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Geomagnetic disturbances and their impact on power systems

Status report 2013

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Summary

This report gives an introduction to geomagnetic disturbances (GMDs) and their impact on technical infrastructure, and mainly on electric power systems. The introduction explains the different mechanisms for power system impact of GMD through GIC (Geomagnetically Induced Currents). Since reactive power is a key issue it is explained more in detail in an appendix. The mechanisms and countermeasures are discussed in connection with well-known geomagnetic events in March 1989 and October 2003 causing blackouts in Québec and Sweden respectively.

Status on GMD impact on power systems is described based on conference presentations during 2012 and 2013 and recent publications. Work on establishing limits for GMD parameters is reported having a Dst value of -2500 nT, which can be compared to Dst reaching -589 at the March 1989 event and at least -950 nT at the 1859 Carrington event. Prediction of GMD and GIC is reviewed showing that forecasts give either 30-60 min or 1-2 days lead-time depending on which data source is used. Ongoing activities include demonstrations of forecasts for both the American and the European continents.

A key actor regarding GMD impact on power system is NERC (North American Reliability Corporation), who are now preparing reliability standards for GMDs. This work is directed by FERC (US Federal Energy Regulatory Commission) in order 779 of 13 May 2013 and has deadlines near end of 2013 and 2014. The NERC GMD task force has issued an important interim report where NERC claims “the most likely worst-case system impacts resulting from a low probability strong GMD event and corresponding large GIC flows in the bulk power system is voltage instability” and not mass destruction of transformers. Still transformers are central to GIC and a transformer design immune to GIC invented in Lund, Sweden has received considerable attention at the IEEE Power and Energy Society General Meeting 2013. Although the focus is on serious GIC events causing blackouts, work is described showing that lower levels of GIC also affect power system operation.

The analysis of GMD has been much facilitated during 2012-2013. This is thanks to the publications of a test system for GIC analysis, data sequences representing a 100 year scenario and that commercial software now has GIC capability. NERC GMD task force has published guidelines for bringing all this together.

Impact of GMD on GNSS (Global Navigation Satellite Systems) and on electronic communication is briefly summarized. GMD events reduce GNSS precision, and affect electronic communications only indirectly through the power supply. Power system operation however currently develops towards dependence on GNSS time signals, which needs to be carefully managed.

Preface

This report has been produced within the PRIVAD (Program for Risk and Vulnerability Analysis Development) framework program. This program is fully financed by MSB (Swedish Civil Contingencies Agency) which is gratefully acknowledged.

Contents

1 Introduction

Solar activity and space weather may affect technical systems that society of today depends on. The most frequently addressed are electric power systems, electronic communication systems and global navigation satellite systems (GNSS), see Figure 1.1. Systems not mentioned here include air traffic and shipping.

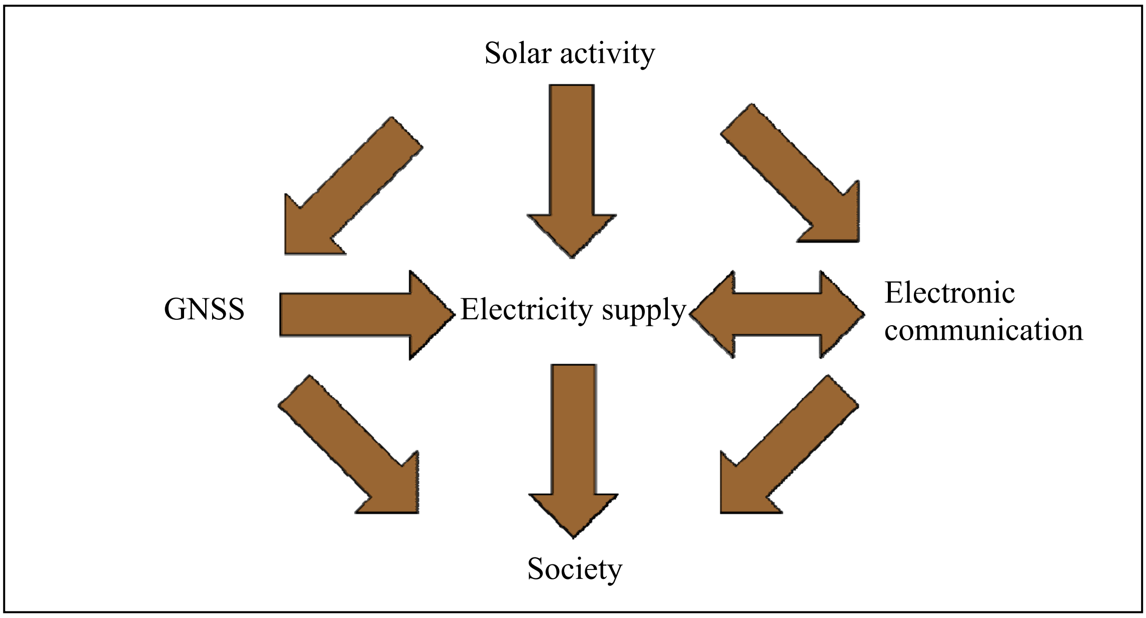

Figure 1.1 Solar activity affects society through technical systems for electricity supply, electronic communication and global satellite navigation (GNSS).

This report first explains the basic mechanisms for how geomagnetic disturbances affect electric power systems and then summarizes the status in the field. It also briefly mentions electronic communications and GNSS.

The contents are based on recent information mainly from publications and presentations, where key sources are the *Conference on Space Weather and Challenges for Modern Society* organized by The International Emergency Management Society (TIEMS) in October 2012 in Oslo, Norway, and the *IEEE Power & Energy Society General Meeting* in July 2013 in Vancouver, Canada. Presentations at a national workshop on GMD and their impact on society held in Lund on 21 May 2012 are also made use of. That workshop and this report are produced as parts of the *Program for Risk and Vulnerability Analysis Development* (PRIVAD) at Lund University, fully financed by the Swedish Civil Contingencies Agency (MSB).

2 Impact on electric power systems – an introduction

Geomagnetic disturbances affect electric power systems through several mechanisms. This brief tutorial gives an overview of these mechanisms, relates actual disturbances to them and exemplifies countermeasures. A similar overview was recently published by the IEEE Power and Energy Society Technical Council Task Force on Geomagnetic Disturbances [1].

