CODEN:LUTEDX/(TEIE-5296)/1-54/(2012)

Industrial Electrical Engineering and Automation

Risk analysis of geomagnetically induced currents in power systems

Rasmus Thorberg

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, LTH, Lund University

ABSTRACT

Solar storms are a phenomenon that has a wide array of adverse consequences on technological systems, power systems in particular. During severe solar storms a geomagnetically induced current (GIC) starts to flow through long conducting structures, such as power lines and pipelines. The probability of solar storms has a roughly linear relation with the sunspot activity level which varies in 11 years cycles and at the moment of writing this thesis we are approaching the maxima of solar cycle 24. This thesis is a risk analysis of GIC in power systems and describes the causes and sources of GIC, the consequences, both on component level and on system level, and the likelihood of occurrence.

When GIC flows through a transformer it causes the core to saturate, which leads to (a) increased reactive power consumption, (b) high levels of harmonics in the power system and (c) localized heating of the transformer. Point a and b are confirmed through simulations. High harmonics levels can cause protective relays to sense false fault conditions and trip. On a system level this can lead to (a) loss of production (b) local blackouts or (c) widespread blackouts. Localized heating of transformers can lead to permanent damage and spare parts and replacement units are associated with having long lead times. Communication and control systems are also subject to GIC and other solar storm related interferences. The thesis also contains a discussion about GIC risk associated to gas pipelines.

The likelihood of solar storms is discussed and a method for determining the exceedance probability of extreme values for solar storms such as a 100-year storm is presented. The exceedance probability of a 100-year storm during 2012-2014 is estimated to 4.7%.

Possible risk treatment strategies and forecasting capabilities are also briefly discussed, in order to briefly illustrate possible risk management schemes.

This report should facilitate risk evaluation and provide the information needed to calculate quantitative risk values with respect to solar storms and power systems.

In order to fully understand the extent of the consequences of a 100-year storm further studies are needed in order to take the complexities of covariance and the interconnectedness of different components and systems into account.

ACRONYMS AND NOTATIONS

ACRONYMS

AC/DC	Alternating Current/ Direct Current
ACE	Advanced Composition Explorer, a NASA space craft launched on August 25, 1997
CME	Coronal Mass Ejection
CP	Cathodic Protection
emf	ElectroMotive Force
FEMA	Federal Emergency Management Agency
GIC	Geomagnetically Induced Current
GPS	Global Positioning System, a satellite based navigation and timing system
HF	High Frequency
ISES	International Space Environmental Service
MSB	Myndigheten för Samhällsskydd och Beredskap
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration, agency of the United States government responsible for aviation and spaceflight
SDO	The Solar Dynamics Observatory, is the first mission to be launched for NASA's Living With a Star (LWS) Program. The mission was launched on February 11, 2010.
SIDC	Solar Influences Data Analysis Center
SOHO	Solar & Heliospheric Observatory, a spacecraft built in collaboration between ESA and NASA to study the sun. The mission was launched on December 2, 1995.
SPE	Solar Proton Event
STEREO	STEREO (Solar TErrestrial RElations Observatory) is the third mission in NASA's Solar Terrestrial Probes program (STP). The mission was launched in October 2006.
THD	Total Harmonic Distortion, a measurement of the harmonic distortion. Defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.

NOTATIONS

$\boldsymbol{B}, B_x, B_y$	Magnetic field
$\boldsymbol{E}, E_x, E_y$	Electric field
μ	Permeability
μ_0	Permeability in vacuum
$Z, Z(\omega), Z(\mu)$	Impedance
ω	Angular frequency
a, b	System specific GIC parameters
V_p, V_s	Voltage, emf
N	Number (integer)
Φ	Magnetic flux
$\frac{d\Phi}{dt}$	Change in magnetic flux, time derivative
R	Resistance
$\mathcal{R}$	Magnetic reluctance
σ	Conductivity
I	Current
P	Effect (heat)
l	Length (of pipe)
$c(Z)$	Ground conductivity factor
$d(\varphi)$	Geomagnetic latitude factor

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1 INTRODUCTION

Solar activity and the likelihood of solar storms vary in 11-year cycles. We are now again approaching a solar maximum and it is therefore of interest to investigate solar storm related risks for power systems. This thesis aims to provide an overview of solar storm related risks, especially risks relating to geomagnetic induced currents (GIC) in transformers. The goal is, with the aid of risk methodology, to investigate and describe the entire chain of events that constitutes a solar storm, its possible consequences and potential risk mitigation activities.courtesy

The thesis is carried out in collaboration with E.ON Sverige AB, who has courteously contributed with workspace, discussions, interviews and data from historical events.

