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Space Weather and Power Grids: Findings and Outlook

An event co-organised by the European Commission's Joint Research Centre,
the Swedish Civil Contingencies Agency and
the NOAA Space Weather Prediction Centre
29-30 October, 2013, Ispra, Italy

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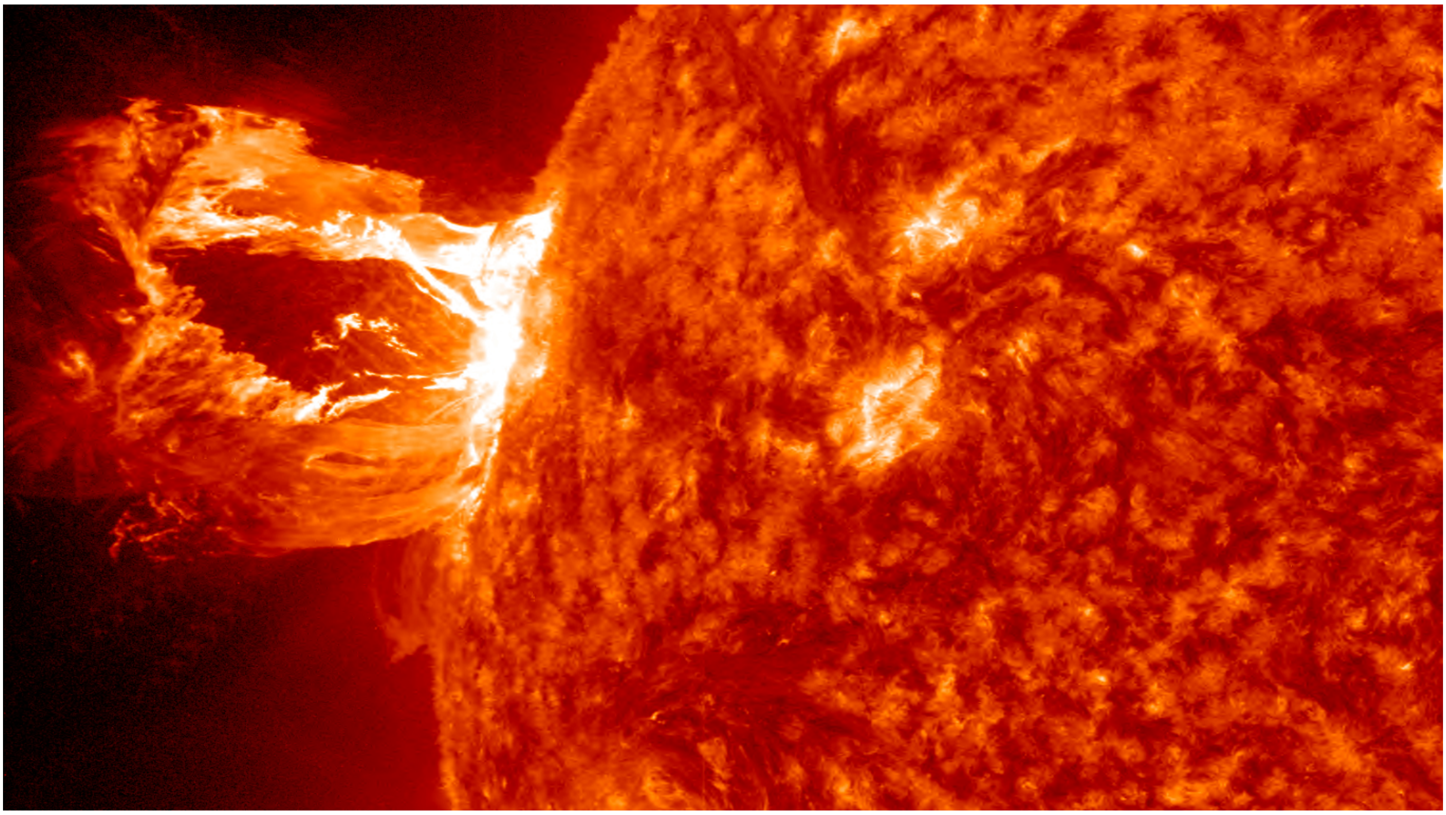

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29-30 October, 2013, Ispra, Italy

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Executive summary

The impact of space weather on the power grid is a tangible and recurring threat with potentially serious consequences on society. Of particular concern is the long-distance high-voltage power grid, which is vulnerable to the effects of geomagnetic storms that can damage or destroy equipment or lead to grid collapse.

In order to launch a dialogue on the topic and encourage authorities, regulators and operators in Europe and North America to learn from each other, the European Commission's Joint Research Centre, the Swedish Civil Contingencies Agency, and NOAA's Space Weather Prediction Centre, with the contribution of the UK Civil Contingencies Secretariat, jointly organised a workshop on the impact of extreme space weather on the power grid on 29-30 October 2013. Topics addressed were space-weather phenomena and the dynamics of their impact on the grid, experiences with prediction and now-casting in the USA and in Europe, risk assessment and preparedness, as well as policy implications arising from increased awareness of the space-weather hazard.

The "Space Weather and Power Grids" workshop was attended by 50 representatives from European and North American power-grid operators, regulators, emergency-response organisers, space-weather experts, academia, the European Space Agency and the European Commission.