2.1 Mechanisms

Solar activity includes *coronal mass ejections* (CMEs), where plasma and magnetic fields erupt from the corona of the sun. The shock wave that precedes the CME also accelerate *solar energetic particles* (SEPs), which are high-energy particles consisting of electrons and ions – mostly protons. The stream of solar energetic particles is called the *solar wind* and during low intensity it is mostly deflected by the geomagnetic field of the Earth, but some SEPs cause aurora in the Polar Regions. In case of a sufficiently large CME however, the SEPs travel faster and modify the *magnetosphere* and cause currents called *electrojects* in the *ionosphere*. This mostly occurs at the auroral circles, but may also happen at lower latitudes. The magnetic field associated with the electrojets perturbs the otherwise constant geomagnetic field, thus creating a *geomagnetic disturbance* (GMD).

In accordance with Faraday's law the changing geomagnetic field induces a *geoelectric field* that drives currents in conductor loops defined by long conductors such as electric power lines and pipelines, their connections to earth and the earth itself acting as a (return) conductor. The current is referred to as *geomagnetically induced current* (GIC). Since the geomagnetic field variations are slow, a GIC is usually approximated by a DC current. When modeling GIC in power systems it is generally agreed that it is most correct to include DC voltage sources in the phase conductors of the power lines. GIC depends on line length as illustrated below.

GIC increases with the length of the line, but so does the resistance that the GIC sees. GIC therefore increases with line length only until line resistance R dominates the loop resistance. The length where this occurs depends on the voltage level but can be already at about 150-200 km as shown in Figure 2.1 from [2][1]. For longer lines GIC approaches a constant value E/R, where E is induced EMF in V per km and R is line resistance in Ω per km.

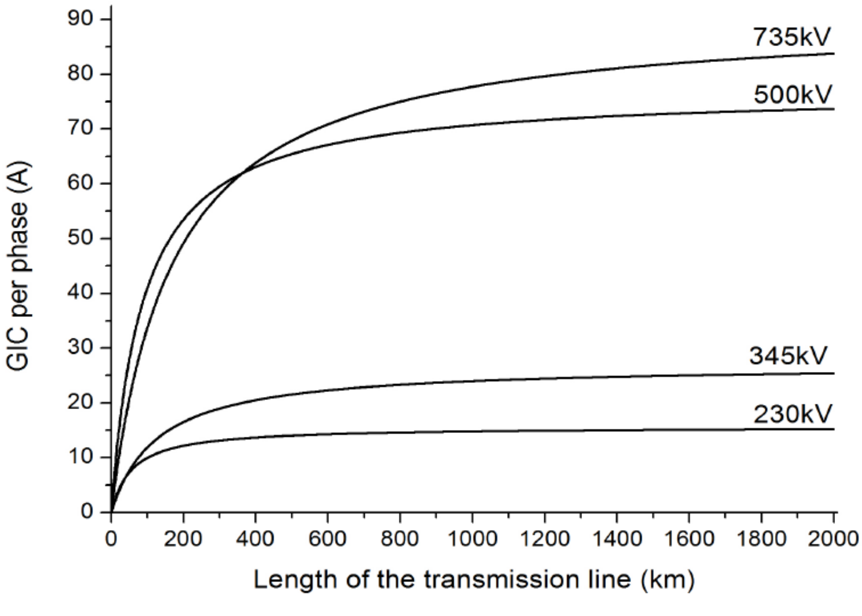

Figure 2.1 GIC increases with line length for short lines, but is independent of line length for long lines [2].

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[1] Also presented by D. H. Boteler in "Impacts of Geomagnetic Disturbance (GMD) Events on Electric Power Systems" supersession at IEEE PES General Meeting, 21-15 July in Vancouver, CA.

Voltages and currents in electric power systems across the world are AC (Alternating Current) quantities with a sinusoidal waveform and a frequency of 50 or 60 Hz. The levels of DC (Direct Current) current coming as GIC are very small compared to the amplitude of the AC currents, but may still have serious consequences. The reason is that even a small DC content in the AC may cause a power transformer to enter *half-cycle saturation*, see Figure 2.2.

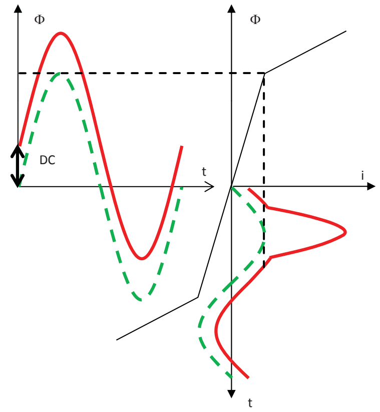

Figure 2.2 Adding a small DC offset in the flux (left) may cause a power transformer in linear operation (dashed) to enter half-cycle saturation (solid), which greatly distorts the current waveform (right). Magnetizing characteristic (black) is shown without hysteresis and further simplified to three straight line sections.

At normal operation practically the entire linear range of the magnetizing characteristic around the origin is used. Only a small DC offset is then needed to shift operation into the saturated part of the characteristic, and as this occurs only at the upper or lower part of the sinusoidal waveform it is distorted in only one of the half-cycles. Half-cycle saturation of power transformers may affect power system operation in three ways:

- Increased reactive[2] losses stress the system;
- Waveform distortion causes relay misoperation;
- Heating may damage the transformer.

The three primary effects have further consequences as seen in Figure 2.3.

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[2] See Appendix A for explanation of reactive power to non-power engineering experts.