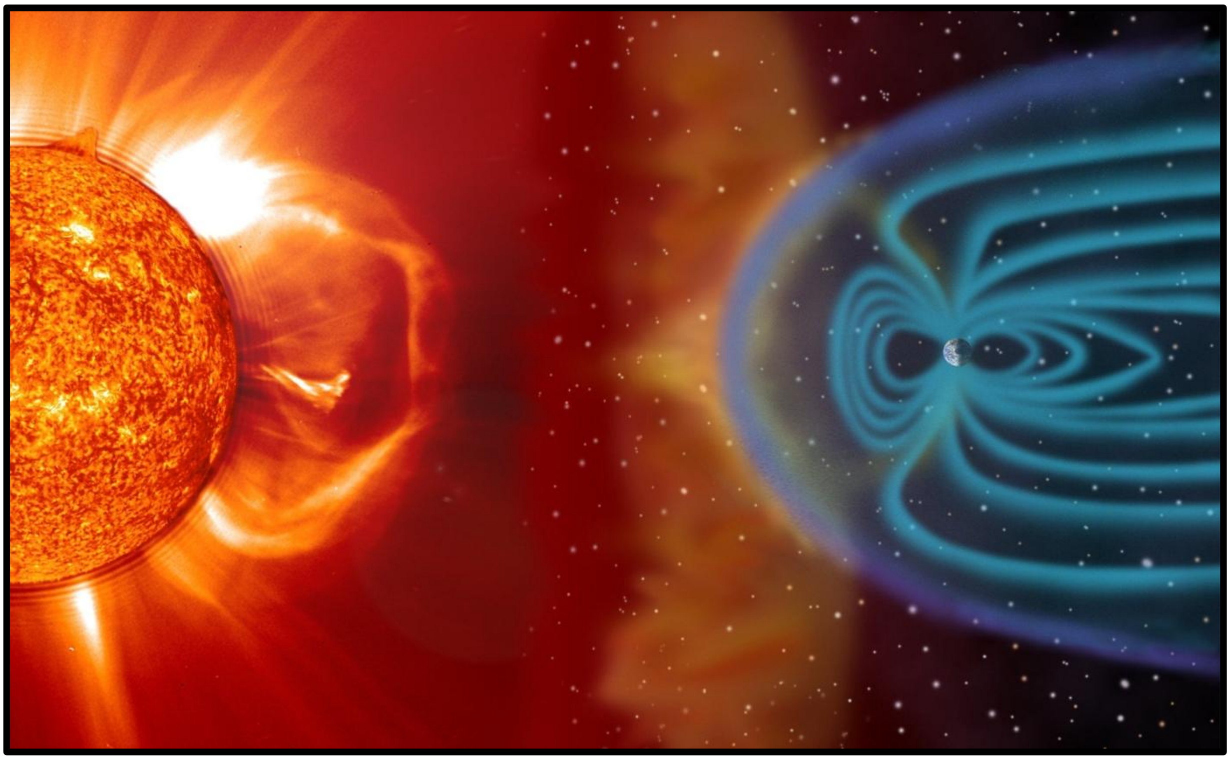

Figure 1: Illustration of a solar storm. A coronal mass ejection is ejected from the sun, travels through space and collides with Earth's magnetic field (courtesy of NASA).

1.1 BACKGROUND

Geomagnetically induced current (GIC) is a phenomenon caused by the interaction between space weather and the Earth's magnetic field (see Figure 1). As violent space weather penetrates the Earth's magnetosphere (often referred to as a geomagnetic storm) it can result in a high current electrojet in the ionosphere. This electrojet can reach several million amperes during geomagnetic storms. As this current varies with time it induces an electric field at the ground level, called a geoelectric field. The geoelectric field will in turn cause a current to flow in the geoelectric field's direction, a geomagnetically induced current (GIC) (Wik, 2008). This current will take the path of least resistance. In areas of high ground resistivity the current will flow through power lines, gas pipelines or other available conductive media such as railway (see Figure 2). GIC flowing through such man-made structures have the potential to cause great harm to it. In general GIC is more likely to be a problem in areas at higher latitudes and with high ground resistivity. For power systems in particular, geometrical and structural setup also have significant influence, transformers located in corners of the power grid and at the end of long power-lines are more GIC susceptible. GIC and geomagnetic storms are not only a problem for power systems; it can also directly influence technical systems such as, HF-radio, GPS, railway, communication systems (both wired and wireless), pipelines and geological surveys (Koskinen et al., 2001). For gas pipelines, GIC can cause a variation in the pipe to soil voltage which can disturb the cathodic protection system (Pirjola, 1999).

