

THE INTERNATIONAL E-PRO™ REPORT



EPRO™
ELECTRIC GRID PROTECTION

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The International E-Pro™ Report

International Electric Grid Protection

A report summarizing the status of national electric grid evaluation and protection against electromagnetic threats in 11 counties.

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Electric Infrastructure Security Council

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International delegates confer at the first Electric Infrastructure Security Summit in Westminster Palace, London, 2010

THE INTERNATIONAL E-PRO™ (ELECTRIC GRID PROTECTION) REPORT

As national power grids have evolved, there has been a steady trend toward ever greater sensitivity to the full range of electromagnetic threats¹. This historic and ongoing situation has resulted in growing concerns in nations all over the world, and evaluation efforts and grid protection measures have been taken, or are in progress, worldwide.

This report reviews international efforts relevant to grid vulnerability and protection, both in regard to electromagnetic threats and for other hazards which can benefit from synergistic resilience investments.

¹ Electromagnetic threats, or “e-threats,” include natural electromagnetic hazards such as geomagnetic current induced by severe space weather or inadvertent electromagnetic interference, Electromagnetic Pulse (EMP), or Intentional Electromagnetic Interference (IEMI). See below for more information.

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1

Executive Summary

The goal of the International E-Pro Report is to provide a high level review of international efforts at power grid protection against electromagnetic threats.

Although it is beyond the scope of this report to provide a detailed, in-depth review of the many activities progressing around the world, the E-PRO Report is designed to provide a global sampling and perspective of efforts underway regarding this critical issue.

We wish to thank the many nations and corporations that contributed to this project, and to express the hope that this report will provide a global context for e-threat protection.

1.1 Introduction

As national power grids evolved, there has been a steady trend toward ever greater sensitivity to the full range of electromagnetic threats. This has resulted in growing concerns by utilities and governments, and efforts to evaluate the potential threats and grid protection measures have been taken by different countries and corporations, internationally.

This report reviews international efforts relevant to grid vulnerability and protection, both in regard to electromagnetic threats and for other hazards which can benefit from synergistic resilience investments. Eleven nations were selected for this review, based on available information indicating relevant in-country efforts, and on adequate international relationships to acquire information. The U.S. was not included in this report due to a parallel FERC Notice of Proposed Rulemaking process that was ongoing during development of this report.

1.2 Report summary and conclusions

■ Electromagnetic Threat Overview

Serious electromagnetic threats (e-threats) to national power grids arise from two different sources.² Natural threats associated with periodic solar phenomena – Coronal Mass Ejections (CME) – can generate large, unwanted direct current (DC) flows through power grids the world over. Malicious threats include effects caused by both high-altitude detonation of a nuclear weapon, and by specially designed EMP devices. While both

² Note – Unintentional electromagnetic interference (EMI), is typically a lower level concern which is known and addressed by power companies, and therefore not addressed by this report.

malicious threat sources generate very high power pulses that can damage unprotected key electrical equipment, computers, and controls hardware, nuclear effects can also generate grid-damaging currents very similar to CMEs.

In recent years, a number of government studies³ have reviewed both of these hazards, concluding that power grids today are far more sensitive and vulnerable to e-threats than at any time in history.

■ **The International Picture**

This report provides a high-level summary of information on international efforts related to e-threats. Most of the countries surveyed have evaluated their perceived risks in this area, and several have put protective measures in place.

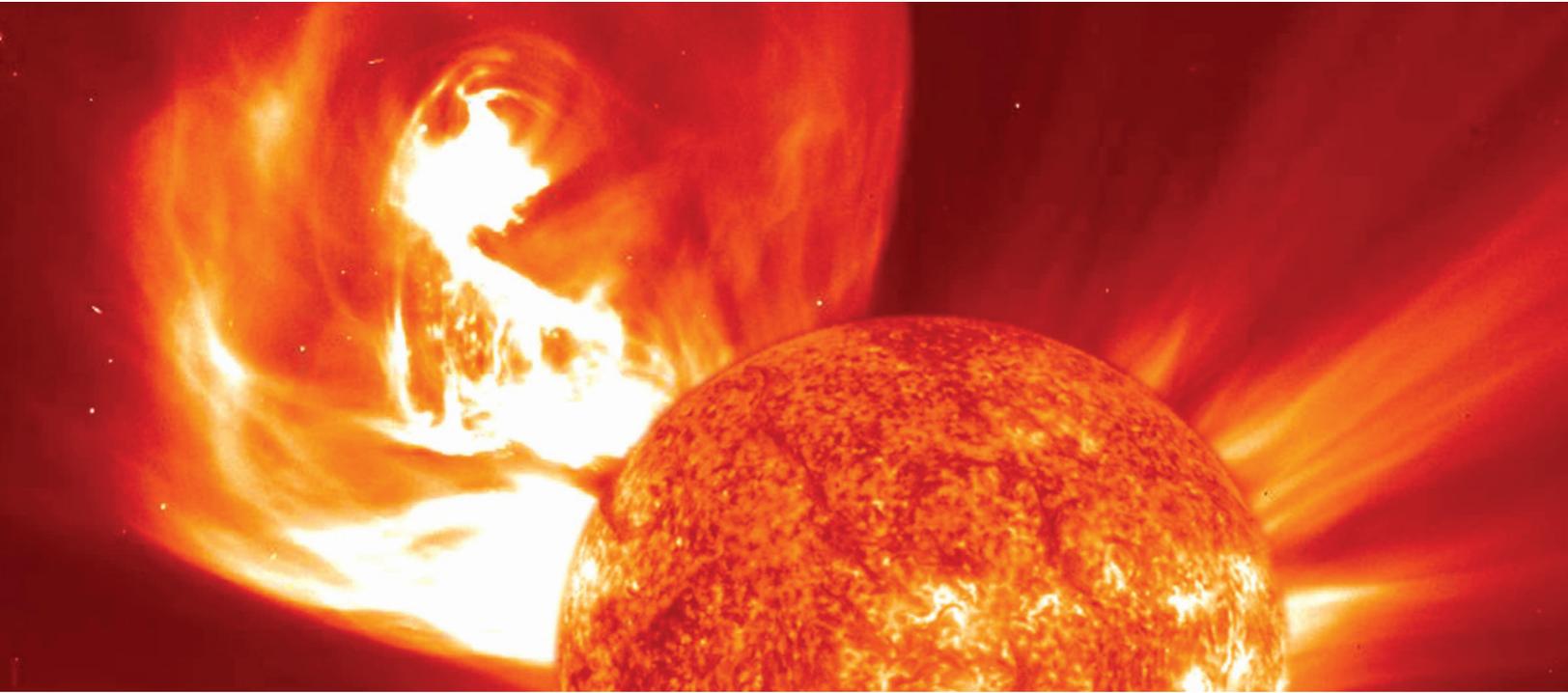
The predominant concern to the largest number of countries investigated is associated with Geomagnetically Induced Current (GIC). While GIC can arise from different causes, the most common cause is associated with Severe Space Weather. As expected, of the eleven countries examined, those most heavily invested in GIC evaluation and protection efforts are typically in the highest latitude zones. However there are several exceptions – as this report found, GIC concerns exist over a wider range of geographic latitudes.

Concerns associated with Electromagnetic Pulse (EMP) and Intentional Electromagnetic Interference (IEMI) were also found in a number of countries. As a malicious threat, efforts in this area were more commonly found in nations facing geostrategic threats. Important analyses and protection activities related to EMP and IEMI have taken place in Switzerland (the International Electrotechnical Commission), the United Kingdom, Israel and South Korea.”

³ For a complete set of report summaries and links, visit <http://www.eiscouncil.org/English/Resources/ResourcesCategory.asp?catid=221>

2

Background



Coronal Mass Ejection from the Sun: NASA

2.1 Solar-induced Geomagnetic Disturbances (GMD)

Overview

Natural threats are associated with severe space weather, specifically coronal mass ejections (CME) that inject energy into the earth's geomagnetic field, causing distortions of the field called geomagnetic disturbances (GMD). These disturbances induce voltage potential at earth's surface and in extra-high-voltage long transmission lines. These induced voltages, in turn, produce quasi-dc currents in the earth and the transmission lines that span large distances, flowing through the ground, transmission lines, and into the transformers that create the "ligaments" of a national power grid.

Depending on the magnitude of the current and the design and condition of a transformer, this unplanned current can cause voltage instability or even damage that can take the transformer out of service. If significant damage occurs, the transformer must be replaced. With replacement times typically measured in months or years, such damage has the potential to shut down large segments of regional or possibly national electric grids for long periods. In addition, protective relays are also susceptible to malfunction due to GMD, which could disrupt normal operation of a power grid. Such induced currents, if not mitigated, could disrupt normal operation of the power grid and result in voltage instability and/or equipment damage. The risk of GMD impact is dependent on a variety of factors, such as latitude, geology, power system topology, equipment age and design, etc.

2.1.1 GMD Phenomenology

A variety of solar weather conditions are of concern to our increasingly technology-intensive society. These conditions, when they occur, can affect national power grids, satellite constellations, air travel and a range of other technology domains.

Coronal Mass Ejections (CME) represent one of the most powerful of these solar weather conditions. When a jet of highly energetic plasma is ejected from the sun on a trajectory that intersects earth, the plasma cloud can distort the earth's magnetic field, inducing current (geomagnetically induced current – GIC) that flows into the extra high voltage (EHV) transformers that support the long distance transmission lines necessary to transfer power through national power grids.

Depending on the design, current condition, age and lifespan of a transformer, the GIC level for a transformer at any one grid node can induce dangerous voltage instabilities in the grid, or even local hot spots in transformer windings, support structure or other hardware elements. Either effect, depending on magnitude, creates risks for both the transformer and the power grid.

2.1.2 Severe Space Weather – Historical context

Based on a study by NASA and the National Academy of Sciences⁴, and on other research that preceded and followed this study, small or moderate level CME events (or massive CMEs that do not impact the earth) occur on an irregular but relatively frequent basis. Low level CMEs impact the Earth several times per year, while massive⁵ CMEs that also hit our planet have occurred with a frequency estimated at approximately once per century. The intensity versus frequency of these CMEs follows typical power law behavior.

The most famous of these occurred in 1859, coincident with very large solar flares observed by British solar astronomer Richard Carrington. This “Carrington Event” was followed sixty two years later by another CME of similar magnitude, the 1921 “Railroad Storm”.

Although both these events reportedly caused severe disruptions of the telegraph system – the only large scale electrical system then in existence – they preceded the development of national-scale power grids. Today’s complex grids, and the EHV transformers that are essential to their functionality, are far more sensitive than the antique global telegraph system.

In short, national power grids, world-wide, were built during one of the intervals between these periodic, massive CME-earth collision events. Although the precise timing of the next massive CME is not known, our knowledge of these effects, and their impact on our power grids, provides an opportunity to plan for the next severe space weather event, before its occurrence.



“Starfish Prime:” U.S. Nuclear Test

⁴ National Academy of Sciences, Severe Space Weather Events – Understanding Societal and Economic Impacts, 2008

⁵ E.g., Carrington Event class. See below.

2.2 Malicious Electromagnetic Threats

Overview

Malicious e-threats fall into two categories – nuclear and non-nuclear Electromagnetic Pulse (EMP) threats.

A “nuclear EMP” threat, also known as High-Altitude EMP (HEMP), creates a powerful, damaging electromagnetic field covering a region sub-continental in scale, likely shutting down critical infrastructures – if unprotected – over very large regions (impact region size depends on weapon yield and height of burst). “Non-nuclear EMP” threats may be even more powerful, but are typically very restricted in the size of the region affected. While both categories could affect many different utilities and infrastructures, by far the most serious risk is to unprotected national power grids, which represent a disaster that may be impossible to recover from⁶.

2.2.1 EMP Phenomenology

Any nuclear detonation produces a flood of gamma rays. When these gamma rays interact with the upper atmosphere, a flood of electrons is produced through a process known as “Compton Scattering.” These electrons, flowing in a current over a huge region of the atmosphere, create a massive, short duration electromagnetic field which can damage modern digital electronics.

These powerful electromagnetic fields are produced on sub-continental scales by detonation of any nuclear device above an altitude of 30 km.

- **Vulnerability**

Today, the technology that has become the foundation of every aspect of society is far more vulnerable than it was even a few decades ago, and modern technology-intensive national power grids are particularly sensitive. The DOE / FERC / DHS Oak Ridge Laboratory report⁷ and other government studies have concluded that, if measures are not taken to protect national power grids against an HEMP strike,⁸ large segments of the national power grid would likely be inoperative for months or years. This, in turn,

⁶ While this effect has been studied in detail for over 50 years as a military threat, research on civil infrastructure vulnerability, though relatively new, is quite extensive. Most of the studies listed in the overview for Section 2.0 examined vulnerability due to both Severe Space Weather and EMP, and research has now shown that our evolving, technology-intensive infrastructures, particularly the power grid, have become quite vulnerable

⁷ For a summary of the report, or a link to the full report, visit <http://www.eiscouncil.org/English/Resources/Resoucelnside.asp?itemId=10369>

⁸ As discussed later in this report, the primary focus of such protection is to make a power grid resilient enough to ensure timely recovery.

would create “cascading infrastructure failures” that could leave large geographic regions without food, water, sewage, communication, transportation, medical care or other basic services for long durations. Irreversible consequences of such “cascading failures” have been named, in testimony by Commissioners of the U.S. Congressional EMP Commission, as threats to societal continuity, which could make large portions of the U.S. population “unsustainable.”

- **The two EMP-pulse time domains – E1 and E3**

The damage done by an HEMP strike is caused by two different time domains of the “pulse” generated by the event. A very short duration “E1” or “early time” pulse can lay down a field of tens of thousands of volts per meter over a region spanning a few thousand kilometers in diameter. An “E3” or “late time” pulse, which lasts for periods from seconds to several minutes, creates disturbances in the local geomagnetic field, creating GIC currents that can damage power grid transformers over large regions, in a manner very similar to natural, severe space weather events.

- **Non-nuclear EMP**

A field similar to the “early time” E1 pulse can be produced by an appropriately designed electronic device, creating a pulse which can actually be far higher in magnitude, though over much smaller regions.

When manufactured as weapons, they are often referred to as “Intentional Electromagnetic Interference” (IEMI) devices. The militaries of more than twenty nations have such weapons, or have them under development.⁹ Such devices are also available for unrestricted commercial sales as “test equipment.”¹⁰ Some of the simpler versions are considered easy to manufacture without special tooling or facilities, and plans for viable devices – even today – are readily available.

2.2.2 EMP – Historical Context

The earliest testing of HEMP took place in 1962, when the United States performed a series of nuclear tests above the atmosphere. In a test code-named “Starfish Prime,” a

⁹ As reported at EIS Summit IV, Washington D.C. May 21, 2014, by Joseph McClelland, Director, Office of Energy Infrastructure Security, FERC

¹⁰ For example, see the specifications for the “EMP Suitcase” manufactured by Applied Physical Electronics, L.L.C., at <http://www.apelc.com/applications.html>

detonation above the atmosphere caused electrical failures more than 800 miles away, in Hawaii.¹¹

These rather unexpected results touched off additional testing, and later in 1962 the U.S.S.R. performed its own tests, detonating nuclear warheads over Kazakhstan. Equipment failures and breakdowns were extensive, even for the far less sensitive electronics in use at the time. Failures included underground and overhead power lines, communication lines and military-grade electronics, even causing a power station to burn down.¹²

After the cold war, the combination of increasing proliferation and rapidly evolving, ubiquitous technology raised concerns over the vulnerability of basic societal utilities and infrastructures, resulting in the wide array of government studies listed above. In terms of power grid vulnerability, the conclusions of these studies are quite similar to their conclusions related to Severe Space Weather. Like a solar CME event, the HEMP E3 pulse creates GIC, affecting electrical grid stability and possibly damaging transformers. And the geographically extensive HEMP E1 pulse can cause disruptions or burnout of power grid controls, relays, communications and diagnostics systems, as well as other components.

Nevertheless, it is important to recognize that EMP E1 damage is expected to cause failure of only a portion of such electronics. Although the ubiquitous use of vulnerable systems could mean essentially non-recoverable failure of an unprotected grid,¹³ this means that cost-effective protection modalities may use a combination of protection of specific, designated core hardware, with pre-planned sparing and associated recovery procedures for expected, occasional failures of other equipment.”

¹¹ See the Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack (Congressional EMP Commission), Executive Summary, P. 4, http://www.empcommission.org/docs/empc_exec_rpt.pdf

¹² For a report on the USSR HEMP Test over Kazakhstan, 1962, with extensive additional sources, visit <http://www.eiscouncil.org/English/Resources/ResouceInside.asp?itemId=10427>

¹³ For example, the DOE / FERC / DHS Oak Ridge Laboratory Study concludes, “EMP threats raise grave concerns about the ability of the modern U.S. power grid to successfully recover from the effects of a major geomagnetic event.” From the Executive Summary, P. ii

See also testimony of Dr. William R. Graham, Chairman, Commission to assess the threat to the United States from electromagnetic pulse (EMP) attack – Statement before the House Armed Services Committee, July 10, 2008 “Their effects [EMP attacks] on critical infrastructures could be sufficient to qualify as catastrophic to the Nation,” and “Depending on the specific characteristics of the EMP attacks, unprecedented cascading failures of major infrastructures could result. In that event, a regional or national recovery would be long and difficult, and would seriously degrade the safety and overall viability of our Nation.”



High Energy Radio Frequency (HERF) Gun

3

Electricity Grid Damage Risk: Top Level Summary

Electricity grids are vulnerable to effects produced by both severe space weather and malicious electromagnetic pulse events. Severe Space Weather events can cause Geomagnetic Disturbances (GMD), with distortions in the earth's magnetic field causing GIC flows through the earth and into power grid components. Following a high altitude nuclear detonation, a "late time" pulse ("E3") lasting from seconds to minutes is produced, which causes similar magnetic field distortion and resulting GIC. GMD / GIC effects caused by either of these conditions have large exposure footprints, on sub-continental scales significant even to a large national power grid. For such a detonation, there is also an "early time" ("E1") pulse, a very short duration electromagnetic field that extends to the horizon determined by the height of the detonation.

3.1 System Operational Concerns

3.1.1 E1 Effects

From a system operational perspective, electric grids require some level of active control to maintain stability. This requires sensors, processors, communications and actuators to help control grid components. HEMP E1 electric fields of, for example, 50,000 V/m, with frequency content up to 1 GHz will damage or destroy a portion of active control elements that fall within the electric field's footprint, and have the potential to damage or destroy grid components themselves.

Immediately following an HEMP E-1 event, it is likely that, with no hardening, enough active control elements will be damaged or destroyed to make it nearly impossible to assess the system condition with any degree of confidence. Under these conditions, assessment would require extensive manual system evaluation which would likely be difficult or impossible, especially given the complicating effect of the consequent cascading failures of other infrastructures.

3.1.2 E3 Effects

In all the severe E-threat simulations sponsored by the US government,¹⁴ large power grid blackouts were a consistent probable outcome of a severe GMD. These studies focused on the mechanisms for power system collapse due to both EMP and natural

¹⁴ To review summaries or find links to the full text of most of these reports, visit <http://www.eiscouncil.org/English/Resources/ResourcesCategory.asp?catId=221>

disturbance environments, and the permanent equipment damage that could result from these disturbances.

During the 1989 Quebec GMD event, the Hydro Quebec grid collapsed within 90 seconds and components were damaged both in Ontario Canada, and in New Jersey. Maximum geoelectric fields in this case were “only” 1.7 V/km, well below the 100-year storm level.

If adequate protection measures and operator training are not in place, the inability of system operators to assess unfolding events further increases the power system vulnerability. This could spread the impacts beyond the boundaries of the initiating disturbance environment, if prompt, appropriate actions are not taken.

The backbone of a large regional power grid is the Extra High Voltage (EHV) network which transmits power across wide areas of the country. When a power grid collapses, in all cases restoration is dependent upon the ability to rapidly restore functionality of this EHV transmission network, through a process known as “Black Start”, wherein the system must be restarted without the benefit of outside power. However, analysis and historical data indicate EHV transformers and circuit breakers, protection relays, and large generators can be damaged by large GIC currents caused by the disturbance conditions.

3.2 EHV Transformer E-threat Risk: Transformer Heating

Transformers have specially-designed magnetic cores optimized to operate under a specified range of conditions at a high level of efficiency. When conditions deviate from these optimal design parameters, efficiency declines.

Any energy not transmitted from primary to secondary windings is ultimately dissipated as heat. In an extraordinary GIC event, high levels of heat can be generated in the core. The core’s ability to handle such sudden heat loads is a measure of its GIC resiliency, and ultimately the resiliency of the power grid. Such resiliency may be enhanced in different ways. For example, a transformer larger than required for its power transfer requirements could be utilized, giving it more resiliency against variations in grid load, reactive power, voltage, and harmonics.

Transformers may be damaged by either Severe Space Weather, or by either E1 or E3 from an EMP event. Transmission and distribution cables attached to transformer primary or secondary windings can be degraded by voltages that exceed the transformer rating,

risking breakdown in winding insulation. A transformer damaged in this manner may also be more vulnerable to other, more conventional stresses, if it is not immediately taken out of service, and transformers damaged by GIC may generate harmonics that cause core heating/overheating of other transformers in a distribution network.

This raises a number of important procedural considerations. For example, if a grid is temporarily shut down after a GMD or EMP event, a damaged transformer may go undetected and may fail upon efforts to reconstitute the power grid.

In this regard, measures for enhancing transformer resilience provide important opportunities to reduce the above risk. Such measures include transformer de-rating, logistical or on-site spares or redundancy, and the use of active protection and mitigation plans, coupled with appropriate procedural protection measures.

3.3 Harmonics, Reactive Power Consumption, and System Instability

There are many issues that can affect the operation of a power grid under normal circumstances. The ability of an e-threat degraded power grid to handle these “normal” issues and continue to operate – even if it does not collapse immediately – would be significantly degraded following a severe (e.g., Carrington class or HEMP) electromagnetic event.

■ Typical Power Grid Operating Parameters

In general, power quality standards must be maintained within certain parameters to avoid damage to grid attached customer equipment. These parameters include voltage, reactive power, and frequency. EPRI, IEC, and IEEE maintain and publish power quality benchmarks and standards that are used around the world (See Chapter 5.1).

The US power grid operates at 60 Hz. Under normal circumstances the power waveform is stable and controlled, with voltage and current generally in phase (or close to it), the ideal grid operational condition. Under such conditions certain loads may be placed on the grid that are inductive in nature, such as motors or industrial process equipment, and voltage and current phase can then deviate significantly. The amount of deviation between voltage and current phase is a factor of “Reactive Power” or simply “Power Factor.” To ensure reliable grid operation, sufficient reactive power must be maintained with “rotating stock” (lightly loaded or unloaded generator capacity) or power factor correction devices (often capacitor banks) to bring voltage and current back into phase.

If reactive power is not properly managed it can cause voltage and/or frequency instabilities that can force loads to be shed and generation capacity to be tripped offline. Voltage harmonics under these normal conditions are usually caused by non-linear loads (such as switching power supplies) that have strong potential to generate harmonics.

- **Grid operating parameters following an EMP event**

Immediately after an E1 Event, an unprotected power grid would likely collapse. If, due to field strength or other reasons, the grid does not collapse, maintaining grid stability in an electromagnetically unhardened grid will be a very difficult task.

Loads are likely to drop off suddenly, generation capacity may become unavailable, the ability to compensate for reactive power may be lost, and out-of-spec transients may be generated. During the subsequent E3 effects, grid transformers – if they continue to operate – are likely to be degraded by GIC, which could drive them to half-cycle saturation, generating significant harmonics. This, in turn can lead to an increase in transients, as capacitor banks are switched in and out of the grid as automatic systems attempt to control voltages, becoming another potential source for transformer damage.