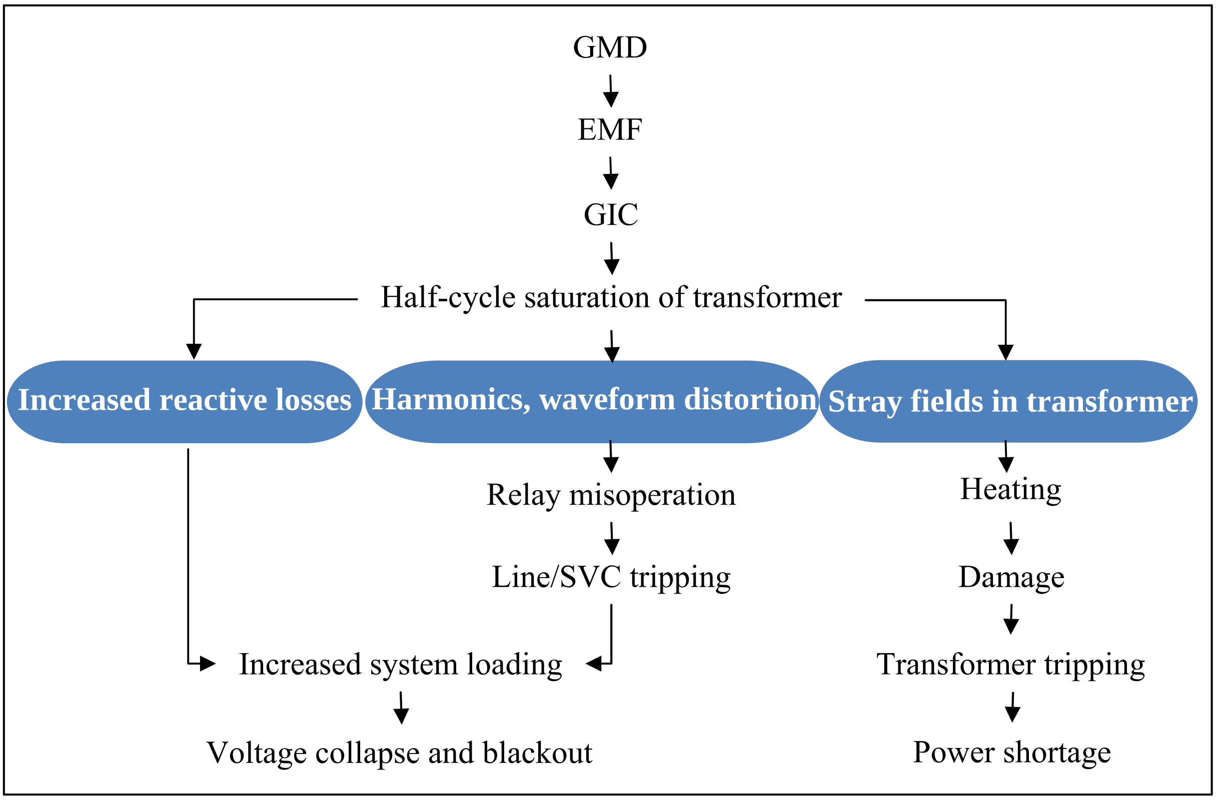

Figure 2.3 Overview of power system impact of GIC with the three effects of half-cycle saturation and their consequences.

The peak value of the distorted sinusoidal waveform changes rapidly with GIC. Protective relays disconnect equipment to avoid overcurrent or overvoltage that may be damaging through overheating and arcing due to short-circuit faults. If such relays react on the peak value of the distorted waveform when peak value of the fundamental is more relevant, GIC will cause unwanted disconnection (tripping) of equipment. Loss of a line, a transformer or a reactive device such as an SVC (Static Var Compensator) typically weakens the system and increases the stress on other lines and transformers. If the situation is already stressed a voltage collapse may occur leading to blackout in at least a part of the system.

The rms value of the distorted current waveform increases with GIC, but less rapidly than the peak value. This has the effect of increased reactive losses in the transformer. To cover these losses the transformer will draw more reactive power through the network. Just like with unwanted tripping, this adds stress to the system. Situations near voltage collapse are characterized by large flows of reactive power and this thus worsens the situation and brings the system closer to a blackout.

When the transformer core enters magnetic saturation it cannot carry more magnetic flux. If the flux continues to increase it therefore has to find new paths outside the core – typically in the tank with oil in which the transformer is immersed. Since the tank and similar structures are not designed to carry AC magnetic flux this will create eddy currents in the structures leading to heating – typically at certain points, so called *hot spots*. Sufficient heat will damage the transformer which needs to be de-energized and taken out of service. This may be done automatically by the Buchholz relay if it detects gas in the oil, indicating that it may have lost its insulating capacity. The disconnected transformer needs maintenance before its put into service again or may need replacement.

2.2 Cases

Some often-mentioned disturbances associated with GIC can be referred to the three mechanisms outlined above.

A strong geomagnetic disturbance hit North America on the 13 March 1989. The transmission system in Québec, Canada, was affected the most and a short sequence of events led to a blackout:

- Half-cycle saturation of power transformers;
- Harmonics cause protection to disconnect 7 SVCs (delivering reactive power) in 59 s;
- Massive reactive power shortage;
- Voltage collapse and system-wide blackout.

The key issue was thus the SVC protection that was overly sensitive to harmonics. The reporting of the event describes damage of transformers, reactors and SVCs, but this was not due to the heating mentioned above but due to excessively high voltage occurring when the network broke up.

The disturbance on 13 March 1989 also had consequences in USA:

- Half-cycle saturation of a nuclear unit transformer in Salem, New Jersey;
- The Salem transformer is damaged by heating and taken out of service.

Photos of the damaged transformer are shown in many publications to illustrate consequences of GIC. Note that the transformer damage did not cause any blackout and was rather parallel to the Québec blackout.

On 23 September 2003 switchgear failed under disadvantageous circumstances and caused a voltage collapse leading to blackout of Southern Sweden and Eastern Denmark. Just five weeks later a GMD called the Halloween storm occurred on 30 October 2003 and affected power supply in Malmö, Sweden:

- Very high GIC of 330 A caused half-cycle saturation of a power transformer;
- Harmonics caused protection to disconnect a 130 kV line;
- As the line was feeding a part of central Malmö with no backup a blackout occurred.

Here it was protection sensitive to harmonics in combination with an uncommon and unfavorable network situation that caused the blackout.

In the light of the events discussed here, GIC causes blackouts mainly when protection operates incorrectly due to harmonics. The Québec event shows that unbalance between supply and demand of reactive power is also critical. But this is a general characteristic of all blackouts due to voltage collapse and need not be due to GIC as shown by the blackout in Sweden and Denmark on 23 September 2003. The transformer failure in Salem, NJ, did not lead to any blackout.

