at low efficiency.

- As mentioned above, energy performance contracting dominates the energy service market. Energy service companies have to do consulting and implementation. Factories do not pay for consulting service. Without project implementation, consulting and engineering cost cannot be covered. Energy service companies have to recover consulting cost from project implementation especially from equipment, which leads the over-equipping of unnecessary devices.

[2] Full list available at: http://regist.cecol.com.cn/

The findings and problems identified from factory survey have been reported to central and local policy makers.

Project activity 2: Pilot factory training

3 pilot factories were selected by the following criteria:

- high energy saving potential
- high willingness and interests of management in motor system energy saving
- scheduled plans of motor system improvement projects.

The training of managers and engineers were conducted in September 2014 in the factories and included the following topics:

- motor system energy saving basics
- how to measure the electric input of motor systems,
- how to interpret and analyze the testing results,
- how to use ILI+ (Intelligent Motor List) [5] to do motor list. ILI+ calculates the motor system energy savings potential, identifies the highest energy saving potential systems from all motor systems and helps to implement a motor systems energy savings project in a continuous way.

Managers and engineers from pilot factories showed strong interests in testing, motor system efficiency assessment and energy savings potential and cost-effective calculation. One factory purchased testing equipment after the training and integrated testing into maintenance routine.

On 2nd September 2014, a training workshop was held for all visited factories. The efficiency fact of motor system, basic and simple motor system efficiency assessment methods and the Topmotors methodology were presented to all participants. ILI+ was disseminated to all participants. It was demonstrated and practiced with all participants. The concept of conducting motor system energy savings projects in a systematic and continuous way was highlighted.

One chemical factory has the plan to replace two old inefficient motors. They were planned to be replaced in the traditional way: same size out and same size in. After the training, the manager realized that the traditional replacing method might not save energy due to the slightly faster rotating speed of new motors. The project team was invited to do on-site testing and propose a full motor system energy saving plan.

Project activity 3: Factory on site testing and implementation plan development

In Jan 2015, the project team conducted on-site testing for pilot factories' pump systems. Not only electric inputs but also liquid outputs were measured by motor and pump experts. The process of testing, energy savings potential calculation and cost-effective analysis were presented to factory managers and engineers. The project team also demonstrated how to use testing result to make a full standard testing report. The standard testing report tool (STR) from

Topmotors Switzerland was localized and given to pilot factories. STR integrates testing results, current system efficiency calculation, improving measures and corresponding cost and improved system efficiency calculation.

Case: Pump system efficiency improvement plan development

This is a circulating cooling system from a chemical factory shown in figure 2. Four same size motors and pumps provide circulating water for one cooling tower. When two pump system are operating, the other two are in standby. Two systems share the same operating hours of one year, which is estimated at 4400 hours each.

Figure 2 Circulating cooling pump system of pilot chemical factory

The electric motor was manufactured in 2006 and has a rated output power of 200 kW shown in figure 3. There is no efficiency information on the nameplate. The rated pump flow is 1000 m^3/h, but there is no information available of rated power and efficiency on the pump nameplate.

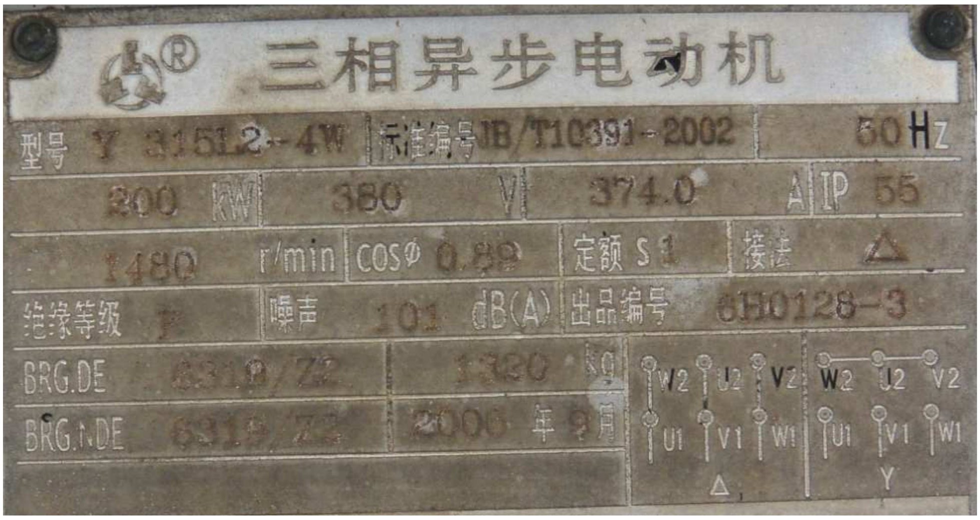

Figure 3 Nameplate of electric motor

Both, the electric inputs of motor and pumps output flow, were measured. The flow pressure was sampled from pressure meters on the pipes.

The testing result of electric motor is shown in figure 4. This motor runs stable during testing period. The average testing input power is 185.0 kW and the load factor is 84.5%. Engineers from factory stated that input current stays stable during the operation for all four seasons.

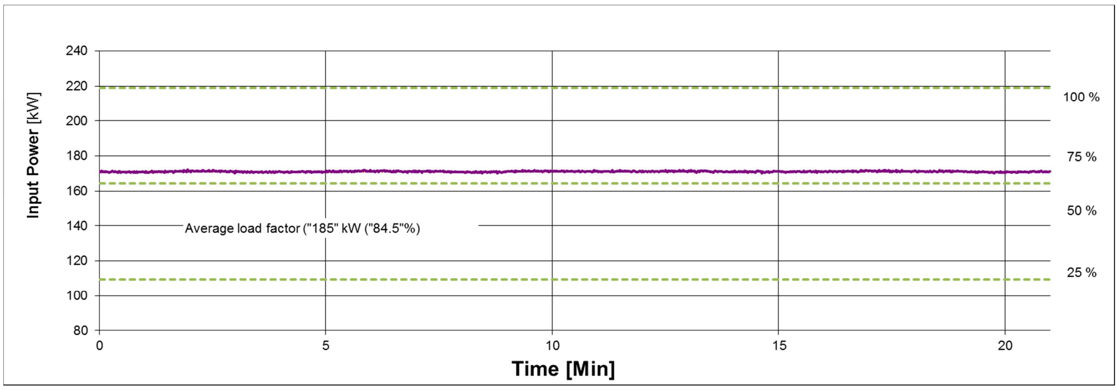

Figure 4 Input power test results

The tested flow of one pump is 1050m^3/h. The inlet valve of the pump is 100% open, but the outlet valve is only 25% open. The pump outlet pressure before the outlet valve is 0.50 MPa, but the system main pipe pressure is 0.345 MPa. Factory engineers have figured out the system flow differences among seasons: summer 2600 m3/h, spring & autumn 2200 m3/h and winter 1800m3/h. The flow and pressure of each season are quite stable.

Efficiency analysis:

Motor: According to its rated voltage (380 V), current (374 A) and power factor (0.89), the calculated rated input power is 219.1 kW and its efficiency is about 91.3%, which is below the requirement of IE1. The load factor of the system is about 84.5%, which indicates the motor runs very close to its rated efficiency - 91.3%.

Pump: No pump efficiency information can be found from the nameplate. According to the rated flow of 1000 m3/h and difference season's operating flow, the pump runs at the right section of Best Efficiency Point (BEP) in the summer and runs close to its BEP area in the other 3 seasons. The real problem is that it uses a throttling method to control the flow. The pressure difference before and after pump outlet valve reaches 0.055 MPa. A lot of energy is wasted at this valve. The pump system efficiency is estimated at 57% in winter by the pump expert.

System optimization measures:

Measure A: replace the inefficient motor with an IE3 smaller size motor. The old motor should be resized according to its loading factor. However, it is not recommended only to replace the motors, as the IE3 motor's rotating speed is slightly faster than the old motor, which might lead to unneeded extra output flow. By replacing the motor, about 4% efficiency can be improved.

Measure B: replace the pump with a load-specified high efficient pump. The new pump cuts the head and maintains the maximum flow requirement of summer time. By replacing the pump, about 8% efficiency can be improved.

Measure C: install a VFD. The flow requirements of difference seasons have been figured out and the difference is quite big. Two options for VFD: one VFD to control two motors or two VFDs to control two motors independently.

The following energy efficiency improvement plan was provided to factory:

Table 3 Cost effective analysis results of different plans

Improvement plan	Measures	Electric energy saving（%）	Annual energy saving （kWh）	Annual cost saving （RMB）	Invest-ment （RMB）	Pay-back time（a）
1	B	8.5%	261,576	196,182	320,000	1.63
2	A+B+C one VFD for two motors	22.5%	622,278	466,709	780,000	1.67
3	A+B+C indepen-dent VFDs	22.5%	622,278	466,709	920,000	1.97

One **additional recommendation** is made:

Not all the motors and pumps need to be replaced. Because currently four pumping systems share same load time for one year, the majority work can be shifted to the retrofitted systems.

Active Policy Improvement in Zhenjiang

The concept of Motor-Systems-Check and motor system optimization was well received by the local stakeholders including local factories, Zhenjiang municipal government, and industrial park administrative committee as well as monitoring agencies like Zhenjiang Energy Conservation Supervision Center. During the implementation of this pilot project, Zhenjiang has made an official '2015-2016 motor system efficiency improvement plan', and will carry out above activities regularly and scale up the pilots to top 50 electricity-intensive motor users in the next one and half years.

A multi-stakeholder cooperation model was created in Zhenjiang that government, industry, third-party and service providers (manufactures, ESCOs, banks etc.) work together to invest technical know-how and fund, so that risks and benefits will be shared. To ensure the enforcement of the policy implementation, monitoring activities will be conducted to evaluate the effectiveness of implementation, factories who reach 500,000 kWh of electricity savings will be awarded and those who didn't phase out in-efficient motors on time will be punished by applying increased industrial electricity price. This new model is tested in Zhenjiang and expected to be expanded to Jiangsu province and China in future.

Conclusion

Although the implementation of the pilot project is still under way, the experiences from the factory survey, the training, the workshop and the testing campaign can reach the following conclusions.

There is large energy savings potential in factories, because most motors' efficiency is below IE2. The efficiency of drive equipment such as pumps, fans and air compressors is also low. Throttling is widely used to control flow and the penetration rate of VSD is still quite low. However, the large savings potential cannot be simply tapped by replacing the old equipment to new ones and install new devices. Scientific and proper management and operation is the key to implement savings potential from daily production.

Training for factory managers and engineers is needed and welcomed. The topics and depth of training should be considered separately for different target groups. Managers need to be trained to explore and manage motor system energy savings projects in systematic and continuous way. Engineers need be trained by practical and operable skills and knowledge, which they can apply to daily work in a short time. The following results of training should be reached: managers and engineers can roughly assess motor system efficiency, identify savings potential, set project implementation priorities and evaluate retrofit plans from energy service companies.

Standardized tools are needed. They can shorten the distance between theoretical knowledge and practical daily work. However, factories have no interest and capacity in developing factory specified document templates and tools. With the standards tool such as ILI+ and STR, factory managers and engineers can start to assess motor systems efficiency. However, some factories are unwilling or do not have the capacity to implement small improvements.

Government agencies could play a stronger roles in such motor system energy efficiency fields. Normally, punishment and incentive are the two most powerful policy tools to push and pull the factories in energy savings. In most cases, government agencies do not pay attention to how the factories reach energy savings goals. In this project, government agencies play a stronger role in the process of energy savings by providing financial support for third-party technical institutes and help to coordinate factory participation. In the factory survey, one government officer joined the project team to open the factory gate. Without the government coordination, the project team could not easily get access to visit 19 big factories.

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Efficiency information requirements and manufacturers approach towards new standards

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Abstract

Energy efficiency requirements exist and are appearing for various types of equipment in the industrial arena, too. In the first wave there were domestic goods and after that fans and pumps have received their efficiency standards. Electrical motors and variable speed drives and systems where those are used will be the next step. At the moment the efficiency class, IE class, has to be informed for electrical motors. EN50598 standard defines a similar IE classification for variable speed drives and also the IES classes for the PDS (Power Drive System), which include a Basic Drive Module (BDM) and a motor.

The existing standard EN60034-30-1 for direct-on-line motors defines that the efficiency has to be informed at three points (at 50%, at 75% and at 100% of load) but in the future more data is needed for motors, which are used with VSDs. The new EN50598 standard defines 8 operational points (speed & torque) for CDM (Complete Drive Module), for which VSD manufacturers have to inform the losses. The same operational points are also needed for the PDS (Power Drive System) meaning the losses of motor and VSD together. [4]

Therefore also the motor manufacturers are in a new position when the implementation measures are issued from the EU Commission for products systems and extended products for compliance to the Ecodesign (ErP) and Energy Labeling Directives and those are followed according to extended product approach. [5] [6]

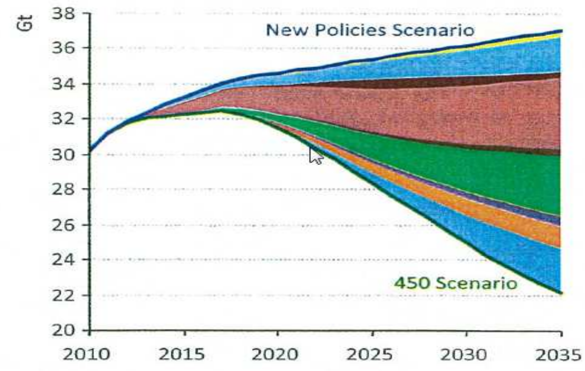
The extended product approach is a methodology to determine the energy efficiency index (EEI) of the extended product (EP) using the speed torque profiles of the driven equipment, the relative power losses of the motor system and the load-time profile of the application. For example it means VSD + motor + the running equipment in the upcoming standards values of losses and efficiency classifications for that kind of packages will be required.