The main workshop conclusions are:

- There is increasing awareness of the risk of space-weather impact among power-grid operators and regulators and some countries consider it a priority risk to be addressed.
- The predictability of space-weather phenomena is still limited and relies, in part, on data from ageing satellites. NOAA is working with NASA to launch the DSCOVR solar-wind spacecraft, the replacement for the ACE satellite, in early 2015.
- In some countries, models and tools for GIC prediction and grid impact assessment have been developed in collaboration with national power grids but equipment vulnerability models are scarce.
- Some countries have successfully hardened their transmission grids to space-weather impact and sustained relatively little or no damage due to currents induced by past moderate space-weather events.
- While there is preparedness in industry against moderate space weather, the vulnerability of the power grid with respect to Carrington-type events is less conclusive and needs to be assessed.
- The assessment of space-weather impact on society needs to consider possible interdependencies between critical infrastructures. These interdependencies are not routinely assessed.
- Effective risk communication is required to bridge the gap between science and policy and to convey the significance of scientific results to decision makers.
- Emergency-response planning for a severe space-weather event needs to consider the full range of potential impacts on critical infrastructure.
- For a severe geomagnetic storm inter-institutional and probably international emergency planning efforts are required as response capabilities of individual countries might be overloaded.
- In the USA work is in progress to augment the existing regulatory requirements for power-grid operations by introducing new standards to better meet the challenges posed by space-weather risk.

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1. Introduction

Many critical infrastructures on the ground and in space are vulnerable to the impact of severe space weather. Of particular concern is the long-distance high-voltage power grid, which is vulnerable to the effects of geomagnetic storms through the induction of Geomagnetically Induced Currents (GICs) that can damage or destroy equipment or lead to grid collapse due to cascading effects. While there is some awareness and knowledge among power-grid operators and regulators of the space-weather hazard, levels of awareness, as well as vulnerabilities, differ from country to country and regionally within North America.

In order to launch a dialogue on the topic and encourage authorities, regulators and operators in European countries and North America to learn from each other, the European Commission's Joint Research Centre (JRC), the Swedish Civil Contingencies Agency (MSB), and NOAA's Space Weather Prediction Centre (SWPC), with the contribution of the UK Civil Contingencies Secretariat, jointly organised a 2-day technical workshop on the impact of extreme space weather on the power grid on 29-30 October 2013 at the JRC's Ispra site. Topics discussed were space-weather phenomena and the dynamics of their impact on the grid, experiences with prediction and now-casting in the USA and in Europe, risk assessment and preparedness, as well as policy implications possibly arising from increased awareness of the space-weather hazard.

The "Space Weather and Power Grids" workshop was attended by 50 representatives from European and North American transmission-grid operators, regulators, emergency-response organisers, space-weather experts, academia, the European Space Agency and the European Commission. The workshop programme and the list of participants are provided in Annex 1 and 2.

2. Summary of topical key findings

The workshop was structured into six sessions, each addressing a specific topic related to the impact of space weather on the power grid. The speakers represented various stakeholder groups in Europe, North America and South Africa, and included academia, utilities and regulatory bodies who commented on the topic from diverse technical, operational and organisational perspectives. In the following sections, the main conclusions from the workshop sessions are summarised.

2.1 Session 1: Awareness, policy action and international cooperation

In this session a panel of five senior speakers from Europe and the USA, including representatives of the Swedish MSB, the UK Civil Contingencies Secretariat, the US Federal Energy Regulatory Commission (FERC), the US Federal Emergency Management Agency (FEMA), and the European Commission discussed strategic and policy issues related to severe space weather and its potential impact on infrastructures.

During the discussions it was acknowledged that awareness of the space-weather risk is increasing. It was pointed out that a validated space-weather risk and impact assessment was required to facilitate the promotion and prioritisation of policy action. This assessment needs to take into account the growing interconnectedness of society and the ripple effect possibly caused by the disruption of one or several critical infrastructures. The European Commission has been tasked with establishing a list of priority risks the EU is facing and has been providing guidance to Member States in preparing national risk assessments. Four European countries (The Netherlands, UK, Sweden and Norway) have identified severe space weather as a major threat to their infrastructures and consequently to society, and they have included reasonable worst-case scenarios in their national risk assessment (Sweden will begin preparing national risk scenarios for space weather in 2014).

The outcome of risk assessment studies feeds directly into the development of contingency plans that will guide emergency response when a severe event occurs. In this context, costs can be reduced by preparing for common consequences of emergencies rather than for every individual emergency scenario. The generic response capabilities already in place or subsequently created are then applicable to various domains. This can be augmented by capacity building to address specific risks, should such a need be identified. This approach is being developed in the UK. In addition, effective risk communication needs to ensure that the information disseminated before or after an event is understood, with particular attention to bridging the gap between science and policy.

In the USA, there are significant legislative developments: FERC has issued a rule on the development of grid reliability standards for geomagnetic disturbances in 2013[1]. While this rule is goal-oriented and does not prescribe methods on how to achieve its objectives, it requires that risk mitigation plans and procedures be coordinated across the region and throughout the interconnections. FEMA has prepared a draft federal response plan for space weather which is proposed to be added to the long-term power outage annex of the Response Federal Interagency Operations Plan.

The key points from Session 1 are:

- Understanding the space-weather impact on critical infrastructures is a multidisciplinary problem and requires the involvement of scientists, engineers, operators and policy makers.
- There is increasing awareness of the space-weather threat among operators and regulators and some countries have included it in their national risk-assessment programmes as a priority risk to be addressed.
- Interdependencies between infrastructures require a holistic approach to understand the consequences of severe space weather on society as a whole.
- There is a need for integrated risk assessment to promote and prioritise policy action. The results of this risk assessment need to be translated into contingency plans to guide response actions.
- Many countries have generic response capacities to deal with the consequences of all kinds of hazards. For some hazards, however, specific contingency plans are also needed, and space weather may be one such hazard.
- Effective risk communication is required to bridge the gap between science and policy and to convey the significance of scientific results to decision makers.
- In the USA, legislation on ensuring power-grid reliability under geomagnetic-storm conditions and emergency-response plans are available at federal level. In addition, a validated notification procedure is in place between federal agencies and the power industry in case of an imminent geomagnetic storm.