2.3 Countermeasures

There are several countermeasures to GIC impact on power system operation. These involve modifying the paths where GIC flow, changing protection settings or system operation routines:

- Installing series capacitors in a long transmission line blocks GIC in that line;
- Replacing solid earthing with a capacitor or a resistor between transformer neutral point and earth blocks or reduces GIC;
- GIC withstand capability of transformers can be improved by selecting the right core type and by increasing the cross-sectional area of the flux paths in the core;
- Protection settings or functioning principle that are less sensitive to harmonics can be used to eliminate misoperation;
- Operators can improve robustness to GMD by new routines where they use all available lines to minimize line loading and put all reactive resources on-line;
- Real-time monitoring and prediction of GIC help operators to be aware of GMD.

After all blackouts it is in the interest of at least the affected system operator to prevent the same blackout from happening again. And series capacitors have indeed been installed on all key lines in the Québec system. These are however costly devices that are mainly installed to increase the MW transfer capacity of the power lines. In both Québec and Malmö the protective relays have been modified to not react to harmonics. E.ON, who operates the distribution network in Malmö has also introduced earthing resistances in some transformers.

Adapting relay protection to react less to harmonics may require new settings or a new device, but is quite straightforward. Changing the earthing of transformers may be more difficult, since transformer specifications and the protection philosophy is typically based on solid earthing. Introducing changes in transformer design is typically done through new requirements in the equipment procurement process. This has been adopted by nuclear companies in Sweden.

Recent development on GMD prediction and GIC impact on power systems will be discussed in the following.

3 Prediction of GMD and GIC

If power system control room personnel can be warned about an approaching GMD, this greatly helps them to take appropriate action. Much effort is therefore spent on improving *situational awareness* through monitoring and real-time predictions of GMD and GIC. When preparing for GMD events it is also of great interest to know an upper limit of their magnitude, since this is necessary when designing a relevant worst case scenario.

3.1 Monitoring and real-time predictions

A straightforward way to gain information about GIC is to measure GIC in earth connections of selected power transformers at transmission level. By displaying the GIC values on one of the screens in the control room, operators become aware of the present situation. GIC measurements are typically treated as operational data by the network operator and are not publicly available.

Another source of information is magnetometers that measure the earth magnetic field and more directly indicate a GMD. The magnetometer data itself can be viewed only as a proxy to GIC, but can be combined with a model of the network and ground conductivity for explicit estimation of GIC. Magnetometer data are easily accessible from public websites. In the Northern hemisphere these can be found at the Swedish Institute of Space Physics (IRF), the Danish National Space Institute, the Finnish Meteorological Institute and Tromsø Geophysical Observatory in Norway as well as Natural Resources of Canada and similar organizations in e.g. Russia and USA. Ten institutes located in Europe have formed the network IMAGE (International Monitor for Auroral Geomagnetic Effects) collecting data from 31 magnetometer stations.

While ground-based measurements give solid evidence of GMD and GIC in real-time, predictions of the situation ahead in time would permit operators to better prepare for possible disturbances. Such forecasts are practical and are based on data from space-based observations. These data arrive on Earth faster than the physical impact of the processes they reflect which makes it possible to issue warnings with a lead-time in the order of an hour or a day depending on the source of the data. The Solar Shield project at NASA [3] works in both time scales and uses data from spacecrafts located at the gravity equilibrium point $1,5\times10^5$ km from the Earth and $1,5\times10^8$ km from Sun:

- “Level 1 forecasts” giving 1-2 days lead-time use data from the SOHO (Solar and Heliospheric Observatory) spacecraft.
- “Level 2 forecasts” based on data from the ACE (Advanced Composition Explorer) spacecraft give a lead-time of 30-60 min.

The ACE data hold observations of the actual solar wind that the Earth is exposed to. These data are fed into magnetospheric magnetohydrodynamic (MHD) simulations that also use information on earth conductivity and power systems to produce estimates of GIC at any point in the system. The SOHO data are remote observations of CMEs on the Sun and are fed into heliospheric magnetohydrodynamic simulations, predicting not only the process from solar wind to Earth impact, but also the process from CME to solar wind. While longer lead-time is attractive to e.g. power system control centers those predictions are more uncertain, partly due to probabilistic components in the algorithm, which is in contrast to the deterministic and more certain results based on the ACE data.

Since several years GIC forecasts based on ACE data have been produced by IRF-Lund together with Swedish electric power industry [4]. Forecasts for one point in Southern Sweden is available at the website of the Regional Warning Center at IRF-Lund [5], while the network companies involved in the project have access to forecasts for several points in the Swedish system. In the EU project EURISGIC (EUropean RISk for GIC) [6] running 2011-2014, European and North American experts now collaborate to combine their expertise which includes the experience from the Solar Shield project. The main project aim is to extend the methodology for GIC calculations to yield continental-wide forecasts for Europe based on ACE data [7].

3.2 Worst case scenario

Scenarios have a great value in all risk management – scenarios from events that already did occur and from possible future events. Worst case scenarios play a particular role since they define the limit for what needs to be managed. As an example, power system planning is to a great extent based on worst case scenarios:

- The *maximum* short-circuit fault current that can occur decides the rating of the circuit breakers that should interrupt that current;
- The *maximum* output of the *largest* power plant that may suddenly be disconnected due to a fault decides what frequency control reserves are needed in a system;

Similarly a worst case GIC scenario would be of great value when formulating requirements on capability of equipment and system operation. Perhaps even more important is that a generally accepted worst case scenario would have a tremendous impact on how policy and decision makers and others that have to manage the consequences should assess geomagnetic disturbances.

Upper limits for geomagnetic disturbances are often proposed starting out from statistics of previous events but can also be based on physics. V. Vasyliũnas represents the physical approach and focuses on the storm severity index Dst in [8]. He arrives at limit of -2500 nT, which he compares to the largest value yet observed being -1760 nT. Dst is a global measure of the average depression of the horizontal magnetic field at Earth's equator and thus closely linked to GIC. The limit results from assumptions on the interaction between plasma and the geomagnetic field in the magnetosphere.

The Dst limit of -2500 nT limit proposed by Vasyliũnas was also mentioned by E. W. Cliver from the Air Force Research Laboratory in his presentation "A Super Storm: Current Limits of Extreme Space Weather" at the TIEMS conference in Oslo. His focus was however rather on the efforts to establish the most extreme Dst level that has been observed. This comes down to scrutinizing a range of proposed figures from various sources and their basis. Having done this he proposes -950 nT which is an average of empirical values for the 1859 Carrington event. He chooses to exclude the value of -1760 nT recorded on September 2 in Bombay, since it can be questioned in many ways. As a reference, Dst reached -589 nT on 13 March 1989.