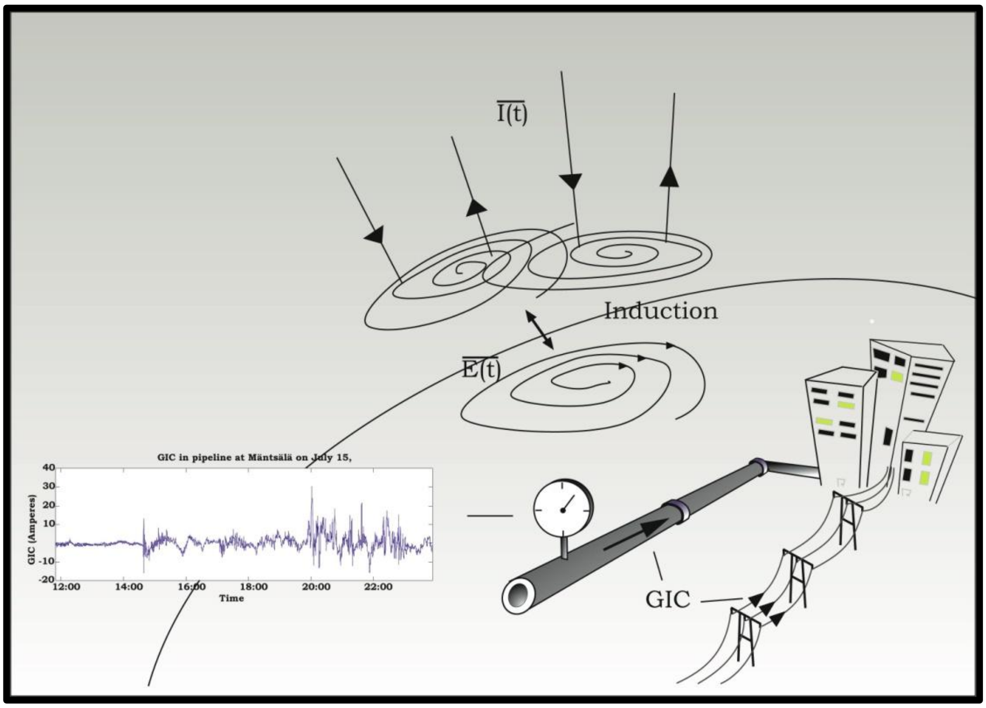

Figure 2: Illustration of GIC generation (courtesy of Antti Pulkkinen).

Even though GIC as a phenomenon was first observed in the telegraph system, as early as 1848 (Barlow, 1849) there have been relatively few studies of the socioeconomic impact of space weather. It was not until the blackout of Hydro-Québec's power grid during the geomagnetic storm of March 1989, which left millions of people without power for up to nine hours, that solar storms widely came to be treated as a risk to society and its critical infrastructure (Baker et al., 2008). E.ON Sverige AB (formerly Sydkraft) has also experienced several GIC related incidents, not least during the, popularly named, Halloween storm of 2003 in which parts of Malmö were left without power for 20-50 minutes. The largest GIC-current ever measured in the world was almost 300 A and was detected in Sweden 2004 (Wik, 2008). While GIC and geoelectric field strengths are orders of magnitude higher at higher latitudes, a covariance between GIC in gas pipelines in Sweden and in Greece has been found – clearly illustrating that this is not a local phenomenon (H-E Edwall, personal communication, June 22, 2011).

As the modern technological society grows more complex and interdependent, governments have become increasingly concerned about threats against critical infrastructures (MSB, 2009).

- In February 2010 a European and North American summit was held with the purpose of discussing international cooperation in the event of a crisis caused by a severe geomagnetic storm. The summit was hosted by the Swedish Civil Contingencies Agency (MSB) and its US counterpart the Federal Emergency Management Agency (FEMA) (MSB, 2010).
- On March 1 2011 an EU-project, European Risk from Geomagnetically Induced Currents (EURISGIC) started with the goal of producing the first European-wide real-time prototype forecast service of GIC in power systems.
- On December 2 2011 MSB hosted a seminar on solar storms and electromagnetic interference (MSB, 2011a).

- In a recently published report on national risk assessment, MSB names solar storms as a national risk for Sweden. The report is part of MSB strategy for protection of critical infrastructure which in its turn is a part of the European program for critical infrastructure protection (MSB, 2011b).

Today, twenty-two years after the Hydro-Québec blackout, we are approaching a new maximum in solar activity and it is of increasing interest to review how well we are equipped to handle the effects of severe space weather.