3.4 E1 Effects on SCADA Systems, Sensors, Relays and Other Components: Operational Degradation or Damage

The heart of an actively controlled power grid is its control and communication systems, typically mediated today by computer control and data acquisition systems.

These SCADA systems can communicate through wired or wireless infrastructure. Often power grid operators will utilize both – with wireless connections, such as microwave links being one of the ways to quickly and efficiently deploy active control systems across an entire network.

While many varieties of SCADA systems are themselves quite vulnerable to E1, today's typical sensors can also be particularly vulnerable. To understand the scale of this concern, it is important to know the failure modes of both critical SCADA systems and sensors, to assess system resilience, and likely availability after an E1 event.

3.5 Effects on Capacitor Banks and Insulators: Vulnerabilities, and system sensitivity to damage of these components

3.5.1. Capacitor Bank Effects

Capacitor banks are key grid elements that allow for compensation of reactive power conditions on the grid. These can be (and often are) automated to respond to certain power-factor situations. If sensors that control capacitor banks are damaged by an E1 event, capacitor banks may respond in unpredictable ways. Some capacitors and capacitor bank controllers/actuators may also be physically damaged. If either of these effects occurs, and the damage is sufficient to prevent effective use of a grid's capacitor banks, the result could be insufficient reactive power and under voltage conditions leading to power grid load shedding, or ultimately grid collapse.

If failure of proper capacitor bank operation causes high levels of harmonic currents, this can also pose reliability and equipment damage concerns to other key components, such as shunt reactor banks. Capacitors connected on the grid (whether as switchable components or as part of a Static VAR Compensator "SVC" used to regulate grid) will present a lower impedance at harmonic frequencies, and high levels of harmonic current can therefore overload these grid elements.

This, essentially, is the chain of events that triggered the Quebec grid collapse in the March 1989 geomagnetic storm, when all seven of their vital SVC's tripped due to harmonics.

3.5.2 Insulator Effects

Insulators are key components to every power grid, providing both operational safety, and isolating power grid conductors from the surrounding environment. Insulators have fairly well understood failure modes: key indicators of insulator reliability are isolation resistance and leakage currents.

During an E1 event, already weakened insulators may experience a flashover failure event and require replacement. Since transmission and distribution lines depend on a long series of insulators, failure of even a single insulator on a power line causes the failure of that line.

4

Summary of **Resilience and Mitigation Options**

When addressing any projected hazard, optimal infrastructure protection generally requires investment in two different dimensions: a combination of (a) resilience planning and (b) pre-planned restoration actions, along with the resources and commitment to implement both. When addressing hazards with the potential to cause wide area power grid outages, with durations projected to range from days to months or even years, such planning becomes, not simply optimal, but essential.

For severe space weather, EMP and related electromagnetic threats this presents an important management challenge. With the whole history of modern power grids fitting within a single estimated (~100 year) severe space weather cycle, and with limited examples of use of EMP-related threats in international conflicts, energy sector managers and stakeholders must find ways to implement requisite planning and implementation efforts without the kind of post-crisis evaluation that is typical for more common types of crisis.

As efforts to address these emerging threats develop in the international community, this can be addressed by development of a common framework of cost-effective best-practice approaches, focused on clear end-state goals and associated priorities, based on commonly accepted international standards or benchmarks. Such a common, internationally-based approach can provide clear guidance and metrics to focus resilience investments and restoration planning, while also creating optimum conditions for national and international cooperation and assistance in post-crisis mitigation and restoration.

4.1 Developing a National Severe Space Weather and EMP Resilience Plan

Resilience can be designed into the grid through the development of risk-based analysis of realistic threat scenarios that help identify critical, vulnerable components, and using this data to prioritize resilience efforts.

This could then be used to develop a Resilience Plan, to include the following requirements:

Hardening – Defining those hardware elements that must be hardened to ensure there remain at least a minimal number of functional, operating power generating stations, substation/switchyard equipment, SCADA resources, and cross-grid communications. A transformer vulnerability and criticality assessment is also essential, to define which transformers and system nodes must be protected, to avoid potential long-term grid down times during transformer repair/replacement.

System Assessment and Fault Finding – Given availability of adequate, if minimal, fully functional power generation, and of an adequate control and data acquisition (and communication) system, the system restoration plan must define requirements for methods to use this power generation system and control and data acquisition system (supplemented with appropriate manual fault finding approaches) to expand restoration to the rest of the grid.

Black Start (System Restoration) - To respond to an EMP event, emergency system restoration plans will need to be re-examined to clarify additional hardening, controls, diagnostics and logistics, sparing, procedures, and training requirements to provide confidence in implementing such a plan.

4.1.1 Severe Space Weather Resilience

Safe and secure operation of the power grid in extreme circumstances depends both on automated equipment and on procedures that typically include manual actions by grid operators. For the former, sensitive automated control equipment must remain functional, to assure maximum protection. For the latter, grid operators require procedures that should be tested against both normal and emergency situations, and operators should be thoroughly trained in both normal and extraordinary grid environments. For Electromagnetic Threats, given the rarity – and severity – of events, these requirements will be particularly important.

- **Roles of automated vs. procedural protection**

Severe Space Weather has the potential to cause widespread catastrophic damage to key power grid assets, as indicated by the full range of U.S. government studies, and data from historical damage-related outages. In such an event, damage to key transmission network infrastructure elements would reduce the restorable portion of a network, and increase restoration time.

Analysis indicates that large EHV transformers, generators, and EHV circuit breakers— if unprotected from GIC — may be vulnerable. If allowed to propagate downstream from EHV transformers, GIC and resulting voltage instability can also put at risk the sophisticated control and protective relay systems that are vital to restoration of power grid operations.

Because these devices are so common and have overlapping responsibilities in control and protection of the network, even relatively small numbers of failures could delay restoration of an entire substation or power plant facility. Where such failures occur in a broad region of the power grid, such failures could put at risk the viability of a restoration plan on any reasonable timeline. High-value, critical EHV equipment is, therefore, a priority for protection, either through hardening or pre-planned sparing and restoration.

- **Procedural measures**

In the event of a widespread failure of the power grid, recovery of partial or full operation requires two critical procedural functions: communication between control and distributed sites, and the ability to correctly diagnose the state of the grid and perform combined SCADA and manual fault finding. In particular, black start operations require that individual grids first establish “islanded” operation, and then establish power connections to neighboring grids.

For black start after an electromagnetic threat, specialized, expanded planning and procedures will be essential, since most conventional blackstart procedures are designed for recovery from scenarios with minimal equipment damage.

Without such modified procedures, communications, and manual fault finding procedures, post event grid restoration in a reasonable time is unlikely.

- **Pre-planned transformer backups and sparing approaches**

EHV transformers and other components critical to grid operations are often expensive, and may require long lead times to replace. In the U.S., in accordance with NERC requirements, grid operators typically identify at least one backup EHV transformer so that they can recover quickly if these high-value items fail.

Stockpiling such transformers is often not a cost-effective solution for a grid owner/operator. For those grid operators that do replace EHV transformers before failure (while the transformer is still functional), a ‘best-practice’ strategy is to place the older transformer in an unpowered configuration, unconnected to the grid, to be stored, protected from the elements, in case of the failure of an operating grid EHV transformer.

- **Automated protection options**

Automated protection options involve embedding protective hardware mechanisms or configurations in the power grid. For EMP E1, this could involve protective measures to assure a critical control system is isolated from the E1 field. For Severe Space Weather or E3, this could involve use of series capacitance systems or current blockers to protect critical EHV transformers.

In that event, it is essential that any such automated method be fully tested to ensure it is both safe and effective. GIC current blockers, for example, will require adequate performance evaluation, testing and in-situ experience to assure they meet the needs of grid operators.

4.1.2 EMP Resilience

- **Backup Power and Sparing**

Availability of facility backup power typically does not imply electromagnetic hardening for such a system. Nevertheless, given E-threat restoration timelines, such an adaptation will be essential for many critical facilities in any EMP event, regardless of the level of overall power grid protection.

In an E1 EMP Environment, the additional planning for electromagnetically-hardened backup power at key facilities would buy time and lessen the impact of a failure of power grid infrastructure after an E1 event. Developing standards for electromagnetically-hardened backup power could aid in capital planning for implementing such measures, and could increase resilience to EMP.

- **EMP Hardening of Communications and Data Acquisition System**

In the aftermath of an E1 event, communications (inter- and intra-grid) will be important to reconstitution efforts for coordination of resources. Resilience efforts can range from keeping back-up emergency radio equipment at key points in a grid operator network stored in electromagnetically-hardened cabinets, to deployment of a fully hardened operational network.

In any resilience and restoration planning effort, it will also be essential to ensure that a critical, minimum level of SCADA control and data acquisition hardware is protected, as a core capability to use during overall grid restoration with pre-planned sparing and related measures.

Over time, SCADA communications networks can be deployed on dedicated grid-operator fiber and an allocated microwave spectrum. Hardened SCADA nodes will facilitate longer-term resilience of active monitoring and control networks.

- **Hardening vs. Logistics Sparing Trade-off**

The “Hardening vs. Spares” equation will be different for each phase. However, development of short, medium, and long term resiliency plans will help ensure realistic resilience options will be available for any E1 grid event. Many such efforts could be incorporated into existing planning activities, which are often more cost-effective when built-in to initial designs.

Ultimately, E1 hardening for a system comes down to a few critical questions: Which systems should be hardened, which should be protected through in-situ or appropriately stored spares, and what are the critical tradeoff decisions that must be made, over time, in deciding which approach to use for different grid components.

- **Rapid System Condition Assessment Procedures and Training**

Development of scenario-appropriate restoration procedures, personnel training and exercises will be critical to increasing the effectiveness of E1 resilience investments.

In any restoration scenario, protected hardware will form the core of a recovery process. But a cost effective approach will require extensive use of spares, with corresponding requirements for manual fault finding / fault isolation, and installation and use of spares. Since these processes will tend to be unique to an EMP recovery event, specialized procedures and training will be essential.

- **Logistics Deployment Model**

The development of logistics sparing models will require long-term planning and coordination with adjacent grid operators. Typically, such models or plans will be based on “reverse engineering” of E-threat expanded blackstart planning. By reviewing the fundamental requirements for such planning, and the grid capability assumptions associated with these requirements, decisions can be made on which hardware must be hardened or directly protected, and which hardware will be left for manual fault finding and logistics spares replacement. Wherever sparing is used as the fundamental protective approach, careful planning of logistics spares deployment will be necessary.

In the longer term, national or recognized international standards for selection of interoperable and interchangeable components could enhance event resilience. Ultimately, this could include greater standardization of grid architectures, component commonality (and storage) to facilitate resource sharing, and training standards so that personnel can more rapidly assist adjacent or even widely separated power grids.

4.1.3 Power Grid Restoration (Post-Event Actions)

- **Severe Space Weather Restoration Measures**

In the event of a severe geomagnetic event that damages critical infrastructure within widely separated parts of regional or national power grids, recovery functions could include utilization of back-up spares and sharing of these assets from unaffected regions to those that need spares. A general ‘big-picture’ plan will be needed to guide efforts to transport these items, especially when their size requires transportation on special vehicles. Planning for realistic assessment for the number, variety and storage of spares, and the logistics of transportation and installation, will be required, and will need to be reviewed to ensure proper coupling with hardening / direct protection planning.

- **EMP Black Start Approaches**

“Each Transmission System Operator (TSO) shall participate in its Reliability Coordinator’s restoration drills, exercises, or simulations as requested by its Reliability Coordinator.”¹⁵ However, typical black start scenarios do not account for extensive damage to grid components, and assume normal communications will be available.

In an EMP blackstart scenario, while a core set of hardened / directly protected equipment will be assumed available, extensive portions of power grid assets will be subject to restoration through pre-planned fault finding and sparing efforts. This will require extensive supplementation of existing blackstart procedures.

4.2 Benchmarks and Standards

4.2.1 IEEE/ANSI Transformer Standards

There are at least three important transformer standards that come into play for exposure to GIC.

IEEE/ANSI standard C57.12 and IEC standard 76 provide for time limits on over-excitation of the transformer. Both of these standards were developed for over-excitation due to either over-voltage or under-frequency operating conditions. What transformer designers have historically neglected is that GIC can also produce over-excitation – and for long periods of time (several minutes to hours). This should inform the design basis and its implications for transformers.

In addition to these standards, IEEE/ANSI C57.110 also defines limitations for transformers exposed to non-sinusoidal currents. These standards were developed to guide design of specialty transformers needed for HVDC or supply to loads with several AC-DC power rectifiers that are a source of harmonic distortion currents. To date, transformer designers have not been required to recognize that GIC can cause higher levels of harmonic current distortion than would be encountered in some of the more traditional applications. Therefore, this standard and design criteria becomes an important tool for understanding the design basis limitations of transformers.

Future standards should provide guidance for improved GIC-withstand for transformers, adequate spare inventories, pre-positioning, and manual fault-finding and management

¹⁵ NERC Standard EOP-005-2 — System Restoration from Blackstart Resources

techniques to build back capability after a blackout, and also require impaired grid operation blackstart procedures.

4.2.2 International Electrotechnical Commission Standards

Recent work has improved understanding of basic factors: a better understanding of the threat environments (and their probabilities); a better understanding of the vulnerability of modern electronic equipment, systems; and the critical infrastructures in which these vulnerable equipment and systems are embedded. This has allowed considerable work to address these issues within the framework of standards. The International Electrotechnical Commission (IEC) has written standards to evaluate and protect infrastructures from these environments. A peer-reviewed scientific paper¹⁶ and a document published by the Oak Ridge National Laboratory¹⁷ estimated the severity of a predicted 100-year storm at 20 V/km (ranging from 10-50 V/km). The geoelectric field created will depend on the regional geology.

Intentional Electromagnetic Interference (IEMI) and associated non-nuclear pulse weapons are still poorly understood in their potential and can vary significantly depending upon the weapon and mode of attack on a facility. Radio Frequency (RF) weapons such as radar equipment can be used as very intense and narrow bandwidth beams that can be directed at a facility, while even simpler pulse devices can generate a much broader range of frequencies from kHz to GHz ranges that can be more intense than those due to the E1-EMP pulse (though with very limited ranges – on the order of hundreds of meters). The key difference will be a much smaller affected area that these devices can cover than those from an EMP.

The EMP and IEMI threats and environments that have been discussed are man-made. However, a natural GMD creates fields that are very similar to the EMP-E3 threat environment (geographic footprint and time variation). Given this similarity, the protection approaches for EMP E3 and GMD are similar.

For E1-EMP, the IEC Sub-committee 77C has been developing protective measures for buildings that are minimally invasive and are cost-effective.

¹⁶ A. Pulkkinen et al., Space Weather Vol. 10, 504003, 2012

¹⁷ J. Kappenman, Metatech Report 319, 2010

4.3 Best Practices

4.3.1 Operational Procedures

Short and mid-term solutions will typically derive from the expectation that, in the event of a very severe E-3 geomagnetic storm or E3 EMP, the currently configured power grid will experience large GIC and permanent damage could occur for a significant number of EHV transformers. By implementing at least minimal (short and mid-term) levels of protection, both procedural and hardware-based, (including protective measures for critical, at-risk transformers), the level of damage risk could be significantly reduced.

- **Resilience, pre-event procedures and planning**

For pre-event resilience purposes, procedural approaches exist today. These procedures are typically implementable only for natural, severe space weather events, for which some warning time may be available. Reducing loading for some of the most sensitive and highly loaded facilities, such as nuclear power plants, with corresponding increases in use of other power generation resources, is one approach. For at-risk transformer nodes, this approach is unlikely to eliminate or drastically reduce risk for a severe space weather event with accompanying high GIC levels. For moderate events, however, it can provide a significant reduction in risk to sensitive, highly loaded transformers.

- **Planning for recovery operations – E-threat adapted blackstart planning**

For recovery operations, procedural protection planning is essential. To be effective, plans and procedures would be developed based on the assumption that at least minimal resilience investments (both procedural and hardware-based protection) have been made. On this basis, plans and procedures may assume a regional blackout will occur, with damage to unprotected grid components in an extended region.

For this scenario, the procedures required would generally fall into the category of adapted black start planning. Unlike conventional black start plans, which assume that communications exist inside and between individual grids and the grid experiences only very limited – if any – damage, an E-threat adapted blackstart plan will call for use of specially prepared communication and fault-finding approaches. As part of such plans, mitigation efforts identified will focus on procedures to ensure that grid operators have a clear path forward that will allow them to most expeditiously determine the state of their grid components and recover grid operations.

4.3.2 Hardware Approaches

Options for hardware approaches to EHV network protection include:

- Transformer sparing
- Resilient transformer deployment
- Transformer de-rating
- Use of series capacitance approaches
- Neutral current damping or blocking

For different grid segments, depending on projected grid and node vulnerability, different combinations of these approaches will be optimum.

While each of these hardware-based methods has unique advantages, overall, use of these approaches can reduce GIC levels and resultant equipment damage/failure, significantly enhancing the likelihood of timely recovery from a severe space weather event.

Neutral current blocking is of particular interest, given its potential to completely block GIC from entering an EHV network. However, successful deployment of such blockers as a safe and effective option will require development of a broadly recognized, peer-reviewed list of critical requirements for safe and effective operation, as well as system-wide analysis and testing.

5

Top Level International E-threat Evaluation and Mitigation Review

5.1 International Electrotechnical Commission: E-threat Standards, Reports and Studies

The International Electrotechnical Commission, based in Geneva, Switzerland, has developed an open-source, unclassified set of descriptive material and standards for use in addressing EMP threats.

IEC Commission material available includes electromagnetic compatibility assessment, EMP threat measurement, simulation and related standards and guidance, and associated information related to protection approaches. Detailed information can be found on the Commission's website.¹⁸

In this section, the threats, standards and corresponding protective approaches are summarized.

5.1.1 IEC E-threat and Vulnerabilities, Based on IEC Standards

Due to increased awareness and recent analysis of e-threats, considerable work to address these issues within the framework of standards has taken place in recent years. The International Electrotechnical Commission (IEC) has written a collection of standards to evaluate and protect infrastructures from these environments. This section will provide an overview of these standards and how they can be utilized to address the protection approaches that can be considered against each of these threat environments.

As described in IEC 61000-2-9 (see Figure 5.1.1), EMP includes three distinct electromagnetic field transients that can be produced by a nuclear device detonated above an altitude of 30 km. It is noted that the HEMP peak fields decrease, but do not disappear, for burst altitudes below 30 km heights and that height also factors into not only the magnitude of the field intensities but also the geographic footprint. The three distinct pulses that are generated from a single detonation are classified as: the early-time (E1), the intermediate-time (E2), and the late-time (E3) EMP. The most important ones are respectively the E1 transient and E3 transients, as many present systems are not actively protected against these environments. The E2 transient falls into the same spectral range and category as naturally occurring lightning although the peak E2 environment can be significantly lower intensity than for peak lightning fields. Therefore standard lightning protection of systems is usually viewed as being more than adequate in protecting against the E2 threat.

18 To review the International Standard, visit http://webstore.iec.ch/preview/info_iec61000-4-32%7Bed1.0%7Den.pdf

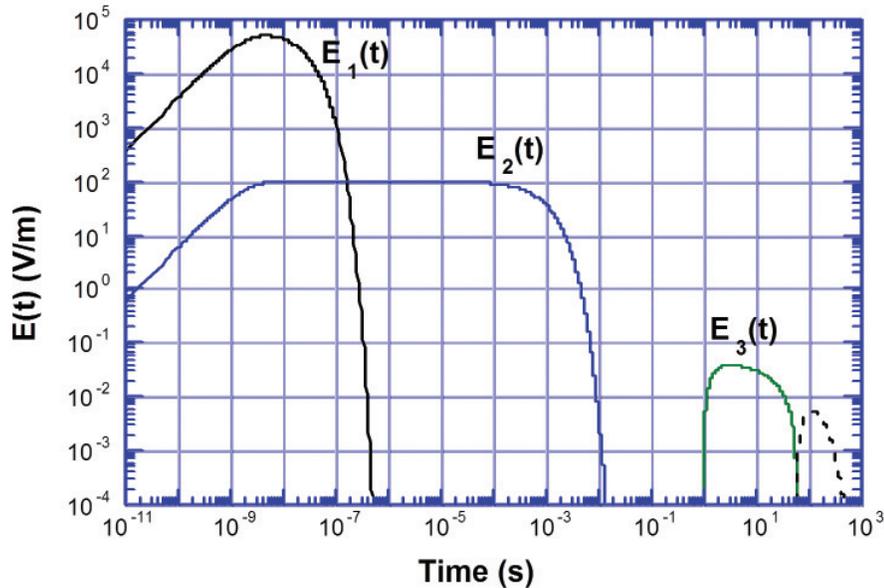


Figure 5.1.1.1 | Three portions of the EMP electric field waveform (E1, E2, E3) in volts/meter from IEC 61000-2-9

The incident E1 EMP creates both a high-level radiated and conducted electromagnetic environment affecting buildings and sensitive equipment housed within them, as the external wiring (power and telecom) can be exposed to the pulsed field, thus creating significant conducted voltages and currents that can penetrate into the building by way of the wiring.

5.1.2 Protection Approaches within the Framework of IEC Standards

For the low frequency spectrum threat environments, severe geomagnetic storms and the E3-EMP produce electromagnetic fields at frequencies in the mHz - Hz range. These fields can couple to the high, medium, and low-voltage grid producing serious operational difficulties to the power grid. Protection methods that have been discussed seek generally to de-couple and prevent induced current flows in these exposed grids.

For building level protection (control centers), it is important that the entry of harmonics into the building be blocked and also take into consideration protection from other associated significant voltage dips, transients and over-voltages and over-currents that could occur in the power supply during the course of the event. Also, it is important to carefully coordinate the backup power supply system to the facility such that it will be able to unambiguously detect such disturbances and smoothly transition into seamless continuation of power supply for critical functions.

For the high frequency threats posed by E1-EMP and IEMI, the approach also needs to take into consideration the frequency range. Since both threat environments have significant spectral content above 10 MHz, this will pose problems for most buildings, since most designs for electromagnetic concerns (if considered at all) fall into the range of AM radio transmission which is below 10 MHz. In some situations of facilities close to FM or cell towers, special measures may have also been taken to harden against those frequency ranges.

For E1-EMP, the IEC Sub-committee 77C has been developing protective measures for buildings that are minimally invasive and are cost-effective. The basic E1-EMP protection approach consists of applying layered hardening as shown in a Figure 5.1.2 taken from IEC 61000-5-6.

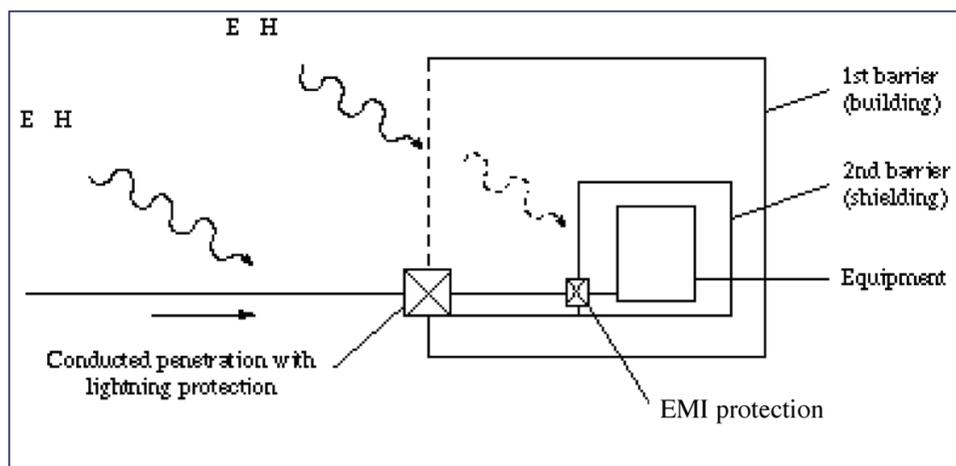


Figure 5.1.2 | Layered Protection of a Facility from IEC 61000-5-6

To determine the amount of hardening required at the room or rack level of sensitive equipment, the first step is to determine key factors including the location of the critical electronic equipment within a facility. Then examine for the amount of attenuation provided by the external facility walls, including all of the various exposures. In addition the immunity level of the electronic equipment needs to be considered for the EMP transients that could result by either radiated and/or conducted entry paths.