[1] Order No. 779 on "Reliability Standards for Geomagnetic Disturbances". It requires the preparation of operating procedures to mitigate the effects of geomagnetic storms in a first step (January 2014), and subsequently vulnerability assessments and mitigation plans from owners and operators (January 2015).

2.2 Session 2: Space weather and GICs

Four speakers from Göttingen University, the Finnish Meteorological Institute, the British Geological Survey, and the University of Cape Town provided an introduction to the solar phenomena that can give rise to GICs on Earth, and discussed the analysis of GIC occurrences and modelling initiatives in the UK, Ireland and South Africa. In addition, the European 7th Framework Programme project EURISGIC was presented.

The session started with a discussion of the main characteristics of Coronal Mass Ejections (CMEs). It was highlighted that CMEs are abundant (10,000 during the last solar cycle) although the great majority are too slow, not Earth-directed, or have polarity orientation unfavourable for magnetic reconnection to trigger severe geomagnetic storms. Of greatest concern are fast CMEs with speeds of more than 2,000 km/s. During the last cycle, 40 of these high-energy events were observed. A prerequisite for triggering severe geomagnetic storms, magnetic reconnection processes are driven by the solar-wind speed and the interplanetary magnetic field (IMF) that has to be oriented southward (anti-parallel to Earth's magnetic field). It was also noted that geomagnetic storms can occur at any time during the solar cycle; they are not centred at solar maximum. With respect to seasonal effects, it appears that events which take place in and around April and September are more likely to lead to relatively high levels of geomagnetic activity ($K_p > 8$[2]).

In contrast to GIC nowcasting, which can provide accurate results if measured real-time magnetic-field data is available, the forecasting of GICs is not yet mature as it relies on the estimation of ground magnetic fields. The EURISGIC project works towards establishing a European prototype forecasting service to produce real-time GIC warnings for the high-voltage power grid. The underlying assumption is that the conductor system can be modelled using a DC model. The results suggest that determination of the maximum magnetic-field variation over time for a given time period (e.g. 30 minutes) is an achievable goal. In addition, the project statistically analyses historical geomagnetic-field measurements in combination with a simplified grid model to derive the probabilities of major GICs and to define worst-case scenarios. Based on the analysis of European data for 1996-2008, the largest modelled 1-minute GIC values in the European high-voltage power grid were found in Northern Europe and more specifically in the south of Norway (400A). Since this data only covers one solar cycle, higher GICs are likely in case of a Carrington-type event.

In several countries (e.g. United States, Canada, UK, Ireland, South Africa) the power industry is collaborating with scientists to help develop models and tools for GIC prediction and grid impact assessment. In a joint effort between industry and scientists, operational services have been developed that provide information on geomagnetic activity and predicted GICs to the transmission grids. In this context, the need for more magnetometer stations to achieve higher-resolution measurements of the magnetic field variation was emphasised. For the UK and Ireland, simplified high-voltage power network models were created and subsequently validated against the 2003 Halloween storm. A Carrington-type event was also simulated, assuming its severity to be eight times that of the 2003 storm. While it is uncertain if this assumption is justified, under these conditions the simulation yields GICs of several hundred A in parts of the UK power grid. With respect to the vulnerability of grid components it was noted that the risk of space-weather impact on transformers may be underestimated. When exposing a transformer of the South African operator ESKOM to a DC of 50 A, rapid heating was unexpectedly found. With some of ESKOM's 100 step-up transformers already slightly damaged

[2] The planetary index K_p provides a measure of the level of geomagnetic activity over a three-hour interval based on magnetometer measurements. The index ranges from 0 to 9.

by previous space-weather events, there is a high likelihood that in case of an extreme event, which is expected to create electric fields of 3-4 V/km (1-minute values), several might be destroyed.

The main conclusions from Session 2 are:

- Geomagnetic observatories are mainly concentrated in the northern hemisphere. More magnetometers should be installed to understand the variability of the magnetic disturbance locally or regionally.
- While nowcasting of GICs provides accurate results, forecasting is technically feasible but not yet mature.
- In some countries, models and tools for GIC prediction and grid impact assessment have been developed in collaboration with national power grids.
- The risk of space-weather impact on power-grid components may be underestimated. Even small GICs have been found to cause transformer damage, possibly leading to rapid or delayed failure.
- Although progress has been made in predictive modelling, further research and validation is needed.

2.3 Session 3: Canadian experience including a severe event

In this session, a speaker from Natural Resources Canada outlined the events around the 1989 geomagnetic storm that severely affected parts of the Canadian power grid and discussed steps taken to improve GIC forecasting capabilities[3].

Being the first major power outage due to space weather, the Hydro-Quebec blackout was a wake-up call for the power industry worldwide. In addition, the loss of power affected industrial production in a number of other sectors. This event changed the risk landscape and posed a challenge both to scientists, who were required to improve their understanding of the geomagnetic activity, and to industry, which needed to start considering the risks related to GIC flow in their power systems. In addition, a higher accuracy of geomagnetic-activity forecasts (including start time, amplitude, and end time) was required to support grid operators. As a consequence, a GIC simulator service was developed in collaboration with the Ontario power transmission operator Hydro One that automates steps in GIC modelling. This service, which is also available as a standalone version which accepts any grid configuration, uses real-time geomagnetic data to calculate the electric field, and then estimates the GIC in a connected power system model. A benchmark GIC model is also available to users for testing purposes in case they want to set up their own GIC model.