1. Introduction

The global economy's growth leads to a steadily expanding demand for energy. Today most of the energy for industry, transportation and household needs is produced by fossils fuels. This also means an increase in CO_2 emissions, resulting in climate change. For securing the future of our planet, it is therefore of vital importance to reduce the causes of climate change and to prevent any further rise in energy consumption sustainably.

There are various policies and scenarios on how the CO_2 emissions should be reduced in the future and also which are the best ways to accomplish the reduction. There are several climate change mitigation scenarios and IEA (International Energy Association) published in their year 2008 report the 450 target; meaning that 450 (ppm) is the maximum upper limit of carbon dioxide in the atmosphere. [1] [2] [3]

All the calculations and estimations show that better use of existing energy is the fastest and cheapest way to act. (Figure 1)



CO_2 abatement	2020	2035
Activity	2%	2%
End-use efficiency	18%	13%
Power plant efficiency	3%	2%
Electricity savings	50%	27%
Fuel and technology switching in end-uses	2%	3%
Renewables	15%	23%
Biofuels	2%	4%
Nuclear	5%	8%
CCS	4%	17%
Total (Gt CO_2)	3.1	15.0

Figure 1. World energy-related CO_2 savings potential by policy measure under 450 Scenario relative to New Policies Scenario

This paper focuses on electrical energy and mainly what is used in the industry by electrical motors and variable speed drives. The development of electricity pricing will have a significant effect on the costs and competitiveness for all electricity users. That is why lowering the level of energy consumption and correspondingly the energy costs will become more and more important in the future.

Besides the obligatory requirements, foremostly economic reasons push forward the optimisation of drive systems by means of electronic speed control. Given the high potential savings in energy (up to 50 per cent), an analysis of the lifecycle costs does always pay off.

2. Agreements for energy efficiency actions

In December 2008, for example, the European Union (EU) agreed on a package of directives and targets for climate and energy, which lays down ambitious goals. Up to the year 2020, the following Europe-wide requirements will apply, which are often also referred to as '20-20-20 targets':
20 per cent less greenhouse gas emissions than in 2005
20 per cent proportion of renewable energies
20 per cent more energy-efficiency

In January 2014, the European Commission presented its road map for the EU's energy and climate policies up to the year 2030. Here, the suggestion goes even further and proposes a binding CO_2 reduction target of 40 per cent compared to the year 1990.

3. Energy efficiency standards and requirements

3.1. Global regulations

Based on global agreements, there are various standards and guidelines that lay down the requirements for an eco-friendly design for all kinds of motor driven equipment. In industrial environment the first step was the standards for electric motors. The standard is explained in more detail in section 4.1.

There are lots of regional and local requirements for the needed minimum efficiency of motors. The most common way of informing the needed level is MEPS; Minimum Energy Performance Standards. The content and efficiency classes and levels vary region by region and new and higher efficiency level requirements appear every year. [8]

The maps presented in the section 3.1.shed some light on the situation now and what is expected for the near future.

The following drawings provide an overview of the present and future regulations for low voltage AC motors.

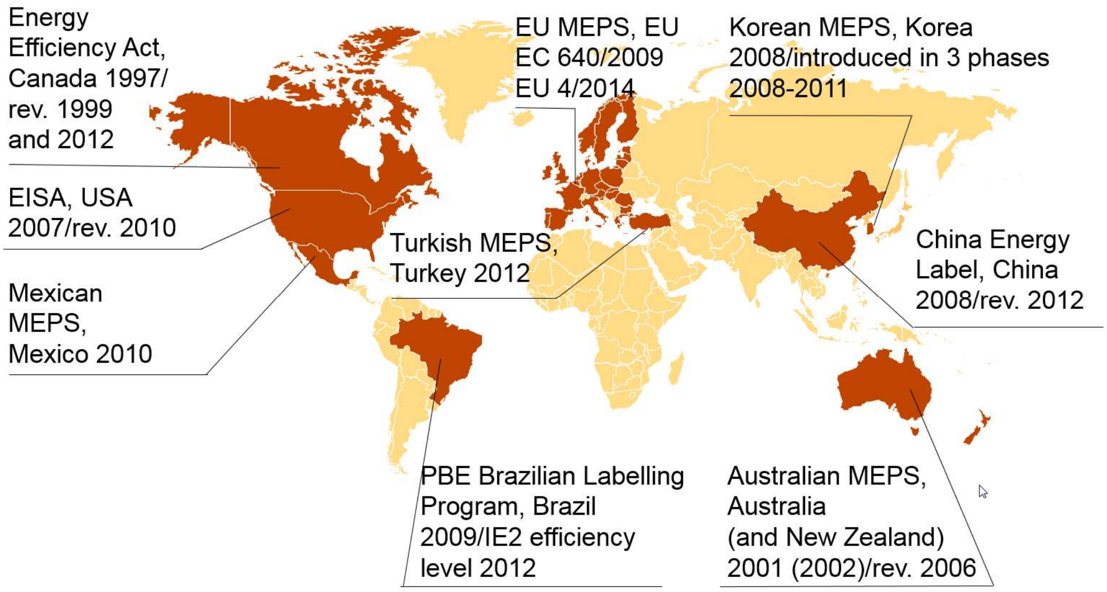


Figure 2. Existing MEPS and other efficiency regulations globally (by end of 2014).

There is ongoing work for regional and local energy efficiency regulations and requirements all over the world. The levels and included motor types vary a lot. Moreover there are indicators that new requirements will also be applied for medium and high voltage motors – and most probably after the new EN50598 standard some kind of MEPS will affect variable speed drives, too.

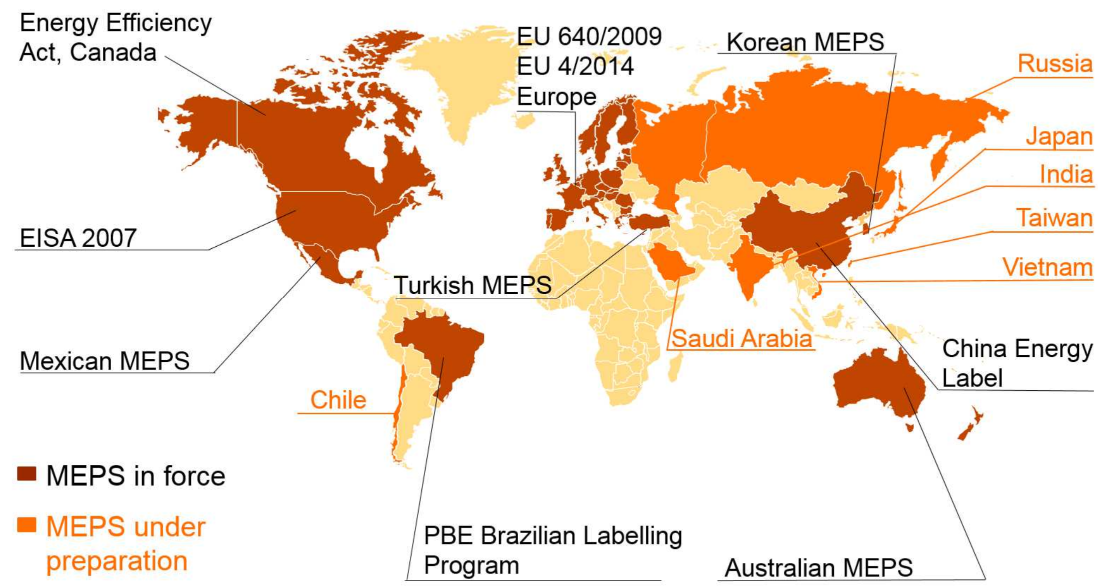


Figure 3. Known MEPS under preparation (in beginning of 2015).

3.2. Energy efficiency regulation procedure

There are different kinds of standards and regulations for energy efficiency. The development for those varies a lot, but let's take again the European Union as an example. The Energy-Using Products (EuP) Directive (2005/32/EC) from July 2005 lays down the requirements for eco-friendly design of power-operated products. In October 2009 a revised version of this directive went into effect, and the EuP Directive became the Energy-Related Products (ErP) Directive (2009/125/EC). [6] [7]

The ErP Directive extends the requirements to cover the eco-friendly design of products relevant to energy consumption, but in other parts it remains unchanged. As a framework directive, however, it is used only for those products for which there is what is called an ‘implementing measure’ with product-specific requirements. For three-phase asynchronous motors, this is the case with the Regulation (EC) 640/2009 and the amending Regulation (EC) 4/2014. [9] [10]

3.3. Time schedule for implementation

Since the 1st of January 2015, motors placed for the first-time on the market with a nominal output power from 7.5 to 375 kW must either reach at least Efficiency Class IE3 or conform to Efficiency Class IE2, but shall then be operated / equipped only with an electronic speed control. Motors with a nominal output power from 0.75 to 7.5 kW placed for the first-time on the market must reach at least Efficiency Class IE2. As from the beginning of 2017, the following regulation will apply: motors placed for the first-time on the market with a nominal output power from 0.75 to 375 kW must either reach at least Efficiency Class IE3 or conform to Efficiency Class IE2, but shall then be operated only with an electronic speed control. [9]

The individual requirements come into force in accordance with the following time schedule (Figure 4).

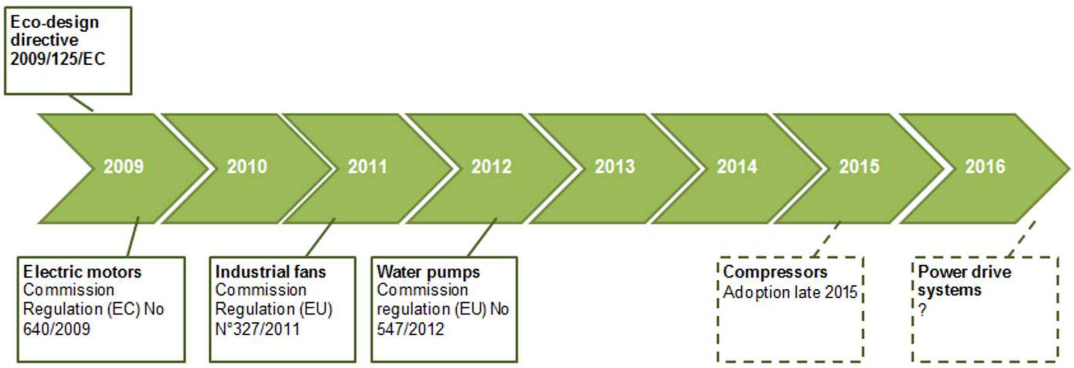


Figure 4. Timeline for various EU Commission Regulations

It should be determined by the operator or planner of the system, which solution is the most energy-efficient because it depends on the application involved. With full-load applications, a direct-on-line motor minimum IE3 class should be selected, while with variable load systems speed control with a variable speed drive can produce substantial savings. Electronic speed control is attained using a variable speed drive, which adjusts the motor’s speed, and therefore the power produced, based on the energy needed.

4. Standards and definitions for the equipment

The new European standard called EN 50598 provides calculation and measurement methods for determination of the "Relative Power Losses = PL" of a CDM or PDS. These "PL" are the per unit losses relative to the nominal power of the CDM / PDS.

The European standard EN 50598 consists of three parts.

Part 1 Refering to the first sentence of its Scope, The European Standard EN 50598-1 provides a general methodology to energy efficiency standardization for any extended product including a motor system by using the methodological guidance of the extended product approach (EPA).

Part 2 In this part energy-efficiency indicators are specified for power drive systems, motor starters and power electronics (e.g. variable speed drive = Complete Drive Module (CDM)) used in an electrically driven work machine in the power range of 0.12 kW up to 1000 kW and losses and efficiency classes are defined:

- Definition of efficiency classes for motor systems and variable speed drives
- Definition of 8 operating points

- Methods for determination (measurement and calculation) of losses at the 8 operating points of a complete motor system and its components
- Measurement methods for variable speed drives
- Losses of the reference motor, the reference CDM and the reference PDS at the predefined 8 operating points

As it was pointed out in section 2, the energy-efficiency of a drive system is significantly more crucial than the sum of the efficiencies of individual components.

Part 3 It is in process within the Cenelec TC 2 Working Group 2. The scope of this CLC/TC 2/WG 2 is "Quantitative eco design approach through life cycle assessment including product category rules and the content of environmental declarations including end of life information". We are still waiting for this standard to be issued.

The standard EN 50598 gives definitions and names for the equipment combinations in a motor driven system. An extended product is the basis for the whole set-up and it should guide and help the driven equipment manufacturers to deliver correct values of the losses in the system. The definitions can be seen from the figure 5. [4]

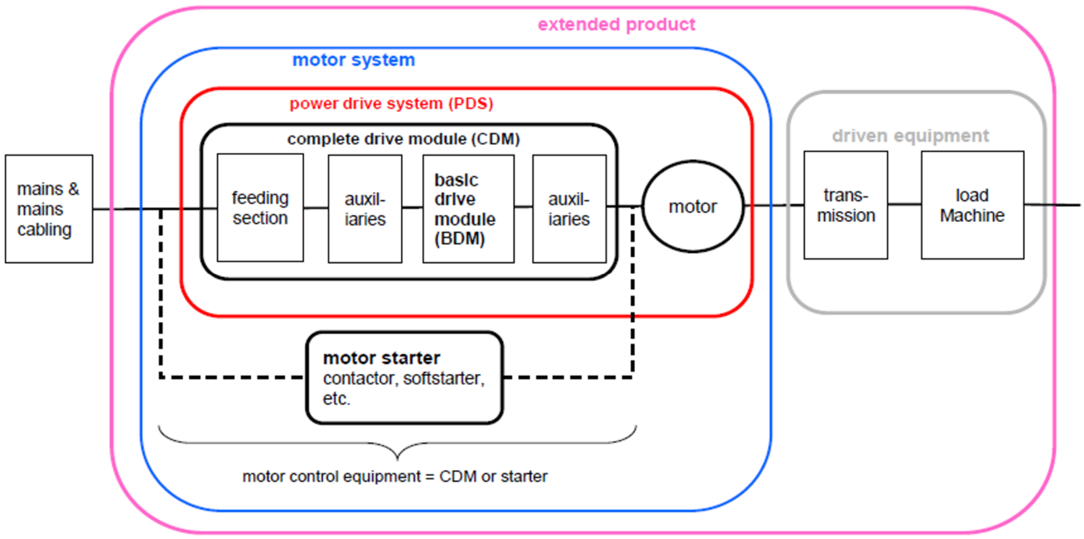


Figure 5. Scope for definitions in the EN50598 standard.