The IEC standards are helpful in that they provide procedural guidance for performing a basic EMP assessment of a facility using a classification system as given in IEC 61000-2-11. They also provide guidance on protection concepts that are described in IEC 61000-5-3. Further, the EMP immunity test standard, IEC 61000-4-25 can be used to help determine actual test levels for facility equipment like equipment, racks, and equipment rooms within the facility. This is done also by looking at the external EMP transients that must be attenuated before they reach the equipment. For example when considering

conducted transients, attenuation or surge suppression is planned to reduce incoming EMP or IEMI transients. Here the most important advances are high quality bulkhead suppression devices that are now entering the market. Another IEC generic standard (IEC 61000-6-6) provides procedures for determining test levels for equipment that takes into consideration locations relative to the threat signal and facility attenuation.

In addition to generic approaches, more exact methods are described, providing a more effective means of determining the levels of protection required for E1 EMP, and/or IEMI. This is a more formal assessment process, which usually includes electromagnetic attenuation measurements from the outside to the inside of the building at the exact location of the electronic equipment. IEC publication IEC 61000-5-9 deals specifically with this process. When this process is followed, the possibilities of over- or under-hardening will be minimized. Figure 5.1.3 provides a brief hierarchy and description of the IEC SC77 standards.

Organizational Overview of IEC SC 77C Publications

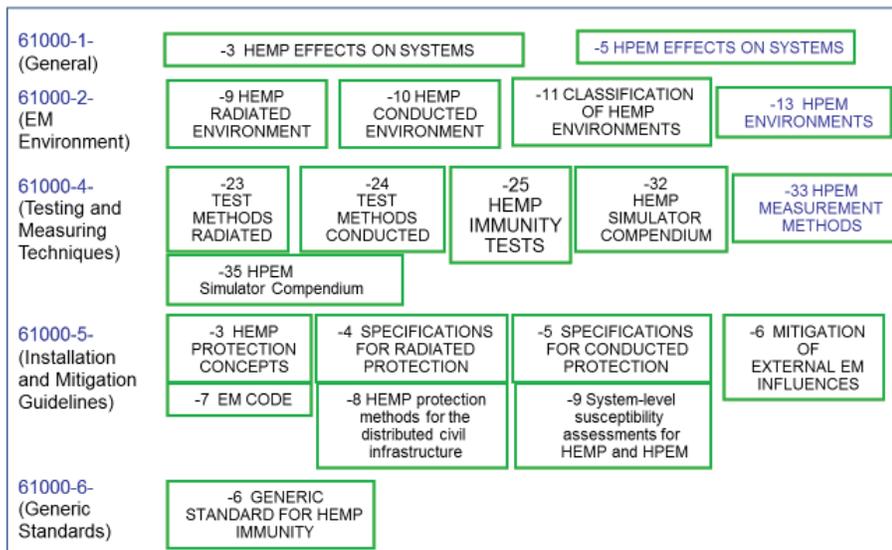


Figure 5.1.3 | Organizational Functions and Hierarchy of IEC SC77 HEMP/HPEM Standards

These standards provide a basic understanding of each of the three threats discussed above, and as noted they provide a means to assess the vulnerability for an existing installation to EMP, IEMI, and severe geomagnetic storms. But they also provide a level of protection for commercial facilities when adopted that are far less expensive than using military standards. These are still voluntary approaches and as further discussed in the next section there are pathways within other existing Non-SC77 standards from both IEC and IEEE that are already more widely applied and can be considered for COTS devices that also provide a higher degree of EMP assurance than normal design considerations.

5.2 European Space Agency: GMD Studies

The European Space Agency has been instrumental in spearheading a number of important initiatives to improve our knowledge of space weather events, including development and deployment a number of space-based instruments.

5.2.1 ESA Space Weather Applications Pilot Project 2003

In April 2003 the European Space Agency (ESA) began a two-year project, the Space Weather Pilot Project, to extend the space weather community in Europe. This took place through outreach activities, collaboration and the development of key space weather applications based on existing or easily adaptable sources of data. This project included a number of “service development activities” that are relevant to GMDs and its effects on the grid such as “Solar monitoring and warnings”, “Operational Airline Risks” and “Use of Space Weather Data in Natural Hazard Warnings”.^{19/20}

5.2.2 SOHO Mission

SOHO (Solar & Heliospheric Observatory)²¹ is a joint ESA/NASA mission that has helped improve our understanding of the sun’s interior and complex atmosphere – home to a variety of giant explosions, including eruptions of solar material known as coronal mass ejections (CMEs). Before SOHO there was disagreement over what a CME headed for earth looked like. By providing simultaneous images of both what was happening on the sun and further out in the corona, SOHO helped define what occurs during a CME. SOHO was launched on December 2, 1995. The spacecraft was built in Europe by EADS Astrium and the overall management was provided by the ESA. The mission was initially expected to be completed by 1998, but received approval for an extension until the end of 2014. SOHO was comprised of 12 main instruments that have implications for GMDs and its effects on the grid.²²

5.2.2.1 Recent SOHO Mission Findings

On March 15, 2013, at 2:54 a.m. EDT, the sun erupted with an Earth-directed coronal mass ejection (CME), a solar phenomenon that can send billions of tons of solar particles into space and can reach Earth one to three days later and affect electronic systems in satellites and on the ground.²³

¹⁹ http://www.esa-spaceweather.net/spweather/BACKGROUND/PHYS_PROC/SOLAR/cme.html

²⁰ http://www.esa-spaceweather.net/spweather/esa_initiatives/pilotproject/pilotproject.html

²¹ <http://soho.esac.esa.int/>

²² <http://sohowww.nascom.nasa.gov/about/instruments.html>

²³ <http://spaceref.com/nasa-hack-space/space-weather-1/earth-directed-coronal-mass-ejection-from-the-sun-released-today.html>

“An image captured at 11:06 a.m. EDT on May 22, 2013, from the ESA/NASA Solar and Heliospheric Observatory shows the conjunction of two coronal mass ejections streaming away from the sun. Earth-directed CMEs can cause a space weather phenomenon called a geomagnetic storm, which occurs when they funnel energy into Earth’s magnetic envelope, the magnetosphere, for an extended period of time. In the past, geomagnetic storms caused by CMEs of this strength have usually been mild.”²⁴

On April 21, 2013, at 12:39 p.m. EDT the third coronal mass ejection (CME) in two days erupted off the sun in the direction of Mercury. “There may be some particle radiation associated with this event, which in the worst case scenarios can impact computer electronics on board interplanetary spacecraft. If warranted, operators can put spacecraft into safe mode to protect the instruments from the solar material.”²⁵

5.2.3 EURISGIC (2011 – 2014)

Though not officially affiliated with ESA, the European Union (EU)-sponsored European Risk from Geomagnetically Induced Currents (EURISGIC) project was formed to lead efforts to protect European critical infrastructure from space weather effects. EURISGIC is composed of members from the Finnish Meteorological Institute, the British Geological Survey, NeuroSpace, the Swedish Institute of Space Physics, the Geodetic and Geophysical Institute (Hungary), the Polar Geophysical Institute of the Russian Academy of Sciences, and the Catholic University (U.S.A.).

“The EURISGIC EU/FP7 project will produce the first European-wide real-time prototype forecast service of GIC in power systems, based on in-situ solar wind observations and comprehensive simulations of the Earth’s magnetosphere. By utilizing geomagnetic recordings, we will also derive the first map of the statistical risk of large GIC throughout Europe. The results of this study will help in the future design of more robust and secure protection against GIC in power transmission grids in Europe, which are anticipated to become increasingly interconnected and geographically wider.”²⁶

²⁴ http://www.nasa.gov/mission_pages/sunearth/news/News052213-m7flare.html

²⁵ http://www.nasa.gov/mission_pages/sunearth/news/News042013-cme.html

²⁶ <http://www.eurisgic.eu/>

5.3 International Insurance and Reinsurance Market and Corporation Studies and Efforts

As the world's largest business sector, and the industry with the closest association with risk projection and analysis, the insurance sector has become increasingly involved in assessing societal risks associated with severe space weather. Many of the world's largest insurance markets and corporations have become involved in assessing the risks, reviewing historical space-weather associated equipment failure data, and projecting their assessment of the implications for risks to societal and business health and continuity.

5.3.1 Lloyd's

Lloyd's has a tradition of early review and analysis of emerging risks. As a result, Lloyd's commissioned a detailed Space Weather Study, discussing risk and impact of severe space weather, based on a review of available historical data. Lloyd's concern over the potential impact of this risk, and the slow pace of stakeholder education about it, is made clear in the introduction to their report: "Space weather describes disturbances that occur in near-Earth space, which can disrupt modern technologies. It is a natural hazard to which human civilization has become vulnerable, through our use of advanced technologies. Businesses are exposed to these new risks [...]"²⁷

"Awareness [...] is patchy and is usually raised after problems have occurred, rather than through a systematic approach that anticipates problems and reduces costs through early and well-targeted mitigation measures."²⁸

In discussing the indirect risks associated with a severe space weather event, Lloyd's refers to the risk of "cascading failures:"

"A space weather event could have wider regional and even global impacts: by triggering cascading failures across systems. A key example of this dependency is our reliance on secure electric power. Space weather can (and has) caused significant disruption to supplies on regional scales and could affect national systems over extended periods of time."²⁹

Finally, the Lloyd's report addresses their probabilistic assessment of severe space weather events, seeing this as an example of a remarkably serious risk, but one that happens so infrequently that business sectors may find it difficult to take into account in

²⁷ "Space Weather: Its impact on Earth and implications for business," Lloyd's. http://www.lloyds.com/~~/media/Lloyds/Reports/360/360%20Space%20Weather/7311_Lloyds_360_Space%20Weather_03.pdf

²⁸ Op. Cit.

²⁹ Op. Cit.

their planning: “Businesses at risk [of major disturbances] from space weather need to plan how they will respond to that risk. [...] It is dangerous to base risk assessment on short-term experience as that may be during periods of mild conditions. Between 2006 and 2010 there has been the lowest level of space weather activity for nearly 100 years. There is also much historical evidence suggesting that severe space weather events have been unusually rare over the past 50 years, and there are concerns that we will see more frequent events in the coming decades.”³⁰

5.3.2 Allianz

Allianz has also been involved in assessing severe space weather. Like Lloyd’s, they have performed their own risk analysis. Expressing concerns very similar to Lloyd’s, they conclude that the effects of a severe event could have quite broad impact: “The effects on electrical infrastructure can be profound. [...] Critical infrastructures, whether they be power generation, telecoms, finance, fuel, food or water, are becoming ever more dependent on electricity and electronics.”³¹

5.3.3 Zurich

Zurich’s published summary of their analysis expresses concern for the potentially widespread impacts of a severe space weather event: “...GIC related damage and disruption to the power distribution grid has the potential to have a very broad footprint across a large region for an extended period [...] It can be considered an unrecognized catastrophic risk due to our increased reliance on technology today.”³²

5.3.4 Swiss Re

Swiss Re has also been involved in analysis and review of the risk of severe space weather. Focusing on the implications for the insurance industry, the Swiss Re report asks: “Are insurance covers, which are mainly limited to sudden and accidental damage, more heavily exposed than before, or less – given the new knowledge about space weather and the possibilities for dealing with it.”³³

³⁰ Op. Cit.

³¹ “Space Weather,” Dr. Rudolf Kreutzer. Allianz. <http://www.agcs.allianz.com/assets/PDFs/GRD/GRD%20individual%20articles/GRD-2009-01-SpaceWeather.pdf>

³² “Solar Storms: Protecting Your Operations Against the Sun’s ‘Dark Side.’” A.V. Riswadkar and Buddy Dobbins; Zurich; <http://www.zurichna.com/internet/zna/sitecollectiondocuments/en/media/solarstorms.pdf>

³³ Op. Cit. From the Preface.

5.3.5 M.O.R.E. 27 Seminar

On 16-17 July 2013, The Geneva Association, jointly with Allianz SE, hosted the MORE 27 Seminar (Management of Risks in the Economy) in Berlin. The topic was ‘Ground effect and other impacts of solar storms on terrestrial infrastructure and consequential losses.’ Geneva Association is the leading voice of the world insurance industry in its dialogue with international institutions. Its membership comprises up to 90 CEOs from the world’s top insurance and reinsurance companies. The Allianz Group serves approximately 78 million customers in more than 70 countries. The seminar was a platform for national and European Union (EU) political bodies with grid operators, power producers, and scientists to discuss issues associated with severe space weather.

Specifically, the object of the seminar was to identify ways of increasing the resilience of communities and infrastructure—including the power grid—independent of the source of the hazard. In the course of restructuring the power grid the robustness and safety of the societal energy infrastructure should have the highest priority. A robust power grid is vital as the backbone of our economy and society. As the electric infrastructure undergoes dramatic re-design to integrate renewable energies, policymakers and energy companies will have an opportunity to take fundamental risk prevention measures.

The M.O.R.E. 27 Seminar discussed:

- The science behind solar activities and storms;
- Potential effects of solar storm on, and vulnerability of, terrestrial infrastructures;
- Potential societal and economic impacts of solar storms; and,
- Mitigation strategies and technologies—state of the art and outlook.

In the keynote address, ‘Space Weather and Insurance,’ Neil Mitchison, of the Joint Research Centre for the European Commission, spoke of the reliance of the insurance industry on so-called ‘f-N’ curves (frequency vs. consequence) and the questions that needed to be asked and answered concerning threats to the power grid. For the purposes of the seminar, the threat focused entirely on the effects of geomagnetic disturbance (GMD) or space weather. He also commented that “insurers are at the spearhead of protecting the citizen.”³⁴

Neil Smith of Lloyd’s chaired the first workshop on the science behind solar activities and storms. In his introduction³⁵ he referred to recent work initiated by Lloyd’s to raise the insurance industry’s awareness of space weather impacts, including their 2010 report and more recent partnership with Atmospheric and Environmental Research (AER) to quantify risks of space weather on earth. The estimated recurrence from a Carrington

³⁴ ‘Space Weather and Insurance,’ Neil Mitchison, Joint Research Centre, presentation to M.O.R.E seminar, 16 July 2013, Berlin

³⁵ ‘Workshop 1—Introduction,’ Neil Smith, Lloyd’s, presentation to M.O.R.E. seminar, 16 July 2013, Berlin

Event-level GMD event was 150 years. While this may not seem to be sufficiently frequent to be of concern, the study-estimated U.S. population at risk of extended power outage from this kind of storm ranges between 20 to 40 million. Such outages, according to the Lloyd's commissioned study, could last from 16 days to 1-2 years, and the total economic cost estimated by Lloyd's could be \$0.6 to 2.6 trillion. It was acknowledged that this may be understated.

The joint AER/Lloyd's report addressing the vulnerability of the North American power grid to severe geomagnetic disturbances (GMDs) was issued in May 2013.³⁶ The conclusion of this report states: "The hazard posed by geomagnetic storms is one of the most concerning due to the potential for long-term, widespread power outage. While the probability of an extreme storm occurring is relatively low at any given time, one will occur eventually. And as the electric infrastructure ages and we become more and more dependent on electricity, the risk of a catastrophic outage increases with each peak of the solar cycle."³⁷

Lloyd's is collaborating with the broader insurance and reinsurance industry, and is engaging with key stakeholders in government and the energy sector. As part of this effort, Lloyd's is also collaborating with the Electric Infrastructure Security Council on a special Three Sector Roundtable project for senior government, energy, and insurance industry representatives. The first venue of this roundtable was held in Washington in May 2013 during EIS Summit IV.

At the end of the second day, Zurich Re's representative pointed out that insurance companies are already, in effect, underwriting this hazard for the power industry and other business sectors, making it important that insurance companies understand the concern, properly estimate the risk and work with customers to lower their risk profile.

36 "Solar Storm Risk to the North American Electric Grid," Atmospheric and Environmental Research (AER), May 2013

37 Op Cit

The following sections describe the power systems and GMD/EMP studies and mitigation approaches found in the countries of interest for this report. The material in these sections was developed through direct communication and coordination with the power companies and/or regulatory authorities in each of the countries. Power grid operators in each nation were the primary source for the information, and representatives of each of these primary sources also provided a review of the final text included.

For background and context, before beginning the below 11-Country Survey, a brief description of the U.S./North American transmission system is appropriate.

U.S. / North American Transmission System Brief Description

The North American electricity system spanning the continental U.S. and most of Canada is comprised of three distinct power grids, also known as “Interconnections.” The Eastern Interconnection located east of the Rockies includes the eastern two-thirds of the continental United States and Canada from Saskatchewan east to the Maritime Provinces. The Western Interconnection located west of the Rockies includes the western third of the continental United States (excluding Alaska), the Canadian provinces of Alberta and British Columbia, and a portion of Baja California Norte, Mexico. The third interconnection comprises most of the state of Texas.

The three interconnections are electrically independent from each other (asynchronous) except for a few direct current (DC) ties that connect them. The Hydro Quebec system of the Quebec province in Canada also operates independent of these three interconnects and is connected with a few DC tie lines. This electricity infrastructure in the continental U.S. represents more than 200,000 miles—or 320,000 kilometers (km) of transmission lines operating at 230,000 - 765,000 volts, approximately one million megawatts of generating capability, and nearly 3,500 utility organizations serving about four trillion Kilowatt-hours (kWh) per year to well over 100 million customers and over 300 million people.

Regulatory oversight for GMD protection and mitigation in the U.S. has begun pursuant to FERC in Order No. 779, which directs NERC to develop emergency operation related reliability standards that address the impact of GMDs in two stages: 1) Operating Procedures to be filed by January 2014, and vulnerability assessment and mitigation plans to be filed by January 2015. All transmission operators of the bulk power system in the North American Bulk Power System will be required to comply with these GMD related reliability standards shortly after the FERC approval. There are currently no legal or regulatory requirements regarding protection or mitigation from EMP or IEMI.

Country	Transmission Line Length (km)	Number of Substations	Operating Voltage(s) (kV)
USA/Canada	320,000	2100	138, 230, 345, 500, 765
United Kingdom	20,000	337	132, 275, 400
Norway	10,900	140	132, 220, 300, 420
Sweden	15,000	150	220, 400
Finland	14,000	100	110, 220, 400
Germany	34,776	430	220, 380
South Korea	31,249	749	154, 345, 765
Japan	NA	NA	187, 275, 500
Australia	43,775	NA	66, 132, 220, 275, 330, 500
New Zealand	12,000	174	110, 220
South Africa	28,995	153	132, 400, 765
Israel	NA	25	161, 400



5.4 United Kingdom

5.4.1 Power Grid Management and Structure

National Grid

The electrical transmission system of the United Kingdom (England, Scotland, and Wales – excluding Northern Ireland) is operated by National Grid, a private, shareholder-owned company. National Grid acts as the Transmission System Operator (TSO).³⁸ National Grid is also the grid owner in England and Wales,

³⁸ <http://www.nationalgrid.com/corporate/Our+Responsibility/At+a+glance/>

though not Scotland, where the transmission network is owned by Scottish Power and Scottish Hydro.³⁹

The transmission system is made up of approximately 20,000 km of transmission lines, with average length 25km. Transmission voltages in England and Wales are 400kV and 275kV. In Scotland the transmission system runs predominantly at 275kV and 132kV, with additional 400kV lines that connect to England and also around Glasgow. There are 337 transformer substations in the network.⁴⁰ There are also four High Voltage Direct Current (HVDC) lines connecting to France (2000MW), the Netherlands (1000MW), Northern Ireland (500MW), and Ireland (500MW).⁴¹ The system operates at very high reliability of 99.99979%.⁴²

The generation system includes installed capacity of 80 GW with a typical split of generation: Coal (39.3%), Gas (27.5%), Nuclear (19.4%), Renewables: Hydro, Wind, and Bioenergy (11.3%), Oil (1%) and other fuel sources (1.5%).⁴³

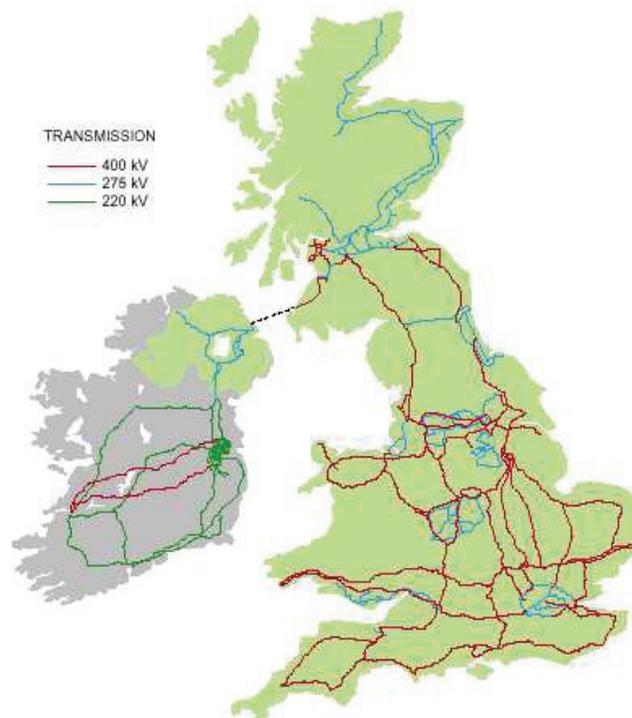


Fig 5.4.1, Electrical Transmission Map of the U.K.

³⁹ National Grid – private communication

⁴⁰ National Grid – private communication

⁴¹ National Grid – private communication

⁴² <http://www.nationalgrid.com/corporate/Our+Responsibility/Reporting+our+Performance/customers/netrel.htm>

⁴³ Energy Trends 2013, Ch. 5 - Electricity

Office of Gas and Electricity Markets (OFGEM)

The chief government authority and regulator in the U.K. is the Office of Gas and Electricity Markets (Ofgem), under the Gas and Electricity Markets Authority. Key responsibilities are defined by legislation under the Gas Act of 1986, the Electricity Act of 1989, the Competition Act of 1998, the Utilities Act of 2000 and the Energy Acts of 2004, 2008, 2010 and 2011, and other statutes.⁴⁴ Ofgem is an independent regulator, directly accountable to Parliament.⁴⁵ In this sense, it is most analogous to the Federal Energy Regulatory Commission in the U.S.

Ofgem is primarily an economic regulator, although the interpretation of ‘in the interests of the consumer’ is now taken to include environmental and security-related interests.

Department of Energy and Climate Change (DECC)

DECC is the government department that decides on energy policy for the UK, equivalent to the U.S. Department of Energy. DECC sets the policies toward which National Grid has to steer its long term investment strategies. Therefore DECC and National Grid work closely together, but there is no regulatory oversight. In an emergency situation, however, DECC has the authority under various acts of parliament to instruct National Grid to take specific actions to meet the emergency.”⁴⁶

Emergency Authorities

Currently, there are no specific regulatory standards for GMD or EMP protection in the U.K. though some emergencies are covered by a variety of procedures.

The Grid Code, Section 2.9 defines actions that National Grid may take in the event of an emergency situation. It leaves the definition of an emergency, however, to the reasonable discretion of National Grid.⁴⁷

The Electricity Supply Emergency Code is a document produced by the DECC that describes the emergency powers that the Government may invoke in the event of a prolonged shortage of electricity supply. As part of the code each Network Operator is obliged to keep up to date plans for rota disconnection (planned, rolling blackout / load shed) of electricity supply.⁴⁸

⁴⁴ OFGEM Annual Report, 2012-2013 (http://www.ofgem.gov.uk/ABOUT%20US/ANNLRPRT/Documents1/Ofgem%20AR_R%202012_13_final.pdf)

⁴⁵ Department of Energy and Climate Change, “Ofgem Review: Summary of Conclusions”, 19 May 2011.