A limit of the Dst index sets the famous GMD events of 1859 and 1989 into perspective, but does not constitute a worst case scenario on its own. Defining such a scenario is the purpose of the recent paper "Generation of 100-year geomagnetically induced current scenarios" [9]. Such a scenario contains explicit horizontal geoelectric field time series that are representative for different ground conductivity and that can be applied to different geomagnetic latitude. The data has 10 s resolution, is publicly available in digital format[3] and can be applied to a range of engineering studies including impact of GIC on power systems. The work is based on the assumption that measurements from any geomagnetic storm event can be scaled to represent a more severe one. The scaling factor corresponding to a 100-year event is obtained by extrapolation of the probability distribution of observed events. The 100-year scenarios use 72 h sequences of observations of the Halloween storm in 2003 from observatories in Finland and Japan. The geoelectric field data analyzed in the paper exhibit a drop in magnitude by a factor of about ten when moving from about 60° to 40° geomagnetic latitude. Based on this, 50° geomagnetic latitude is suggested as a threshold between high and low latitude in the GIC context. Combining the data from the two observatories with two values for ground conductivity gives four geoelectric field scenarios, with maximum values as shown in Table 3.1.

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[3] See working documents of NERC GMD Task Force at the NERC website.

Table 3.1 Maximum geoelectric field in the four 100-year scenarios developed in [9].

Maximum geoelectric field	Resistive ground	Conductive ground
Above 50° geomagnetic latitude	20 V/km	5 V/km
Below 50° geomagnetic latitude	2 V/km	0,5 V/km

In the paper the geoelectric data are translated to GIC through a simple linear relation. This gives GIC time series with peak 10-s values of 350 A for a location above the 50° geomagnetic latitude with the conductive ground. Altogether this gives four GIC time sequences that can be considered approximately representative for any location on Earth.

4 Impact on electric power systems – an update

Although the key mechanisms for impact on electric power systems described above are fairly well known there is considerable development recently in connection with this:

- It is not easy to predict which mechanism will dominate a future GIC event, but consensus seems to be coming up.
- Analyzing GIC impact has been facilitated by new versions of established commercial power system simulators now being available with GIC capability.
- Much effort is spent on understanding and developing transformers and a GIC-immune design has been presented.
- Government level organizations begin to establish action plans for how to handle the issue of GIC impact on power systems.

These four aspects will be outlined in the following.

4.1 Severity of disturbances

A scenario with mass-destruction of system transformers has been associated with GIC for a long time and also recently by John Kappenman in [10] and at the supersession on “Impacts of Geomagnetic Disturbance (GMD) Events on Electric Power Systems” at IEEE PES General Meeting, 21-15 July in Vancouver, CA. Should this happen, the consequences would certainly be severe since replacing hundreds of transformers would take years and society would suffer from power shortage caused by the reductions in power transfer capacity. The damage to the Salem nuclear plant transformer at the 1989 event contributed to the conception that this is the key consequence of GIC to worry about.

In contrast to this, the North American Reliability Corporation (NERC) holds a voltage collapse caused by reactive power shortage associated with GIC as the most important consequence. In the conclusions of their interim report from 2012 [11] it says:

> *The most likely worst-case system impacts resulting from a low probability strong GMD event and corresponding large GIC flows in the bulk power system is voltage instability, caused by a significant loss of reactive power support (var) and a simultaneous dramatic increase in the reactive power demand. The lack of sufficient reactive power support was a primary contributor of the 1989 Hydro-Québec GMD-induced blackout. NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. The work of the GMD Task Force documented does not support that result for reasons documented in this report.*
>
> *(NERC, 2012 Special Reliability Assessment Interim Report)[11]*

The mission of NERC is to ensure the reliability of the North American bulk-power system and it is NERC who develops and enforces reliability standards that transmission system operators (TSOs) must comply with. NERC thus has a key role for avoiding system blackouts in North America and must be well-informed and balanced in its assessment of various blackout mechanisms. The presentations and discussions at the TIEMS conference in Oslo in October 2012 and the IEEE General Meeting in Vancouver in July 2013 give the impression that in the power engineering community there is practically consensus about the NERC conclusion.

In terms of power interruption a voltage stability-induced blackout may be country-wide and typically affects all consumers in that area. The time needed for restoration of system operation is a few hours up to tens of hours. Although the power interruption affects many consumers, no equipment is necessarily damaged and restoration is normally complete with no consumers left without power. This is in strong contrast to outages related to natural disasters like storms, flooding or earthquakes, where extensive equipment damage occurs like in the case with GIC-induced transformer destruction. In these situations restoring power supply is a lengthy and demanding process often close to rebuilding the power system.

Voltage stability is a limiting factor and possible cause for blackout in many transmission systems and linking GIC to this brings GIC close to normal TSO routines for planning and operation. Reactive power balance as well as relay protection performance which is critical to the GIC-related blackout mechanisms must of course be monitored. But this is done anyway for many other reasons and adding a new cause for relay misoperation and for increased reactive losses should be straightforward for any TSO to manage.

Voltage stability is however a less transparent problem than mass destruction of transformers. The many persons involved in emergency management without expertise in power system stability thus need to leave much assessment to the TSOs.

Impact of GIC on electric power systems largely focuses on blackouts, but may affect system operation also during less severe conditions. It is shown in [12] that generation is dispatched differently when GIC levels increase in the PJM (Pennsylvania-New Jersey-Maryland) system. Normally generators are dispatched by “economic merit” with lowest cost generation first. But when reactive transfers in the network are approaching their limits generation is redispatched “out of economic order” so that the limits are not exceeded. PJM uses *location marginal pricing* to manage congestion which means that the real-time price of electricity is higher in areas supplied through lines where the transfer limits have been reached. This includes reactive limits reached due to GIC and consequently GIC has an impact on the electricity price. The Nordic electricity market uses marginal pricing and price areas, where the price may differ between the areas but is always the same within each price area. In this system the reactive power changes due to GIC are reflected mainly in the reactive output of generators which is controlled by automatic voltage regulators. This reactive power output is monitored but the data is typically not logged.