4.1. Low voltage AC motor efficiency standards

For electrical motors there are several standards for efficiency requirements. Globally there is the IEC60034-30-X standard for rotating electrical machines. Part 30-1 is called Efficiency classes of line operated AC motors (IE code) and it is already valid and used as the basis for MEPS all around the world. The next phase will be the IEC60034-30-2, which defines the efficiency classes for AC motors fed from electronic converters and the work for that standard has already started. [11]

4.1.1 Ongoing standardization

Standards are used by voluntary agreement and become legally binding when those are included in regulations and/or laws ~~and~~/or business agreements. The international standard IEC 60034-30, in effect since October 2008, defines the Efficiency Classes (IE Code) for low-voltage line operated motors:
IE1 (standard efficiency)
IE2 (high efficiency)
IE3 (premium efficiency)

Now the IEC 60034-30 standard will be divided into two parts:
Part 1 Efficiency classes of line operated AC motors (IE code)
Part 2: Efficiency classes of variable speed AC motors (IE-code)

The scope of the IEC 60034-30 standard, Part 1 Line-Operated Motors, has been extended in comparison to IEC 60034-30 and was published in March 2014 (Fig. 6) . [4} [11]

Line fed motors Efficiency	Converter fed motors Efficiency	Converters (CDM) losses related to rated power	Power Drive systems (PDS) losses related to rated power
IE0 – not used	IE0 – u.c.	IE0 – more than 25% higher than reference value	IES0 – more than 20% higher than reference value
IE1 – can be mostly technically achieved	IE1 – u.c.	IE1 - reference value ±25%	IES1 - reference value ±20%
IE2 – can be achieved by enhancement	IE2 – u.c.	IE2 – more than 25% lower than reference value	IES2 – more than 20% lower than reference value
IE3 – needs significant amount of techniques	IE3 – u.c.	IE3 – u.c.	IES3 – u.c.
IE4 – will require new techniques	IE4 – u.c.	IE4 – u.c	IES4 – u.c
IE5 – experimental new technologies	IE5 – u.c.	IE5 – u.c	IES5 – u.c
IE6 – not used	IE6 – u.c.	IE6 – u.c	IES6 – u.c
IE7 – not used	IE7 – u.c.	IE7 – u.c.	IES7 – u.c.
IE8 – not used	IE8 – u.c.	IE8 – u.c.	IES8 – u.c.
IE9 – not used	IE9 – u.c.	IE9 – u.c.	IES9 – u.c.

Figure 6. Development for energy efficiency classification for various products

The IE2 motors in the European Union markets have to bear a label or sticker about the need of a variable speed drive as shown in the figure 7. [9] [10]

Figure 7. Information plate required for the IE2 AC motors in the European Union.

4.2. Standard for low voltage AC Complete Drive Module

In the standard EN50598-2 the efficiency classes for variable speed drives are defined for the first time. For AC motors the efficiency class (IE class) is defined according to the efficiency rating of the motor at (100,100) operating point meaning 100% of the speed and 100% of the torque of the nominal point. For the variable speed drive the point where the IE class is defined is (90,100) meaning 90% of nominal speed and 100% of frequency of the nominal point. Moreover for the variable speed drive the actual losses (in watts) are used for the valuation, unlike the efficiency rating like in the motors case.

In addition to the IE classification the EN50598-2 standard also requires information of the losses of the drive at 8 operation points. Those points are defined to help the end users and driven equipment (pumps, fans etc.) manufacturers to define an extended product Energy Efficiency Index (EEI) value for the whole system.

The figures 8a and 8b show the 8 operating points where the losses of RCDM (Reference Complete Drive Module) have to be informed. The point (90,100) (90% of nominal frequency & 100% of nominal current) is the point where the IE class for the CDM (Complete Drive Module) is defined.

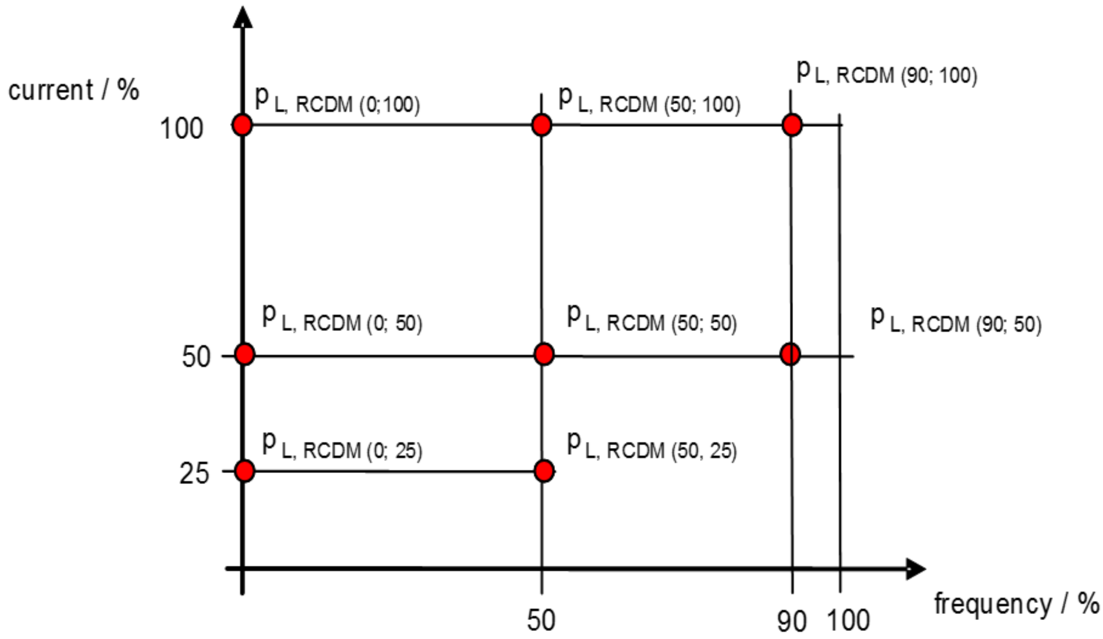


Figure 8a. Operating points where the losses have to be given for RCDM (Reference Complete Drive Module)

4.3. Standards for the low voltage power drive system

The efficiency classes for electric drive systems are defined for 100% torque and 100% motor speed. It's important to notice the difference of the definition point between CDM (Complete Drive Module) where the point is 90% frequency and 100% current compared to PDS (Power Drive System) where the definition point is 100 % speed and 100% Torque. The definition points for RPDM (Reference Power Drive System) are shown in Pic 8b.

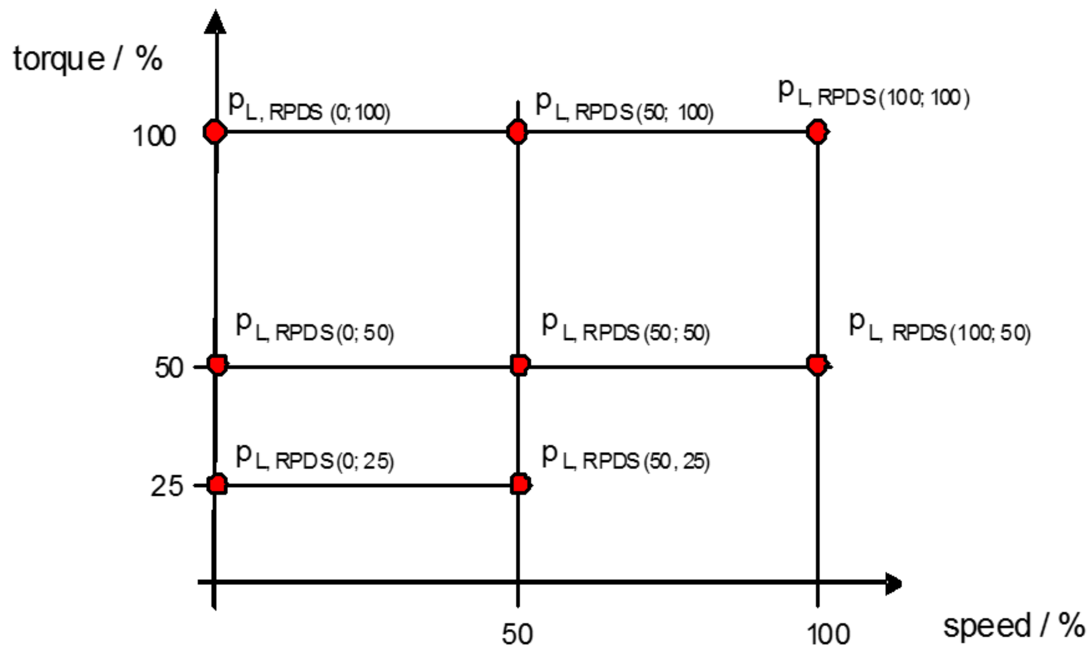


Figure 8b. Operating points where the losses have to be given for RPDS (Reference Power Drive System)

5. Efficiency classes

5.1. Efficiency classes of electric drive systems (motor systems)

The standard EN 50598-2 defines the relative losses of the electric drive system for efficiency classes IES0 to IES2. Compared to an IES1-system (reference PDS) the IES2 system has 20% less and the IES0 20% more losses (Figure 9).

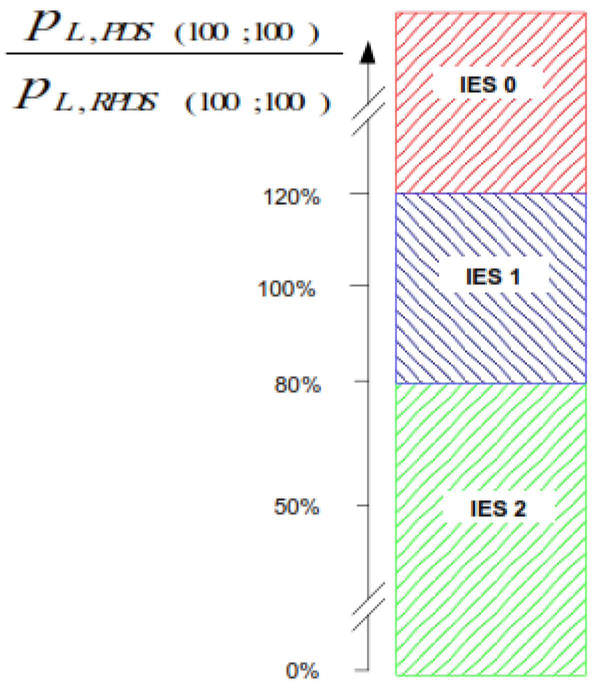


Figure 9. Illustration of IES classes for a PDS (Power Drive System)

The addition of efficiency classes is not possible, as an IE2 variable speed drive and an IE2 motor do not automatically result in a complete IES2 system. Higher ordinal numbers in IE class in general mean reduced losses. Thus, an IE2 motor and an IE2 CDM do not necessarily translate into an IES2 class combination. Moreover, an IE1 motor and IE1 CDM combination certainly do not belong to IES2 class.

5.3. Efficiency classes of variable speed drives

In order to not consider possible operation in overmodulation condition and for reasons of comparability the efficiency classes of variable speed drives are defined for the 90/100 operating point (100% current / 90% motor frequency). The standard EN 50598-2 defines the relative losses (in relation to the nominal output power) of variable speed drives for the efficiency classes as IE0 to IE2. Compared to an IE1 variable speed drive (reference CDM) an IE2 variable speed drive has 25% less and an IE0 25% more losses (Figure 10). [4]

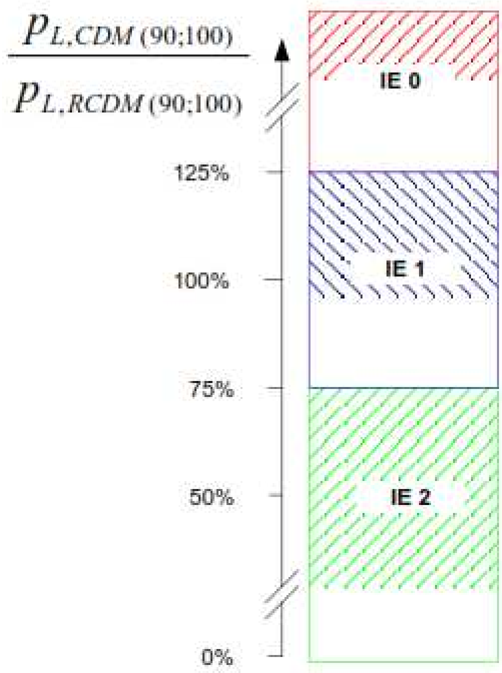


Figure 10. Illustration of IE classes for a CDM (Complete Drive Module)

6. Manufacturers' approach

6.1. Low voltage AC motors

There have been efficiency requirements for low voltage AC motors since the end of the 1990's, which means that motor manufacturers have defined models and strategy for different markets globally.

Depending on the local MEPS requirements, the minimum efficiency class might be IE1, IE2 or IE3 and there are some regions where there are no MEPS in force. Based to the generally available information all the main motor manufacturers have suitable models for markets where they are selling their goods.