Recently, the geomagnetic and grid conditions at the time of the Hydro-Quebec blackout were recreated by the operator based on historical data. The results of this simulation suggest that the cause of the blackout was increased reactive power losses that eventually led to voltage collapse at a total consumption of 1,770 MVAR[4]. Following the grid collapse, Hydro-Quebec implemented measures to render their transmission network less vulnerable to space-weather impact, e.g. through automated undervoltage load shedding and shunt reactor operation, as well as series compensation. Further simulations using the power grid's 2012 configuration and subjecting it to multiples of the 1989 MVAR consumption indicate that the Hydro-Quebec grid would now remain stable up to almost five

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[3] Due to technical reasons, the planned video-link with Hydro-Quebec in Montreal could not be established. However, their presentation was provided after the workshop and its main conclusions are included in this session summary.

[4] The unit MVAR stands for Mega Volt-Ampere-Reactive. It measures reactive power in a transmission grid.

times the 1989 conditions. These simulations, however, did not consider the additional impact of other potential GIC-related problems, such as transformer heating, harmonics, voltage asymmetry, etc.

The key findings from Session 3 are:

- The collapse of the Hydro-Quebec network in 1989 led to the realisation that magnetic storms can adversely affect power systems and was a wakeup call for the power industry.
- Recent studies by Hydro-Quebec that recreated the 1989 geomagnetic and power-grid conditions showed that the likely cause of the blackout was slow voltage collapse due to reactive power consumption.
- The blackout caused ripple effects in several industrial sectors resulting in considerable economic losses.
- Simulations using the 2012 power grid configuration indicate that the Hydro-Quebec grid can currently withstand almost five times the 1989 conditions and remain stable.
- A GIC simulator service using real-time geomagnetic activity data and accepting different grid configurations is available to the power industry in Canada.

2.4 Session 4: USA experience – NOAA's facilities and their use

In Session 4, four speakers from NOAA and PJM[5], the largest electricity operator in North America, introduced the monitoring and prediction facilities of NOAA's Space Weather Prediction Centre and discussed the real-time use of the SWPC's products.

The SWPC is the official source of space-weather alerts and warnings in the USA. For risk communication purposes NOAA has developed five-tier severity scales for radio blackouts, radiation storms and geomagnetic storms. In a video link with the SWPC in Boulder the space-weather notification process was outlined. When the SOHO or STEREO satellites observe a CME directed towards Earth a geomagnetic storm watch is issued. This is followed by a warning when the CME hits the ACE satellite[6] 1-3 days later at which point first indications of the orientation of the IMF become available. Warnings are typically issued 15-45 minutes before geomagnetic storm onset. Once the CME impacts the geomagnetic field and the storm begins, the SWPC issues an alert. In this context it was noted that the NOAA space-weather scales saturate for $K_p = 9$ events which causes the very large and really extreme events to be assigned the same severity value. In case of necessity, the SWPC notifies its customers and government directly via telephone to circumvent this problem.

While there is progress in model development, forecasting capabilities are still limited due to gaps in understanding the orientation of the IMF with respect to the Earth's magnetic field at the time of the occurrence of the CME at the Sun. The CME must reach the ACE spacecraft for forecasters to get a good understanding of the IMF and the likely intensity of the ensuing geomagnetic storm. The SWPC is working closely with the US Geological Survey (USGS) on the development of an Electric-field (E-field) model. The first step will be to accurately specify the E-field - a nowcast product that essentially captures the current conditions regionally. The SWPC is also working with NASA on the transition of a geospace model. This model will assess and eventually forecast how the magnetosphere responds to a CME and will be a key element in the effort to forecast electric fields. NOAA also collaborates actively with the USGS to improve ground-conductivity models. A sparseness of magnetometer

[5] Pennsylvania, Jersey, Maryland Power Pool.
[6] The ACE (Advanced Composition Explorer) satellite is positioned at the L1 Lagrange point at a distance of about 1.5 million km from the Earth.

stations was noted and more are needed to establish a satisfactory baseline for the magnetic field, ideally in the vicinity of conductivity boundaries or where physical infrastructures are located.

The predictability of space-weather phenomena is still limited and partly relies on data from ageing satellites. However, NOAA is working with NASA to launch the DSCOVR spacecraft in early 2015. DSCOVR will replace the ACE spacecraft and ensure continuity of solar wind measurements and the critical short-term, high-confidence geomagnetic storm warnings. There are also exciting new initiatives underway that may produce important breakthroughs such as the Sunjammer mission. Sunjammer, scheduled for launch in 2015, is a solar sail demonstration/research mission which deploys a huge, ultra-thin sail, using the pressure of sunlight to provide propellant-free transport. This technology will allow for an operating location further away from Earth than the L1 orbit and provide much needed additional lead time (one hour) to geomagnetic-storm warnings.

PJM Interconnection, which is a part of the Eastern Interconnection grid in the USA, coordinates the movement of electricity in all or parts of 13 US states and the District of Columbia, thereby serving 61 million people. GIC monitoring was put in place following the 1989 storm when a generator step-up transformer at the Salem nuclear power plant failed due to GICs. Procedures have not greatly changed since and current operational mitigation strategies foresee a more conservative way to operate the grid when measured GIC magnitudes persist for 10 minutes above a threshold of 10A. This includes the resetting of transfer limits, redispatching of generation, reducing transformer loading, and increasing voltage. The existing measures should provide protection from the effects of moderate geomagnetic storms but there is concern about the potential impact of severe space weather. As a consequence, PJM has started investigating reactive power losses and studies the maximum credible GIC scenario to better understand the grid response to extreme events. Following the 2003 Northeast blackout in North America, PJM has implemented measures to be better prepared for reactive power losses. It judges that these measures will also help to render the grid less vulnerable against GIC impact.