4.2 Power systems analysis

Analyzing the impact of a GMD event on a power system typically involves three consecutive computational steps:

1. Determine the *geoelectric field*;
2. Combine the geoelectric field with earth conductivity and a DC model of the power system to obtain *GIC*;
3. Compute *power system behavior* using an AC model of the power system where GIC impact mainly on transformers is included.

If a worst case analysis is the goal, the scenarios proposed in [9] form a convenient starting point by providing time sequences of geoelectric field values. Taking such values further to GIC has hitherto been managed by prototype software developed by GIC researchers in collaboration with TSOs. This situation has however recently changed thanks to an interest in GIC from vendors of commercial power system analysis software. Now power system simulators such as PowerWorld [13] of PowerWorld Corporation and PSS/E [14] of Siemens-PTI have GIC functionality. Their products, which are normally used only for AC systems analysis, have been extended with models of mainly transformers that also take GIC into account. The AC analysis has been extended with DC analysis to yield GIC and the new products with GIC functionality thus conveniently manage both the second and the third computational steps mentioned above. The two simulators mentioned here are very different, but will most likely have great impact on GIC analysis among system operators:

PSS/E is one of the most widespread power system simulators and many system operators such as the Nordic TSOs and major DSOs maintain their common most detailed and most used network model in PSS/E format.

PowerWorld is an interactive tool for power flow calculations with emphasis on visualizations that can be understood also by politicians and other non-power engineering specialists. A demo version for evaluation is available for free but has a 12-bus limitation. An educational version managing somewhat larger systems comes with a textbook [15] and is extensively used in power engineering education at university level.

Further supporting the power system simulations including GIC effects is the test system that has been jointly published [16] by experts in GIC and power system simulation. It is a hypothetical system with 18 buses (nodes) and two voltage levels 500 and 345 kV, see Figure 4.1. The transformers in the model are of several types to permit exploration of the associated differences with respect to GIC. The applications include validation of a single power system simulator and benchmarking of several simulators. It also gives insight into how DC and AC behavior can be combined in component models and what data is needed for analyzing GIC impact on power systems. While being too large for the free evaluation version of PowerWorld, it can be run with the educational version.

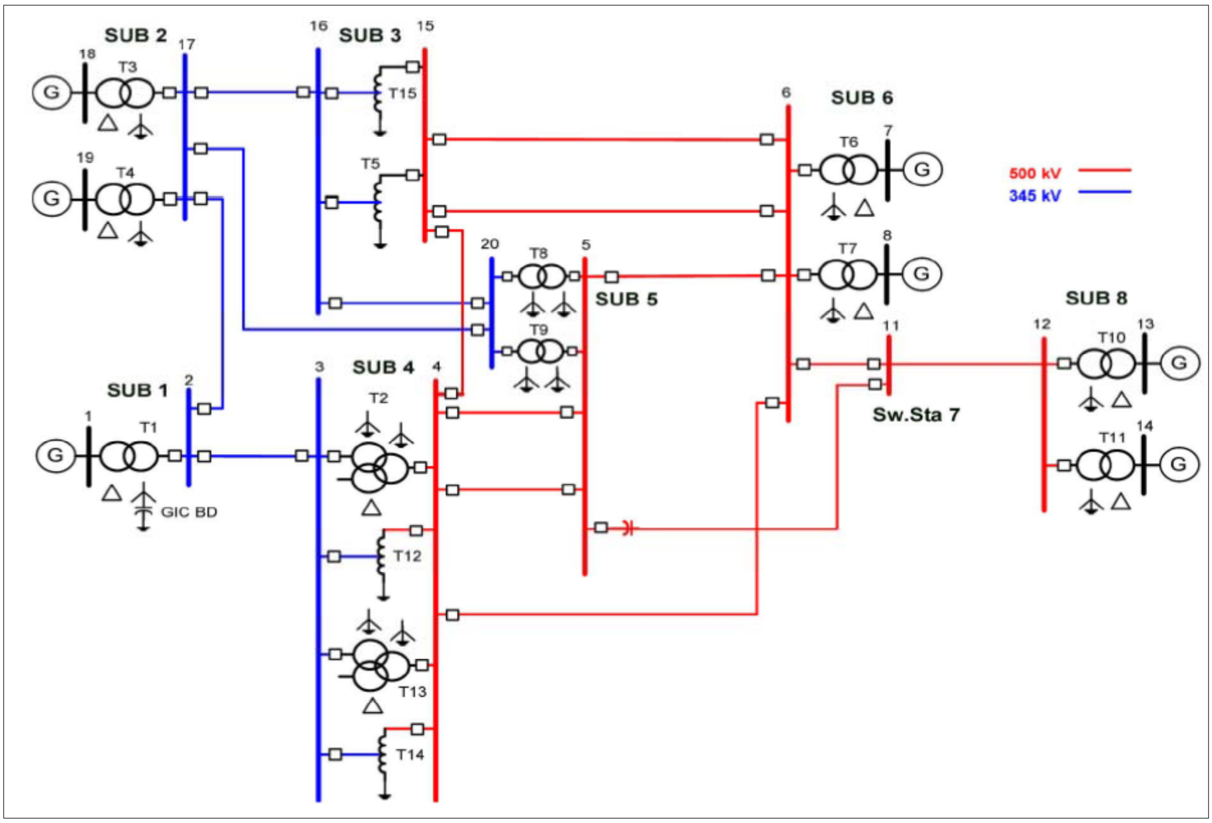

Figure 4.1 Test system for GIC analysis [16].

With commercial software available, the next challenge is the data needed to describe DC behavior of power system components. This is normally not considered in power system analysis and with no DC data available, an effort in this field is required for each system in order to analyze GIC impact on it. This work is supported by guidelines [17] published by NERC. The document which is still a draft describes the proper modeling of power system components for GIC studies and uses the test system in Figure 4.1 to illustrate the multitude of such components. When it comes to time sequences it mentions the 100-year GIC scenario discussed above [9]. The NERC guidelines also work as a tutorial to explain the inner working of GIC calculations in the commercial power system simulators.