1.2 GOAL AND SCOPE

The goal of this report is to provide a comprehensive analysis of risks relating to solar storms and power supply, especially risk relating to geomagnetic induced currents. This will be achieved with the aid of risk methodology, by investigating and describing, the entire chain of events that constitutes a solar storm, its possible consequences, and potential risk mitigation activities.

It will not be practical to provide quantitative risk values for the identified risks on the general level of this report, since the risk values will vary from component to component and likewise on a system level. The report will instead aim to provide general qualitative information needed to calculate these quantitative risk values. The report could also be an aid during risk management for any risk relating to highly disturbed space weather. For these reasons the structure of the report is planned to guide the reader through the different risk elements which will be described in the following chapter.

2 RISK ANALYSIS OF SOLAR STORMS

Risk is a central concept in this report and a short introduction to the subject of risk and risk management should be helpful both in understanding the method and as a reason behind the layout of this report.

For reasons of simplicity and generality definitions and methods relating to risk and risk management are taken from ISO 3100:2009; Risk management – Principles and guidelines (International Organization for Standardization, 2009).

Risk is here defined as: "effect of uncertainty on objectives" (International Organization for Standardization, 2009, p. 1). This definition can seem a bit vague, but in the context of this report the implications are quite concrete. Here a risk is the likelihood of and the adverse effects that highly disturbed space weather have on power systems. The objective is hence the uninterrupted production, transmission and delivery of power and the uncertainty relates to occurrence of highly disturbed space weather. This definition is quite unproblematic since there are very few upsides from solar storms.

In order for an organization to handle risk rationally and effectively, it is important to understand the risk source and its consequences correctly. This can be achieved by using a systematic and structured risk management method, see Figure 3. Each of these process steps will in their turn contain several sub processes, not described in any detail here (for detailed descriptions please refer to (International Organization for Standardization, 2009, p. 13-21)).

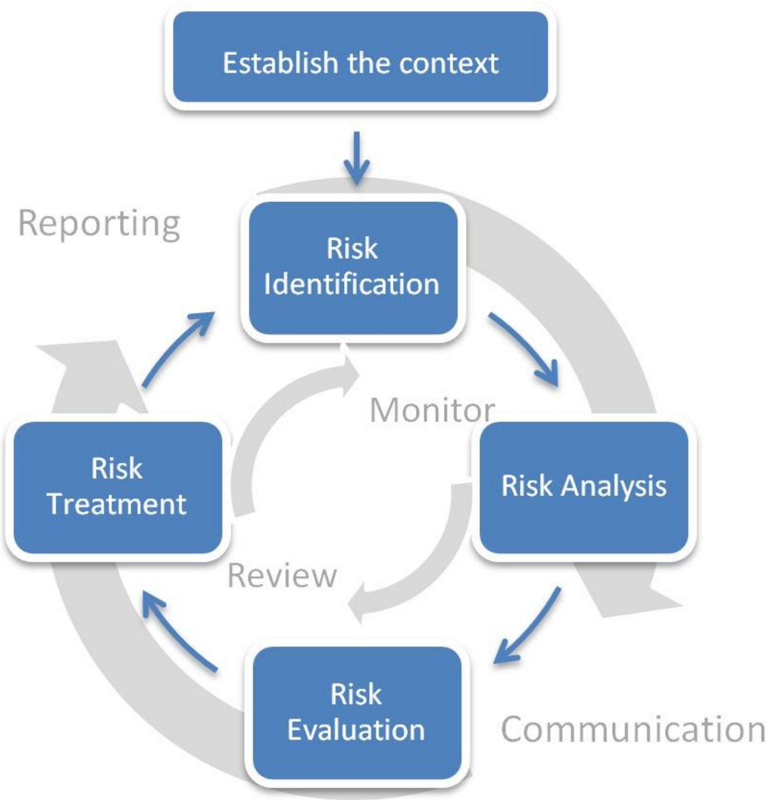

Figure 3: Overview of ISO 31000 risk management process (courtesy of Nils Rosengren).

- The goal of risk identification is to generate a comprehensive list of risks based on those events that might create, enhance, prevent, degrade, accelerate or delay achievement of objectives.
- Risk analysis involves considering the causes and sources of risk, their consequences and the likelihood of occurrence. It is also important to consider the interdependence of different risks and their sources.

- The purpose of risk evaluation is to assist in making decisions about the need and priority of risk treatment. This involves comparing the risk level found during analysis with the risk tolerance of the stakeholders and other requirements.
- Risk treatment is the step of selecting and implementing options for modifying the risk.