The main conclusions from Session 4 are:

- There is a broad range of SWPC products available that support numerous industrial sectors in better protecting their infrastructures and services.
- The NOAA space-weather scales saturate for $K_p = 9$ events which causes the very large and really extreme events to be assigned the same severity value.
- Mid- to long-range forecasting is hampered by the limited understanding of the IMF’s orientation with respect to Earth’s magnetic field.
- The predictability of space-weather phenomena is still limited and partly relies on data from ageing satellites. NOAA is working with NASA to launch the DSCOVR spacecraft in early 2015 to replace the ACE satellite and ensure continuity of solar-wind measurements and the critical short-term, high-confidence geomagnetic-storm warnings.
- Some electricity operators have GIC monitoring and operational strategies in place against moderate space-weather events.
- Measures to make the power grid more resilient against conventional blackouts may coincidentally help to render the grid less vulnerable against GIC impact.
- From a GIC point of view, the length of the whole power system is of importance rather than the length of individual lines.

2.5 Session 5: Risk assessment and management

Discussing more generally the space-weather disaster risk management cycle, six speakers from NASA, the North American Electric Reliability Corporation (NERC), the JRC, UK National Grid and the UK Civil Contingencies Secretariat addressed prevention, preparedness and response aspects.

For prevention and mitigation purposes it is important to know the severity of extreme events, information which then filters into scenario building and risk assessment. Given its direct applicability to subsequent engineering analyses the determination of the geo-electric field is of particular importance. Approaches to derive electric-field scenarios are either event-based (historical storm data), statistical (magnetometer data and extrapolation), theoretical (state-of-the-art models), or a mix of these three. First results at NASA indicate that state-of-the-art models manage to provide a fairly accurate representation of the electric field observed during the Halloween storm. This suggests that models have the capability to reproduce realistic extreme conditions. The studies also show that in case of an extreme geomagnetic storm the event boundary would move south towards 40 degrees magnetic latitude.

NASA and NOAA closely work together with NERC, a non-profit organisation responsible for establishing and enforcing mandatory electric reliability standards with authority in the US and Canada and subject to oversight from FERC and Canadian authorities. In response to NERC's 2012 report on the effects of geomagnetic disturbances on the bulk power system, a GMD[7] task force was formalised to develop methodologies and tools for industry to assess the risk of geomagnetic storms and rank mitigation options. These tools are tailored for use by operators and planners. NERC also operates a voluntary spare-equipment database with a focus on long lead-time equipment to facilitate the recovery process in case of a severe event. The products and schedule of the GMD task force are aligned with the requirements of FERC Order No. 779.

The UK National Grid carried out an assessment of the potential space-weather risks to their transmission system. Widespread transformer damage and the subsequent collapse of the interconnected grid are considered extremely unlikely. A Carrington-type storm, assumed to have a 100-year return period, would damage a small number of transformers and in spite of high financial losses to the operator, there would be little impact on the end users. Other effects of space weather, such as reactive power loss and harmonic effects, or transformer degradation, are expected to be more frequent but are considered low-impact events with local, temporary effects. National Grid relies on operational and design mitigation to cope with geomagnetic storms. Operational measures include the return to service of all circuits, extra reactive power support, or the connection of all Supergrid transformers to distribute the GIC. Design measures provide for inherent security and include GIC-resistant transformer design, a higher number of transformer spares, voltages below 400 kV, etc. National Grid has also commissioned studies to develop transformer fragility functions with respect to GIC impact. Assuming a 1 in 100-year event, it is estimated that at most 10-20 transformers would suffer thermal damage and be taken out of service. This constitutes 1% of all transformers in the grid. With the available transformer spares an event of such magnitude is considered manageable. Space-weather protocols and emergency-information exchange between the stakeholders are tested during targeted control-room exercises.

The UK Civil Contingencies Secretariat is developing national multi-stakeholder response plans for space weather, taking into account the wide range of potential impacts, such as loss of power, disruption of HF and satellite communications, GPS, etc. Emergency response can be complicated by interdependencies between critical-infrastructure sectors, a potential vulnerability that is not always

[7] GMD: Geomagnetic disturbance

fully assessed. For instance, many infrastructure sectors are critically dependent on the availability of electricity. Should the power grid be affected, there will be ripple effects throughout society. Increasing the resilience of the grid is therefore of paramount importance. In this context it was pointed out that operators have to be aware that the reliance of Smart grids on GPS timing potentially adds vulnerability to the grid. Currently, loss of GPS capability is not a problem for the UK power industry as critical transmission-grid systems use atomic clocks as timing backup. An emergency exercise simulating the local loss of the power grid is planned for April 2014. With respect to space-weather forecasting and prediction, the UK Met Office has created its own capabilities and is developing its capability and mechanisms to provide alerts to industry and government.

For assessing the overall risk of space-weather impact on society due to loss of power, severe geomagnetic-storm scenarios, network disruption models and loss-estimation methods have to be coupled. This integrated modelling system also needs to be able to account for possible interdependencies. The JRC has developed a platform for assessing the risk and resilience of critical infrastructures with a focus on interdependencies. Provided that impact models are available, this platform is generally applicable to all types of incident triggers, and hence also to space-weather impact.

Following the conclusions of the 2011 Space-Weather Awareness Dialogue[8], the JRC asked whether there would be support for an emergency exercise to provide a stress test for response capabilities both nationally and internationally. A severe geomagnetic storm would put several complex critical-infrastructure systems into interaction with each other, and a dedicated exercise would help to identify gaps and weaknesses in emergency procedures. Generally, the idea was well received, in particular to test stakeholder responsibilities and communication protocols. There was some scepticism as to the carrying out a full-blown emergency exercise which might be too ambitious. Rather, there should be a focus on specific aspects of the problem.