⁴⁶ Private Communication from National Grid

⁴⁷ http://www.nationalgrid.com/NR/rdoonlyres/67374C36-1635-42E8-A2B8-B7B8B9AF2408/59911/00_GRID_CODE_FULL_I5R3.pdf

⁴⁸ https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/79195/RevElectSupply.pdf

The code (ESEC) is subject to continual development, review and testing. The responsibility for this lies with the Energy Emergencies Executive Committee (E3C).

The National Emergency Plan for Gas and Electricity describes the arrangements established between the electricity industry and DECC for the safe and effective management of electricity supply emergencies.⁴⁹

None of these authorities have been exercised, to date, for GMD or EMP. National Grid has done all of the U.K.'s evaluation studies and mitigation efforts voluntarily.

5.4.2 E-threat Evaluation Studies and Reports

House of Commons Defence Committee

The understanding of the threat from and impacts of GMD and EMP is evolving rapidly in the U.K. GMD and EMP are both considered relevant threats, though most of the focus on vulnerability evaluation has focused on GMD.

On 8 February, 2012, the House of Commons Defence Select Committee released their report: "Developing Threats: Electromagnetic Pulses (EMP). In regard to GMD risks and impacts, the report concluded that "a severe event could potentially have serious impacts upon UK infrastructure and society more widely. . . The consequences of EMP events must be addressed specifically: generic civil contingency plans which address blackouts and temporary loss of electronic infrastructure caused by a range of events are not sufficient. Space weather is a global threat and may affect many regions and countries simultaneously."⁵⁰

For nuclear EMP threats, the Committee concluded that sources for current risk are confined to countries with nuclear capability, but it was deemed possible that Iran and other rogue states could develop an EMP strike capability in the future. "While the risk may at present be low, the potential impact of such a weapon could be devastating and long-lasting for UK infrastructure. The Government cannot therefore be complacent about this threat and must keep its assessment of the risk under review. It is therefore vitally important that the work of hardening UK infrastructure is begun now and carried out as a matter of urgency."

⁴⁹ https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47867/6912-national-emergency-plan-gas-electricity.pdf

⁵⁰ House of Commons Select Defence Committee *Developing Threats: Electromagnetic Pulse (EMP)* 8 February, 2011 (<http://www.publications.parliament.uk/pa/cm201012/cmselect/cmdfence/1552/1552.pdf>)

National Grid: Space Weather and GMD Policy Briefs

Also in 2012, the National Grid issued two policy briefs on Space Weather and Geomagnetic Disturbances, which stated that for a 1-in-100 year storm, modeling studies predicted “Potentially 9 transformers in England and Wales and a further 8 in Scotland [could be] damaged or taken out of service, [producing] severe disruption, possibly leading to temporary collapse of the system.”⁵¹ This represents, however, less than 2% of the system’s transformers in the system, and there are sufficient spares to replace the damaged transformers.⁵² This finding has been updated, and current analysis finds that power outages would most likely be local.⁵³

Royal Academy of Engineering

In February 2013, the Royal Academy of Engineering released its report “Extreme Space Weather: Impacts on Engineered Systems and Infrastructure”. The report concluded that:

*“The reasonable worst case scenario would have a significant impact on the national electricity grid. Modeling indicates around six super grid transformers in England and Wales and a further seven grid transformers in Scotland could be damaged through geomagnetic disturbances and taken out of service. The time to repair would be between weeks and months.”*⁵⁴

5.4.3 Resilience and Mitigation Planning and Status

GMD Effects on the National Grid System

National Grid recorded adverse effects on their system on July 14, 1982, March 13 and 14, 1989, October 19 and 20, 1989 and November 8, 1991. On March 14, 1989, two 5-limbed transformers of identical design, one at Indian Queens, one at Norwich Main, were tripped offline by Buchholz relay alarms within a short time of each other. Both were subsequently returned to the factory for repair and were found to have core bolt insulation damage. To date, this is the only instance of equipment damage in the National Grid system attributed to GMD. No measurements of GIC from 13-14 March are available, but subsequent modeling suggests that GIC of the order of 40-50 Amps could have been flowing in the transformer neutrals.⁵⁵

⁵¹ National Grid, *Space Weather Policy Brief*, February, 2012

⁵² National Grid, *Geomagnetic Disturbances Policy Brief*, December, 2012.

⁵³ National Grid – private communication

⁵⁴ http://www.bmreports.com/bsp/bsp_home.htmhttp://www.raeng.org.uk/news/publications/list/reports/space_weather_full_report_final.pdf

⁵⁵ National Grid – private communication

Other adverse GMD/GIC effects during these events included increased reactive power consumption with associated voltage instabilities, negative sequence current alarms, and harmonic disturbances on the system. There were also indications of failure of protection signaling communication channels, but no instances of mis-operation of protection equipment were seen.⁵⁶

National Grid Voluntary Actions for GMD

National Grid has been active in recent years in implementing resilience and mitigation for GMD since the storm of March 1989.

In preparation for Solar Max 23 (2000-2001), a GIC monitoring system was installed by National Grid and Metatech. After Cycle 23, however, this first effort stalled and the equipment was not maintained and eventually decommissioned.⁵⁷

Beginning in 2003, National Grid performed an audit of all its EHV transformers. As a consequence National Grid adopted design standards for its transformers to ensure a higher level of GIC withstand. The policy is to use only three-limb replacement transformers – the design National Grid has determined to be the most resistant to adverse effects of GIC – wherever possible within the network. A further audit of all EHV transformers was completed in May 2011. Transformers found to have a design more vulnerable to GIC were identified.⁵⁸

In addition to transformer design criteria, National Grid's transformers are grounded through resistors that will dampen but not block GICs. Series capacitors were considered for some transmission lines in past years, but were not chosen due to calculated adverse effects on the network.⁵⁹

In another component of the analysis, grid nodes and junctures, called Grid Supply Points (GSPs) were analyzed to identify how many transformers at each GSP are at-risk. The GSPs themselves are also modeled to identify the points most likely to be adversely affected in the event of a GMD.⁶⁰

In preparation for Solar Max 24 (2012-2013) National Grid initiated discussions with the space weather community, with DECC and with the UK Cabinet Office.

After discussions with space weather experts, including representatives from EIS and Storm Analysis Consultants, National Grid concluded that it must update its definition of 'extreme event' from its previous benchmark of the 1989 storm to an event comparable

⁵⁶ National Grid – private communication

⁵⁷ National Grid – private communication

⁵⁸ National Grid, Space Weather Policy Brief; February 2012

⁵⁹ National Grid – private communication

⁶⁰ National Grid, Space Weather Policy Brief; February 2012

to the 1859 Carrington event. A benchmark of 5000 nT/min (equivalent to the 1921 Railroad Storm, and approximately 10 times larger than the 1989 Quebec disturbance) was set in September 2010.⁶¹

In 2010 National Grid began a collaboration with Manchester University to investigate and characterize GIC effects on transformers of various designs, with plans to expand the model to include generator step-up transformers (GSUs). National Grid plans to continue and expand these efforts, to include the evaluation of hardening devices where they are determined to be cost-effective and to support efficient system operation.⁶²

National Grid used output from a British Geological Survey (BGS) study to model the likely impact of extreme GMD on the GB network in terms of expected transformer failure. National Grid concluded that, although damage was likely, the extent of the damage would not be catastrophic, and within the capacity of National Grid to manage with only minor disruption to end customers.⁶³

In 2011 National Grid, in partnership with the British Geological Survey (BGS), developed a model for calculating a “nowcast” of GIC flow (called MAGIC), based on real time magnetometer information from BGS.⁶⁴

During 2011 National Grid reassessed its holding of transformer spares in the light of the raised benchmark for an extreme space weather event, and changed its policy by increasing its spares holding. (The specific benchmark number for spare transformers is considered commercially sensitive.)⁶⁵

Beginning in 2011, National Grid installed GIC monitoring equipment on all transformers at four of its substations. The data gathered from the GIC monitors is input into the Smart Asset Monitoring system, and can be viewed in real time, though not all of the monitors are fully functional at all times due to technical issues.⁶⁶

National Grid also participates in EURISGIC, an EU project on assessing and modelling space weather impacts on the European system as a whole.⁶⁷

⁶¹ National Grid – private communication

⁶² National Grid, Space Weather Policy Brief; February 2012

⁶³ National Grid – private communication

⁶⁴ National Grid – private communication

⁶⁵ National Grid – private communication

⁶⁶ National Grid – private communication

⁶⁷ <http://www.eurisgic.eu/>

Exercises for major grid GMD event

National Grid has held three internal exercises on a major GMD event. The event has been calibrated to lie between 1989 storm and 1859 storm in severity. This has been used to practise procedures, increase awareness of space weather effects among control room staff, test communication channels and improve business procedures. Further exercises are planned as part of the regular programme for testing emergency response procedures.

High-Altitude EMP (HEMP)

As noted above, the National response to EMP was included in at the House of Commons Defence Select Committee 2012 report. The U.K. government views this problem as a strategic threat, to be dealt with through deterrence. At the 2012 EIS Summit held in London, Secretary of State for Defence Phillip Hammond stated: “Let me be crystal clear; an EMP attack using a nuclear weapon against or affecting the United Kingdom or our vital interests or those of our allies would be considered a nuclear attack on the U.K.”⁶⁸

Intentional Electromagnetic Interference (IEMI)

National Grid recognises the IEMI threat to the system, and puts it in the same risk category as cyber security. National Grid is currently working with QinetiQ to assess and mitigate the threat from IEMI. As part of this effort, several of National Grid’s sites have been visually assessed for IEMI vulnerability, with mitigation solutions implemented in some new critical infrastructure sites. Depending on criticality and cost assessments, existing infrastructure could also be hardened against IEMI.⁶⁹

Actions used to combat the IEMI threat include: to reduce access and increase standoff distance to critical assets through the use of closed circuit (CCTV) monitoring to improve situational awareness of security staff, and restricted vehicle access; replacement of older fencing with a mesh design to reduce the IEMI threat; ensure that cabling is as short as possible (transformers and generators are positioned closely to control centers, and use of underground cabling where possible); removal of unused antennae; low numbers of window apertures; use of walls constructed of several layers so that each layer provides a degree of RF shielding; and ensuring electrical grounding is substantial.⁷⁰

⁶⁸ EISS III London Report: Conclusions and Recommendations, May 14-15, 2012. (<http://www.eissummit.com/images/upload/conf/media/EISS%20III%20London%20Report.pdf>)

⁶⁹ National Grid – private communication

⁷⁰ National Grid – private communication

5.4.4 Summary

The UK National Grid has taken important steps in EMP/GMD resilience. Key points of interest are:

Transformer GIC withstand design – National Grid has determined that replacement transformers on the national grid should be of three-limb design, for robustness against GIC impacts. They have also completed a survey of all system transformers, identifying vulnerable transformers.

GIC Monitoring – The U.K. has installed a GIC monitoring capability and the GIC monitors are tied into the real-time Smart Asset Monitoring System, supplying situational awareness that aids in executing the operational procedures.

For GIC planning purposes, National Grid has updated its definition of “Extreme Event” from the 1989 Quebec storm to the 1921 Railroad storm.

Transformer Spares – National Grid requires a spare transformer stockpile.

IEMI protection – National Grid has determined that risk management strategies for IEMI are similar in nature to those for cyber security. As such, several sites have been assessed and mitigated for IEMI through component hardening and increased security measures.

No explicit National Grid policy or practice exists for HEMP. However, the extensive efforts by the House of Commons Defence Select Committee on this subject indicate a growing national interest in efforts for EMP protections. Meanwhile, the fact that both GMD and IEMI are addressed will certainly have HEMP protection benefits.



5.5 Norway

5.5.1 Power Grid Management and Structure

Statnett SF

The Norwegian electrical transmission system carries electricity over 10,900 km of transmission lines and operates at four voltages: 420 kV (2700 km), 300 kV (4800 km), 220 kV (600 km), and 132 kV (2900 km).⁷¹ In addition, there is a 580 km submarine HVDC cable connecting to the Netherlands (700 MW) and 3 HVDC cables (120 km) connecting to Denmark (1000 MW).⁷² There are 140 substations and 330 transformers, on the 50 Hz system. The electrical transmission system of Norway is owned and operated by Statnett SF, a state-owned monopoly company, which also acts as the transmission system operator (TSO)⁷³. Distribution networks are also natural local monopolies, while generation and supply is deregulated and competitive.⁷⁴

The total generation capacity of the system is 31.746 MW of installed capacity. 95% of the generation capacity is hydroelectric, with the remainder produced by thermal (4%) and wind (1%).⁷⁵

Norwegian Water Resources and Energy Directorate (NVE)

The Norwegian Water Resources and Energy Directorate (NVE) is the electricity regulator under the Norwegian Energy Act of 1991. Under the Act, electricity generation and supply companies operate under de-regulated free-market competition, while Statnett SF operates as a monopoly regulated by NVE.⁷⁶

⁷¹ NVE – private communication

⁷² <http://www.northseacycling.com/reports/tonstad.html>

⁷³ <http://www.statnett.no/en/About-Statnett/History-in-brief/>

⁷⁴ Annual Report 2011 – The Norwegian Energy Regulator NVE

⁷⁵ Op. Cit

⁷⁶ Op. Cit

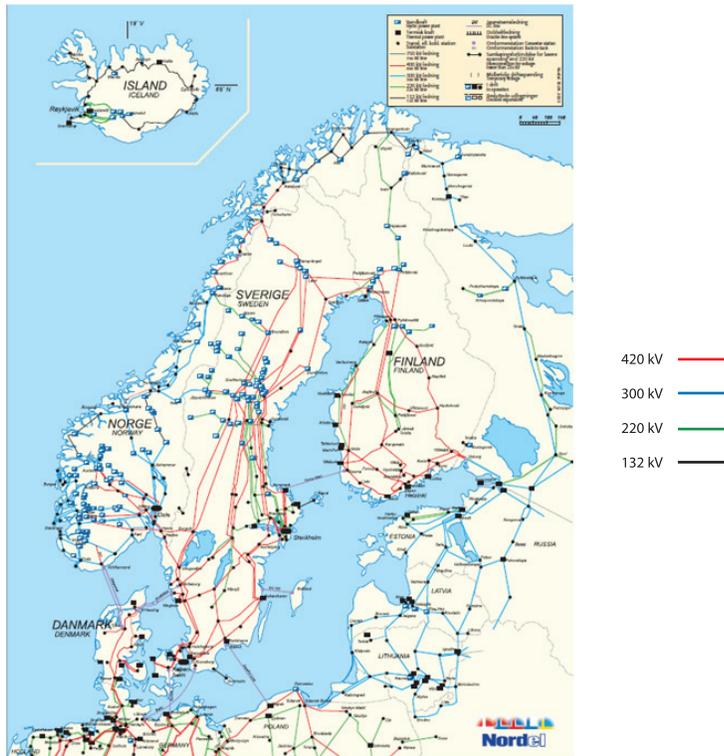


Fig 5.5.1 Map of the Norwegian (and Scandinavian) electrical transmission system.⁷⁷

Regulations relating to power system operation for handling of extreme situations – the Contingency Regulations – came into force on 1 January 2005. These regulations aim to address extreme situations and are not relevant for normal operation. These regulations require Statnett SF to continuously update measures necessary to ensure there is energy supply balance, especially during the winter, when power demand is higher and hydroelectric reservoirs are lower.⁷⁸

The preparedness provisions of the Energy Act were last amended in January 2012 including additional requirements of the Contingency Regulations concerning preventive security, contingency planning and crisis management. Since 2005, NVE has intensified oversight of energy companies to include risk assessment, safety and preparedness for extraordinary events, including natural disasters, accidental mechanical failure and deliberate acts of destruction. In addition, NVE conducts regional contingency exercises several times per year to test and improve recovery in case of disruptions to electricity or other supporting critical infrastructures. NVE also has an active research and

⁷⁷ Trond Ohnstand, GIC Experience in Norway, Risk Assessment and Mitigation in View of Existing and Future Transmission System, TIEMS Conference, 22 October 2012.

⁷⁸ Annual Report 2011 – The Norwegian Energy Regulator

development program for energy security, efficiency, and environmental impact.⁷⁹

There are, under the Regulations, specific requirements for GMD, though most are of a broader nature but have been interpreted by NVE and Statnett to include GMD and EMP.

The most specific reference is found in attachment 3 to § 5-6 of the regulations:

“3.2.11 Evaluation of consequences of geomagnetic induced current shall be carried out, and appropriate measures to protect main grid and production transformers shall be implemented.”⁸⁰ This requires all main transformer operators to ensure that the transformers are secure during a space weather event.

Other sections of the regulation (§4-1 and §5-1) broadly provide outcome-based requirements. For example, §4-1 states that the energy company shall: “..keep operations going, restore function and perform duties required under any extraordinary situation in a safe and efficient manner”.⁸¹ These regulations mean that Statnett must assess risk and vulnerability, and develop their own preparedness and recovery plans against all kinds of threats (natural, technical and antagonistic threats), and within the Government’s requirements for critical infrastructure protection (CIP).

§5-1 of the regulations requires protection against: “Storms and other natural damage; Fire and explosion; Serious technical failure; Burglary, vandalism, sabotage and other criminal acts,”⁸² which is interpreted to include both GMD and EMP.⁸³

There is one other specific requirement under §7-14 for any system that relies on accurate time reference to have at least two independent sources of time clocking. In practice this means that in addition to GPS time, accurate terrestrial cesium/atomic clocks must function as a backup.⁸⁴

In §2-7: Exercises; all Norwegian electricity companies are obligated to exercise for relevant extraordinary situations, which includes GMD events. These exercises are completed annually (though GMD is just one of many possible scenarios).⁸⁵ §2-7 also requires a communications plan for major grid GMD event, which is communicated from NVE through the “Kraftforsynings beredskapsorganisasjon” (KBO) organization. KBO organizes all major electric grid companies and producers for shared information and common preparedness for repair. KBO also acts as the command structure during extraordinary events. The organization is led by the NVE, and all major energy companies

⁷⁹ Annual Report 2011 – The Norwegian Energy Regulator

⁸⁰ Norwegian Energy Regulations (in Norwegian) (<http://lovdata.no/for/sf/oe/xe-20121207-1157.html#map005>)

⁸¹ Op. Cit

⁸² Op. Cit

⁸³ NVE – private communication

⁸⁴ Norwegian Energy Regulations (in Norwegian) (<http://lovdata.no/for/sf/oe/xe-20121207-1157.html#map005>)

⁸⁵ Op. Cit

are members, and obligated to follow instruction during national emergencies.⁸⁶

Finally, §7-14 and §7-15 specifically require protection for control systems (SCADA, etc) for critical assets (specified as class 2 and class 3 system assets) against EMP and EMI.⁸⁷ In fulfillment of this requirement, control systems and communications (including data) are protected against EMP and EMI through shielded rooms, shielded covers or protected spare parts stored in shielded areas.⁸⁸

5.5.2 E-Threat Evaluation Studies and Reports

Recorded GMD Impacts

Statnett finds GIC flows in their network routinely, and have measured flows up to 25 Amps in a transformer neutral. To date, there has been no serious or widespread system damage due to GMD, though a few instances are worth noting:

During a solar storm on February 18, 1999, there was an increase of capacitor reactive power from a Static VAR Compensator (SVC) at Sylling. On November 22, 1999 GIC flows caused a 90 MVAR shunt capacitor at Kristiansand to be activated. And during a solar storm on November 9, 2004 – a Buchholz relay tripped and disconnected a transformer tripped at Lyse.⁸⁹

Metatech Vulnerability Analysis, 2000

In 2000, an Evaluation of the Vulnerability of the Statnett and Svenska Kraftnat (The Swedish TSO) Transmission Networks to the Effects of Geomagnetic Storms, was conducted by Metatech in 2000. The study concluded that both transmission networks (which are interconnected) can develop very high GIC levels under moderate to severe GMD scenarios. The Statnett system was found to draw up to 1400 MVAR during moderate GMD scenarios and up to 2700 MVAR for severe GMD.⁹⁰

The study found that in the 400kV network, even under moderate storm conditions, there are 15 transformers with GIC flows greater than or equal to the 300 Amps (100 Amps per phase), and 78% of the 400kV transformers have GIC levels sufficient to cause half-cycle saturation. Looking at the entire 172kV – 400kV system, the average GIC

⁸⁶ KBO (<http://www.nve.no/no/Sikkerhet-og-tilsyn1/Kraftforsyningsberedskap/KBO/>)

⁸⁷ Norwegian Energy Regulations (in Norwegian) (<http://lovdata.no/for/sf/oe/xe-20121207-1157.html#map005>)

⁸⁸ NVE – private communication

⁸⁹ Trond Ohnstand, *GIC Experience In Norway, Risk Assessment and Mitigation in View of Existing and Future Transmission System*, TIEMS Conference, 22 October 2012.

⁹⁰ Metatech Report 2000

flows in the transformers was found to be 29 Amps per phase for an East-West oriented geoelectric field and 48 Amps per phase for a North-South field.⁹¹

New NVE Study of GNSS Vulnerability

NVE is working on a study of Global Navigation Satellite System (GNSS) and vulnerabilities in the Norwegian energy system to disruption or loss of GPS time. The study is planned to be finalized in the Fall of 2013.⁹²

To date, there have been no studies on vulnerability to nuclear EMP.

5.5.3 Resilience and Mitigation Planning and Status

Statnett's current mitigation for GMD includes several activities. GIC monitors have been placed on several of the transformer neutrals. GIC forecasts from NOAA are routinely monitored and used for early warning of possible negative system impacts. Emergency plans and procedures regarding extreme magnetic storms are in place, and they are tested periodically as part of the Norwegian KBO organization exercises for extraordinary events. Control center personnel receive training on operations under GMD conditions.⁹³

Planned future activities include a GIC study for the planned expansion of the power system, which is envisioned to include an additional 4000 km of transmission lines and 70 additional transformers by 2030. There is also a planned analysis of the technical specifications for transformers, with the goal to make the transformers in the system less vulnerable to GIC. In addition the relay protection settings for shunt capacitors will be reviewed and updated in order to prevent unwanted tripping during a GIC incident.⁹⁴

Regarding EMP and IEMI, control systems, communications, and data centers are protected using shielding (covers for certain systems or entirely shielded rooms), and protected backup systems that would be vulnerable to EMP/IEMI are stored in shielded areas.

⁹¹ Metatech Report 2000

⁹² NVE – Private Communication

⁹³ Trond Ohnstand, *GIC Experience in Norway, Risk Assessment and Mitigation in View of Existing and Future Transmission System*, TIEMS Conference, 22 October 2012.

⁹⁴ Op. Cit

5.5.4 Summary

Norway's experience in dealing with GMD and EMP include the following:

GIC and EMP/IEMI regulatory requirements – Norway's Contingency Regulations specify that Statnett SF must mitigate risks associated with GMD and EMP/IEMI. The requirements are "performance based", and do not prescribe any specific actions that must be taken, or technology that must be used.

GIC Study and Monitoring – Norway commissioned an extensive study of GIC impacts on its systems in 2000, and has a robust GIC monitoring capability, supplying situational awareness that aids in executing emergency operational procedures.

Emergency Operation Plan Testing – Norway requires that plans be in place for dealing with extraordinary situations, and requires the plans to be tested periodically.

Future Grid Planning With GMD and EMP In Mind – Norway's planned expansion will be done using technology determined to be more resistant to GMD and EMP, thus building in resilience and increasing the reliability of the whole system.