Motor manufacturers offer information about motor MEPS and also different kinds of tables and tools for customers so that they can choose the correct type of motor for their needs.

The next challenge for motor manufacturers will rise when the IEC60034-30-2 will define the efficiency (or losses) information for motors which will be operated with a variable speed drive. There are also discussions ongoing for similar efficiency standards for high voltage motors but no information available yet. So the work for new efficiency standards for other type of motors has only started and the results will be seen in the future.

6.2. Low voltage AC variable speed drives

There are neither MEPS nor other regulations for variable speed drives efficiency requirements at this moment anywhere. There is in the EU at the moment a Regulation document in preparation within the EU Commission for implementing the Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors and variable speed drives and repealing Regulation 640/2009/EC.

The first standard defining how the losses in variable speed drives should be measured, calculated and informed was released in the European Union in December 2014 as standard EN50598. Therefore the subject is very new for the VSD manufacturers at this moment, which means that they are creating their strategy and approach towards the market and customers' needs. [4]

Data from five variable speed manufacturers in the EU market were investigated from the Internet by searching the words 'EN50598' and 'ecodesign' and 'IE and IES classifications'. In this paper there is no comparison of the data available. Instead a list is provided of what could be found in the beginning of March 2015. Those five VSD manufacturers are presented anonymously, i.e. A, B, C, D and E. Some of those also have low voltage AC motors in their offering.

Manufacturers A, B and C have separate ecodesign pages where the EN50598 standard has been clarified.

There was an article about the subject on manufacturer D's pages, but no results through search function from pages from manufacturer E.

Manufacturer A gives information that one series of their variable speed drives belongs to the IE2 class, which is the highest one defined in the EN505098-2 standard. The manufacturer also claims that when that type of VSD is connected to an IE2 or IE3 or IE4 motor, the highest IES2 class will be achieved.

Manufacturers B & C do not specify in which class their variable speed drives are. They do not define any IES classifications either.

Manufacturer C provides over 150 verified statements for the loss values (IES) for individual motor and variable speed drive pairs, showing losses at several operation points (speed, current) and inside the operational area from zero speed and zero torque up to 100% of nominal speed and 100% of nominal torque.

No calculation tools were found for defining IES classes, the main reason being that only the DOL (direct on-line) motors are categorized in the motors standards nowadays. The tools will abound when the IEC60034-30-2 standard for converter fed motors is ready and more data about the motor losses at partial load operating points is available from various manufacturers.

7. Summary

Energy efficiency is becoming more and more important globally because of the rising energy demand and electrical energy demand is higher than for other kind of energy.

Low voltage AC motors have had efficiency standards and regulations since the late 1990's and manufacturers have been dealing with the requirements and information needs from markets and customers for a long time already.

On the other hand, users should be able to comply with common agreements and regional and local regulations and limitations that apply to energy efficiency. Efficiency standards are appearing for other components in the motor driven systems, like pumps, fans and variable speed drives.

For that purpose there are tens of committees and working groups with mandates from various authorities (EU, countries) preparing new standards (IEC, EN) and regulations (MEPS) to create minimum levels of accepted losses and efficiency levels for various equipment like pumps, fans, compressors, motors, variable speed drives and so on. Thus the direction is geared towards a system efficiency approach where the total losses in the system are important – not only efficiency or losses of an individual component in the system.

The manufacturers for the listed equipment face new challenges in order for them to make the required information available to their customers and employees, which in many cases leads to lots of work like calculations and measurements. The challenge at this moment is that the subject is new and the needs from markets are just developing. Therefore MEPS and other regulations for electrical motors vary a lot in different regions and even between countries within those regions.

At this moment manufacturers' approach towards the new EN50598-2 standard is mainly concentrated to explaining what the standard means for end users and for e.g. the system performance of a VSD and a motor and a VSD package. When markets and end users get familiar with the standard and especially if MEPS for VSDs begin to be widely used, the demand for information from manufacturers may reach unprecedented numbers.

References

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[2] IEA Energy Outlook 2008, International Energy Agency, 2008, ISBN: 978-92-64-04560-6

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[4] EN 50598 (Parts 1-3), Ecodesign for power drive systems, motor starters, power electronics & their driven applications

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[7] Eco-design directive 2009/125/EC

[8] MEPS, see e.g. Energy labelling and standards programs throughout the world, report by Lloyd Harrington and Melissa Damnics, The National Appliance and Equipment Energy Efficiency Committee, Australia, 2004

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[10] Amending Regulation (EC) 4/2014

[11] Rotating electrical machines IEC60034-30-1 standard

Figure sources

1. IEA 2008 report and IEA 2010 report
2. Figure based on data gathered by ABB
3. Figure based on data gathered by ABB

4. Figure based on data gathered by ABB

5. EN50598 standard

6. IEC 60034-30 standard

7. The sticker on motors, as stipulated by CEMEP (European Committee of Manufacturers of Electrical Machines and Power Electronics)

8. a) and b) EN50598 standard

9. EN50598 standard

10. EN50598 standard

Fluid Systems 3

Advanced auxiliary cooling system for energy efficient ships

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Abstract

A bulk carrier ship was utilized as the case vessel for studying the development potential in the ship auxiliary cooling systems. These systems consist of central coolers between the sea water cooling system and low temperature (LT) fresh water cooling system connected to the high-temperature (HT) cooling water circuit. The HT and LT water are utilized for cooling the engines and several auxiliary ship processes, and the water distribution is usually realized with only a few large pumps, traditionally both with fixed speed. Even if the heat energy in LT-water is currently dumped to the sea, the LT-water could be utilized for heating certain targets directly or it could be used as the heat source for heat pumps.

This study quantified the fuel saving potential that could be achieved with advanced flow control. The preliminary results show that once operating the ship in ISO conditions, the saved fuel with controlling the main pumps in this system could be over 4% of the case ship total fuel consumption, yearly. Furthermore, a new topology and some alternative control methods for the ship cooling water system are discussed. The main principles for the improvements are the utilization of several distributed variable speed pumps and a balanced ring network. Similar principles have been applied in modern district heating and cooling systems. In addition to producing a delivery head lift, these pumps are used to adjust temperatures in the supply and return lines.

1 Introduction

Energy efficiency of a ship requires both efficient production and efficient use of the energy onboard. The most important decisions regarding ship energy efficiency are made at the early concept design phase, when the choices regarding the ship capacity, main dimensions and the basic machinery and fuel for the ship are made. After these decisions, the improvement potential lies in subsystem optimization onboard.

Examining the energy balance of the case vessel, a B.Delta 37 bulk carrier with a low-speed main diesel engine for producing the propulsion power for the ship and three medium-speed auxiliary diesel engines for producing the necessary electricity onboard, the majority of the energy consumption is required for producing the propulsion power for the ship. The overall engine fuel utilization in the case vessel that represents a typical bulk carrier is presented below in Figure 1.

ENGINE FUEL ENERGY UTILIZATION

Engine energy production	MWh/a
Propulsion power	19355
Electrical energy	5195
Economizer heat	2478
HT whr	699
Lost	26165

Total engine fuel energy used	53892
Total engine fuel energy utilized	27726
Overall engine fuel efficiency	**51,4 %**

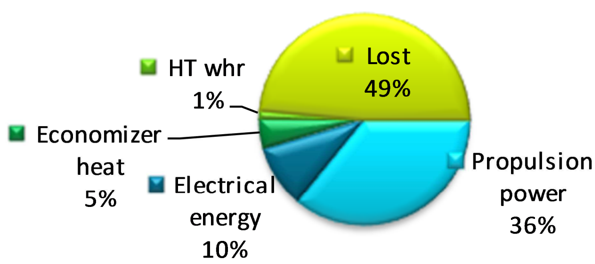

Figure 1 The big picture of the engine fuel energy utilization in B.Delta 37 bulk carrier vessel

Once examining the energy balance calculation in more detail, we can calculate the impact of the various ship systems in the total energy balance. Traditionally, the majority of the energy saving efforts in ship design are directed into optimizing the hull form or choosing an efficient main engine since the improvement in these two fields of design leads to the most substantial fuel savings, as shown in Figure 2. Many academic references can be found related to ship hydrodynamic improvements. We will focus on the ship machinery optimization in this study. The various heat flows in a vessel draw an increasing attention in the design process as more than half of the fuel energy is converted to waste heat energy in the exhaust and cooling circuits, and the number of publications related to the main machinery of the ships is increasing. For instance, G. Shu et al. (2013) studied various ways to recover the waste heat from a marine two-stroke engine and their economy. The technologies reviewed were installing a power turbine, evaporator for fresh water production, electricity production with a Rankine cycle, cooling power or ice-production with sorption refrigeration and combined WHR systems. M. Hatami et al. (2014) reviewed the various heat exchanger technologies for efficient transfer of the waste heat and presented some necessary equations for modelling and analysis of these heat exchangers. As the modern low-speed marine engines are very efficient and the waste heat produced is low grade heat, finding feasible pay back times for the WHR equipment has been difficult in shipbuilding. Also, ships are often operating with lower speed than what they were designed for, in order to save fuel in operation. This leads to even lowered possibilities for waste heat recovery from the machinery, and it should be considered in the design of these systems.

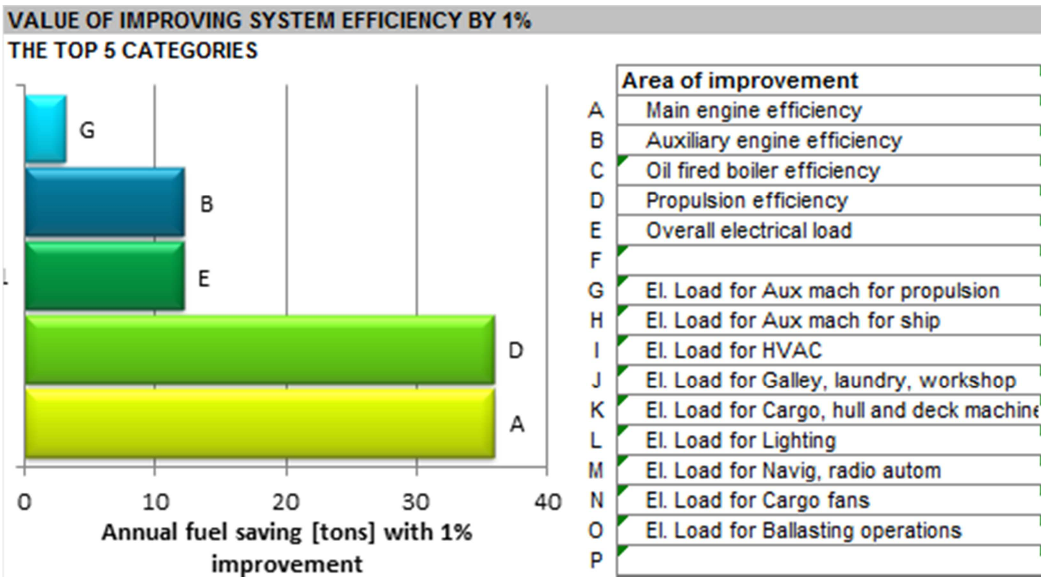

Figure 2 Calculation of the fuel saving impact of saving 1% in the ship consumers or largest consumer groups in the case bulk carrier ship.

Nevertheless, the total energy saving potential in the ship systems depends, not only on the total impact in the fuel consumption, but also on the improvement potential that the systems have. Therefore, by understanding the design requirements of ship systems, we can identify from the bulk carrier ship energy balance an interesting group of energy consumers with considerable saving potential, the ship auxiliaries for propulsion (and ship systems). This group consists mainly of pumps and fans for circulating the fuel, various cooling (or heating-) water, air or lubrication oil. The largest energy saving potential of the equipment in this group can be found on equipment that has medium to large power requirements and that is more or less constantly utilized. In addition to this, there has to be possibility to control this equipment without jeopardizing the functionality of the machinery.

All ship systems are usually dimensioned for a large variety of operating conditions, such as tropical temperatures as well as winter conditions. Also the systems must function when the machinery is operated at full load. Consequently, the ship systems are practically operated at partial load conditions during their life time. In this study we choose the two largest pumps in the ship auxiliaries-group that run more or less constantly for quantifying the improvement potential and present some principal solutions for improving the operational efficiency of these systems. The chosen system for examination is the sea water and LT water cooling system of the ship. The LT stands for “low temperature”, as there are both LT and HT (high temperature) cooling water circuits required for the diesel engines.

The chosen cooling systems are an interesting target for a study, since LT water could also be utilized in certain other applications for further energy savings in ships. Examples of these processes would be to utilize the LT-water as heat source for a heat pump, in order to produce heat in higher temperature for the ship consumers or even utilizing the LT water for preheating an Organic Rankine Cycle –type of small waste heat utilizing power plant that Cayer et al. (2008) examined. Both of these processes would benefit from having as high temperature as possible in the returning LT water after the components that the system serves.

2 Cooling system of a cargo ship

Figure 3 below presents a very simplified set-up of the bulk carrier cooling water system, where only the largest targets to be cooled are shown and the several smaller consumers are combined together, in order to simplify the study. The system consists of the sea water cooling circuit that cools down the LT circuit, as utilizing sea water directly for the consumers would require utilizing more expensive equipment due to the corrosion risk. The LT circulation serves both the main engine and some related equipment as well as the auxiliary engines and some other ship systems, such as air conditioning compressors. The HT-water circuit of the main engine is also partly cooled by the LT circuit even if the heat in the HT circuit is mainly utilized in a fresh water generator. The HT-water of the running auxiliary engines can be utilized for stand by-heating of the engines that are not run, and the additional heat in this circuit is internally cooled in the LT circuit of the auxiliary engines. In the example system there is one sea water pump utilized for circulating the sea cooling water through the central cooler, and meanwhile on the LT side also one LT water pump is utilized for circulating the water in the entire LT water system. There is also a smaller LT water pump that is used once the ship is in harbor, which is already creating savings in the system, compared to a common set-up of the cooling system with only one large LT water pump utilized in all situations. The redundancy of the system is usually ensured by installing two pumps in parallel in the main systems, which is not shown in the principal scheme below. The temperature of the LT water after the central cooler is typically controlled by the three-way valve after the cooler.