The key findings from Session 5 are:

- Initial modelling efforts of severe-event scenarios suggest that there is the capability to reproduce realistic extreme conditions.
- It is expected that during a Carrington-type occurrence the event boundary would move southward towards 40 degrees magnetic latitude. This would encompass a significant part of Europe and North America.
- The design-basis reference geomagnetic storm needs to be defined for benchmarking purposes.
- The risk assessment of space-weather impact on society needs to consider possible interdependencies between critical infrastructures. These interdependencies are not routinely assessed.
- Scenario development and risk assessment efforts are hampered by a lack of equipment vulnerability models. Efforts are underway to close this gap.
- In some countries there are concerns about limited availability of spare transformers and a lack of manufacturing capacity.
- Emergency-response planning for a severe space-weather event needs to consider the full range of possibly affected critical infrastructures.
- With the use of Smart grids and the increased dependence on GPS timing the power industry might be inadvertently building additional vulnerability into their systems.

[8] E. Krausmann (2011) The Space-Weather Awareness Dialogue: Findings and Outlook, EUR 25016 EN.

- Developing a common language between scientists and engineers facilitates risk communication.
- A severe geomagnetic storm would affect large geographical areas simultaneously and cause ripple effects due to interdependencies between affected critical infrastructures. This requires inter-institutional and probably international response planning efforts as response capabilities of individual countries might be overloaded. It might be beneficial to test certain aspects of the response during a dedicated international emergency exercise.

2.6 Session 6: Looking forward: operator requirements and regulation

The workshop concluded with a discussion of operator and regulatory requirements with contributions from Norwegian and Swedish transmission grid operators, FERC and ESA.

Sweden has significant experience with geomagnetic disturbances that caused the tripping of overhead lines, transformers or shunt reactors. However, space weather has on no occasion resulted in damage to the transmission system. Based on lessons learned from past experiences, an improved earth fault protection system was introduced to achieve selective tripping. Transformers were hardened through design, and today about two thirds of the transformers in the transmission system are 3-limbed, 3-phase core transformers that can withstand a DC of 200 A for 10 minutes in the neutral at full AC load. The remainder of the transformers do not fulfil these specifications as they are older. As an additional precautionary measure, no critical transmission grid-system is dependent on GPS. The robustness of the system to moderate space weather was proven during several G4 and G5 events (on the NOAA scale) where only tripping occurred in a few cases. With respect to a Carrington-type event or worse, the Swedish National Grid believes that the transmission grid will collapse due to reactive power consumption and voltage instability before transformers can incur any serious damage. In this case, post-collapse start-up times are estimated to be about one hour for the transmission grid, and six to eight hours for the distribution network.

The Norwegian transmission grid also experienced several cases of small (5-15 A) to higher (>20A) GIC events. The highest GIC measured was 40 A in a transformer neutral. This resulted in a voltage drop of 1-2 kV in a 420 kV system which is, however, not considered problematic. GICs are measured at six monitoring stations in the south and north of the country with the aim to establish a correlation between the K_p index and GIC levels in transformers. Norway has to date not suffered any blackouts or partial transmission-grid outages due to space weather. With respect to the impact of an extreme geomagnetic storm, the Norwegian grid operator also judges that the transmission grid will collapse due to voltage instability before critical network components are seriously damaged or fail. Nonetheless, to mitigate the risk associated with space weather operators need advance information on potential events affecting Earth. Early warning on solar activity is required with a lead time of 3-4 days. Once it is certain that a CME is Earth-directed (1-3 days before impact), information on affected regions, the likely strength of the geomagnetic storm, and the time of impact is needed. When the geomagnetic storm is imminent (2-4 hours desired lead time), the operator requires information on the potential regional effects, the K_p index, and the expected duration of the event.

ESA has generated a set of technology roadmaps, one of which is in the space-weather effects domain. The energy sector was identified as a potential area for service deployment using space systems. As a consequence, the Space and Energy roadmap was consolidated with a focus on power grids, taking as a starting point the Space Situational Awareness programme preparatory phase. Subsequently, high-priority technology fields of interest for collaboration with the energy sector were identified: For forecasting purposes, solar wind measurements and models relating solar-wind data to geomagnetic disturbances and GIC, are of crucial importance. Geomagnetic and GIC models are critical for the specification of extreme events. The roadmap is currently in the review phase and will eventually be implemented through ESA's technology programmes.

Before the 1960s, several storms with severities higher than that of the 1989 event occurred and yet no major impacts are documented. In the USA, the expansion of the power grid to extremely high voltage started in the 1960s and FERC considers it possible that this caused vulnerabilities to unknowingly be introduced into the transmission system. Some design and operational mitigation measures are in place, and there is hope that the US power grid can withstand a 1989-type of storm. The current regulatory framework is in the process of being updated to better meet the challenges of potential space-weather impact on the power grid. In this context it was emphasised that the main objective of the new legislation is to guarantee the continued functioning of the grid rather than protect the system's hardware. As a consequence, grid collapse rather than widespread transformer damage or failure is also not considered an acceptable option when there is the capability to prevent it from happening.

The key points from Session 6 are:

- Some countries have successfully hardened their transmission grids to space-weather impact and sustained relatively little or no damage due to currents induced by past moderate space-weather events.
- While there is preparedness in industry against moderate space weather, the vulnerability of the power grid with respect to Carrington-type events is less conclusive and needs to be assessed further.
- In some European countries it is believed that in the case of a severe space-weather event the grid will collapse due to reactive power consumption and voltage instability before transformers can be damaged. However, grid collapse might not be an acceptable consequence.
- Operators require early-warning information that includes the strength of the geomagnetic storm, the regions it will affect and the time and duration of impact to mitigate the risk to the power grid.
- There are existing or planned European space-weather forecasting capabilities but further developments are needed. This includes agreement on how best to share forecasts and alerts more widely.
- In the USA work is in progress to augment the existing regulatory requirements for power-grid operation by introducing new standards to better meet the challenges posed by space-weather risk.