5.6 Sweden

5.6.1 Power Grid Management and Structure⁹⁵



Svenska Kraftnät

The Swedish electric transmission system is owned and operated by Svenska Kraftnät (Swedish National Grid). Established in 1992, Svenska Kraftnät is a state-owned public utility, and is the Transmission System Operator (TSO) for Sweden. Svenska Kraftnät is financed by the fees paid by regional grids and major electricity producers for use of the national grid.⁹⁶ The regional and local distribution networks are owned and operated by other companies.

The transmission system consists of approximately 15,000 km of transmission lines, operating at 220 kV and 400 kV at 50 Hz, and 150 transformers.⁹⁷ There are also 6 undersea HVDC cables linking Sweden to its neighbors: two 285 kV (380 & 360 MW) links to Denmark, one 450 kV (600 MW) line to Germany, one 450 kV (600 MW) line to Poland, and two lines to Finland: 400 kV (500 MW) and 500 kV (800 MW).⁹⁸

Total electricity generation in the Swedish system in 2011 was approximately 150.5 TWh (hydro 44.1%, nuclear 40.5%, biofuels and waste 8.5%, wind 4%, natural gas 1.2%, coal 0.8%, oil 0.5%, peat 0.4%).⁹⁹

⁹⁵ http://www.svk.se/Global/02_Press_Info/Bilder/Bilder_och_Logotyper/400kV_vinter_fotograf_Thomas-Wiklund.JPG

⁹⁶ <http://www.svk.se/Start/English/About-us/>

⁹⁷ Svenska Kraftnät, 2012: Skydd mot geomagnetiska stormar- elektromagnetisk påverkan på kraftsystemet. Dnr. 2011/805

⁹⁸ Source Svenska Kraftnät

⁹⁹ http://www.iea.org/textbase/nppdf/free/2013/sweden2013_excerpt.pdf

Swedish Energy Markets Inspectorate

Electric power generation in Sweden is deregulated to promote price competition. Electricity transmission and distribution networks are run as monopolies, regulated by the Swedish Energy Markets Inspectorate (Ei).¹⁰⁰ In their role, Ei are responsible for ensuring that Svenska Kraftnät adheres to the regulations of the energy market.

Swedish Energy Agency

The Swedish Energy Agency sets national energy policy. The Agency's mission is to promote the development of Sweden's energy system with the overall goal of economic competitiveness and minimum ecological impact.¹⁰¹ To date in Sweden, there are no specific requirements in statute or in regulations regarding GMD or EMP mitigation.

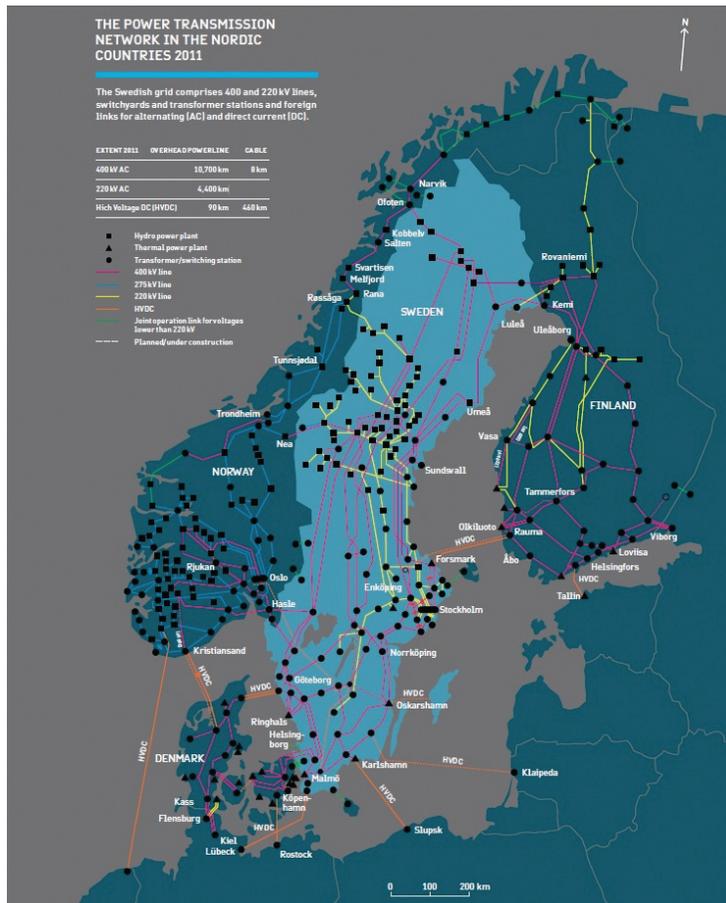


Figure 5.6.1 Map of Swedish transmission grid. ⁹³

¹⁰⁰ <http://ei.se/en/Electricity/>

¹⁰¹ <http://www.energimyndigheten.se/en/About-us/Mission/>

The National Electrical Safety Board

The National Electrical Safety Board is a Swedish administrative authority responsible for publishing regulations for high currents, electrical safety and electromagnetic compatibility (EMC). The Board also supervises electrical installations and investigates electrical accidents. During an extraordinary event the board supervises necessary repairs and provisional measures in grids so that installations can be carried out without delay, and with appropriate security. After an extraordinary event the Board is responsible to ensure that repairs and provisional measures in grids and plants do not persist longer than necessary.¹⁰²

Swedish Electrical Utilities

The Swedish Electrical Utilities is owned by Swedish Energy (Swedish Industry Association) and the Svenska Kraftnät. The overall aim is to rationalize the industry-wide research and development and also to encourage cooperation between business and industry, society and the academic community. Their work is organized into six program areas where research or other activities can be funded: Hydro power, Electricity and Heat Production, Nuclear Power, Transmission and Distribution, Electricity End Use, and Strategies and Systems.¹⁰³

5.6.2 E-threat Evaluation Studies and Reports

Svenska Kraftnät Study: Protection against geomagnetic storms – electromagnetic impacts on the power system 2012

Sweden has experienced many grid disruptions due to GIC, detailed in the Svenska Kraftnät report, showing the number of G5 storms and impacts:¹⁰⁴

There have been 11 G5 events since 1958, which gave rise to 13 days with some grid disruptions. This means that historically Sweden has experienced about two G5 events per solar cycle.

For Sweden, the ground conductivity in the South is much lower than in Northern Sweden. This outweighs the effect of proximity to the polar auroral zone, and greater GIC impacts occur in Southern Sweden. GIC flows are also enhanced on coastlines. The area around Oskarshamn and Malmö has been affected by solar storms in the past (see last entry in the list below).¹⁰⁵

¹⁰² <http://www.elsakerhetsverket.se/en/>

¹⁰³ <http://www.elforsk.se/In-English1/>

¹⁰⁴ Svenska Kraftnät, 2012: Skydd mot geomagnetiska stormar- elektromagnetisk påverkan på kraftsystemet. Dnr. 2011/805

¹⁰⁵ Op. Cit.

Typically east-west transmission lines are more affected by GIC than the north-south lines, due the fact that the electrojets that generate GIC are usually East-West oriented which gives rise to an east-west geoelectric field. However, GIC flows have been demonstrated to be more strongly related to the magnitude than to the direction of the geoelectric field.¹⁰⁶ The conclusion: all power lines, regardless of geographical main direction, can be equally exposed to GIC flows.

Disruptions in the Swedish main grid

1958-02-11: 2:58 to 04:07

Four transformers tripped via differential protection function and seven 220 kV lines. A total of 29 circuit breakers were activated with a concentration in central Norrland but also down to Nässjö.

1960-11-13: 7:29 to 13:10

The 220 kV lines tripped 22 times. Affected area was southern and central Norrland.

1972-08-04 – 05

A transformer and a 400 kV line tripped. Major disturbances in North American networks.

1982-07-14: 01:54 to 02:02

Three 400 kV lines and three 220 kV lines tripped. First, at 3:26 am it was possible to hook up the wires again. Previous attempts had failed. Synchronous compensator in Kolbotten also tripped. According to reports say there was a geo electric field of 3-6 V / km, and maximum flow change to 2500 nT / min.

1991-03-24:

Nine 220 kV lines and a transformer tripped.

2000-04-06 - 2000-04-07:

Observed the highest ever GIC in a power plant. This occurred in the generator transformer T2 in Oskarshamn and current was measured at almost 300 A.

2003-10-29: 7:11 to 7:46

A 400 kV and a 220 kV line tripped in Blekinge respective Härjedalen. In addition, the transformer T2 in Oskarshamn had abnormally high temperature. Magnetic field change is reported to about 500 nT / min.

2003-10-30: 20:55 to 21:03

Two 400 kV transformers in Östersund and Örebro tripped. It is stated that a geo electric field of 2 V / km and magnetic field change to 400 nT / min with a maximum deviation of about 2000 nT from normal values.

2003-11-20: 18:05

A 400 kV line tripped in Blekinge.

Disruptions in the Swedish regional grids

1960-11-13:

Seven 130 kV lines tripped in southern Sweden.

1982-07-14: 1:54 to 2:30

In July 13 nine 130 kV lines tripped. Four transformers to SJ's (Swedish State Railways) web feed also solved. Consumption Dropout in Malmö (20 MW in 13 minutes) and Gusum (20 MW).

1989-03-13 - 1989-03-14:

A geomagnetic storm activity was observed in Northern Europe that was five times as great as that caused Hydro Quebec collapse. Five 130 kV lines tripped in Sweden.

1989-09-19:

Seven 130 kV lines tripped.

2003-10-29: 07:12

A 130 kV line tripped in Östergötland.

2003-10-30: 21:03 to 21:08

A 130 kV transformer in Norrköping and three 130 kV lines (Malmö, Örebro and Constance) tripped which lead to a blackout in Malmö and 50,000 customers were without power for 20 to 50 minutes.

In characterizing transformer resilience under GIC, the transformer configurations thought most vulnerable to GIC effects are single-phase units and autotransformers. Five-legged, three-phase are less sensitive, and the most robust are three-legged three-phase. Age is also important (though probably counterintuitive): for two transformers of different generations but the same voltage and power rating, it is the older transformer that is more likely to be more inherently resistant to GIC, because generally the electric,

¹⁰⁶ Risto Pirjola, Geomagnetically Induced Currents During Magnetic Storms, IEEE Transactions on Plasma Science, Vol. 28, no 6, December 2000.

magnetic and thermal margins in the construction are smaller in newer transformers.¹⁰⁷

Generator Step-Up Transformers (GSU) are also more susceptible to GIC compared to system transformers, because GSUs are usually operated at near the 100% of the rated load. This means that they generally have a higher operating temperature, which in turn makes them sensitive to an additional rise in temperature due GIC.¹⁰⁸

Svenska Kraftnät recognizes that the Finnish grid is more resistant to GIC due to its design. One reason is that Fingrid uses only full transformers while Svenska Kraftnät widely uses autotransformers. Finland also uses reactive coils to ground their 400 kV transformers, which was determined not to be possible in the Swedish grid. The trade-off is that while the Finnish grid is more resistant to GIC, it is less efficient.¹⁰⁹

Metatech Vulnerability Analysis, 2000

In 2000, an Evaluation of the Vulnerability of the Svenska Kraftnät and Statnett SF (The Norwegian TSO) Transmission Networks to the Effects of Geomagnetic Storms, was conducted by Metatech. The study concluded that both transmission networks (which are interconnected) can develop very high GIC levels under moderate to severe GMD scenarios. The Svenska Kraftnät system was found to draw up to 5900 MVAR during moderate GMD scenarios, and up to 11,500 MVAR for severe GMD.¹¹⁰

The study found that in the 400kV network, even under moderate storm conditions, there are 15 transformers with GIC flows greater than or equal to the 300 Amps (100 Amps per phase), and 78% of the 400kV transformers could have GIC levels sufficient to cause half-cycle saturation. Looking at the entire 172kV – 400kV system, the average GIC flow in the transformers was found to be 29 Amps per phase for an East-West oriented geoelectric field and 48 Amps per phase for a North-South field.¹¹¹

5.6.3 Resilience and Mitigation Planning and Status

During the 1980s, the design of the ground fault protections was changed. The introduction of harmonic stabilized inverse time relays for disconnections of small zero sequence currents, the so-called JS3, improved the selectivity in the main grid. Protection relay changes in the 80s also led to positive effects in terms of resistance to GIC.¹¹²

¹⁰⁷ Svenska Kraftnät, 2012: Skydd mot geomagnetiska stormar- elektromagnetisk påverkan på kraftsystemet. Dnr. 2011/805

¹⁰⁸ Op. Cit.

¹⁰⁹ Op. Cit.

¹¹⁰ Metatech Report 2000

¹¹¹ Op. Cit.

¹¹² Svenska Kraftnät, 2012: Skydd mot geomagnetiska stormar- elektromagnetisk påverkan på kraftsystemet. Dnr. 2011/805

In Sweden there are 313 transformers connecting the main grid to the distribution grids. 211 of these are three-legged core-form transformers and 102 are five-legged core-form transformers or single-phase units. The first category, which is the most resistant to the GIC, constitutes 67% of the grid connected transformers.¹¹³

Svenska Kraftnät's policy is that transformers, as much as possible, must be of the three-legged three-phase configuration. As older transformers are replaced, this type of transformer is becoming more common, which will steadily enhance grid resilience to GIC. Svenska Kraftnät also requires that the new three-legged core-form transformers shall have the withstand capacity for direct currents of 200A for 10 min with simultaneous full load current. The main concern is transformer heating, and this requirement should mean that the transformers will be able to handle even higher DC current for periods of less than 10 minutes. Moreover, the transformers in the main grid usually have a low base load, further adding to thermal margins.¹¹⁴

Sometimes it is not possible to choose this type of transformer, possibly due to transportation or availability issues. When forced to choose a transformer that is not of the three-legged core type, the transformer's exposure to GIC can be reduced by introducing a resistor to the transformer neutral grounding point. However, Svenska Kraftnät is concerned that transformer neutral grounding protection could increase GIC flows to other transformers in the region. Only when a transformer is deemed to be at greater risk than others will grounding resistors be considered for the identified transformer. Other protection options are ground fault trips set at 120 Amps of zero, differential protection, and temperature and dissolved gas monitoring.¹¹⁵

Modeling of GIC in the system provides, at present, only theoretical calculation results. In order to improve the models, measurements from real GIC disturbances must be used. Presently, such GIC data is gathered at just one site in the country and lies outside of Svenska Kraftnät's control. The introduction of several measuring points would provide a better understanding of the real GIC flows in the system. Measuring harmonics would also help to clarify how transformers are affected by GIC.¹¹⁶

Fingrid is currently measuring GIC at five different sites. Upon request from Svenska Kraftnät, Fingrid has expressed interest in sharing data in real time if Svenska Kraftnät establishes its own GIC measurement capability. This represents an opportunity to begin to build a cooperative effort among Nordic TSOs on GIC measurement, envisioned to

¹¹³ Svenska Kraftnät, 2012: Skydd mot geomagnetiska stormar- elektromagnetisk påverkan på kraftsystemet. Dnr. 2011/805

¹¹⁴ Op. Cit.

¹¹⁵ Op. Cit.

¹¹⁶ Op. Cit.

include Norway, and possibly Russia.¹¹⁷

Finally, In the event that the power system is affected by a GIC, operational measures can also be taken by Svenska Kraftnät, such as canceling planned repairs in order to have as many system components as possible in operation to “share” GIC flows. Also, to reduce the risk of voltage collapse, additional generation can be spun up to smooth out the current transmission and reduce large power transfers.¹¹⁸

5.6.4. Summary

Sweden’s experience with GICs and Svenska Kraftnät’s efforts to mitigate GIC effects include the following:

- Nearly a dozen G5 class GMDs have affected the Swedish grid in the last ~50 years.
- Svenska Kraftnät’s policy is now to use three-legged, core-form transformers wherever possible in the grid.
- Svenska Kraftnät plans to expand its GIC monitoring capability.
- Svenska Kraftnät may consider the use of neutral ground protection for identified high-risk transformers.
- Svenska Kraftnät now uses a design criteria for GIC withstand for all new transformers of 200 Amps DC for 10 minutes.

¹¹⁷ Svenska Kraftnät, 2012: Skydd mot geomagnetiska stormar- elektromagnetisk påverkan på kraftsystemet. Dnr. 2011/805

¹¹⁸ Op. Cit



5.7 Finland

5.7.1 Power Grid Management and Structure



FINGRID high voltage landscape towers¹¹⁹

Fingrid Oyj

The main electric power transmission grid of Finland is supervised and developed by Fingrid Oyj, the Transmission System Operator (TSO). Fingrid also owns and operates the majority of cross-border connections (Norway, Sweden, and Russia) and Finland's electricity network is part of the Nordic power system and electricity market.¹²⁰ While Fingrid forms the central part of the Finnish power system, 12 other companies are authorized for regional distribution.¹²¹ Electricity network operations in Finland are run as a monopoly and require a grid permit from the Energy Market Authority (EMV).

The Finnish electricity network is divided roughly into the main transmission grid, regional networks and distribution networks. The main grid is used in long-distance transmission connections and high transmission voltages. The total length of the power lines in the main transmission grid is about 14,000 kilometers. The main transmission network consists of 440 kV, 220 kV, and 110 kV transmission lines, and includes over 100 substations.¹²²

¹¹⁹ To view this photo in its original context, visit: <http://www.fingrid.fi/en/news/photo-gallery/Landscapetowers/Pages/default.aspx>

¹²⁰ <http://www.emvi.fi/data.asp?articleid=231&pgid=127&languageid=826>

¹²¹ <http://www.emvi.fi/data.asp?articleid=1067&pgid=220>

¹²² <http://energia.fi/en/electricity-market/electricity-network/network-structure>

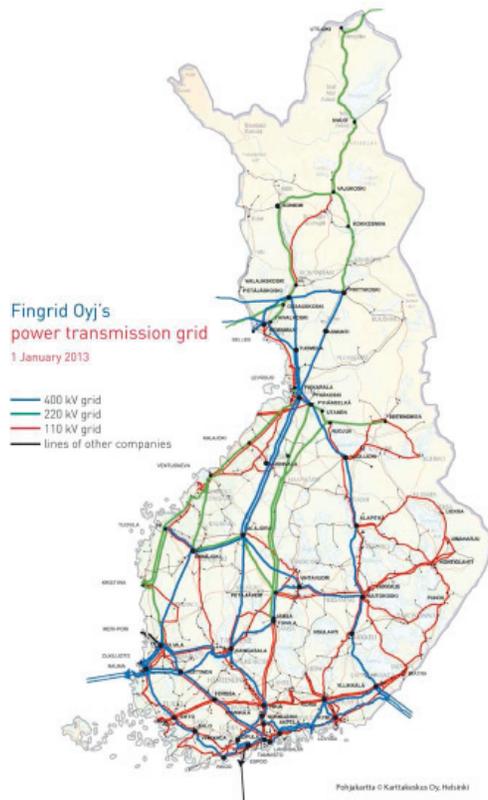


Figure 5.7.1 Power Transmission Grid of Finland¹²³

In 2012 the domestic power production was 67.7 TWh, and total consumption was 85.2 TWh. The most important energy sources for electricity generation are nuclear power (25.9%), hydropower (19.5%), coal (8.1%), wood fuels (11.8%), natural gas (7.4%), peat (4.9%), waste fuels (0.9%), and wind power (0.6%). The remaining 20.5% is imported, mainly from Russia, but also from Norway and Sweden.¹²⁴

Authorities

The Ministry of Employment and the Economy (MEE) controls permit applications concerning power lines,

and issues statements on land use and planning matters for the grid. The Energy Market Authority (EMV) is subordinate to the MEE and carries out oversight of the electricity and gas market for and in cooperation with the ministry, the Finnish Competition Authority and various other authorities.¹²⁵

The National Emergency Supply Agency (NESA, also under the MEE), is tasked with developing and maintaining security of the power supply. The Department of Energy Supply within NESA and Fingrid co-lead a group called Voimatalouspooli, which, along with other companies in the market, focuses on security of energy supplies.¹²⁶

The Radiation and Nuclear Safety Authority of Finland (called STUK) is responsible for environmental and safety requirements for nuclear energy in Finland.¹²⁷

Neither GMD nor EMP is currently covered by legislation or regulation outside of the normal economic, safety, and environmental regulations of the market as listed above.

¹²³ <http://www.fingrid.fi/EN/COMPANY/COMPANY/POWERTRANSMISSIONGRID/Pages/default.aspx>

¹²⁴ <http://energia.fi/en/statistics-and-publications>

¹²⁵ http://www.tem.fi/en/energy/electricity_market

¹²⁶ <http://www.nesa.fi>

¹²⁷ http://www.stuk.fi/stuk/en_GB/index/

5.7.2 E-threat Evaluation Studies and Reports

To date, there have been no major disruptions of the Finnish electrical grid due to GMD, though large GIC's have been measured in the system, beginning in the mid-1970s with GIC monitors installed at three substations. In 1979, GIC flows of up to 165 Amps were measured in the neutral grounding wires of a transformer at the Huutokoski substation, and 1999, GICs of up to 200 Amps were measured in the neutral of a transformer at Rauma. In March 1999, GIC's of up to 53 Amps were measured at the Pirttikoski substation.¹²⁸

Some small incidents were recorded, however. On October 29, 2003, a protection relay malfunctioned in Lapland, and the probable cause was attributed to GIC. This event was during the same solar storm event that led to a black-out in Malmo, Sweden. During the same storm, the tripping of a 220 kV reserve transmission line running between Finland and Norway also occurred.¹²⁹

A DC-injection test to measure effects on 400 kV transformers was conducted by Fingrid in 1999 to test for transformer heating. After a 2 hour and 30 minute test on the transformer being evaluated, where DC current was stepped up from 50 – 230 Amps, a temperature rise of 120°C was measured at the interior top yoke clamps, and a rise of 110°C was measured at the interior bottom yoke clamp. No dissolved gasses in the oil were found, and the heating was determined to be acceptable. High phase distortion due to half-cycle saturation was also measured, and the transformer consumed 55 MVAR at a DC current of 200 Amps.¹³⁰

5.7.3 Resilience and Mitigation Planning and Status

Finland is certainly subject to GMD effects several times per year. Probable contributors to the resilience of the Finnish system to GIC are several mitigation steps:

Series capacitors have been installed on all long 400 kV transmission lines in Finland (10 total lines are series compensated). Half-cycle saturation of transformers due to GIC is still believed possible, but the exposure to GIC's in the system has been greatly reduced.¹³¹

¹²⁸ Jarmo Elovaara, *About the Grid Effects of GIC's in Finland*, Presentation: 8th European Space Weather Week, November 28, 2011 (Updated January 6, 2012)

¹²⁹ Op. Cit

¹³⁰ Matti Lahtinen & Jarmo Elovaara, "GIC Occurrences and GIC Test for 400 kV System Transformer", IEEE Transactions on Power Delivery, Vol. 17, No. 2, April 2002, Page 555-561

¹³¹ Jarmo Elovaara, *About the Grid Effects of GIC's in Finland*, Presentation: 8th European Space Weather Week, November 28, 2011 (Updated January 6, 2012)

Only 3-limb and 5-limb, 3-phase, core-form transformers are used in the Finnish grid, which have the highest magnetic reluctance of all transformer types and are therefore most resistant to GIG effects.¹³²

The transformers on the 400 kV and 220 kV grid are grounded using current limiting reactor coils. The added reactance of the coil is used to limit fault-current magnitudes, but the additional resistance of the coils means it acts as a grounding resistor, which dampens GIC magnitudes.¹³³

Relay settings have been set to higher levels in order to reduce mis-operation under GIC conditions.¹³⁴

For these reasons, Fingrid does not have any special operational procedures for dealing with GIC, because their analysis of the vulnerability of their grid to GIC is low, so long as current design criteria are continued in the future.¹³⁵

5.7.4 Summary

Finland's basic approach to GMD protection is simple and hardware based:

The transformers used are of the design most resistant to GIC, and any new transformers will also be of the same type;

Their long transmission lines are series compensated, which blocks GIC flows in those lines; and

Their transformers are grounded using coil reactors that dampen GIC flows in the transformer neutrals.