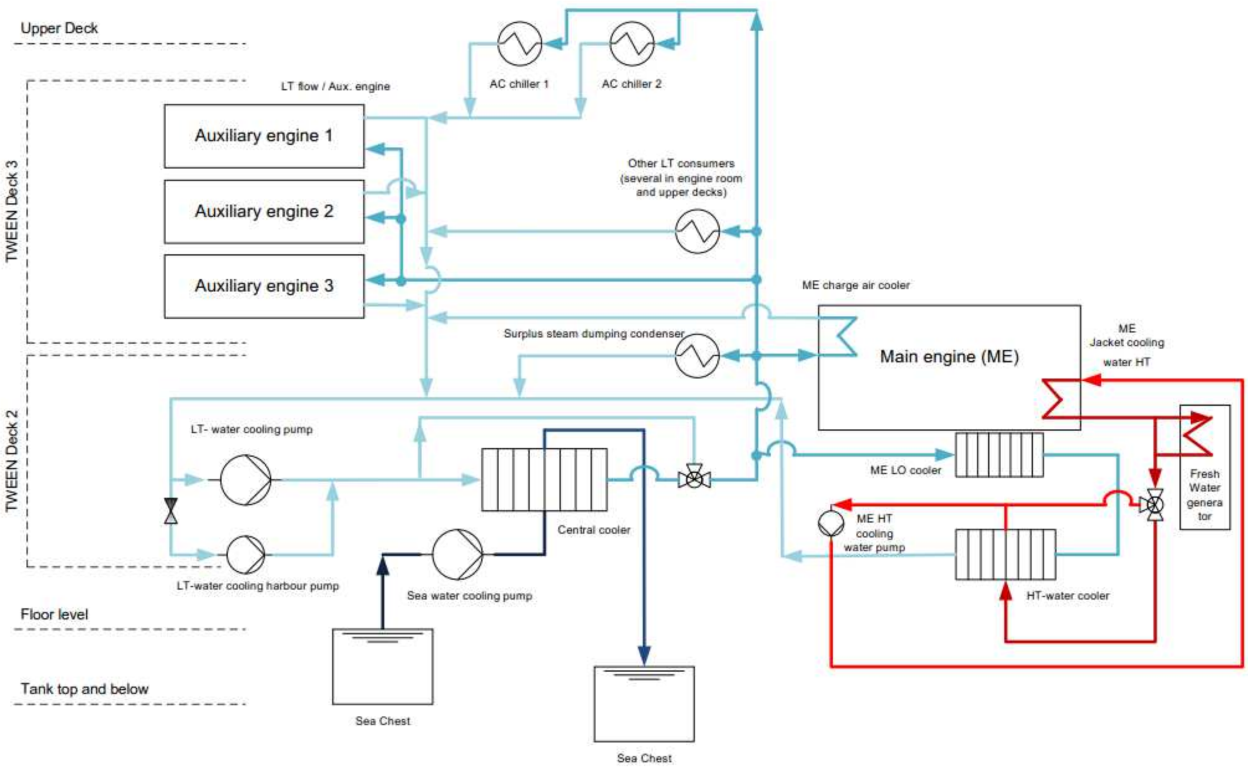

Figure 3 A simplified schematics of the case vessel cooling water system.

The cooling system components are dimensioned in such a way that the system is capable of transferring all heat from the equipment when the majority of the equipment is utilized at its full power in the design conditions. On top of this, certain fouling or safety margins are added. The system is, therefore, often over-dimensioned even for constant operation in the design conditions since the average load of the engines and other equipment is usually much lower than 100%.

An important characteristic in the ship cooling water process of the case vessel is that a lower temperature of the LT water results in better efficiency in the main engine, as well as for some other equipment. Therefore the temperature set point of the LT water is kept as low as the system parameters allow, which limits the theoretical possibilities of reducing the sea water flow. This is an example of the importance of considering the global efficiency, even if optimizing a subsystem.

3 Ship case and saving calculations

An energy balance calculation for the case ship was formed based on the design data of the case vessel. This data consists of the average estimated operational profile of the ship, the propulsion power requirements for the various load conditions, as well as the average electricity and heat requirements for the ship processes and the ship machinery parameters. Further, the ship system design data, together with the engine operational data from the engine manufacturer [MAN 2015 1,2] was used to estimate the amount of energy transferred from the equipment to the cooling circuit. The values for dimensioning conditions and ISO-operational conditions are presented in Table 1 below. The yearly share of hours at each operational mode is also included in the table. The first row described the conditions that are the basis for dimensioning the equipment and the second row presents the values for ISO conditions, with full load on the main engine, and average load for the other consumers. According to the operational profile, the main engine load varies between 40% and 75% at sea. In port, only the auxiliary engines are utilized. The column on the right summarizes the heat flows in the LT circuit, cooled by the sea water.

Table 1. Approximated Energy flow (load) data (in kW), including the yearly operation profile for the case vessel (with approximately 6 MW two-stroke low speed marine diesel engine)

	Yearly operation hours	Jacket water cooler	Lubrication oil cooler	Scavenge air cooler	AC chiller	Surplus steam dumping condenser	Auxiliary diesel engine	Other LT consumers	Central cooler
Dimensioning case, tropical conditions		950	600	1980	350	450	583	166	5662
ISO, 100% ME load	-	930	590	1940	150	10	465	66	4046
ISO, Scantling draught 74,4% ME load	1226,4	760	540	1490	150	10	465	66	3366
ISO, Scantling draught 39,0% ME load	1226,4	520	420	440	150	5	465	66	1951
ISO, Design draught NCR load 67,8% ME load	919,3	720	520	1220	150	5	465	66	3031
ISO, Design draught slow steaming 35,1% ME load	919,3	485	400	330	150	0	465	66	1781
ISO, Ballast draught 63,7% ME load	919,3	690	500	1100	150	0	465	66	2856
ISO, Ballast draught slow steaming 25,0% ME load	919,3	415	360	100	150	0	465	66	1441
ISO, Maneuvering	96	0	0	0	150	0	498	66	776
ISO, Harbour loading	936	0	0	0	150	0	1026	66	616
ISO, Harbour unloading	1176	0	0	0	150	0	1026	66	776
ISO, Harbour stand still	456	0	0	0	150	0	423	66	516

The mass flow of the LT water in the design conditions was also obtained from the engine project guide and from the ship design data. The temperature of the LT water in the design conditions was 36°C, and by knowing these two variables, the total temperature difference over the single components in the LT-water cooling system could be evaluated with the following equation (1):

$$Q = \dot{m} \cdot c_p \cdot \Delta T \qquad (1)$$

where Q denotes the heat power transferred to the cooling system from the equipment, $\dot{m}$ is the mass flow and c_p is the heat capacity of the LT-water. ΔT denotes the temperature difference over the equipment. In this study we assumed that the dimensioning case, presented in the first row of table 1 set the limit for the maximal temperature differences in the process for all conditions.

The pumping power required for the pumps was estimated by using a generic equation (2):

$$P = \frac{\dot{m}}{\rho} \cdot \frac{\Delta p}{\eta} \qquad (2)$$

where ρ is the density of the fluid and $0 < \eta < 1$ denotes the efficiency of the pump. In this study, a constant value of 0.6 was assumed for both LT-water and sea water cooling pumps for describing the total efficiency of the pump, including motor losses. Δp is the pressure difference required for the pump, and this value depends on the total system design. For the preliminary calculations in the study, the reference values from the case vessel design material were used to describe the pressure loss in the LT water and sea water pumps. The design pressure loss for the LT-water pump was 3bar and for the sea water pump 2,5bar, and they are mainly based on the requirements for the main engine, since the main engine has the largest components with the largest pressure losses in the system, after the entire central cooler.

The power for the LT water and sea water pumps was estimated with the above equation for setting a base case for the study. The energy saving possibilities for the system lie in examining the last column (on the right) in Table 1, the load on the central cooler, compared to the dimensioning value. With fixed flows for the cooling waters, the temperature difference over the cooling system components varies, but if the flow is controlled, instead, the power required for the pumps can be reduced. Once recognizing possibility to reduce flow on the pumps, the new power requirements were estimated with the affinity laws, as Menon (2011) suggests. According to affinity laws, the pressure difference (or pump head) is proportional to the square of the flow rate and the pumping power is proportional to the cube of the mass flow rate,

$$\frac{p}{p_0} = \left(\frac{\dot{m}}{\dot{m}_0}\right)^2 \qquad (3)$$

$$\frac{P}{P_0} = \left(\frac{\dot{m}}{\dot{m}_0}\right)^3 \qquad (4)$$

where subscripts 0 refer to design point.

Once the ship energy balance data was combined together with the estimated power for the pumps in different flow control scenarios, the fuel saving potential could be estimated. In this study we focused on the cooling water flows around the central cooler component, which means that the preliminary results were not restricted by possible demands for water flow in single components of the cooling system. Instead, the minimum flow for each component in the cooling system was set by the component specific maximum temperature differences.

The variables in the calculation were, thus, the operating profile that had an impact on the ship energy needs for various consumers. The variable LT-water consumer cooling requirements is presented in table 1. The ambient conditions were considered through the main engine parameters that were affected by both air temperature and cooling water temperature. The sea water temperature had an impact on the central cooler and the supply temperature of LT-water into the (LT-) system was assumed to be kept 4˚C above sea water, with certain limits, however.

4 Preliminary results

As a result of this paper, evaluation of the total fuel saving potential of controlling the flows in the fresh water cooling circuits was made. The reference case for calculation was the situation with no control on either sea water or LT-water pumps. The situation with no flow control on either pump with the average operational profile was analyzed first. Second, we assumed that the ship would operate in tropical conditions specified in Table 1, and and the flow could be reduced in both, LT-water and sea water pumps to 30% from the dimensioning flow. Finally, the calculation, using the operation profile in Table 1, was conducted for the constant operation in ISO conditions, defined by the engine project guide. This means that the sea water temperature would be 21˚C, and the LT-water set-point temperature 25 ˚C. The results of the study, the energy saving potential in the major pumps in the cooling water system, are presented below in Table 2.

Table 2. Preliminary results of estimating the energy saving potential in the major pumps in the cooling water systems for a B.Delta 37 bulk carrier. The minimum flow is set to 30% of the dimensioning value.

	LT-pump(s) yearly kWh	Diff. To Base Case	Sea water pump yearly kWh	Diff. To Base Case
No flow control, "base case"	483 325	-	484 413	-
Flow control, Constant operation in tropical conditions with SW temp 32C, air 45C	213 084	270 242	55 606	428 807
Flow control, Constant operation in ISO conditions with SW temp 21C, air 25C	128 178	355 147	13 260	471 153

In the ISO operational conditions, with the average operation profile, the total fuel consumption of the ship would be 4733 t/a, of which 1256 t/a is the amount of fuel required for the auxiliary engines. When considering the theoretical saving potential in the sea water and LT-water cooling pumps, the yearly fuel consumption of the auxiliary engines would be reduced to 1051 t/a that results in theoretical saving potential of 206 t/a, 4,35% of the ship total fuel consumption.

5 Discussion of the alternatives for the efficient LT-water cooling system topology

Since this study does not include modelling the piping in detail, the local pressure losses are not quantified and the possible solutions for the cooling system topology are discussed only on general level. As shown in Figure 3, in the existing cooling circuit, the water distribution is realized with only a few large pumps. In practice, local pressure losses caused by valves create difficulties to control the flow and, consequently, significant amount of cooling water is unnecessarily circulated in the system. Figure 4 below presents an even simpler version of the current LT-water circulation, and its main components. If flow control is applied on the LT water pump, it has to be verified that all the consumers receive enough cooling water. For instance, the necessary pressure difference for the consumers located on the upper decks might drop too much, if speed control is applied directly to the traditional cooling system. This can be avoided, for example, by installing automatic or manual on/off control valves before each consumer that keep the design mass flow through the consumers, while the LT water pump can be controlled by keeping a right pressure difference in the system. However, this type of control does not allow the full potential of flow control in the system, estimated in the previous chapter, since the flow over single components cannot be adjusted.

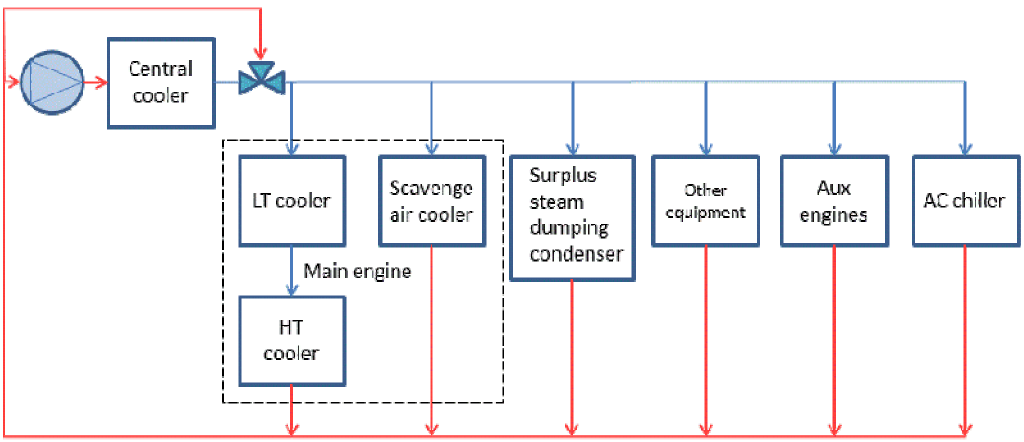

Figure 4 Simplified presentation of the current LT-water circulation with only one main pump for the system

Therefore, a more balanced cooling water network and, eventually, increased individual control for the system sub-components would be required, when aiming for full or nearly full utilization of the energy saving potential of the cooling system estimated in the previous chapter. Laajalehto et al. (2014) proposed a new district heating (DH) system for a case network of residential buildings. They utilized a new control of DH water, 'mass flow control', and a ring topology of piping for a better control accuracy of the DH water flow systems. Even if the target with the reference system was heating application, the same principles could be applied to any cooling application, as well as to ship cooling water systems.