A conventional way of describing risk is by first describing the source of the risk, followed by the likelihood of occurrence, ending with a description of the consequences. This formula effectively communicates the three elements, root cause, likelihood, and consequence and promotes a consensus in understanding of the risk and how to evaluate it. By then analyzing the likelihood of occurrence and the impact on objectives, the risk can then be evaluated either qualitatively or quantitatively.

The chapter that follows is a short review of three noteworthy historical events and their consequences that will give a background to the phenomena and illustrate the risk. Then follows a general review of the risk source with solar storms, the chain of events that starts in the interior of the Sun and ends as a geomagnetic storm on Earth and a discussion about the probability of solar storms. The third part of the report examines the component level consequences, i.e. how the power system components are affected. The fourth part continues the analysis by discussing the system level consequences and system interdependencies. This is then followed by a discussion about likelihood of solar storms. The risk analysis is finally concluded by a short review of possible risk treatment alternatives, a short summary and conclusions.

3 REVIEW OF HISTORICAL SOLAR STORM EVENTS OF PARTICULAR INTEREST

While solar storms as a phenomenon have only been known for about a century and a half, there have occurred several storms in this period that have had adverse effect on human technological systems. In the following chapter three of these events will be discussed since they are of particular interest in the context of this report. The first event is both the earliest and strongest storm on record. The second event is the storm that has had the largest consequences for power systems and arguably the first time GIC was put on the agenda as a high risk for power systems. The third and last event in this chapter is one of the most recent storms and one that has had the largest consequences for power systems in the southern part of Sweden.

3.1 THE CARRINGTON EVENT, SEPTEMBER 1, 1859

The Carrington event, named after British astronomer Richard Carrington, is both the strongest and one of the earliest ever recorded geomagnetic storms.

3.1.1 CONSEQUENCES

On the morning of September 1st 1859 Richard Carrington observed a previously unknown phenomenon, an extremely intense solar flare. The geomagnetic storm struck 17 hours later and it lasted for days. Reports of the storm came from all over the world. Auroras where observed as close to the equator as the Caribbean. By some reports it was bright enough to read newspapers by the light of the aurora alone (Phillips, 2009). Telegraph systems went down all over Europe and North America, in some cases even giving electrical shocks to operators and causing fires (Baker et al., 2008).

3.1.2 WORST CASE SCENARIO

There have been later storms of similar magnitude with respect to some parameters, but all in all the Carrington event is thought to be the strongest storm in the last 500 years (McCracken et al., 2001; Townsend et al., 2003). Thus the Carrington event has often been used as a basis for worst case scenarios involving severe space weather. This does of course not preclude that a bigger storm may occur at any time and thus it is not reasonable to use this event as a basis for a worst case scenario without any further statistical analysis (Pulkkinen et al., 2012).

CONSEQUENCES OF A SIMILAR STORM TODAY

While the probability of a storm of the same magnitude is very low the consequences to society could be daunting. In 1859 the use of electricity based technology was in its infancy and the consequences of the Carrington event were very limited. If such an event where to happen today it is very hard to assess the damage to society due to the increasingly complex interdependency of society's critical infrastructure. A recent study by the US National Academy of Sciences estimated the cost to society in the range of US$1 trillion to US$2 trillion during the first year alone with recovery times of 4 to 10 years (Baker et al., 2008).

3.2 THE HYDRO-QUÉBEC EVENT, MARCH 13, 1989

At 2:44 a.m. on March 13th 1989 a 100 ton static VAR capacitor at Chibougamau sub-station, Québec, Canada, tripped and went offline due to GIC causing a protective relay to sense overload conditions.

3.2.1 CONSEQUENCES

The tripped VAR capacitor caused a cascade of failures throughout the Québec power grid; most notably five transmission lines from James Bay were tripped causing a loss of 9,450 MW. The total load in the grid at the time was about 21,350 MW. A mere 75 seconds after the first capacitor went down most of the province was left without power. Automatic load reduction systems tried to restore balance in the power system by disconnecting towns and regions but failed. This cascade of spreading failures was much too fast for any meaningful form of manual intervention by operators to take place. 6 million of Hydro-Québecs customers were left without power for up to 9 hours.

About 200 other separate events due to the storm were also reported from North America (see Figure 4), of which the catastrophic failure[1] of a step-up transformer at the Salem Nuclear Power Plant in New Jersey was probably the most serious one (see Figure 5) (Baker et al., 2008).