¹³² Jarmo Elovaara, *About the Grid Effects of GIC's in Finland*, Presentation: 8th European Space Weather Week, November 28, 2011 (Updated January 6, 2012)

¹³³ Op. Cit

¹³⁴ Op. Cit

¹³⁵ Op. Cit



5.8 Germany

5.8.1 Power Grid Management and Structure

The German electricity transmission system acts as the central electricity transit hub in the mainland European electricity market, and includes interconnections to Sweden, Denmark, Poland, the Netherlands, Luxembourg, France, the Czech Republic, Switzerland and Austria. There are four key Transmission System Operators (TSO) in Germany.¹³⁶ The transmission grid in Germany is operated at 380 and 220 kV.

Amprion GmbH

The Amprion GmbH transmission system is comprised of approximately 11 000 km of lines and approximately 160 transformer stations, the largest transmission system in Germany.¹³⁷

TenneT TSO GmbH

In Germany, the TenneT TSO Germany GmbH transmission system is approximately 10,700 km in length and contains 115 transformer stations. The network covers approximately 140, 000 square kilometres from the border of Denmark to the Alps.¹³⁸

TransnetBW GmbH

TransnetBW GmbH (TransnetBW), part of the EnBW Energie Baden-Württemberg group, operates the transmission system in Baden-Württemberg and consists of 3,236 km of high-voltage lines and over 80 transformer stations.¹³⁹

50Hertz Transmission

50Hertz Transmission GmbH is responsible for the transmission grid in the northern and eastern parts of Germany, the areas previously occupied by the former German Democratic Republic (East Germany). It covers an area of 110,000 square kilometres, has approximately 9,840 km of lines and contains 75 transformer stations.¹⁴⁰

¹³⁶ Source: Federal Ministry of Economics and Technology (BMWi)

¹³⁷ <http://www.amprion.net/en/portrait>

¹³⁸ <http://www.tennet.eu/de/en/home.html>

¹³⁹ <http://transnetbw.com/>

¹⁴⁰ http://www.50hertz.com/cps/rde/xchg/trm_de/hs.xml/index.htm?rdeLocaleAttr=en&rdeCOQ=SID-7DD7452F-9A17FDD3



Figure 5.8.1. Electricity transmission network in Germany (380/220 kV)

Generation

Electricity generation in Germany was 609 terawatt-hours (TWh) in 2011, composed of 262 TWh coal (43 %), 118 TWh renewable energy (19 %), 108 TWh nuclear power (18 %), 83 TWh Gas (14 %) and 38 TWh other sources (6 %).

As of 31 December 2011, 174.2 GW of generating capacity was connected to the electricity system: Solar (18.7%), Wind (17.5%), Coal (11.7%), Natural Gas (11.1%), Lignite (10.4%),

Other Sources (8.8%), Nuclear (6.9%)¹⁴¹, Pumped Storage (5.3%), Biomass (3.2%), Hydro (2.9%), Oil (2.2%), Waste (7.7%), Landfill Gas (0.2%), Marsh Gas (0.2%), Sewage (0.1%), and Geothermal (<0.1%).¹⁴²

In recent years, renewable energy sources have grown to over 38% of total generation capacity and to around 20 % of total produced electricity in Germany. Due to significant changes in the structure of generation (including, importantly, the decision to phase out nuclear power by 2022) the increase in renewable energy sources means that more generating capacity is now connected directly to the distribution systems rather than to the transmission systems.¹⁴³ However, since most of the wind power is installed in Northern Germany and the load centers are located in the South, more electricity is transported within Germany via the transmission grid. Consequently, massive grid expansion is planned in the upcoming decades in order to comply with this new system needs. This change could reduce overall system efficiency and resilience since more electricity is transported over longer distances via the transmission grid.

ENTSO-E and UCTE, BMWI, and BNetzA

The planning and operation of the German transmission grid is based on the rules of the European Network of Transmission System Operators (ENTSO-E) as it is defined in the Union for the Coordination of the Transmission of Electricity (UCTE) policies, including the handling of exceptional contingencies.¹⁴⁴ The Federal Ministry of Economics and Technology (BMWi)¹⁴⁵ oversees these activities in Germany, and the regulatory authority (within BMWi) in charge of enforcing the regulations is the Federal Network Agency for Electricity, Gas, Telecommunications, Post, and Railway (Bundesnetzagentur or BNetzA)¹⁴⁶

There are currently no statutory or regulatory requirements specifically regarding GMD or EMP within this policy framework.

5.8.2 E-threat Evaluation Studies and Reports

In Germany, no specific measures have been taken up to now to protect the grid from GMD caused by solar storms or by weapons. The BMWI has commissioned a theoretical

¹⁴¹ To be phased out in Germany by 2022

¹⁴² *Kraftwerksliste der Bundesnetzagentur*, Federal Network Agency, 2013.

¹⁴³ Op. Cit

¹⁴⁴ <https://www.entsoe.eu/about-entso-e/a-proud-history/ucte/>

¹⁴⁵ <http://www.bmwi.de/EN/root.html>

¹⁴⁶ http://www.bundesnetzagentur.de/cln_1932/EN/General/Bundesnetzagentur/About/AboutTheBundesnetzagentur_node.html

“pre-study” on the threat to the transmission system.¹⁴⁷ The study identified no events in the past that could be linked to GMD events, concluding that it was not clear if a GMD poses a serious threat to the German transmission network as it is the case in more northern states in Europe, e. g. Norway.

The study did recommend, however, beginning a GIC monitoring program in the transmission grid to measure the GIC in the transformers and related impacts on grid operation. Measuring devices are currently being installed at selected locations in the transmission grid. The monitoring project is planned for three years, and when completed, should provide more detailed and sound information on the scope of the GIC threat to the German system. Depending on the results of the monitoring results, future works could include development of grid modelling capability for GIC, better solar physics understanding and early warning, and development of operational procedures for use by TSOs, should the threat be determined to warrant them.

5.8.3 Summary

Though Germany is in the nascent stages of studying and addressing the GMD/EMP risk for its electrical networks, there are a few points of interest that should be noted:

1. Germany has begun a GIC monitoring campaign, with monitors being placed at several key grid points.
2. The change in German energy policy away from nuclear and toward renewables will affect the resilience for GMD/EMP in two important ways:
 - a. More electricity will be transported over the transmission grid since the distance of electricity generation and consumption is increased, on average, potentially leading to higher GIC vulnerability.
 - b. Depending on how the phase-out of nuclear power plants is done, and on the long term plans for handling and cooling spent nuclear fuel rods, this change could reduce the concern of nuclear accidents caused by loss of outside power (LOOP) events.

¹⁴⁷ Herman Luhr, *Effect of Geomagnetic Storms on the German Electricity Transmission Network: Progress and Research Needs*, German Research Center for Geosciences, June 21, 2012



5.9 South Korea

5.9.1 Power Grid Management and Structure



KEPCO

The South Korean electricity transmission grid is owned and operated by the state-run Korean Electric Power Corporation, or KEPCO. The power generation component is nominally based on free market competition, though all six of the generation companies (five fossil fuel and one nuclear/hydro) are owned 100% by KEPCO, making it effectively a vertically integrated company. The six generation companies compete with each other to improve price and cost efficiency. KEPCO produces a combined 79.3 GW of power for South Korea (30.5 % coal, 25.4% natural gas, 23.6% nuclear, 10.1% oil, 8.1% hydro, and 2.3% from wind and other alternative energy sources).¹⁴⁸

The EHV transmission system operates at three voltages, 765, 345, and 154 kV. The total length of the transmission system is 31,249 km, and by voltage class the line lengths are 835 km at 765 kV, 8,653 km at 345 kV, and 21,761 km at 154 kV. The system contains 749 substations with 271,247 MVA of transformer capacity.¹⁴⁹ There is also a 115 km (180 kV) undersea HVDC transmission line that connects mainland South Korea and the island province of Jeju (see map, fig. 5.9.1).

¹⁴⁸ KEPCO Annual Report 2012

¹⁴⁹ Op. Cit

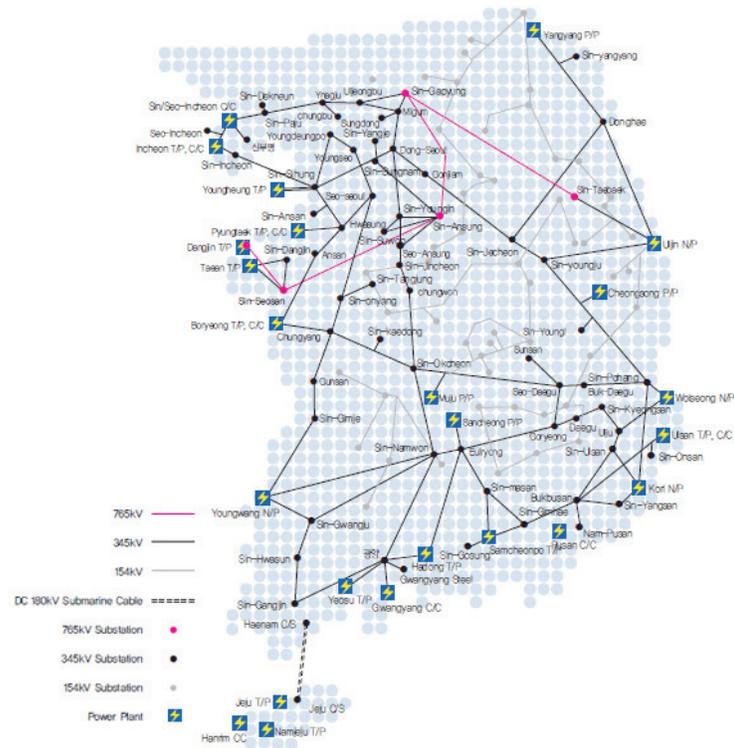


Fig 5.9.1 – Map of South Korean Transmission Grid¹⁵⁰

Korean Electricity Regulatory Commission

The Korean Electricity Regulatory Commission (KOREC) was established as principally an economic regulator for the electricity sector. Its principle duties are licensing, promoting fair completion, ratepayer protection, and supervision of restructuring and operation of the electricity system.¹⁵¹ KOREC is affiliated with the Ministry of Knowledge Economy, which is responsible for business and trade.¹⁵² Within KOREC, the Electricity Market Division is responsible for the overall operation of the electricity market and reviewing proposed changes to electricity rates. The Electricity System Division provides oversight of the reliability and operation of the transmission and distribution systems.¹⁵³

There are currently no statutory or regulatory requirements enforced by KOREC relating to GMD or EMP.

¹⁵⁰ http://www.geni.org/globalenergy/library/national_energy_grid/south-korea/southkoreannationalelectricitygrid.shtml

¹⁵¹ <http://www.korec.go.kr/>

¹⁵² <http://www.mke.go.kr/language/eng/>

¹⁵³ <http://www.korec.go.kr/>

5.9.2 E-threat Evaluation Studies and Reports

In December 2012, the Korea Meteorological Administration and Seoul National University of Science and Technology jointly conducted a study on GMD effects to the South Korean power system.

In this study, predicted GIC flows in one section of the KEPCO grid were calculated. The study calculated GIC flow in the Singapyeong-Sintaebaek 765kV transmission line, the longest 765 kV in South Korea at 154.7 km. The authors assumed a geoelectric field value of 1.7 V/km (chosen because this was the field value experienced in Quebec which caused the 1989 blackout). They calculated maximum GIC flows of 216 Amps through the transformers at either end of the line.¹⁵⁴

While severe geomagnetic disturbances are generally less frequent at middle latitudes such as South Korea (34~38 degrees North), as is demonstrated in section 5.13 of this report, the largest loss of EHV transformers due to GIC took place in South Africa, at approximately the same latitude as South Korea (though South Africa is South rather than North of the equator.)

Electromagnetic Pulse

South Korea considers itself under continuing threat of attack by North Korea. In regard to EMP, to-date, “South Korean readiness [for] EMP attack has only considered the military facilities.”¹⁵⁵



On December 14, 2010, a workshop was held by senior technical and engineering staff at LIG/NEX1 in support of the Korea Agency for Defense Development (ADD). The topic was critical infrastructure hardening against HEMP.

Figure 5.9.2 Projected 50 km Height HEMP Profile¹⁵⁶

¹⁵⁴ Journal of the Korean Institute of Illuminating and Electrical Installation Engineers (2012) 26(12): <http://dx.doi.org/10.5207/JIEIE.2012.26.12.056> ISSN 1229-4691(Print) ISSN 2287-5034(Online)

¹⁵⁵ Lee, Byun, and Lee, Journal of Safety and Crisis Management, Vol. 2, No. 2, 2 December 2012, pp. 44-48.

¹⁵⁶ Davidson Scott, *HEMP Hardening Workshop – Day 1*, ember 14, 2010

South Korea has reviewed specific potential HEMP scenarios. One hypothetical example discussed was a missile launch from Musudan-ri Missile base to a position just north of the 38th Parallel, where the weapon would be detonated at altitude. In this example the missile would remain over North Korean territory, but still yield significant EMP field strength over Seoul and industrial centers in the northern sectors of South Korea, with effects over the whole of the Korean peninsula. Such a scenario would produce maximum HEMP E1 fields > 50 kV/m over Seoul (See Figure 5.9.2).¹⁵⁷

Such high E1 fields would certainly damage SCADA systems, and the accompanying E3 fields would be significantly higher than the 1.7 V/km used for the GMD calculation cited above, driving GICs of hundreds to thousands of Amps through the transmission system. For example, if the IEC standard of 40 V/km is used for EMP E3 (which is conservative, well below the peak field values indicated in Figure 5.9.2), South Korea could expect over 23 times the calculated current cited above or 5,082 Amps DC in the Singapyeong-Sintaebaek 765kV transmission line. Such extremely high currents would run through the entire KEPCO system and likely damage or destroy several transformers.

5.9.3 Resilience and Mitigation Planning and Status

To date, KEPCO has determined that GMD is a remote threat to their system and there are currently no mitigation plans in place for GICs.

South Korean authorities are taking the threat of a North Korean EMP more seriously, though activities to date are sensitive/classified. From unclassified sources however, the protection activities that are underway only focus on the military, while the civilian critical infrastructures remain unprotected.

“EMP weapons represent one of the most ominous threats to national security in the near term, and it is worth noting that the vulnerability of the nation’s critical infrastructure is not confined separately to the society (or civilian) or to the military sectors. ... We ought to manage this change and move from near-denial that our critical infrastructures are threatened by EMP attacks to acceptance of this reality, and undergo a paradigm shift in out conception and perception of the impacts of such attacks.”¹⁵⁸

¹⁵⁷ Davidson Scott, *HEMP Hardening Workshop – Day 1*, ember 14, 2010

¹⁵⁸ Lee, Byun, and Lee, *Journal of Safety and Crisis Management*, Vol. 2, No. 2, 2 December 2012, pp. 44-48.

5.9.4 Summary

Given South Korea's assumptions for hypothetical scenarios and field strength, a nuclear EMP attack would inflict widespread damage on the South Korean society. While unclassified sources do not provide any measures South Korea may have taken to protect civil infrastructures, it is clear Seoul has concerns for the safety and security of critical assets and military facilities. South Korea's current progress in protection of such facilities was not made available for this report.



5.10 Japan

5.10.1 Power Grid Management and Structure

Federation of Electric Power Companies

The electric grid of Japan is owned and operated by ten separate privately-owned companies: The Chugoku Electric Power Company; Chubu Electric Power; Hokuriku Electric Power Company; Hokkaido Electric Power Company; Kyushu Electric Power; The Kansai Electric Power Company; The Okinawa Electric Power Company; Tokyo Electric Power Company; Tohoku Electric Power; and Shikoku Electric Power Company. Each is vertically-integrated, providing generation, transmission, and distribution to one of ten delivery regions (Fig 5.10.1). The companies are all members of an industry association: the Federation of Electric Power Companies (FEPC).¹⁵⁹

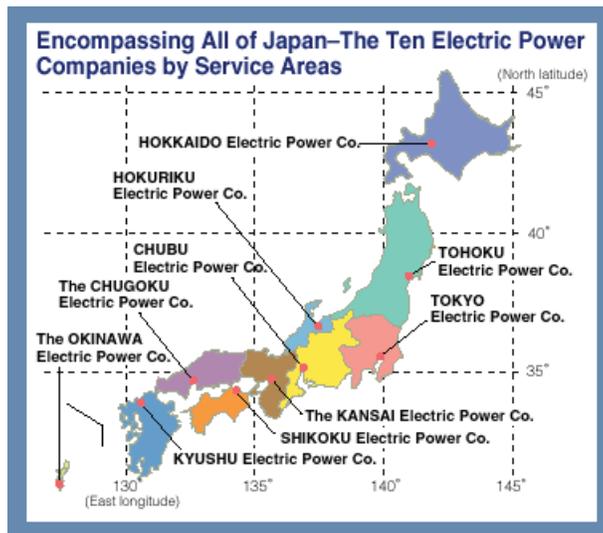


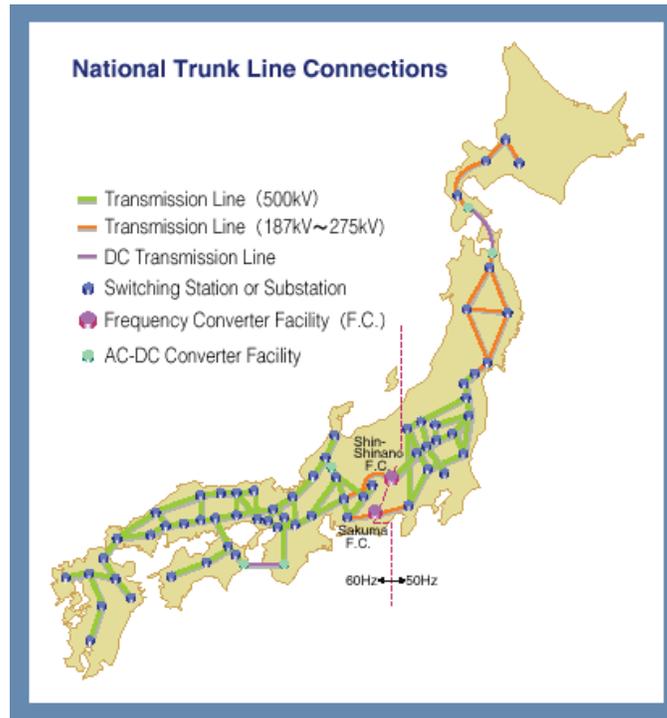
Figure 5.10.1 Map of Japanese Power Companies¹⁶⁰

The ten power companies supply their electrical power loads within their regional service areas, but are also linked by extra high voltage (EHV) transmission lines throughout the country. The majority of the transmission system operates at 500 kV, while lines within the Hokkaido system operate at 275 kV and 187 kV. There are also 275 kV lines near the AC frequency converter facilities

at Shin-Shinano and Sakuma. The Tohoku and Hokkaido systems are connected by a 250 kV HVDC transmission line (undersea + overhead), and the Kansai and Shikoku systems are connected by a 500 kV HVDC link. (Fig 5.10.2)

¹⁵⁹ <http://www.fepec.or.jp/english/>

¹⁶⁰ http://www.geni.org/globalenergy/library/national_energy_grid/japan/index.shtml

Figure 5.10.2 Japanese Grid EHV Transmission Interconnects¹⁶¹

Ministry of Economy, Trade and Industry

The ten electric companies in Japan are overseen by the Ministry of Economy, Trade, and Industry (METI). Within METI, the Agency for Natural Resources and Energy contains two divisions, the Electricity Market Division and the Electricity Infrastructure Division. In June 2004, The Electric Power System Council of Japan (ESCJ) was established and designated by METI as the recognized organization “to support transmission, distribution and other related operations” in Japan. In this regard, ESCJ is somewhat comparable to NERC in the U.S.

To date, there are no statutory or regulatory requirements within METI or ESCJ regarding GMD or EMP.

Since the Great East Japan Earthquake and Fukushima nuclear accident in March 2011, METI determined that it must review the Japanese “Basic Energy Plan,” METI established the Fundamental Issues Subcommittee under the Advisory Committee for Natural Resources and Energy to deliberate and make recommendations.

¹⁶¹ http://www.geni.org/globalenergy/library/national_energy_grid/japan/index.shtml

The Subcommittee released a report summarizing a number of major issues,¹⁶² including discussions of Japan's planned reliance on nuclear energy, which had been envisioned to provide more than half of Japan's electricity through 2030.

5.10.2 E-threat Evaluation Studies and Reports

In 2000, Chubu Electric contracted with the Metatech Company to perform modeling and analysis of the vulnerability of their network to GIC flows. As part of this effort, Chubu also began a GIC monitoring project to gather GIC flow data at two transformer substations (Shinano and Fukumitsu), which supported the development and validation of the GIC model of the transmission system.¹⁶³

Because of Japan's mid to low-latitude (30° - 45° N), most power grids in central and southern Japan are not often exposed to significant GICs, which occur more regularly at higher latitudes. Interestingly, however, during two relatively weak geomagnetic disturbances that occurred in 2001, significant GIC flows occurred in transformer neutrals.

On April 11, 2001, a low level GMD event lasting about 3 hours produced peak GIC flows of 4 Amps in the neutral of the monitored transformer at the Shinano station and peak flows of nearly 30 Amps at the Fukumitsu station. Later that year, on November 6, 2001, during a shorter but more intense storm (characterized as a Sudden Storm Commencement event) that lasted only 20 minutes, a peak GIC value of 42 Amps was reached, and GIC flows above 10 Amps were sustained for about 12 minutes.¹⁶⁴

These observations (as well as those outlined in Chapter 5.13) demonstrate that both prolonged durations and significant magnitudes of GIC are possible at mid-latitude locations.

In addition, since these measurements were carried out simultaneously at two points in the transmission system, they provided an excellent opportunity to check the accuracy of the Metatech model. The remarkable accuracy of the consequent model validation generated confidence in use of the model to accurately predict GIC flows through other transformers in the network under different storm scenarios. For example, a storm of the magnitude of the March 1989 storm (had it been over Japan instead of over Quebec) was modeled. GIC levels at these same locations were predicted at more than a factor of three times higher than those observed on April 11, 2001.

¹⁶² http://www.meti.go.jp/english/press/2011/1220_05.html

¹⁶³ CIGRE Paper 39-304/2002-03-26, Erinmez, Majithia, Rogers, Yasuhiro, Ogawa, Swahn, Kappenman

¹⁶⁴ Op. Cit

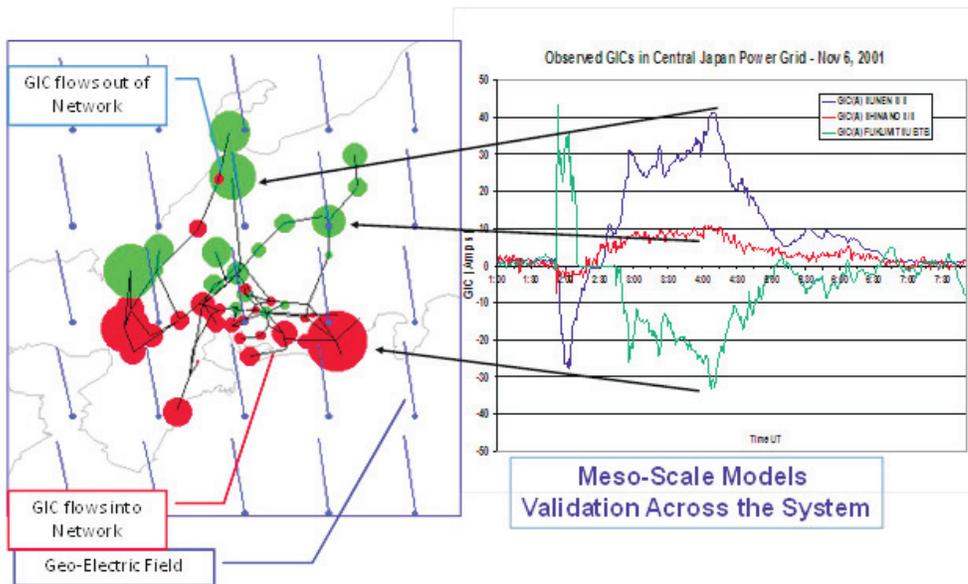


Figure 5.10.3 Observed & Calculated GIC – Nov 6, 2001 in Southern/Central Japan with the SSC and ring-current intensification of Nov 6, 2001.¹⁶⁵

5.10.3 Resilience and Mitigation Planning and Status

Notwithstanding the results of the modeling effort – and the actual GMD event – Chubu electric later discontinued the GIC monitoring program, and currently there are no ongoing GMD-related programs within the METI or the FEPC. To date, there have been no recorded incidents of disruption or failures within the Japanese electricity sector attributable to GMD.¹⁶⁶

5.10.4 Summary

The Fukushima nuclear power plant disaster was precipitated largely by the loss of power from the electric transmission system, and coincident destruction of backup diesel power systems. A significant GMD or EMP event has the potential to cause a similar, and possibly more serious, loss of outside power (LOOP) event in Japan. While Japan has focused on changes to its power generation posture – in particular the nuclear power sector – the risk of GMD has not prompted further study or risk mitigation strategies.