The characteristics of the ring network enable equal pipe length and pressure losses for each auxiliary process. Figure 5 presents a simplified diagram of the ship LT-water cooling circuit, with the ring network topology applied. The principle of equal pipe length from central cooler to each subcomponent, including the return line is visualized in Figure 5. This type of system eliminates, in practice, the problems that flow control would cause in the traditional system, regarding the sufficient pressure for the consumers located farthest from the LT-pump. Due to the equal pipe length, the network is naturally balanced and flow control of the LT water pump reduces the flow more or less equally for all of the consumers.

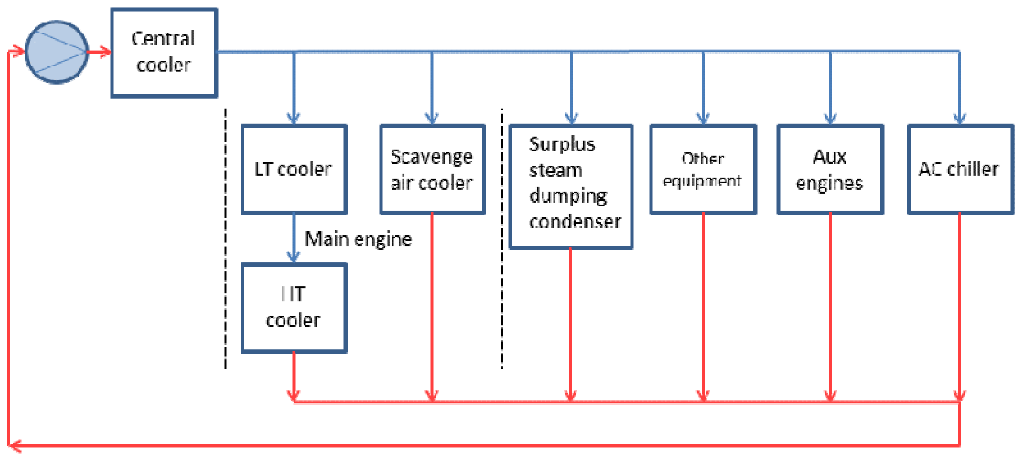

Figure 5 Simplified ring network arrangement of the LT-water cooling system

The aim of the design could be removing the by-pass line with the three-way valve, shown in Figure 4. However, the ring network alone is not capable of optimizing, or in other words, reducing the flow to the minimum for the single components in the system, but the flow is reduced equally for all components. Considering the Table 1, with the estimated heat flow for the system single components, it is clear that individual control would be required for the components, if the full or near full saving potential in the LT-pump would be desired. Currently, the consumer with the highest demand of heat would set the requirement for the flow for all components.

Better control might be achieved with several distributed variable speed pumps that also allow larger temperature rise between supply and return lines. This way, the requirements of each of the subcomponents can be considered. Figure 6 presents further control possibilities with several smaller pumps where local valves might be removed as well. However, the problem with this kind of system would be the investment cost of all pumps and the related control. Also, it should be considered that the key components in the cooling system must be redundant, which usually means that for every pump there is a stand by unit also. This should also be considered in the profitability analysis.

Nevertheless, the system could be realized also as a combination of the systems presented in Figure 5 and Figure 6, where individual flow control would be allocated only for certain consumers or groups of consumers. This way, a balance between the investment costs for system and the operational efficiency could be achieved.

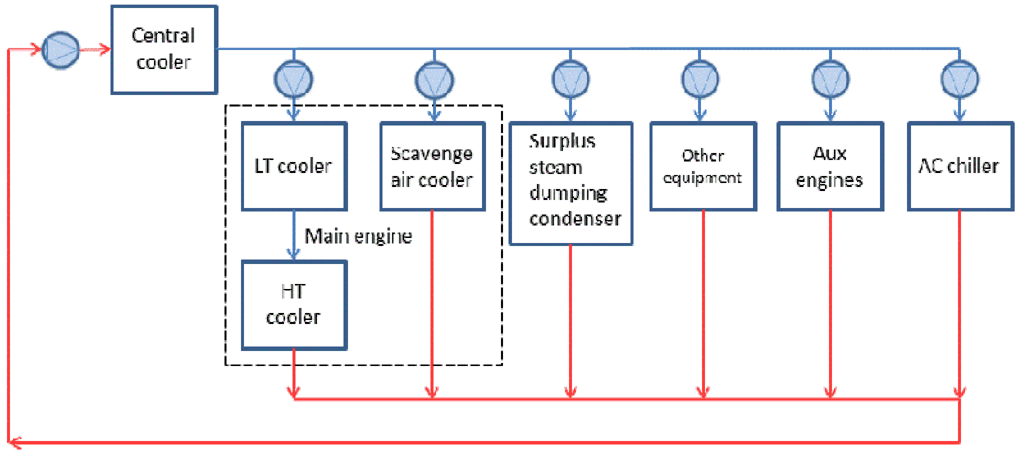

Figure 6 Ring network topology and individual control of the components in the LT water system

6. Conclusions

Based on the results, the total fuel saving potential of reducing the LT-water and sea-water cooling pump flow seems to be considerable even in the tropical operational conditions for the case vessel. This is mainly due to the large amount of operation committed at slow speed. When examining operation in ISO conditions, the theoretical saving potential grows further.

The saving potential on the sea water cooling pump accounts for a bit more than half of the estimated energy saving potential in the study, and due to the rather simple, one point connection to the LT-water system, this control system has been recognized earlier and examined in several occasions. For example Su et al. (2014) presented a method to evaluate the savings with this system and Elg et al. (2014) implemented the control of the sea water cooling pump in the multi-domain simulation model of the B.Delta 37 bulk carrier ship. The flow control of the sea water cooling pumps is widely applied to both new and existing ships currently. However, the flow control of the LT-water is not as simple to be realized and there lies the further development potential of this study.

The calculations of finding the saving potential in the cooling system were conducted in such a way that we only examined the total amount of heat flows from individual consumers to the central cooler and fixed the maximum temperature difference in the central cooler based on the maximum temperature in the design situation. Further study is needed to evaluate the requirements for individual control of the components. Examples of these requirements could be to ensure adequate flow for certain system key components for maximizing the ship global energy efficiency, such as the main engine charge air cooler. Also, components that might have sudden, large cooling requirements in the actual operation, such as the steam dumping condenser, would require that the system is adapted quickly to these sudden changes. An individual pump could be necessary for these targets. Even components or groups of components that are located on the upper decks of the ship might benefit from individual pumps.

In general, the purpose of this study is to open up the topic of ship power plant auxiliary cooling system optimization and to show that there is some considerable saving potential in these systems that exist in some form onboard every ship, regardless of the ship type. As there would be several directions for the study, starting from defining the system design values to writing optimization algorithms for the operational system, we started from describing a common case from a ship designer's perspective and froze certain starting values in order to analyze the theoretical saving potential in a typical system.

This study made several simplifications of the systems. In general, the starting point for the calculations of the saving potential was that the mass flow in the different parts of the LT-cooling system was fixed. The reason for this is that from a ship designer's perspective the flows are often given by the equipment manufacturers, and optimizing the design values for the equipment is a wide topic that is worth examining separately. Actually, further saving potential could be found by stretching the design limits. Nevertheless, this topic should be studied together with respective equipment manufacturers.

The bulk carrier case, described in this study is known as the simplest type of ship, regarding the machinery. Also, the subsystems in the machinery should, preferably, be as simple as possible, especially regarding maintenance. From both the ship builder's and owner's perspectives, the installation costs should not be considerably larger than they are for the existing system. In practice, any changes made to the current state-of-the-art systems should be very well justified. Furthermore, a ship designer balances always between ensuring adequate redundancy for the key systems and operational energy efficiency of the systems. For instance, any change in the LT-water temperature or flow might have a negative impact on the system key component efficiency. Therefore, the holistic approach should be included in any sub-system optimization. Thus, the next steps for the study are to implement the elements described in this chapter, for improved efficiency in the ship auxiliary cooling system, in the simulation platform for the ship, presented by Elg et al. (2014). This gives the possibility to consider the major physical characteristics in the system and to ensure that the global efficiency of the ship is kept at maximum.

Acknowledgements

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36-VFD controlled pumping unit in circulation lubrication system

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Abstract

Oil circulation lubrication is typically used in the applications, where the bearings or other lubrication points will require lubrication and cooling during the machine run. Such machines are for example paper mill drying sections, big gear boxes, steel rolling mill bearings, hot gas fans etc. The Oil circulation lubrication system consist of six main items; Oil pumping station with oil tank, pressure lines, return lines, flow meters, possible sump units and control and monitoring devices. This paper will show how the variable frequency drives (VFD) are used for pressure control of the pumping station and how a VFD allows an automated cold start- up of the oil circulation system. In both case we will see that the user can save energy in the pumping process which makes the circulation lubrication system and with it the machine it is a part of more environment and user friendly.

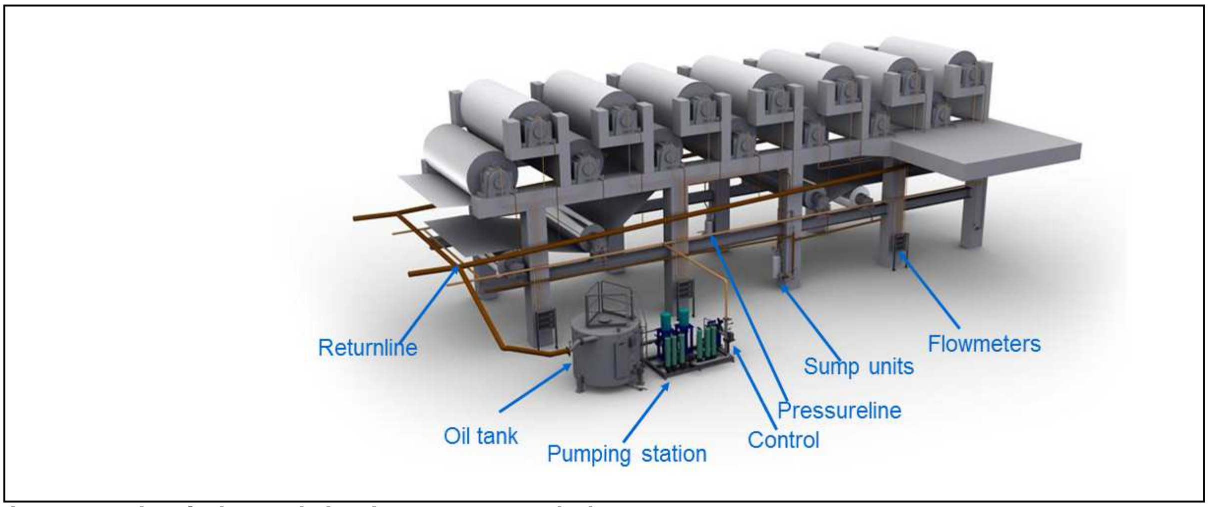

Figure. 1. Circulation Lubrication system main items.

Pressure control in Circulation lubrication pumping station with Variable Frequency Drive

Oil circulation lubrication is typically used in the applications, where the bearings or other lubrication points require lubrication and cooling during the machine run. An oil circulation lubrication system consist of six main items; oil pumping station with oil tank, pressure lines, return lines, flow meters, possible sump units and control and monitoring devices. From the pressure and oil temperature control point of view the pumping station is the most important part of system.

In an oil circulation system's pumping station there are normally two parallel pumps: one in operation and one in stand-by mode to allow continuous machine operation in case the pump in use fails. Usually positive displacement (PD) pumps are used, which could be gear, gerotor or screw type pumps. The pumping station tank is equipped with heaters to heat up the oil during cold start-up (figure 3) and a heat exchanger to keep the pressure line oil temperature constant. The coolant used in the heat exchanger either can be water or air. Typical operation pressure for the pumps is between 4 to 6 bar. The oil temperature in the outgoing pressure line usually is between +40…+50°C.

The flow rate in the pressure line is a function of pressure and oil temperature. If the pressure and oil temperature in the pressure line varies a lot then also the oil flow to the lubrication points varies. This can lead to possible over- or under lubrication in the lubrication points which can result in costly machine downtime and repairs. It therefore is very important to keep the oil pressure and temperature at the right and constant level to provide the required oil flow to the lubrication point.

The traditional way to control the output pressure in the pumping station is to use a relief valve (figure 2 10). In smaller systems this can be a spring loaded valve, for bigger capacities a pneumatic control valve is used. The pumping station's pump is running with constant speed and the flow and pressure to the system is controlled by the relief valve. These valves require a continuous flow through the valve. To cover this additional demand the total pumping and cooling capacity must be dimensioned 10 – 20 % above the system capacity that would be required by the lubrication points only. This continuous flow through the valve to the tank generates heat and energy losses that not only increases the system's running costs but all the pumping station components must be dimensioned according to this higher (an theoretically not needed) capacity. This solution is cost effective to be manufactured, it doesn´t include any possibility to control pump speed itself, though.