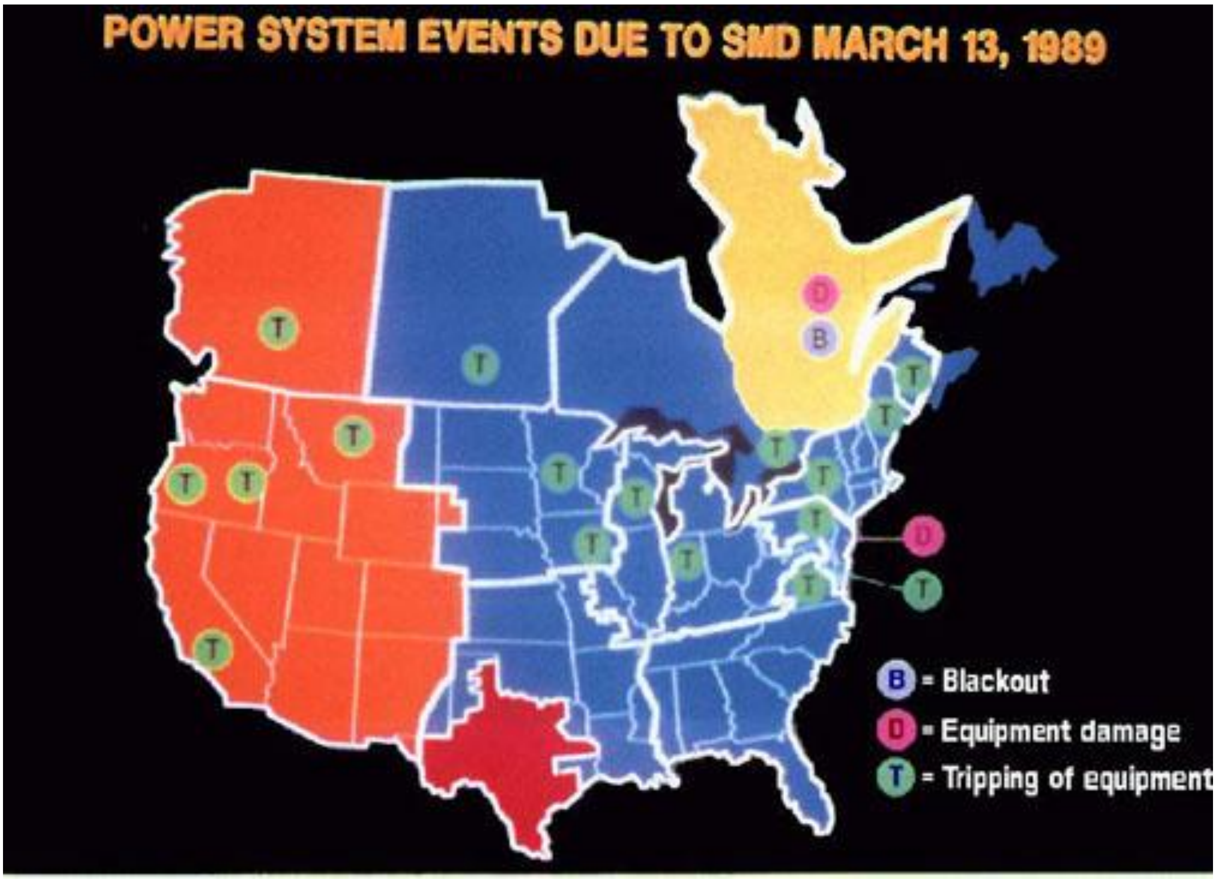

Figure 4: Illustration of GIC related failures from the storm March 13 1989 (Electric Power Research Institute).

[1] "A catastrophic failure is a sudden and total failure of some system from which recovery is impossible. Catastrophic failures often lead to cascading systems failure." (Wikipedia, 2012)

Figure 5: Close-up view of a part of the transformer that was damaged at the Salem Nuclear Power Plant (courtesy of Peter Balma).

RISK TREATMENT IMPLEMENTED AFTER THE EVENT

Shortly after the blackout Hydro-Québec organized a task force to analyze the events and propose corrective measures. According to (Hydro-Québec, n.d.) the following measures have since been applied:

- Recalibration of protection systems and rising of the trip level. This tactic has proven effective, since there have been very intense magnetic storms since 1989 but they have not caused any problems.
- Establishment of a real-time alert system that measures disturbances on the power grid during magnetic storms.
- Modification of power system operating procedures. In the event of a disturbance, Hydro-Québec reduces power flow on lines and direct-current interconnections, and suspends all major switching operations.
- Installation of series compensation on power lines to enhance grid stability. This measure has been very effective in mitigating the impact of magnetic storms.