3. Conclusions and recommendations

The impact of space weather on the power grid is a tangible and recurring threat with potentially serious consequences on society. Moreover, unlike for most other risks, the assessment of space-weather impact requires a multidisciplinary effort by scientists, engineers, operators of critical infrastructures, and policy makers. The discussions during the workshop showed that industry is increasingly aware of the possible impact of geomagnetic storms on their transmission grids, and regulatory bodies are updating legislation to address the challenges posed by space-weather risk. This, coupled with industry's experience with moderate space-weather events, has led to design improvements to harden critical transmission-grid components, as well as to the preparation of operational mitigation measures. Nonetheless, for both Europe, North America and South Africa the grid response to a Carrington-type event is less conclusive and further research is required to clarify this issue.

The workshop participants welcomed the initiative by the JRC, MSB and NOAA to organise this event and to provide a forum of exchange among the relevant stakeholders. The discussions helped to establish the status quo and identify gaps, while at the same time providing a basis for the prioritisation of actions for future incident prevention and consequence mitigation. The main conclusions of the workshop can be summarised as follows:

- There is increasing awareness of the risk of space-weather impact among power-grid operators and regulators and some countries consider it a priority risk to be addressed.
- The predictability of space-weather phenomena is still limited and relies, in part, on data from ageing satellites. NOAA is working with NASA to launch the DSCOVR solar-wind spacecraft, the replacement for the ACE satellite, in early 2015.
- In some countries, models and tools for GIC prediction and grid impact assessment have been developed in collaboration with national power grids but equipment vulnerability models are scarce.
- Some countries have successfully hardened their transmission grids to space-weather impact and sustained relatively little or no damage due to currents induced by past moderate space-weather events.
- While there is preparedness in industry against moderate space weather, the vulnerability of the power grid with respect to Carrington-type events is less conclusive and needs to be assessed.
- The assessment of space-weather impact on society needs to consider possible interdependencies between critical infrastructures. These interdependencies are not routinely assessed.
- Effective risk communication is required to bridge the gap between science and policy and to convey the significance of scientific results to decision makers.
- Emergency-response planning for a severe space-weather event needs to consider the full range of potential impacts on critical infrastructure.
- For a severe geomagnetic storm inter-institutional and possibly international emergency planning efforts are required as response capabilities of individual countries might be overloaded.
- In the USA work is in progress to augment the existing regulatory requirements for power-grid operations by introducing new standards to better meet the challenges posed by space-weather risk.

Overall, the use of space-weather and ground-conductance data is more widespread in North America than in Europe. However, European transmission networks appear to be less vulnerable to geomagnetic storms than North American ones. Possible factors could be the reduced exposure due to a greater distance from the magnetic pole, lower voltage lines, or different transformer designs. Further studies are required to shed light on this issue, in particular in view of strategic decisions to upgrade the power grid to more high-voltage lines or to expand the network to areas farther north.

Based on the conclusions of the workshop, recommendations for action targeting stakeholders in science, industry and policy were formulated:

Recommendations for science:

1. The predictability of space-weather phenomena should be improved by updating and validating existing models to reduce uncertainties, or by creating new models where necessary.
2. There is a need for developing integrated risk-assessment methodologies and tools that consider potential interdependencies between critical infrastructures. This is essential for providing a

realistic estimate of the impact of severe space weather on the power grid, and as a consequence on society.

3. Benchmark GMD events must be identified to define the severity of geomagnetic storms that power-grid operators must look at for potential impacts. This is a prerequisite for adequately addressing GMD mitigation strategies.
4. Impact models for power-grid components are required for worst-case scenario building in support of risk assessment. Cooperation with industry should be sought to facilitate this issue.
5. In order to plan their response decisions, power-grid operators need regional information on the expected time and location of impact, as well as on the severity and duration of the geomagnetic storm. Forecasting capabilities need to be enhanced to this end.
6. There is a need for cooperation between industry and science to model the power grid's response behaviour to the impact of GIC, the impact on individual grid components, and appropriate countermeasures.

Recommendations for operators:

1. Operators should be aware of the risks to their transmission systems in case of severe space weather when areas normally unaffected by geomagnetic storms are likely to be hit.
2. Before implementing new technological developments into the power grid, their influence on the overall vulnerability of the system to space weather should be assessed. This applies also to other sectors, where for risk mitigation is required for potentially vulnerable new technologies.
3. Consideration of the potentially serious effects of major GICs in power systems should encourage operators to harden their systems, and to have response plans ready in case of an alert.

Recommendations for agencies:

Further study is needed in the following areas:

1. Assessment of the vulnerability of critical infrastructures to severe space weather, and where relevant inclusion in overall risk and resilience assessment.
2. Communication of space weather risk to stakeholders, and ensuring that emergency plans which consider the full range of critical infrastructures possibly affected are developed and tested.
3. Mechanisms to ensure that space-weather alerts are available to all stakeholders. A European information-sharing capability on space weather could draw on the example of the European Response Coordination Centre.
4. Development of protocols to ensure consistency in the prediction of geomagnetic storms in both timing and intensity by different space-weather service providers.
5. Identification of the reasons for the differences across countries in the relevant legislative frameworks, and consideration of what further measures may be needed to ensure the integrity of power-grid systems and the availability of their services.