The Japanese government did not provide open source information on EMP risk or protection.

¹⁶⁵ Source: Metatech, NOAA Space Weather Week Presentation, 2002

¹⁶⁶ Japanese embassy – private communication



5.11 Australia

5.11.1 Power Grid Management and Structure

Australian Energy Market Operator

In July 2009, the Australian Energy Market Operator (AEMO) began operating as a single, industry-funded national energy market operator for both electricity and gas, and functions as the Transmission System Operator (TSO). AEMO is also responsible for the planning and coordination of development of the national transmission network as the National Transmission Planner (NTP). This strategy is intended to improve transmission planning arrangements within the Australian transmission system, by shifting the planning focus away from individual jurisdictions, broadening them to the national grid as a whole through an annual national transmission network development plan. The plan will not replace local planning, nor be binding on transmission businesses or the Australian Energy Regulator (AER.)¹⁶⁷

Five regional transmission companies make up the AEMO: Powerlink (Queensland), Transgrid (New South Wales), SP AusNet (Victoria), Electranet (South Australia), and Transend (Tasmania). These regional TSOs are referred to as Transmission Network Service Providers (TNSP). There 43,775 km of transmission lines in the Australian transmission system, operating at 500, 330, 275, 220, 132, and 66 kV. In addition, there are three system interconnections: Queensland and New South Wales are connected by the 63 km Directlink, Victoria and South Australia are connected by the 180 km HVDC Murraylink, the world's longest underground power cable, and the 375 km Basslink undersea HVDC cable connects Victoria and Tasmania.¹⁶⁸ (See Figure 5.11.1).

Power generation in Australia is deregulated and is supplied by a mix of sources: coal (57% of generation capacity, 79% of output), natural gas (21% of generating capacity, 11% of output), hydro (16% of generating capacity, 7% of output), wind (4% of generating capacity, 3% of output), and solar (about 1% of capacity and output). In 2011-2012, 199 TWh were generated.¹⁶⁹

¹⁶⁷ State of the Energy Market 2009

¹⁶⁸ State of the Energy Market 2012

¹⁶⁹ Op. Cit



Figure 5.11.1 Map of the Australian Transmission System¹⁷⁰

Australian Energy Regulator

Historically, government utilities ran the entire electricity supply chain in all states and territories of Australia. Beginning in the 1990s, generation, transmission, distribution and retail were separated. Generation and retail now operate under competition, while the transmission and distribution networks operate as regulated monopolies. The Australian Energy Regulator (AER) has held this regulatory role since 2005 and enforces

the regulations called for by Chapter 6A of the National Electricity Rules.¹⁷¹ | ¹⁷² These rules are economic in nature, and do not contain any provisions regarding grid resilience for GMD or EMP.

5.11.2 E-threat Evaluation Studies and Reports

Australia has not experienced a grid fault, disruption, or failure that has been attributed to GMD (or EMP). As such, the subject of GMD effects on the Australian system had received little attention until 2011, when a pilot project was initiated to monitor GIC flows in the Australian transmission network. The study began in 2012, and is a collaboration between the AEMO, the regional Transmission Network Service Providers (TNSOs), the Australian Bureau of Meteorology (BOM) Space Weather Branch, and several Australian Universities.¹⁷³

¹⁷⁰ Australian Energy Market Operator (AEMO) <http://www.aemo.com.au/Search?a=Regional+Boundaries+for+the+National+Electricity+Market>

¹⁷¹ State of the Energy Market 2009

¹⁷² <http://www.aemc.gov.au/Electricity/National-Electricity-Rules/Current-Rules.html>

¹⁷³ Marshall, R.A., et al. (2013), *Observations of Geomagnetically Induced Currents in the Australian Power Network*, Space Weather, 11,6–16, doi:10.1029/2012SW000849.

The GIC monitors were installed in transformer neutrals at 8 locations: Chapel Street and George Town in Tasmania (220 kV); Hazelwood Terminal Station¹⁷⁴ and Moorabool Terminal Station in Victoria (500 kV); Para in South Australia (275 kV); Bannaby and Bayswater in New South Wales (500 kV); and Middle Ridge in Queensland¹⁷⁵ (330/275 kV), (See Figure 5.11.2) The system became operational in 2012, and data has been recorded and analyzed from two of the monitors so far. The monitors are connected to the substation SCADA systems and data is transferred to the regional TNSP control centers and to the AEMO. The data are also correlated with the geomagnetic observatories (magnetometers) at Canberra and Cullgoora.¹⁷⁶

On July 14-15, 2012, a relatively minor storm (NOAA geomagnetic levels G-2 and Kp-6)¹⁷⁷ associated with a CME Sudden Storm Commencement (called Sudden Impulse – SI in the paper) event was measured on the system. GIC currents were measured with a maximum of 5.3 amps at the Middle Ridge station and 4.1 Amps at the Para station, and had high correlation (~90%) with the magnetometer measurements (which also yield East-West geoelectric fields) at Canberra and Cullgoora. The corresponding geoelectric fields were very small: ~ 0.06 – 0.07 V/km. Previous magnetometer measurements indicate geoelectric fields 6-10 times larger, with concomitant, expected GIC flows of more than 25 amps, scaling to even larger GIC levels during larger solar storm events.¹⁷⁸

5.11.3 Resilience and Mitigation Planning and Status

Operational Procedures

The AEMO has published Power System Security Guidelines which include “Management of Solar Storms – Geomagnetic Disturbances (GMD).”¹⁷⁹ In preparation for, during, and following a GMD event, the BOM Space Weather Branch can issue a Severe Space Weather Watch based on Solar observation data. The Watch provides advanced warning of greater than 12 hours that a solar impact may occur. If an impact is imminent, based on Solar Wind data (collected from the ACE Satellite), a GIC Warning providing 30-60 minutes lead time is issued to the TSOs. These warnings may be of Short or Sustained duration. In addition to the pre-storm warnings, AEMO and the TNSPs have real-time situational awareness during storm events because the GIC monitoring system described

¹⁷⁴ Not yet operational – expected date TBD

¹⁷⁵ Additional monitors are being installed at Murarrie (110kV) near Brisbane and Bowen North (132kV) in North Queensland – expected date TBD

¹⁷⁶ Marshall, R.A., et al. (2013), Observations of Geomagnetically Induced Currents in the Australian Power Network, *Space Weather*, 11,6–16, doi:10.1029/2012SW000849.

¹⁷⁷ Provided by NOAA Space Weather Prediction Center

¹⁷⁸ Marshall, R.A., et.al. (2013), Observations of Geomagnetically Induced Currents in the Australian Power Network, *Space Weather*, 11,6–16, doi:10.1029/2012SW000849.

¹⁷⁹ AEMO, *Power System Security Guidelines*, 18 June, 2013.

above is telemetered to the AEMO and TNSP control centers.¹⁸⁰ Below are the operational procedures issued by AEMO:

*“AEMO may initiate the following actions in response to a **severe** GMD;*

1. *AEMO may instruct the restoration of out of service transmission lines and transformers as well as discontinue planned transmission outages, including;*

i) Interconnectors,

ii) Equipment impacting on main system transformer loadings,

This action allows the GIC to be split between more transmission lines and transformers and also lowers the 50 Hz loading per transformer. This enables the transformers to run cooler and hence have more headroom for GIC heating effects and less saturation effects.

2. *AEMO will maximize reactive reserves across the power system.*

3. *During a severe GMD, the TNSP may advise AEMO of revised transformer ratings, allowing the transformer to operate at cooler temperatures, to prepare for the onset of stray flux heating from the GIC.*

4. *During a severe GMD, the TNSP may advise AEMO of their intent to take out of service a transformer(s) due to the high impact of the GIC.*

In circumstances where a low intensity GMD is received but GIC is at alarm levels, as supplied by the TNSP, AEMO will take action as if a severe GMD has been received.”¹⁸¹

¹⁸⁰ AEMO, “Solar Storm Threat”, EECON NSW 2013 Conference, Presented by Mark Miller

¹⁸¹ AEMO, *Power System Security Guidelines*, 18 June, 2013.

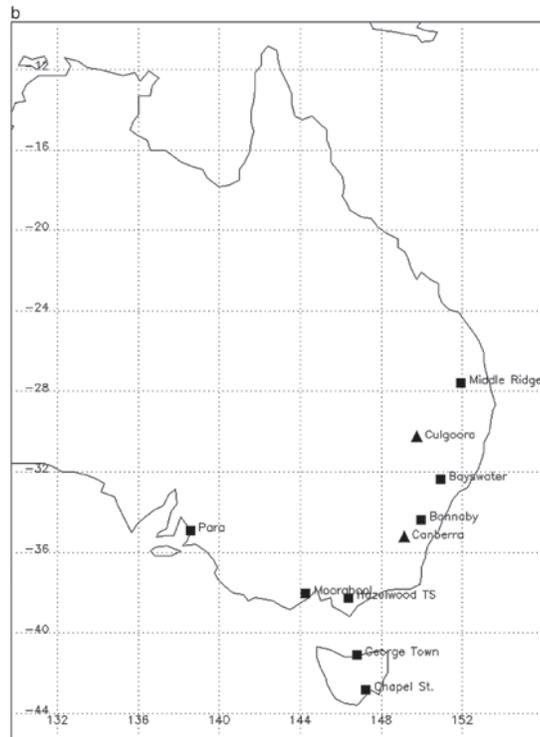


Figure 5.11.2 GIC monitoring sites in Australia. GIC monitors are represented by the square symbols and magnetometer stations by the triangle symbols.¹⁸²

5.11.4 Summary

Although Australia has historically had almost no experience with GMD events, a recent study measured GICs in the transmission system. A fairly extensive GIC monitoring pilot study has begun in Australia, which will lead to better understanding of GMD/GIC effects on the system.

AEMO now has in place GMD-specific operational procedures to mitigate effects of GMD on their systems. Though AEMO acknowledges that operational procedures are somewhat limited compared to hardware-based solutions, they have deemed them acceptable, since GMD risk is considered to be much lower than for other systems (such as Quebec).¹⁸³

¹⁸² Marshall, R.A., et.al. (2013), *Observations of Geomagnetically Induced Currents in the Australian Power Network*, Space Weather, 11,6–16, doi:10.1029/2012SW000849.

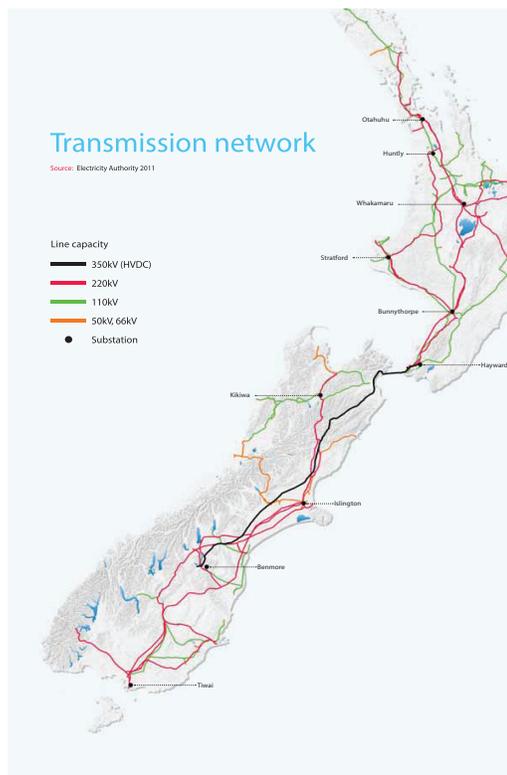
¹⁸³ AEMO, "Solar Storm Threat", EECON NSW 2013 Conference, Presented by Mark Miller



5.12 New Zealand

5.12.1 Power Grid Management and Structure

Transpower



The national electrical grid of New Zealand is owned and operated by Transpower, a State-owned company. Transpower builds and maintains the transmission network and also acts as the system operator.¹⁸⁴ The system provides approximately 40,000 GWh per year to the residents and commercial entities of New Zealand. Transmission is carried by approximately 12,000 km of transmission lines. There are 174 substations, which contain more than 1000 transformers as well as switchgear, structures and buswork, and reactive support equipment, and 2300 circuit breakers.¹⁸⁵

Figure 5.12.1. Map of the New Zealand Transmission System

The EHV portion of the AC transmission system runs at two voltages: 220kV, 110kV. There is also a 610-kilometer, High-Voltage DC (HVDC) link that connects the AC transmission grids on the North and South Islands. The HVDC link has two poles called Pole 2 and Pole 3 that operate at +/-350kV. Three 40km long submarine power cables cross the Cook Strait.¹⁸⁶

¹⁸⁴ <http://www.ea.govt.nz/about-us/documents-publications/electricity-nz/>

¹⁸⁵ Transpower Asset Management Plan, 2010

¹⁸⁶ http://en.wikipedia.org/wiki/HVDC_Inter-Island

The total generation capacity of the system is about 10 GW and comes from a mixture of Hydro (54.4%), gas (15.9%), Coal (10%), Geothermal (7.3%), Wind (6.1%), Cogeneration (3.9%), Diesel (1.8%), and other sources (0.6%).¹⁸⁷

Electricity Authority

The regulator for the New Zealand electricity sector is called the Electricity Authority (the Authority) created in statute under the Electricity Industry Act of 2010 (the Act). The Act requires the Authority “to promote competition in, reliable supply by, and the efficient operation of, the electricity industry for the long-term benefit of consumers. Pursuant to the requirements of the Act, the Authority developed the Electricity Industry Participation Code 2010 (the Code) and the Electricity Industry Enforcement Regulations 2010 (the Regulations), which have been in effect since November 2010. The Authority is required to make and administer the Code and to monitor and enforce compliance with the Act, the Code, and the Regulations.”¹⁸⁸

Applicable Regulations

Most of the focus of the Electricity Authority is to act as an economic regulator. There are no specific references to geomagnetic disturbances or electromagnetic pulses in the Code or the Regulations. The Code does, however, incorporate by reference the Emergency Management Policy 2012.¹⁸⁹ The Emergency Management Policy defines three levels of event severity. “Contingent events”, the lowest level, are typically single asset failures that should be managed without load shedding.¹⁹⁰

More serious events are called “extended contingent events” and are defined as events with estimated impact, probability, and cost such that proper management may include load shedding. Scheduling and dispatch of reserve capacity and pre-event management are also included.¹⁹¹

Consistent with the fact that Transpower has developed and implemented both operational and hardware approaches to contend with GIC, GMD would be categorized as an extended contingent event in regards to severity, and would be classified as a “Grid Emergency.”

The most severe events are called “uncommon events” where the estimated impact, probability, and cost are such that no pre-event plan other than unplanned load shedding is deemed appropriate. The Emergency Management Plan also defines and includes Civil

¹⁸⁷ <http://www.ea.govt.nz/about-us/documents-publications/electricity-nz/>

¹⁸⁸ <http://www.ea.govt.nz/act-code-regs/>

¹⁸⁹ Emergency Management Policy, 2012, System Operator (Transpower)

¹⁹⁰ Same concept as N-1 reliability requirement

¹⁹¹ Emergency Management Policy, 2012, System Operator (Transpower)

Defense Emergencies and Extended Emergency Events, which would also be appropriate categories for GMD and/or EMP events.¹⁹²

5.12.2 Resilience and Mitigation Planning and Status

New Zealand had been previously considered to have a low vulnerability to GMD events due to a few factors: relatively short transmission line lengths, predominantly north-south transmission line orientation, and middle latitude (~ 35° - 45° South). This outlook changed after a geomagnetic storm affected New Zealand's South Island on November 6, 2001.¹⁹³ The GMD event resulted in a transformer fault and subsequent trip at Halfway Bush, as well as the tripping of the SVC at Islington.¹⁹⁴

Hardware Approaches

The HVDC link connecting the North and South Islands can produce small amounts of stray DC current that is injected into the South Island AC transmission lines by entering and exiting grounded, “wye” connected power system transformers. In response, Transpower has designed and installed neutral ground resistors and DC current measuring devices (referred to as LEMs) on grid connected transformers vulnerable to stray DC currents from the HVDC link¹⁹⁵. This action, which began in 1990, has an ancillary benefit in protecting those transformers and the AC system in general from GIC, as they are also quasi-DC currents that enter the AC system through the same grounding points.

Since 1990 Transpower has designed and installed neutral grounding resistors and LEMs on transformers at all sites with grounded wye transformers, including: Clyde, Cromwell, Waitaki, Aviemore, Benmore, Ohau A/B/C, Tekapo B, Timaru, Ashburton, Islington, Bromley, and Kaiwharawhara.¹⁹⁶ To date, 32 transformers have been equipped with neutral grounding resistors, and 2 HVDC transformers have been equipped with neutral current blocking capacitor devices.¹⁹⁷

Modeling

Transpower has also modeled the effects of GIC on the lower South Island power system. Transpower is currently expanding the DC current monitoring network as part of its HVDC Pole 3 Project. In addition, newer transformers designed with higher DC/GIC withstand have replaced older, more vulnerable transformers. Configuration changes

¹⁹² Emergency Management Policy, 2012, System Operator (Transpower)

¹⁹³ SPACE WEATHER, VOL. 10, S08003, doi:10.1029/2012SW000806, 2012

¹⁹⁴ Transpower GIC update

¹⁹⁵ SPACE WEATHER, VOL. 10, S08003, doi:10.1029/2012SW000806, 2012

¹⁹⁶ DC Currents in the New Zealand AC Power System, Michael Dalzell, Transpower New Zealand

¹⁹⁷ Transpower – private communication

have also been introduced. For example, at the Invercargill substation, an additional transformer has been installed to share the DC/GIC current between 3 transformers (rather than the previous 2) which reduces the DC/GIC flow within each individual transformer.¹⁹⁸

Data captured by the LEMs will also aid in future modeling of GIC in the power system. The improved model will be used to guide decisions for future investment in GIC mitigation such as transformer neutral grounding resistors or possibly capacitor neutral current blockers.¹⁹⁹

Operational Procedures

Transpower also has operational procedures in place, which include management pre-event, during event, and post-event. These procedures are outlined in a System Operation's document entitled "Management of Geomagnetic Induced Currents", updated in September 2010, and have been well tested for efficacy.²⁰⁰

In brief, when the LEMs indicate that transformers are experiencing GIC currents at levels that may stress the transformers, the procedure calls for removal of selected transmission lines from service. While such action reduces the security of power supply, it has the effect of maintaining a minimum "N-1" reliability standard, allowing the power system to continue operation. This process has proved effective during past GIC incidents."²⁰¹

Transpower subscribes to the U.S. NOAA Space Weather Operations Center solar activity warning system. When Transpower receive a warning that there may be sufficient GMD level to cause adverse power system effects, the System Operator monitors the system and implements the operational procedure as necessary.²⁰²

5.12.3 Summary

New Zealand's experience in dealing with GMD includes:

1. GMD power grid incident – In spite of multiple factors implying minimal risk, New Zealand's power grid experienced a transformer fault and trips due to a GMD event during a modest solar storm. As a result, New Zealand's power authority has been proactive in developing protective strategies for GMD.

¹⁹⁸ <http://www.ea.govt.nz/search/?q=geomagnetic+disturbance>

¹⁹⁹ Transpower GIC Update

²⁰⁰ Transpower System Operations Division: Manage Geomagnetic Induced Currents

²⁰¹ <http://www.ea.govt.nz/search/?q=geomagnetic+disturbance>

²⁰² Op. Cit.

2. Operating procedures for GMD – New Zealand’s fundamental approach is to take lines out of service that connect to vulnerable transformers. This is opposite to the NERC-recommended operational procedure, which calls for putting lines back into service as a preventive posture for GMD.
3. GIC Monitoring – New Zealand has a robust GIC monitoring capability, and the GIC monitors are tied into the operation control centers, supplying situational awareness to aid in executing the operational procedures.
4. Hardware approaches for GMD – New Zealand has outfitted 32 of its key transformers with neutral grounding resistors, which have been in place since in 1990, and capacitive blocking devices have been installed on two HVDC transformers. This technology has thus been fielded now for over two decades. In that time it has been effective in protecting transformers from stray DC current, while not adversely affecting system performance.



5.13 South Africa



5.13.1 Power Grid Management and Structure²⁰³

ESKOM

ESKOM is important, not only to South Africa, but to the broader continent as well. It generates approximately 95% of the electricity used in South Africa and approximately 45% of the electricity used in Africa.²⁰⁴ Eskom is a vertically integrated, state-owned company, responsible for generation, transmission, and distribution in South Africa, and is the South African Transmission System Operator (TSO). The transmission network consists of 28,995km transmission lines and 153 substations, and operates at 765, 400, and 132 kV.²⁰⁵

Electricity generation in South Africa was 241.4 TWh in 2011-2012, supplied mostly by Coal (90.4%), as well as Nuclear (5.6%), Independent Power Providers (1.7%), Pumped Storage (1.2%) / Hydro (0.8%), and Gas Turbines (0.3%).²⁰⁶

²⁰³ Image from: Eskom Integrated Report, March 31, 2012

²⁰⁴ <http://www.eskom.co.za/c/article/233/home/>

²⁰⁵ Eskom Integrated Report, March 31, 2012

²⁰⁶ Op. Cit.

South African grid map

The map indicates the South African power network

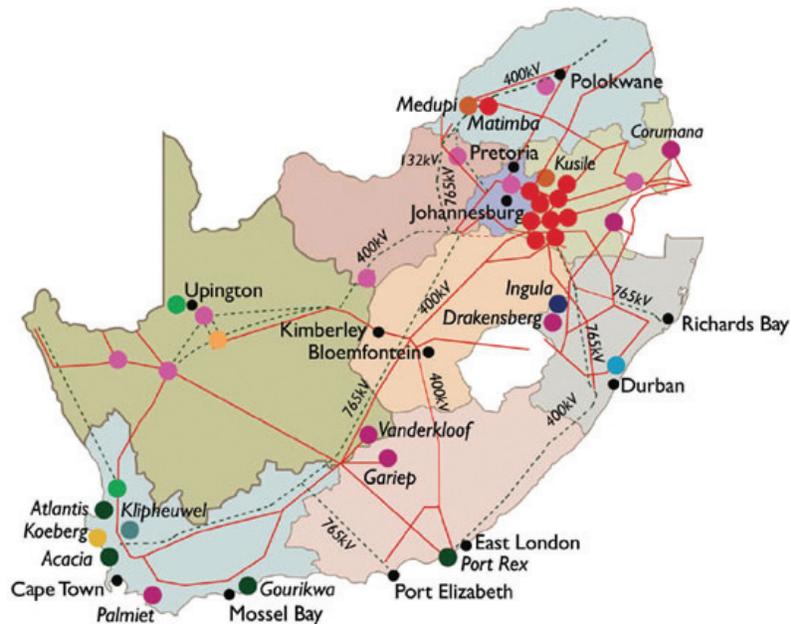


Figure 5.13.1 Map of the South African electricity network.²⁰⁷

National Energy Regulator

The government agency responsible for regulation of Eskom is the National Energy Regulator (NERSA).²⁰⁸ In addition to electricity, NERSA also regulates the piped gas and petroleum industries. NERSA is primarily an economic regulator, deriving its authorities from the Energy Regulation Act of 2006.²⁰⁹ There are no specific legislative or regulatory provisions regarding GMD.