4.3 Transformers

Transformers play a central role in GIC impact on power systems. This is evident in Figure 2.3 and the photos of the Salem transformer damaged at the 1989 GMD event have reinforced this. This motivates further work on transformers. This section reports work to further analyze GIC impact on transformers, methods to manage situations where transformers are damaged and the development of a transformer design that immune to GIC.

While the transformer damage may be caused by a single strong GMD event, an alternative is that it is caused by accumulated effects of several events. In fact this may be a more likely cause of GIC-induced transformer damage. Measurements in South Africa reported in [18] show a correlation between GIC at the GMD event during the Halloween storm 2003 and the amount of dissolved gases in transformer oil, which is used for condition monitoring. It contributes to the explanation of transformer damage that lead to transformers in the South African system being taken out of operation later 2003 and in 2004. These findings further prove that GIC has serious effect on power systems also at mid- and low-latitude regions, for which there was previously no evidence.

In case many transformers were to be damaged – by GIC or by any other causes – this may pose a substantial challenge for the electricity supply. The main reason is that replacing a transformer is not easy. If spare transformers exist, transporting the heavy device takes time. More important is if all spare transformers are needed and are not numerous enough. Manufacturing of large transformers is done only at few locations and at a limited pace, which may cause lead times up to months. Motivated by this, US Department of Homeland Security (DHS) initiated the Recovery Transformer or *RecX* project[4]. The goal of the project team involving DHS, EPRI, ABB and CenterPoint Energy is to develop an EHV transformer that can be energized anywhere in seven days. An exercise conducted in October 2012 proved the concept when a 345/138 kV autotransformer was transported in 20 h and energized after five days. To permit transportation by truck, weight and size restrictions dictate that the transformer must be built in modules (one per phase) that can be shipped individually.

Transformers in network locations with the highest GIC levels may be worth protecting. The simplest method is to replace the direct connection between ground and neutral with a resistor or capacitor. This increases the impedance in the GIC path and thus reduces the GIC itself. It protects the transformer in a cost-efficient way but also tends to divert the GIC to neighboring transformers. An alternative is to install a transformer that is immune to GIC. Such a design has been invented at Lund University, Sweden, and was recently presented in at the IEEE PES General Meeting [19], where it received great attention. The basic idea is to lead the GIC through additional compensation windings that cancel its effect on the transformer core. If the design, which has been studied in simulations, proves practically feasible it offers an alternative at key locations such as large power plants at the edge of the system where GIC levels are generally higher.

4.4 Requirements

In order to develop reliability standards that mitigate the effect of GMDs, that are acknowledged in the NERC report [11], the US Federal Energy Regulatory Commission (FERC) issued a Notice of Proposed Rulemaking on 18 October, 2012 on “Reliability Standards for Geomagnetic Disturbances”. It directs NERC to prepare the standards and submit them for FERC approval:

- In a first step the standards require “*owners and operators to develop and implement operational procedures*[5] *to mitigate the effects of GMDs and ensure grid reliability”. NERC also needs “to identify and evaluate facilities most at risk for disruption, with special attention paid to facilities that provide service to critical and priority loads*”.
- The second step requires “*affected companies to conduct initial and continuing assessments of the potential impacts of GMDs on grid equipment and the grid as a whole. Relying on these assessments, affected companies would then develop and implement procedures to ensure the reliable operation of the bulk-power system. These procedures should not be limited to operational procedures and enhanced training alone, but rather focus on what needs were identified in the assessment*”.

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[4] In presentation by Brandon Wales, DHS, at the TIEMS conference on *Space Weather and Challenges for Modern Society* in 22-24 October 2012 in Oslo, Norway

[5] Underlining in quoted text has been done by the author of this report.

The proposed deadlines were 90 days and six months respectively after the final ruling. This was however found too aggressive and in the final ruling of order 779 on 13 May 2013 these were changed to six and 18 months corresponding to end of 2013 and 2014 respectively.

The US development indicates that geomagnetic disturbances are now recognized as a phenomenon that needs to be properly managed. The involvement of FERC and NERC also show that this may not be done in an arbitrary way, but the strategies of involved companies must meet common standards. In Europe, the entity corresponding to FERC is the European Network of Transmission System Operators for Electricity (ENTSO-E). It can be expected that European reliability standards for GMD – if they are introduced – would be issued by ENTSO-E. That organization is currently heavily involved in formulating "European Planning Standards and Connection Codes" and also has a working group on Critical System Protection. This connects to the European Program for Critical Infrastructure Protection (EPCIP) under the European Commission, which currently seems more active in the area of GMD than ENTSO-E.

5 Impact on other systems

As indicated in Figure 1.1, solar activity affects not only electric power systems but also global navigation satellite systems (GNSS) and electronic communication. At the workshop in Lund 21 May 2012 on solar activity and its impact on society two presentations dealt with these issues.

Hans Åkermark works as consultant for the Swedish Post and Telecom Authority (PTS). According to his presentation, the main influence of solar activity on mobile and fixed call telecommunication is through the electric power supply. Most nodes in the telecommunication network have some sort of backup power supply. Depending on its importance the nodes withstand a few hours up to days of normal operation with no ordinary electricity supply. Since communications increase in case of a power outage, the actual capacity is however lower in practice. The dependence on electricity has motivated a close cooperation between PTS and the electric power sector.

Gunnar Hedling is project manager at Lantmäteriet working with SWEPOS; a national network of reference stations for GPS to obtain cm precision. His presentation showed that GNSS precision exhibits variations with daily and yearly cycles, with best conditions in mornings and in summer. Superimposed on this is also a longer cycle coinciding with the sunspot cycle. To support their customers who depend on high-precision position measurements, they have developed an Android application with a map of Sweden that indicates the current situation regarding precision in measurements.

GPS signals are essentially accurate time signals, and while navigation is its primary application they are used also for other purposes. A Svenska Kraftnät report on measures against GMD impact [20] goes through possible impacts on the power system and suggests actions to take based on this. While transformers and protection are naturally mentioned, the issue on timing and GPS signal dependence is the first action listed in the concluding chapter. It is also noted that the situation regarding sources for time signals throughout the system needs to be surveyed. In addition to having an uncertain current situation, it is established that there is clear trend towards increased GPS dependence, starting with the EMS software currently being installed in the national control center.