The damaged step-up transformer at the Salem Nuclear Power Plant had to be replaced. If existing spare parts could not have been found the lead time for production of replacement parts would have been close to 2 years, even if the order where given top priority. The total cost for repairs and replacement electricity for the owner Public Service Electric and Gas was later estimated to be above US$ 20 million (Baker et al., 2008).

3.3 "THE HALLOWEEN STORM", OCTOBER 30, 2003

Two CMEs hit Earth close to each other in time. The first erupted from the Sun at 11:10 (UTC) on the 28th of October 2003 and hit Earth about 19 hours later at roughly 06:10 (UTC). The second CME erupted at 20:49 (UTC) and reached Earth at 16:20 (UTC). At 20:04 (UTC) the storm peaked and the geoelectric field reached values of 2 V/km in the Malmö region (Wik, 2008).

3.3.1 CONSEQUENCES

This storm had a wide array of consequences for different technological systems. The most interesting incidents in power systems are discussed here and a detailed list of GIC related incidents in the Swedish power system is given in the Appendix. Among other affected systems can be mentioned, the Wide Area Augmentation System (WAAS), a navigation system based on GPS, operated by the Federal Aviation Administration, which was out of service for 30 hours and also the ADEOS-2 satellite that was severely damaged due to the storm (Baker et al., 2008).

SWEDEN

On October 30 21:07 (local time, UTC+1) 2003, a blackout[2] occurred that lasted for 20-50 minutes and affected 50 000 customers in Malmö and surrounding areas. The root cause was a relay in the 130 kV system. The relay was set too sensitive to the third harmonics (150 Hz) of the fundamental frequency (50 Hz) which was a result of transformer saturation due to GIC caused by geoelectric field values of 2 V/km (Malmgren, 2003; Wik, 2008).

Also during the Halloween storm, a transformer at a Swedish nuclear power plant experienced a 13˚C increase in top oil temperature in a transformer containing 69 tons of oil before mitigating action were taken to allow the transformer to cool down (H. Swahn, personal communication, September 15, 2011).

SOUTH AFRICA

The same storm is reported to have caused significant transformer damage in South Africa. Over 15 transformers in South Africa were damaged during this period, some beyond repair (Marusek, 2007; Gaunt & Coetzee, 2007).

3.3.2 RISK TREATMENT IMPLEMENTED AFTER THE EVENT

Two transformers have been replaced at the Swedish nuclear power plant. One of them has a new design aimed at making it more robust to GIC. The other one has had a resistor placed between the ground and the neutral, giving it a higher tolerance to GIC but possibly moving the problem elsewhere in the power system (H. Swahn, personal communication, September 15, 2011).

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[2] Not to be mistaken for the voltage collapse the 23rd of September 2003 that affected large areas of southern Sweden and Denmark.

4 SOLAR STORMS AND THREAT LEVEL

In this chapter the source of solar storms will be reviewed: The chain of events that starts in the interior of the Sun and ends up as a current flowing through the power system.

4.1 THE SUN

The Sun is the source of most of the terrestrial space weather and, with the possible exception of a nova shockwave, it is the only natural source of GIC that we probably need to consider.

The Sun is essentially a massive fusion reactor about 333 000 times the mass of Earth. Even though the Sun has been studied for millennia it is still an area of intense research and much remains to be understood.

Some basic understanding of the sun, and its activity cycles (see Figure 6) and a general understanding of the source of space weather is important to have in order to understand the findings and reasoning throughout the report.