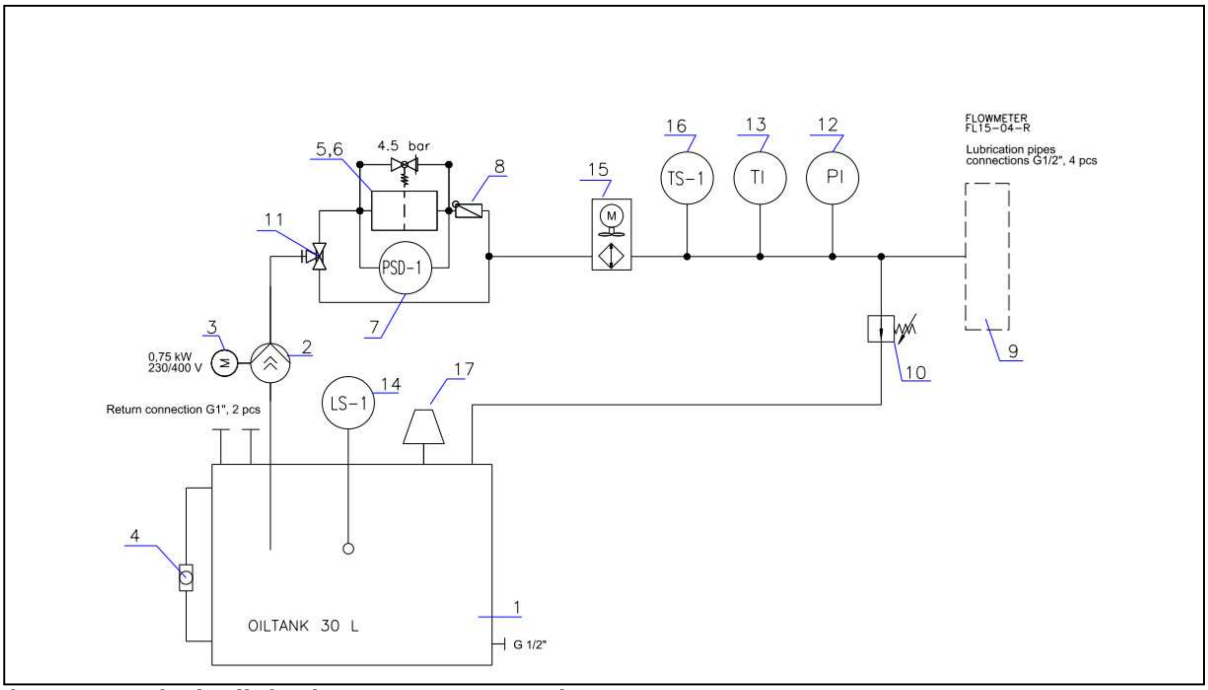

Figure 2. Typical relief valve pressure control

A much more efficient way in pressure control is to use electric motors in combination with frequency converters to control their speed. Figure three (3) shows a typical PI schema of a circulation lubrication system with motors and their frequency converters (A51,A52) and the pressure transmitter (PT 23) in the pumping station oil outlet. The pressure transmitter monitors the pressure and the signal is used to control the rotational speed of the electric motors with frequency converters. With this kind of control it is possible to pump exactly that amount of oil, which is flowing through the bearings. The pumping station control immediately reacts to any required adjustments to the oil flow of individual lubrication points. The pressure control is very accurate and it allows also a higher adjustability in the total system's oil flow, if required. This layout has no need for oversizing components anymore and it allows the control of the motor speed itself and with it the pump output flow.

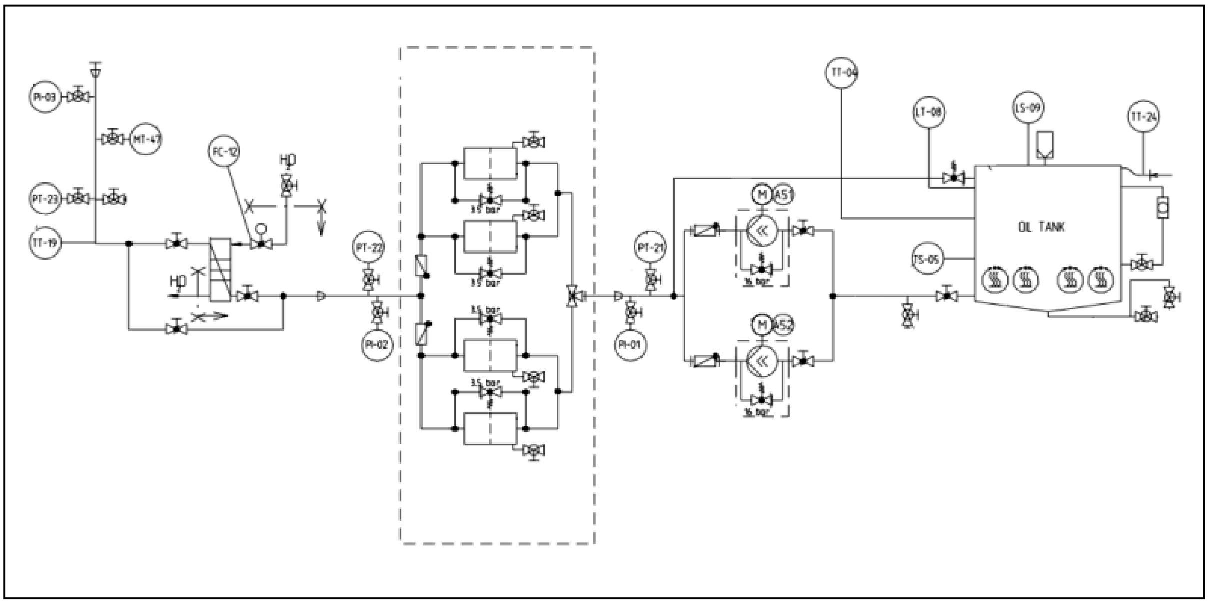

Figure 3. PI-Schema of circulation lubrication pumping station.

For VFD controlled PD pumps one should remember that the output flow is proportional to speed, but the pressure can be independent of speed. Compared to e.g. centrifugal pumps power and energy savings are not achievable as quickly when speed is reduced because of the PD pump specific behavior. A PD pump is operated with wider speed range than rotary dynamic pumps. With that higher speed range and the behavior of PD pumps, that load could be high also with low speeds, which can negatively impact the pump and motor. With low speed and high load the motor could require an additional fan for sufficient cooling. Despite being able to control the motor speed it still is important to select the right size motor and pump for the specific application to avoid that the drive train runs with too low speed and high load. Torque ripple, heat generation and that the motor's rotation speed start to oscillate could be the result if the drive train is too big for the specific pumping station. [1]

Cold start- up in Circulation lubrication pumping station with Variable Frequency Drive

Machines that are lubricated by circulation lubrication systems usually run 24/7 year round. Time after time the lubricated machine, like paper machine, do need service and the machine and with it the lubrication system will be shut down. During the stop the temperatures of the machine and its lubrication system decrease. With lower temperatures the lubricant's viscosity increases.

The lubrication system is designed to operate in temperature range of +40…+60C. A significantly cooler lubricant has higher viscosity and will require higher pressure to flow through the lines. This higher pressure can make the sealing system in the lubrication points fail, i.e. lubricant can leak and be lost for the application and pollute the machine's environment respectively. Because of this potential problem it is crucial to have a controlled cold start- up process. Figure 4 shows the phases of an ideal cold-start up.

In phase 1 the tank of lubrication system is heated. The lubrication system control switches the electrical resistances on to heat the reservoir. The oil temperature is adjusted to the desired level by an electrical thermostat (figure 3 TS-5).

In phase 2 the pumps are started. The setting parameter of pressure is about 0,5…1 bar. The oil is allowed to recirculate through the pressure piping and drain return piping back to the reservoir. In the end of pressure line there are by-pass-valves which allow oil to flow directly to the return line. The bypass valves in the loops open automatically. During delay time 1, the temperature of the returning oil does not affect the transition to the next phase. After the oil has returned to the measuring point, the oil temperature is measured with a temperature transmitter (figure3, TT-24). The oil can be heated with electrical resistance and / or heat exchanger.

In phase 3 the interlocking of lubricating system is switched off which means that the lubricated machine is allowed to run. By-pass valves at the end of the pressure lines are closed. Oil pressure is increased up to the level of 1…2bar pressure. After some delay the oil has flown through lubrication points back to the pumping center with a low pressure and reached the temperature measuring point (Figure 3 TT-24). After this the oil pressure is increased linearly step by step to the desired normal operating pressure based on the temperature of the returning oil. The oil can be heated with electrical resistance and / or heat exchanger

In phase 4 is the normal operation. Outgoing pressure is now controlled and kept constant by pressure transmitter in beginning of pressure line (figure 3 PT23) and the oil temperature is kept stable with heat exchanger and temperature transmitter (figure 3TT-19).

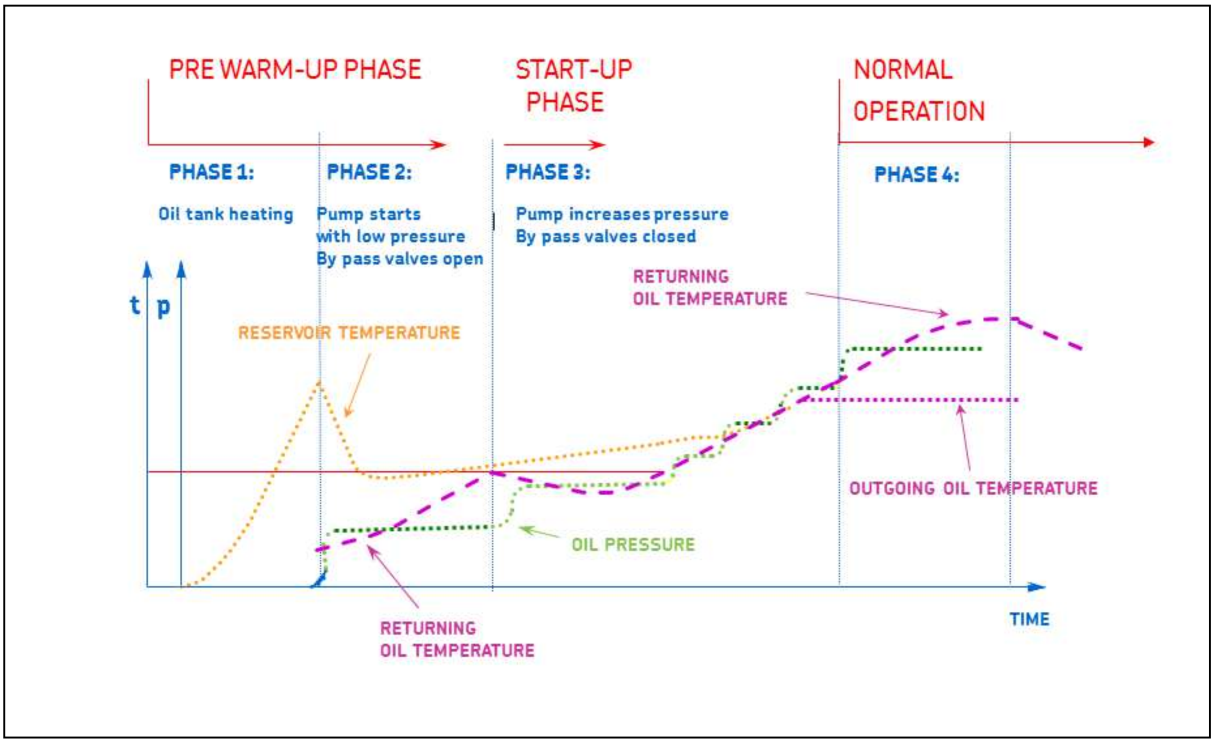

Figure 3. Automatic cold start-up

This automatic cold start up only is possible with a VFD controlled motor.

In a traditional lubrication system with relief valve control the pump and motor run with full speed and the only possibility to control the oil flow to the system is with the relief valve. Adjusting the flow through the valve (to adjust the flow in the pressure lines to the lubricating points) is a manual operation and requires an operator on site.

Benefits to use VFD in Circulation lubrication pumping station

The benefits of VFD motor control in circulation lubrication system are quite clear. First of all it gives energy savings of 10-30% to the conventional relief valve control. There is calculated and tested result from customer side that in Paper machine dryer section the PD pump control with VFD could mean 28000 kWh savings/year when compared to a pumping unit without VFD control.

Figure 4 shows an example from Sweden. Initially the circulation lubrication system's pressure control was done with a relief valve. In the beginning the lubrication points total flow was engineered to be 700 l/min with a relief valve needed flow of 200 l/min leading to a total flow of 900 l/min. Because of changes in the machine its total flow need was decreased to 600 l/min over the years. This increased the drivetrain overflow to 300 l/min (50% of the actual machine need!) of oil with a pressure of 4 bar which was relieved though the valve back to the tank. Because in relief valve control there is no way to control the speed of pump and motor, means that the lost flow generate 28000 kWh energy lost in year.

	Conventional system	System with VFD
Required oil flow today (l/min)	**600**	**600**
Additional oil flow for pressure regulation+overflow (l/min)	**300**	**0**
Total oil flow (l/min)	**900**	**600**
Energy needs for drivetrain-motors and pump (kWh/year) e.g.	**80 000**	**52000**
Energy lost trough relief valve (kWh/year) e.g.	**28000**	**0**
Total energy saving with VFD (kWh/year)		**28000**

Figure 4. Sample calculation for Circulation system with required oil flow 600 l/min.

By controlling pump output flow or pressure directly to the process requirements, small variations can be corrected more rapidly by a VFD than by other control forms, which improves process and system performance [1]. The pumping station could be engineered more optimum way which lead to smaller dimensioning of pumping unit and cooling, example of we could reduce total output flow 650 l/min to 500 l/min could mean that we could use drivetrain with 18,5 kW motor instead of 30 kW motor. The drivetrain is designed with most optimum way. VFD is giving more accurate operation to the pumping station and in circulation lubrication system make possible to control cold start up with ramp up feature and heating. With this we avoid flood in bearing housings.