5.13.2 E-threat Evaluation Studies and Reports

For many years, it was conventional wisdom that solar-induced GMD would have no significant effect on power systems at middle or low latitudes. After the “Halloween Storms” of October 29-31 2003, there was a realization that the onset of damage in fifteen large transformers in South Africa, eventually leading to their failure, correlated very

²⁰⁷ Eskom Integrated Report, March 31, 2012

²⁰⁸ <http://www.nersa.org.za/Default.aspx>

²⁰⁹ <http://www.nersa.org.za/Default.aspx> >Electricity>Legislation>Acts

closely with this GMD event, leading to the conclusion that GMD events can indeed affect power systems in low latitude regions.²¹⁰

A snapshot of the geoelectric fields for South Africa during the Halloween Storm is shown in figure 5.13.2. The GICs observed over the three days were mostly less than 5 Amps, with several short-duration spikes of 10 – 15 Amps. Eskom has determined that as many as 15 large (400 kV) power transformers were permanently damaged from internal heating due to the storm events of October 29-31, 2003.²¹¹

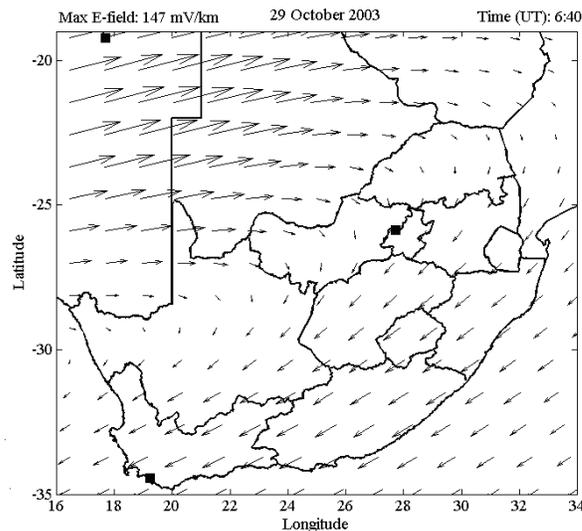


Figure 5.13.2 Grid of Interpolated Horizontal Electric Field over Southern Africa October 29, 2003 (Halloween Storm)²¹²

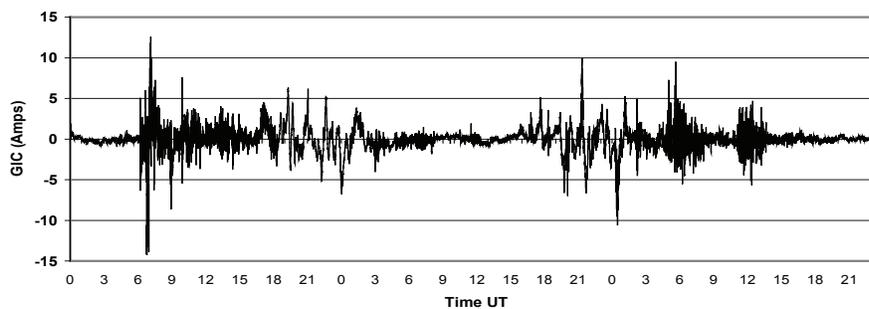


Figure 5.13.3 Observed GIC in region during storms over Oct 29-31, 2003.²¹³

²¹⁰ C.T. Gaunt, Reducing Uncertainty, An Electric Utility's Response to Severe Solar Storms, TIEMS Conference Proceedings, 2012

²¹¹ Makhosi, T., and G. Coetzee (2004), Generator transformer damage in Eskom network, paper presented at Workshop on Transformers and Geomagnetic Currents, EPRI, Washington D. C., 23 Sept, 2004.

²¹² C.T. Gaunt, Reducing Uncertainty, An Electric Utility's Response to Severe Solar Storms, TIEMS Conference Proceedings, 2012

²¹³ Makhosi, T., and G. Coetzee (2004), Generator transformer damage in Eskom network, paper presented at Workshop on Transformers and Geomagnetic Currents, EPRI, Washington D. C., 23 Sept, 2004.

Low-level, long duration GIC caused heating in the transformers, weakening them and leading to eventual failures in the several months following the storm.²¹⁴



Figure 5.13.4 Transformer Damage from 2003 Halloween Storm²¹⁵

Examples of thermal damage caused by GIC reported in November 2003:

“The condition of twelve 400 kV GSU transformers, each rated 700 MVA, at the Tutuka and Matimba power stations and six 275 kV GSU transformers at Lethabo power station is checked regularly, with some units equipped with on-line DGA instruments. After the severe geomagnetic storm at the beginning of November 2003, often referred to as the “Halloween storm,” the levels of some dissolved gasses in the transformers increased rapidly. A transformer at Lethabo power station tripped on protection on 17 November. There was a further severe storm on 20 November. On 23 November the Matimba #3 transformer tripped on protection and on 19 January 2004 one of the transformers at Tutuka was taken out of service. Two more transformers at Matimba power station (#5 and #6) had to be removed from service with high levels of DGA in June 2004. A second transformer at Lethabo power station tripped on Buchholz protection in November 2004.”²¹⁶

In 2005-2006, ESKOM determined that it would be prudent to install GIC current monitors at several sites in the system. Twenty-one (21) of these GIC “loggers” have

²¹⁴ Op Cit.

²¹⁵ Kappenman, EIS Summit Presentation, September 2010 (Image courtesy of ESKOM, Makhosi T., Coetzee, G.)

²¹⁶ Gaunt, C.T., Coetzee, G. “Transformer failures in regions incorrectly considered to have low GIC-risk”, Power Tech 2007, IEEE Lausanne

been installed at 15 main transmission station sites across the ESKOM system, and are currently monitoring and logging GIC measurements in the system.²¹⁷

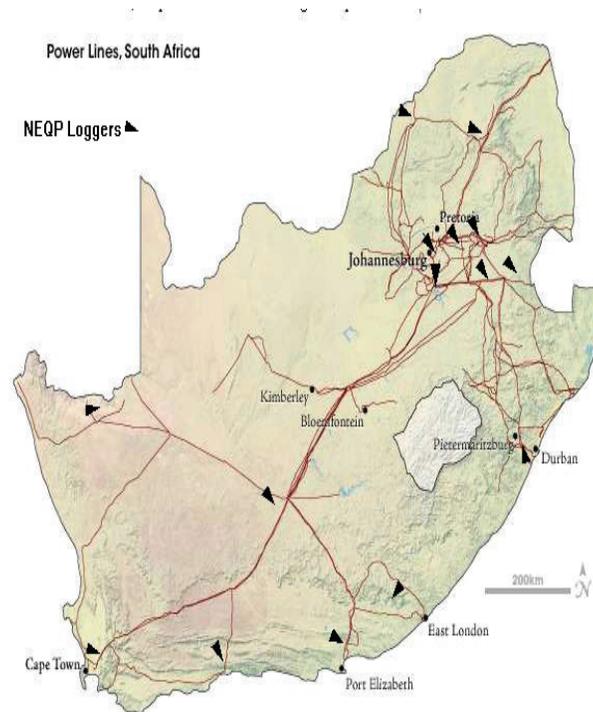


Figure 5.13.5. GIC monitoring sites in the ESKOM Network.²¹⁸

5.13.3 Resilience and Mitigation Planning and Status

The aftermath of the Halloween Storm of 2003 raised the awareness of GMD and its possible effects on the South African electrical transmission system. ESKOM has recognized the risk posed by GMD, and has taken initial steps, such as the GIC monitoring system described above. The GIC monitor data are not yet telemetered to the ESKOM control centers (as is the case in Australia, see section 5.11), so there is not yet real time situational awareness for GIC during storms. GMD operational procedures or hardware protection have not yet been implemented in the ESKOM system.

ESKOM has recognized their system's vulnerability and lack of resilience to many threats, including GMD. They are in the beginning stages of a "Resilience Project" to increase their ability to handle such incidents, though they are hampered by a lack of accurate

²¹⁷ ESKOM – private communication

²¹⁸ Malcolm Van Harte (ESKOM), *Solar Storm Resilience*, NERC Workshop 25 July, 2013.

models/forecasting. Approaches that may currently be employed during a GMD event are to stop maintenance activity to allow maximizing VAR support, bringing additional lines into service, and spinning up additional generation (though this has not yet been codified in a specific operational procedure). Future actions could include isolating particularly critical plants or transformers, or possibly breaking the system into seven separate “islands” to reduce GIC flows.²¹⁹

5.13.4. Summary

The experience of the South African Halloween storm, with the above-reported ESKOM assessment of extensive, GIC-induced transformer damage, is an important reminder that GMD can affect mid- to low-latitude countries. Long-duration, low GIC flows (several amps) can be enough to weaken transformers, though there may be no immediately apparent damage or system instability. South Africa is in the early stages of increasing its resilience to GMD, through the use of better GIC monitoring and consideration of operational procedures to mitigate GIC flows.

²¹⁹ Malcolm Van Harte (ESKOM), *Solar Storm Resilience*, NERC Workshop 25 July, 2013.



5.14 Israel

5.14.1 Power Grid Management and Structure

Israel Electric Corporation

The electrical system in Israel is owned and operated by Israel Electric Corporation, which is a state-owned (99.85% share) enterprise.²²⁰ Israel Electric Co. is a vertically integrated company, including generation, transmission, and distribution.²²¹



The Israeli transmission grid operates at two voltages, 400 kV and 161kV. The 400kV network is roughly 60km wide (East-West), and about 180km long (North-South). The 161kV network is much larger: 100km East-West, and about 400km North-South. There are approximately 25 substations containing roughly 400 transformers.²²² Israel's electric grid is an "Electricity Island"; there is no connection to the electricity grids of any of Israel's neighboring countries.²²³

Fig 5.14.1 Israel EHV transmission network

²²⁰ http://www.iec.co.il/EN/IR/Documents/IECs_Presentation.pdf

²²¹ http://www.narucmeetings.org/Presentations/Shpira_Israel.pdf

²²² Source: Israel Electric Corporation

²²³ http://www.iec.co.il/EN/IR/Documents/IECs_Presentation.pdf

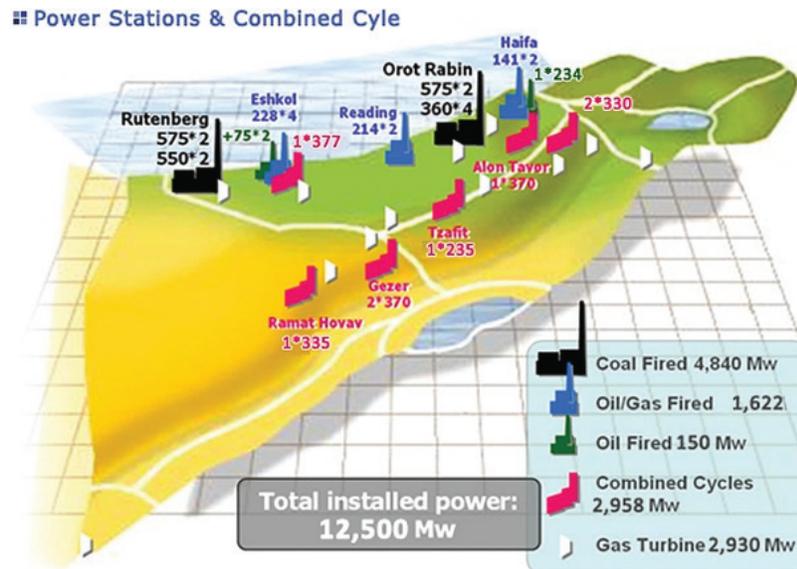


Fig 5.14.2 Summary of Israel electric grid major generation stations²²⁴

As shown in Fig 5.14.2, there are five power stations on the Mediterranean coast powered by coal, natural gas and heavy fuel oil. There are also 12 inland stations powered by jet, heavy duty and combined cycle gas turbines.²²⁵ Total generation capacity of the system is 13.25 GW.²²⁶

Ministry of Energy and Water Resources

Israel Electric Co. is overseen by two divisions of the Ministry of Energy and Water Resources: the Electricity Authority and the Office of Energy Infrastructures.²²⁷ It is regulated by the Public Utility Authority, an independent authority under the Minister of Energy and Water Resources.²²⁸ The legislative authority granted to the Electricity Administration is drawn from two laws: the Electricity Sector Law and the Electricity Law. Electricity Administration regulations are issued and enforced pursuant to these two laws.²²⁹ There are, however, no provisions in the laws or regulations for electric grid security or protection for GMD/EMP.

²²⁴ http://www.iec.co.il/EN/IR/Documents/IECs_Presentation.pdf

²²⁵ <http://energy.gov.il/English/Subjects/Electricity/Pages/GxmsMniElectricityGeneration.aspx>

²²⁶ http://www.iec.co.il/EN/IR/Documents/IECs_Presentation.pdf

²²⁷ <http://energy.gov.il/English/AboutTheOffice/Pages/GxmsMniOfficeStructure.aspx>

²²⁸ <http://www.pua.gov.il/11-he/homepage.aspx>

²²⁹ <http://energy.gov.il/English/Subjects/Electricity/Pages/GxmsMniElectricityAdministration.aspx>

5.14.2 E-threat Evaluation Studies and Reports

EPIC Israel, Phase 1

In 2012, the Ministry of Energy and Water resources contracted with EIS Council to complete a vulnerability study (EPIC Israel) of the Israeli grid.²³⁰ The study found that, without the protective measures now under development (see below), Israel's electrical grid was vulnerable to both GMD and EMP effects. Prior to the study, it was considered that the vulnerability of Israel's electric grid to GMD and EMP might be low due to the relatively small size of the grid and its moderate latitude (29° - 33° North). Power grid scaling studies done for EPIC Israel demonstrated that electric grids with dimensions of 50 to 100km are large enough to act as effective "antennas" for GIC. This means that the Israel Power Grid, before protection, did not benefit from its small size.²³¹

The study found that for very low geoelectric fields (1 V/km) a significant percentage of unprotected 400 kV transformers would see GIC flows of 5 Amps or more.²³² While geomagnetic disturbances are generally less frequent at low latitudes such as Israel's, as section 5.13 reported, the largest loss of EHV transformers due to GIC took place in South Africa, at approximately Israel's latitude (though on the opposite side of the equator). Thus, severe space weather can certainly impact countries at Israel's latitude, and geoelectric fields of tens of amps would induce GIC flows ten times as large.

Of course, space weather is not the only threat Israel must face. EMP is taken seriously by the Israeli government. EMP E3 as defined by IEC (unclassified) is 40 V/km. Such a geoelectric field would drive higher levels of GIC through the system.

5.14.3 Resilience and Mitigation Planning and Status

Israel Electric Co., the Ministry of Energy and Water Resources, and other governmental bodies recognize the risk of EMP and GMD and, although details are restricted for security reasons, a variety of plans and measures, selected from the full range of operational and hardware-based mitigation measures, are already being taken to address and mitigate these vulnerabilities.

²³⁰ EPIC Israel Final Report: Assessment of Israel Power Grid Vulnerability to EMP and Related Electromagnetic Threats, 22 January, 2013 (FOUO)

²³¹ Op. Cit.

²³² Op. Cit.

5.14.4 Summary

Israel has completed a comprehensive vulnerability analysis of the entire nation-wide Israel Electric Co. system. While details are restricted, additional analysis, plans and protective measures are in progress to mitigate those vulnerabilities, to achieve a high level of EMP/GMD resilience for Israel's electric infrastructure.

6 | Conclusion

While the United States is considered a leader in evaluating the risks of electromagnetic threats to national power grids, there has been less awareness of the work going on elsewhere. There has, in fact, been significant progress made in a number of countries, and it is hoped that this report will help provide a more complete view of the international status of e-threat evaluation and mitigation efforts.

This report has provided a top level summary of e-threat studies, investigations and protective measures by countries and selected international corporations, associations and institutions. While not addressing every national power grid, the report surveyed most of the Western nations and institutions that have made a significant investment in this area. The countries surveyed were the United Kingdom, Finland, Sweden, Norway, Germany, South Korea, Japan, Australia, New Zealand, South Africa and Israel. Institutions surveyed included the Switzerland-based International Electrotechnical Commission, the European Space Agency, and a number of the world's largest insurance and reinsurance markets and corporations: the Geneva Association, Lloyd's, Allianz, Swiss Re, and Munich Re.

International GMD, Severe Space Weather Studies, Regulations and Mitigation Efforts

The most common focus of e-threat evaluation and protection efforts was Severe Space Weather. This was true both for institutions and organizations, and for surveyed countries.

■ High Latitude Countries: Scandinavia

The Scandinavian countries, all at similar, high latitudes, appear to be among the most advanced in both historic and planned efforts for e-threat mitigation.

Norway's risk mitigation regulatory requirements are somewhat unique, including both GMD and EMP/IEMI risks as part of performance based, risk mitigation requirements, and requiring GMD and EMP-resistant approaches for planned expansion. Coupled with their detailed study of GIC impact on the Norwegian grid and their robust GIC monitoring and real-time reporting, Norway's e-threat regulatory environment, data gathering, monitoring and modeling appear to place it among the most robust of all the nations studied.

Sweden, at basically the same latitude as Norway and having seen grid-impacts from many G5-class GMD events over the last five decades, also considers GIC an important concern. While their planning and regulatory requirements do not appear to include

the same level of mandated e-threat resilience as Norway, Sweden clearly takes GMD risk seriously. Svenska Kraftnät has adopted a policy of using three-legged, core form transformers wherever possible. Like their Norwegian neighbors, they also expect to enhance their level of protection, planning for increased GIC monitoring and considering use of neutral current blockers for critical, high risk transformers.

Finland completes the picture of Scandinavian GMD protection efforts. Finland already makes exclusive use of EHV transformers which have the highest level of resistance to GIC, and plans to continue doing so. GIC is also reduced by use of series compensation for the country's long transmission lines, and by grounding their transformer neutrals using coil reactors.

■ **The United Kingdom and Germany**

While both the United Kingdom and Germany are at almost identical latitudes, their GIC investigation and protection efforts appear to be at very different states of development.

The United Kingdom's National Grid has taken several important steps to address GMD concerns. National Grid, the primary UK electricity provider is involved in a major, ongoing investigation of the UK power grid in regard to GMD. GIC monitoring has been installed, with the data monitored in real time, and new transformers installed in the grid will be of the robust three-limb design, adding to flexibility already in-place due to existing transformer spares.

Germany, relative to both the United Kingdom and its Scandinavian neighbors to the north, is at a much earlier stage in planning and utilizing e-threat protection approaches. For example, Germany has begun a GIC monitoring process. Over time, Germany's changing energy policy to include more renewables and less nuclear sources is likely to become a significant factor in such e-threat planning.

■ **Asian GMD vulnerability studies: Japan and South Korea**

For Japan and South Korea, the Asian nations studied, detailed GMD vulnerability studies have been performed, and some of this work appears to be valuable for the broader community, providing specific GIC measurement and model projection results that were used to confirm excellent model validation. While the detailed studies suggested there may be significant risk, the available unclassified information suggests that little has thus far been done to address GMD.

■ **Australia and New Zealand**

Moving further south to (low-latitude) Australia and (moderate latitude) New Zealand, it is important to note that both of these nations have studied GIC, and installed extensive GIC monitoring with real-time reporting.

Two items appear to be particularly important to note, as we look for lessons learned for U.S. and international GIC protection measures.

GMD protection approach opposite to NERC recommendation: New Zealand’s approach to reducing GIC vulnerability is to take lines to vulnerable transformers out of service, an approach opposite to the NERC-recommended GIC operational procedure.

Neutral grounding resistors now tested for over two decades: New Zealand has been using neutral grounding resistors on its key transformers for the past twenty four years. In that time, the system operator has built up considerable experience validating transformer GIC protection without adverse system performance effects. More recently, neutral current blocking capacitive devices were also installed on two HVDC transformers, and have been in service. It may be instructive and helpful for energy sector stakeholders to work with New Zealand, to look into reviewing detailed operating and performance data.

- **Israel and South Africa**

At almost identical latitudes, though on opposite sides of the equator, both South Africa and Israel, for different reasons, appear to be taking e-threat concerns seriously.

South Africa has experienced significant problems associated with GIC, even at their comparatively low latitude. ESKOM’s assessment is that the loss over a period of months of a large percentage of their transformer fleet would likely not have happened, were it not for GIC associated with the “Halloween” storm. Under some circumstances, ESKOM’s analysis concluded, long duration, low GIC flows can dangerously weaken transformers. South Africa plans, ultimately, to increase its GMD resilience through improved GIC monitoring and, potentially, operational procedures.

For **Israel**, comprehensive GIC vulnerability analysis created concern for the potential E3 GIC-inducing effects of HEMP. Details of Israel’s past, current and planned steps to mitigate these risks were not made available for this report, for security reasons.

International Institutions

- **The European Space Agency (ESA) and EURISGIC**

The European Union has had an important role in expanding both awareness and knowledge of space weather. From the ESA / NASA SOHO Solar Physics Mission, to the ESA Space Weather Applications Pilot Project and earth-based GIC infrastructure protection initiatives like EURISGIC (“European Risk from Geomagnetically Induced Currents”), the European Union has been increasingly active in addressing space weather GMD concerns.

■ **The International Insurance Sector**

The Geneva Association, Lloyds, Allianz, Swiss Re and Zurich have all performed or commissioned independent studies or held conferences addressing Space Weather risks for power grids and other critical infrastructure. As the Lloyd's study concludes, largely summarizing the assessment of the broader insurance sector, "Space weather can (and has) caused significant disruption to supplies on regional scales and could affect national systems over extended periods of time."²³³

International EMP / IEMI Vulnerability Studies, Regulations and Mitigation efforts

Among the nations studied, there are several that have both shown an interest in this area, or have taken steps toward analysis or mitigation.

■ **The United Kingdom**

The United Kingdom's House of Commons Defence Select Committee included EMP as a primary effort within the Committee's threat assessment study, and National Grid has taken steps to improve the security of key sites against IEMI threats.

■ **Norway**

In Norway, (performance-based) contingency regulations require the Statnett SF electricity provider to mitigate risks associated with GMD as well as EMP/IEMI, and pre-planned system expansion efforts are mandated to provide improved resistance to both natural and malicious e-threats.

■ **Israel**

Israel has completed a major study of the national power grid vulnerability to both EMP and GMD, and, although the details were not provided for security reasons, steps are in progress toward hardening Israel's power grid.

■ **South Korea**

In South Korea While studies have taken place looking at Seoul's vulnerability to HEMP, the unclassified information provided for this report did not indicate that work has taken place to harden grid assets.

²³³ From the Lloyd's Severe Space Weather Study. See below for more details.

International Institutions

- **The International Electrotechnical Commission**

Among the nations and institutions studied, the International Electrotechnical Commission provided the most comprehensive information on EMP assessment, evaluation and standard setting. The Geneva-based commission developed, and has made publicly available, resources addressing electromagnetic compatibility assessment and EMP threat measurement and simulation, as well as EMP field definitions, and a variety of other material related to EMP protection.

EPROTM
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