6 Conclusions

Based on literature and conference presentations during 2012 and 2013 this report attempts to review the field of geomagnetic disturbances and their impact mainly on the electric power system. The impression is that the field is developing rapidly. An important reason is that FERC and NERC in USA take action towards reliability standards covering GMD. In connection with this, the general view of what the worst case scenario looks like has shifted from mass-destruction of system transformers to a voltage collapse-induced blackout.

The NERC requirements may lead to replacement of equipment leading to insufficient GIC capability. This may be a future opportunity for the transformer design immune to GIC invented in Lund.

Several steps have been taken to facilitate analysis of power system analysis in connection with GMD: GIC capability has been included in commercial power system simulators. A 100-year GMD scenario has been proposed that can be used to analyze specific systems and as a starting point for such work a small benchmark simulation model has been developed.

Progress is being made in forecasting and methods are demonstrated with application to both the American and the European continents. Important next steps are that the forecasts reach the right stakeholders and that these have appropriate action plans when the next serious GMD event occurs.

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A. Appendix What is reactive power?

To understand reactive power, it is easiest to first explain *active power*, which is closer to everyday life. Home appliances as well as car engines have active power ratings in *W* (*Watts*). Similarly energy in *kWh* (kiloWatthour =1000 *Wh*) is how we measure electricity consumption. Active power and energy are closely related in that active power is *energy* per time unit and indeed 1 *kWh/h = 1 kW*.

All this is easily applicable to constant DC currents and voltages, where active power in *W* is the product of current in *A* (*Amps*) and voltage in *V* (*Volts*). AC waveforms are not constant but sinusoidal as seen in Figure A.1, which can be observed using an oscilloscope.

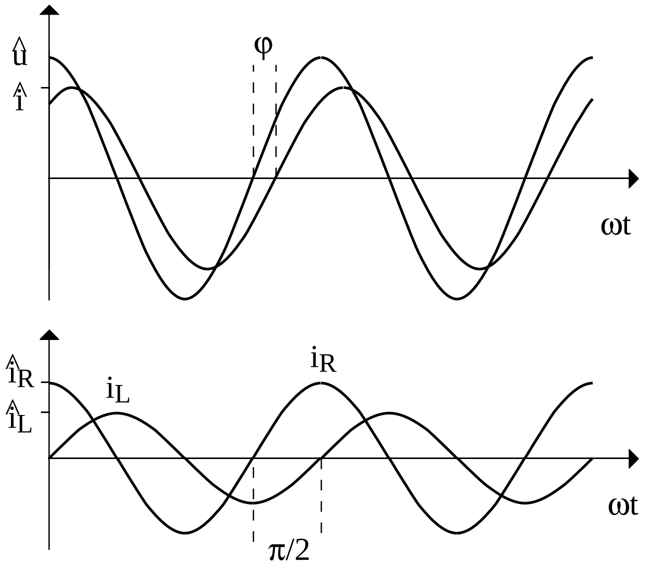

Figure A.1 Voltage *u* with peak value *û* across a mains connected single-phase load with resistive and inductive characteristic (upper). The current *i* with peak value *î* divided into a resistive component i_R and an inductive component i_L (lower).

The resistive part i_R of the current *i* is in phase with the voltage *u* and crosses zero at the same instants. Multiplying the voltage waveform with the i_R waveform gives instantaneous power, shown as p_R in Figure A.2.

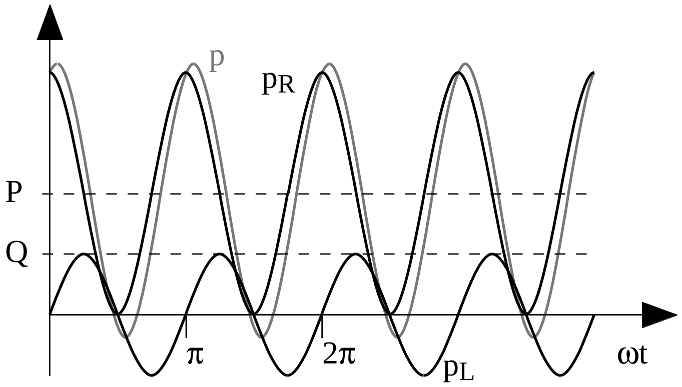

Figure A.2 Multiplying the voltage and current waveforms yields instantaneous power. Combining the voltage u with the total current gives *p* (grey), while using *u* and i_R or *u* and i_L gives p_R (black) and p_L respectively.

p_R shows the time variation of power related to a resistive current and could represent heat from a heating element. Usually *active power* refers to *P*, which is the average value of p_R.

The active power P could have been easily determined as the product of the RMS values of the voltage u and current i_R. The voltage in many European mains outlets 230 V is an RMS value and the current rating in A that can be read on fuses is also an RMS value. A fuse marked 10 A can thus feed a maximum 2300 W to an appliance connected to 230 V mains outlet.

Reactive power is instead linked to the inductive component of the current related to magnetic fields typically in windings such as those in transformers. The magnetic fields of power lines also have inductances associated with them.

Let us repeat the exercise above using the inductive current component i_L in Figure A.1. Multiplying this with the voltage u gives the instantaneous power p_L seen in Figure A.2. It can be shown that p_L is the rate of change of the magnetic energy stored in the (e.g. transformer) inductance. This inductance can be thought of as an electromagnet which is magnetized in one direction, then demagnetized and magnetized in the other direction and so on. The peak value of p_L, denoted Q in Figure A.2, is the *reactive power*.

Reactive power is given in *var* and quantifies the currents related to magnetic fields in e.g. transformers, power lines and electrical machines. p_L has zero average, which means that the average active power drawn by an (ideal) inductance is zero and thus that the energy that an inductance consumes is zero *kWh*. Still reactive power is important since the reactive component of the current acts to increase the total current and thus the loading of lines and transformers in the power system.

Reactive power is relevant not only to inductances but also to capacitors and the (electrostatic) energy stored in them. The waveform for a capacitive current i_C would look like i_L but turned upside down and the same applies for p_C relative to p_L. While inductances draw reactive power, capacitors produce reactive power and can actually supply inductances with reactive power. Properly used this may reduce the loading of lines and transformers. Vice versa, when reactive resources are lost near voltage collapse, this loading instead increases which may be critical.