Conclusion

Using a VFD with PD pumps in oil circulation systems instead of controlling the flow with a valve not only saves energy by eliminating the mandatory flow through the control valve but also provides significant opportunities to reduce costs by downsizing the driveline itself. In addition the automated start up process reduces variability and possible problems compared to manual adjustment / control of the process.

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Case Study on the Variable Speed Drive-based Fan Impeller Contamination Build-up Detection

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Abstract

Fans are multiple and number and versatile in use. They may be located in processes where they are susceptible to contamination build-up. These contaminants will eventually lead to the breakdown of the fan. If the contamination build-up could be monitored the cleaning can be time perfectly.

In this paper, a variable speed drive-based method for the detection of contamination build-up is presented. The method can be used in rotational speed controlled fans without any modifications to the existing system. The presented method is tested with an industrial fan case study.

Introduction

Fan systems are present in all industrial sites in various applications. Fans may be responsible for cooling, supplying fresh air and removing exhaust gases and therefore they may be vital parts of production lines and worker safety. Especially, in processes where there are contaminants in the transferred air, the fan is prone to build up contaminants on the fan impeller. If untreated, the contaminants will eventually lead indirectly to the breakdown of the fan. Traditionally, these fans are periodically cleaned or checked for contaminants so that the breakdown of the fan can be avoided. However, the checking of the contamination build-up is usually done with visual inspection and is always a subjective opinion of the maintenance professional. In addition, periodical cleaning may be done too early, since reliable information about the actual degree of contamination is not available. Thus, there is need to find an objective estimate of the degree of contamination.

It is well known that when the contaminants build-up on the fan impeller, the mass of the impeller increases. Thus, the direct measurement of the fan mass would give an objective estimate of the contaminations as presented here. However, in industrial fan systems the direct measurement of mass of the fan impeller would be impractical and would need an additional measurement sensor. However, as the contaminants build-up on the fan impeller the increasing mass will also effect the rotational inertia of the impeller.

The rotational inertia (later referred to as inertia) of the fan can be indirectly measured with the measured torque and rotational speed. By applying a known torque and observing the rotational speed the inertia can be estimated. This has been used in various motion control applications to identify the surrounding system [1]. However, using directly the measurements of the rotational speed and torque have two challenges. First, there is need for additional sensors, second, the aerodynamics of the fan have an effect on the torque requirement and need to be taken into account.

The first challenge can be solved by using the estimates given by the variable speed drive, also called the frequency converter. Variable speed drives have become common in large fan systems since it is a simple way to accurately and energy efficiently control the fan output [2]. For example, with induction motors the rotational speed and torque can be estimated based on a motor model, the stator currents, DC link voltage and the switch states of the variable speed drive. It has been shown that the absolute accuracy of the estimates are 2 rpm and 4% of the measured rotational speed and measured torque scaled to the motor nominal torque, respectively [3]. In addition, it has been mentioned that the repeatability of the control and the estimates is higher than the absolute accuracy [4]. However, for this approach to be valid it is assumed the fan is run with a variable speed drive.

The second challenge can be overcome by using a selected rotational speed range in the start-up of the fan where the aerodynamic effects of the fan can be ignored. A rotational speed where 95% of the fan torque requirement is assumed to be a result of the inertia is selected as the rotational speed range where the aerodynamic effects can be ignored. The method where the two challenges are overcome is presented in [5]. However, the reference only discusses torque controlled fans, whereas rotational speed control is more common and will require changes to the use of the presented method.

In this paper, the approach by [5] is explained and the use of the method in rotational speed controlled fan systems is presented. The presented method is used in an industrial case study and the results are discussed. Finally, the paper is concluded.

Method for contamination build-up detection

In [5], the fan is started with a torque step. During the start-up, the rotational speed of the fan first increases linearly and then the acceleration starts to decrease, until the final rotational speed is reached. The behavior of the rotational speed of the fan with a torque step start up can be seen in Fig. 1.

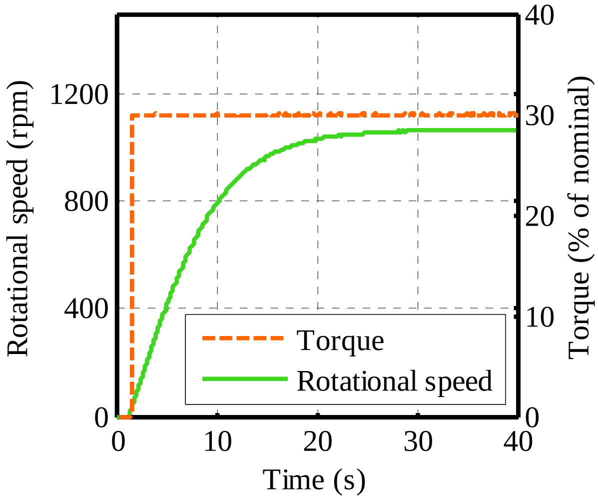

Fig. 1. Fan start-up using a torque step.

In [5], the torque and the rotational speed estimates are saved with a 10 ms sampling time and then filtered with a 10 samples long median filter. Time instances from the filtered signal are selected where the rotational speed is between 30 rpm and $\sqrt{1-0.95}n_{\text{final}}$, where n_{final} is the final rotational speed acquired with the applied torque. The rotational speed range is selected so the stiction at low rotational speed and the aerodynamic effects at the high rotational speeds are excluded from the collected samples. The slope *k* of the rotational speed at this rotational speed range is found using linear fitting, in addition, the average of the torque T_{average} is calculated from the time instances. Thus, the inertia of the impeller *J* can be estimated with

$$J = \frac{T_{\text{average}}}{k} \tag{1}$$

It has to be noted that the inertia does include also other inertias such as the motor inertia. However, the impeller inertia is significantly higher than other inertias so, they can be ignored. In addition, only the difference in the inertia between start-ups is needed, thus the other constant inertias incorporated in the calculation do not affect the detection. In the contamination build-up detection, the inertia in monitored over time and from the trend of the inertia the amount of contaminants can be monitored.

It has been shown in [5] that a 0.4% change in the impeller inertia was reliably detectable in the laboratory measurements. The 0.4% change corresponds to 50 g of added weight on the outer edge of the 0.63 m diameter impeller. The measurements were done using different fan operating points and it was concluded that the aerodynamic behavior of the fan does not have an effect on the detection method. It was also noted that using different startup torques result in slightly different estimates of the impeller inertia, thus similar startups should be compared with each other. Moreover, the temperature of the motor has an effect of the estimation method. The restrictions given above show that the estimation method has numerous elements that should be controlled for the estimation method to work in ideal conditions. It is apparent that not all of these are controllable in normal conditions where industrial fans are operated.

Impeller rotational inertia detection in rotational speed controlled fans

Torque controlled fans are rare in industrial environments. Most fans are rotational speed controlled, thus the presented method cannot be used as is. An example of the startup of a fan with rotational speed controlled fan is given in Fig. 2. It can be seen that the constant torque startup in Fig. 1 differs significantly from the rotational speed ramp start up in Fig. 2.

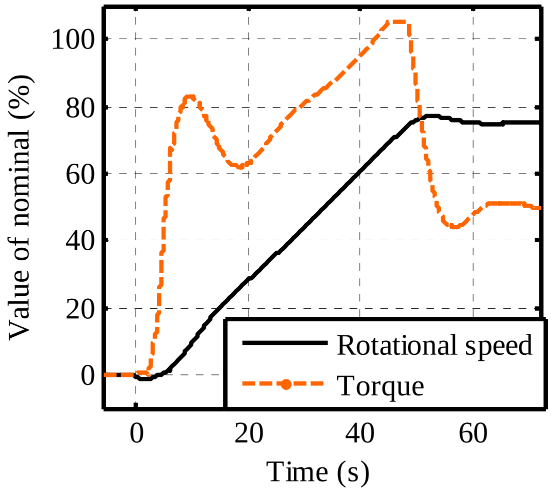

Fig. 2. Fan startup using a rotational speed ramp.

In rotational speed controlled fans, the detection of the impeller inertia increase is initiated as in [5]. The rotational speed and torque estimates are saved with a 10 ms sampling interval and median filtered with a 10 samples long filter. Generally expressed the inertia can be calculated from these samples with

$$J = \frac{\sum_{k=a}^{b} T(k)\Delta t}{2\pi\frac{(n_b - n_a)}{60}}, \quad (2)$$

where T is the torque in discrete time steps, b is the index where the discrete time rotational speed n_b corresponds to $\sqrt{1-0.95}n_{\text{final}}$ and a is the index where n_a is 30 rpm and Δt is the sampling interval.

However, it was noted that even though the general expression does give good indication of the increase in the inertia, using a simplified method gives more consistent estimates. It was found that using the first peak of the torque at 10 seconds in Fig. 2 will give the best estimation results. The impeller inertia is calculated so that ±2 seconds time frame around the torque peak, corresponding to discrete time indexes α and β. The torque is averaged between these incidences. The slope k of the rotational speed in linearly interpolated between the incidences α and β. The inertia is then calculated

$$J = \frac{\frac{1}{\beta - \alpha + 1}\sum_{i=\alpha}^{\beta} T(i)}{k} \tag{3}$$

Using the first peak method will allow the use of a quasi-constant torque and thus the use of the original method with only a minor variation. It has to be noted that the peak in the torque is a normal result of the PID control responsible for the rotational speed control. However, if the first torque peak is above the rotational speed range defined by 30 rpm and $\sqrt{1-0.95}n_{\mathrm{final}}$, the first peak method may not be used, but the general expression should be used instead.

Industrial case study

An industrial fan at Finnsementti Oy cement factory in Lappeenranta, Finland was monitored to confirm the operation of the contamination build-up detection presented in the previous section. The industrial fan is responsible for transferring heat gases from a cement kiln to preheat the coal mill. The gases contain pollutions that gets stuck on the fan impeller. The fan driven with a 75 kW, 1480 rpm induction motor and the fan has impeller diameter of 1.4 m. The industrial fan can be seen in Fig. 3.

Fig. 3. Case study radial fan responsible for transfer of heat gasses from the cement kiln to the coal mill.

The fan is variable speed driven with an ABB ACS800 variable speed drive. The rotational speed and torque estimates provided by the variable speed drive were low pass filtered with 500 ms and 100 ms time constant, respectively. These filtered estimates were saved with a 10ms sampling interval. In hindsight an unfiltered estimate would have been more reasonable to be saved since post processing is done to the gathered signals. The data was gathered between 14.2.2014-15.12.2014 which corresponds to nearly 7 000 h of gathered data. No changes were made to the operating parameters of the case fan.

In Fig. 2 the normal startup of the case fan is presented. It can be seen that the start of the fan is slow by taking almost 45 seconds to reach the desired rotational speed. The first peak method was then used in the detection of the impeller inertia as explained in the previous section. In Fig. 4, the estimated impeller inertia is presented. It can be seen that the inertia increases steadily as a function of the operating time as can be expected as the impeller accumulates dirt. At 6 000 h a cleaning operation is performed to the fan.

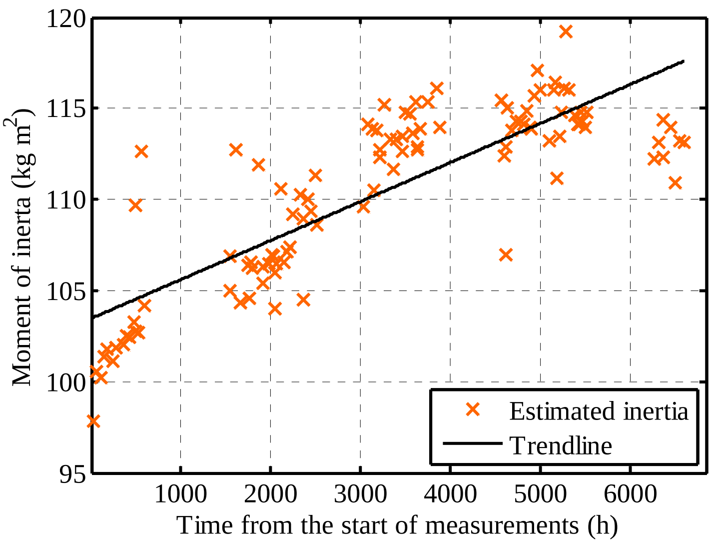

Fig. 4. Estimated inertia of the case fan as a function of time. At approximately 6 000 h a cleaning operation was performed to the fan. Contaminants corresponding to an inertia of 2.5 kg·m^2 were collected from the impeller.

Approximately 5 kg of dirt is removed from the impeller in the cleaning operation. It can be approximated that with the 1.4 m diameter impeller this would correspond to approximately 2.5 kg·m^2. The corresponding drop in the impeller inertia is visible in Fig. 4. However, the inertia does not return to its original level. This may partly be a result of the cleaning since after the data acquisition it was found that not all of the dirt was removed. Regardless of this, the results indicate that the presented method is able to correctly detect the inertia of the impeller even in unideal industrial conditions with unchanged operating parameters of the variable speed drive.

Conclusion

Variable speed drives are common in large industrial fans. These fan may be responsible for transferring air that contains pollutions that stick to the fan impeller. The contaminant will eventually lead indirectly to the breakdown of the fan. The breakdowns can be avoided with correctly timed cleaning operations.

In this paper, a variable speed drive based contamination build-up detection method is presented. It uses the variable speed drive estimates of the rotational speed and torque at the startup of the fan. The method was used in an industrial fan to verify the operation of the presented method. It was found that the impeller contamination can be detected with the presented method without making any changes to the variable speed drive.

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