Annex 1: Agenda

29th October 2013
0900 - 1050

Session 1: Awareness, policy action, and international cooperation

Chair: Alois Sieber, JRC, Italy

0900 - 0915	**Defining the key challenges for policy action** • S. Lechner, Director, IPSC, JRC
0915 - 1015	**Policy framework and policy action - presentations by:** • Helena Lindberg, Director General, MSB, S • Rick Waggel, Office of Energy Infrastructure Security, FERC, USA • Thomas de Lannoy, DG ECHO, EC • Philippa Makepeace,Deputy Director, Civil Contingencies Secretariat, UK • Leviticus Lewis, DHS/FEMA, USA
1015 - 1050	**Panel discussion with all presenters from this session**

29th October 2013
1105 - 1310

Session 2: Space weather and GICs

Chair: Elisabeth Krausmann, JRC

1105 - 1140	**CMEs and their magnetic and electric consequences** • Volker Bothmer, Göttingen University, D
1140 - 1205	**GICs across Europe: the EURISGIC initiative** • Ari Viljanen, Finnish Meteorological Institute, FI
1205 - 1230	**Analysis of GICs in the UK and Ireland** • Alan Thompson, Geological Survey, UK
1230 - 1255	**GICs and their effects on electric grids** • Trevor Gaunt, University of Cape Town, SA
1255 - 1310	**Discussion**

29th October 2013
1400 - 1500

Session 3: Canadian experience, including a severe event

Chair: Neil Mitchison, JRC

1400 - 1440	Video link to Québec, Canada **The 1989 solar storm in Canada, and subsequent developments and simulations** • Sébastien Guillon, Hydro-Québec, Canada + colleague
1440 - 1505	**NRCan space weather activities in support of power utilities** • David Boteler, Head, space weather group, Natural Resources Canada
1505 - 1515	**Discussion**

Session 4: USA experience – NOAA's facilities and their use

Chair: Bill Murtagh, NOAA

29th October 2013
1530 - 1730

Video link to Boulder, Colorado, USA **Live demonstration of NOAA's monitoring and prediction facilities** • Bill Murtagh and Bob Rutledge, NOAA, USA	1530 - 1615
Real-time use of NOAA's real-time monitoring and prediction • Frank Koza, PJM Interconnection LLC, USA	1615 - 1640
Use of NOAA's information for subsequent analysis and model calibration • Chris Balch, NOAA, USA	1640 - 1705
Discussion	1705 - 1730
End of first day's proceedings	1730

Session 5: Risk assessment and management

Chair: Emmelie Andersson, MSB, S

30th October 2013
0900 - 1230

Definition of a benchmark geomagnetic distrurbance, and its consequences • Antti Pulkinnen, NASA, USA	0900 - 0930
The consequences of action and inaction for a severe event • Tom Burgess, NERC, USA	0930 - 1000
A flexible platform for assessing GIC related risks at European Level • Georgios Giannoploulos, JRC	1000 - 1030
Preparedness in the UK National Grid: use of monitoring and prediction • Andrew Richards, National Grid, UK	1050 - 1120
Emergency planning: mitigating the effects on society • Chris Felton, UK Cabinet Office	1120 - 1145
Communication and coordination of response: planning for an exercise • Neil Mitchison, JRC	1145 - 1155
Discussion	1155 - 1230

Session 6: Looking forward: operator requirements, regulation

Chair: Marcelo Masera, JRC

30th October 2013
1400 - 1630

Lessons learned from impacts of GIC and the development of the Swedish power grid • Stefan Arnborg, National Grid, Sweden	1400 - 1425
Operator requirements: information, timing, reliability • Trond Ohnstad, Statnett, Norway	1425 - 1450
An ESA analysis of technology requirements • Alain Hilgers, ESA	1450 - 1520
Regulatory requirements in the USA • Rick Waggel, Office of Energy Infrastructure Security, FERC, USA	1520 - 1550
Next steps: discussion with intervention from JRC, MSB, NOAA, UK CO	1550 - 1630
Close of workshop	1630

Annex 2: Participant list

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Abstract

The impact of space weather on the power grid is a tangible and recurring threat with potentially serious consequences on society. Of particular concern is the long-distance high-voltage power grid, which is vulnerable to the effects of geomagnetic storms that can damage or destroy equipment or lead to grid collapse.

In order to launch a dialogue on the topic and encourage authorities, regulators and operators in Europe and North America to learn from each other, the European Commission's Joint Research Centre, the Swedish Civil Contingencies Agency, and NOAA's Space Weather Prediction Centre, with the contribution of the UK Civil Contingencies Secretariat, jointly organised a workshop on the impact of extreme space weather on the power grid on 29-30 October 2013. Topics addressed were space-weather phenomena and the dynamics of their impact on the grid, experiences with prediction and now-casting in the USA and in Europe, risk assessment and preparedness, as well as policy implications arising from increased awareness of the space-weather hazard.

The "Space Weather and Power Grids" workshop was attended by 50 representatives from European and North American power-grid operators, regulators, emergency-response organisers, space-weather experts, academia, the European Space Agency and the European Commission.

The main workshop conclusions are:

- There is increasing awareness of the risk of space-weather impact among power-grid operators and regulators and some countries consider it a priority risk to be addressed.
- The predictability of space-weather phenomena is still limited and relies, in part, on data from ageing satellites. NOAA is working with NASA to launch the DSCOVR solar-wind spacecraft, the replacement for the ACE satellite, in early 2015.
- In some countries, models and tools for GIC prediction and grid impact assessment have been developed in collaboration with national power grids but equipment vulnerability models are scarce.
- Some countries have successfully hardened their transmission grids to space-weather impact and sustained relatively little or no damage due to currents induced by past moderate space-weather events.
- While there is preparedness in industry against moderate space weather, the vulnerability of the power grid with respect to Carrington-type events is less conclusive and needs to be assessed.
- The assessment of space-weather impact on society needs to consider possible interdependencies between critical infrastructures. These interdependencies are not routinely assessed.
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