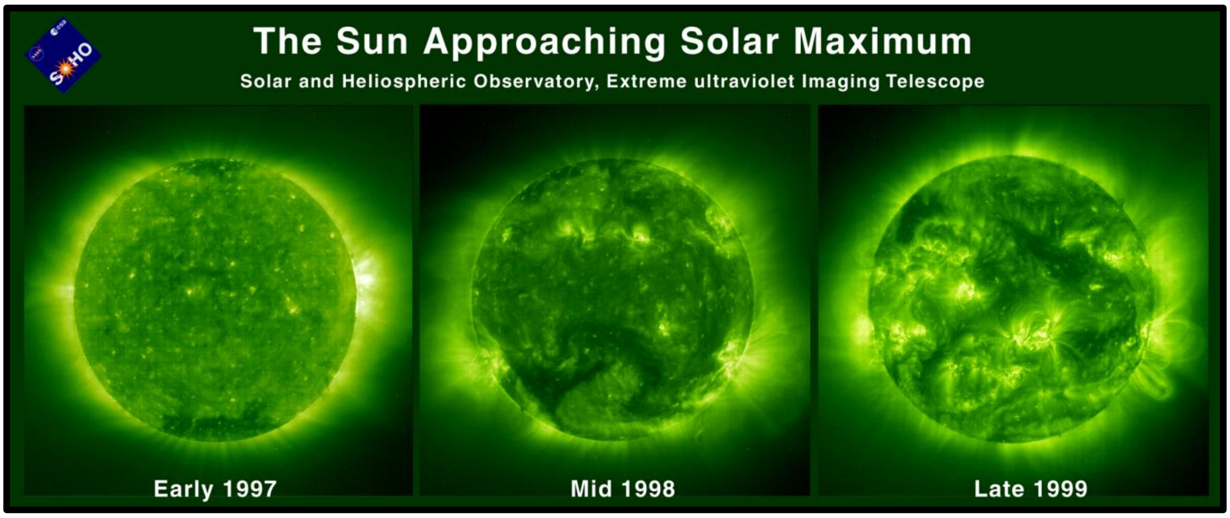

Figure 6: The Sun at different stages in the solar cycle (see Figure 8 for solar cycle data) (courtesy , SOHO), starting with low activity in 1997 and ending with high activity in 1999.

4.1.1 A SHORT HISTORY OF SOLAR ACTIVITY

The earliest evidence that the Sun is not static came from the observation of sunspots in the early 17th century. Sunspots had been seen long before then, but it was not until the use of telescopes spread in Europe around 1610 that sunspot studies began for real. Due to the scarcity of observations for a period, that has later come to be known as the Maunder minimum, we do not have reliable sunspot number data until 1749 (see Figure 7).

It was first about 100 years later in 1843 that the German astronomer Samuel Heinrich Schwabe discovered a pattern in the variation in the number of sunspots. He had discovered the 11 year solar cycle, also known as a Schwabe cycle, after 19 years of intense studies of the sun[3]. Some 70 years later, George Ellery Hale

[3] Schwabe's reason for studying the Sun every day for 19 years was to prove the existence of a hypnotized new planet inside the orbit of Mercury, which he had named Vulcan.

discovered[4] the magnetic properties of sunspots. He found that the magnetic field in the sunspots area was 1000 times greater than that of Earth. He also concluded that the solar cycle was actually roughly a 22-year long magnetic cycle containing two Schwabe cycles with opposed magnetic polarity, this 22-year cycle is today known as a Hale-cycle. “The 11-year solar cycle” is still the most widely used term since the magnetic polarity of the sunspots seldom has any impact. In this report any further reference to solar cycle refers to the 11-year Schwabe cycle.

4.1.2 SUNSPOTS AND THE SOLAR CYCLE

The number of sunspots still today remains a common way to measure solar activity and is by far our longest running data set for solar activity. In Figure 7 one can clearly see the periodicity of the solar cycle from the sunspot data. The cycles have been defined as beginning at the minimum point of the cycle with the occurrence of sunspots with changed magnetic polarity compared with the previous cycle. The current cycle, named “Solar Cycle 24”, was announced by NASA to have begun on January 4 2008 (Phillips, 2008).

In January 2012 NASA predicted that solar cycle 24 will peak in February 2013 with a maximum of 96 sunspots (monthly average) (see Figure 8), estimated to be the smallest in over 80 years (Hathaway, 2012).

Sunspots are the site of origin for most solar storms. They are perceived as dark areas on the surface of the Sun and they are in the same size range as Earth. The reason for their apparent darkness is that they have about 2000K lover temperature compared to the surrounding area and thus they emit less light. The lower temperature is due to the strong magnetic fields that counteract the convection of hotter material moving towards the surface. As the magnetic activity of the Sun increases towards the solar maxima, more and more areas of intense buildup of magnetic energy are formed. This energy can then be released in complex ways that are not completely understood. There are several phenomena that seem to be connected to release of magnetic energy, solar flares and coronal mass ejection (CME) being the most interesting in the context of this report, since they are the phenomena that can cause GIC.

Much of what’s going on inside the Sun and how it affects Earth is still unknown and this is an area of intense research. For example the NASA program Living With a Star (LWS) provides missions to improve our understanding of how and why the Sun varies, how the Earth and Solar System respond, and how the variability and response affects humanity in space and on Earth (NASA, 2011).

There are many and more modern ways to measure the activity of the Sun than the counting of sunspots. But since sunspots are so closely related to the creation of coronal mass ejections which is the root cause of GIC, counting sunspots is a very practical measure of Sun activity.

[4] The discovery of the Zeeman effect made remote measurements of magnetic field-strengths possible through analyzing the properties of spectral lines in the sunlight.

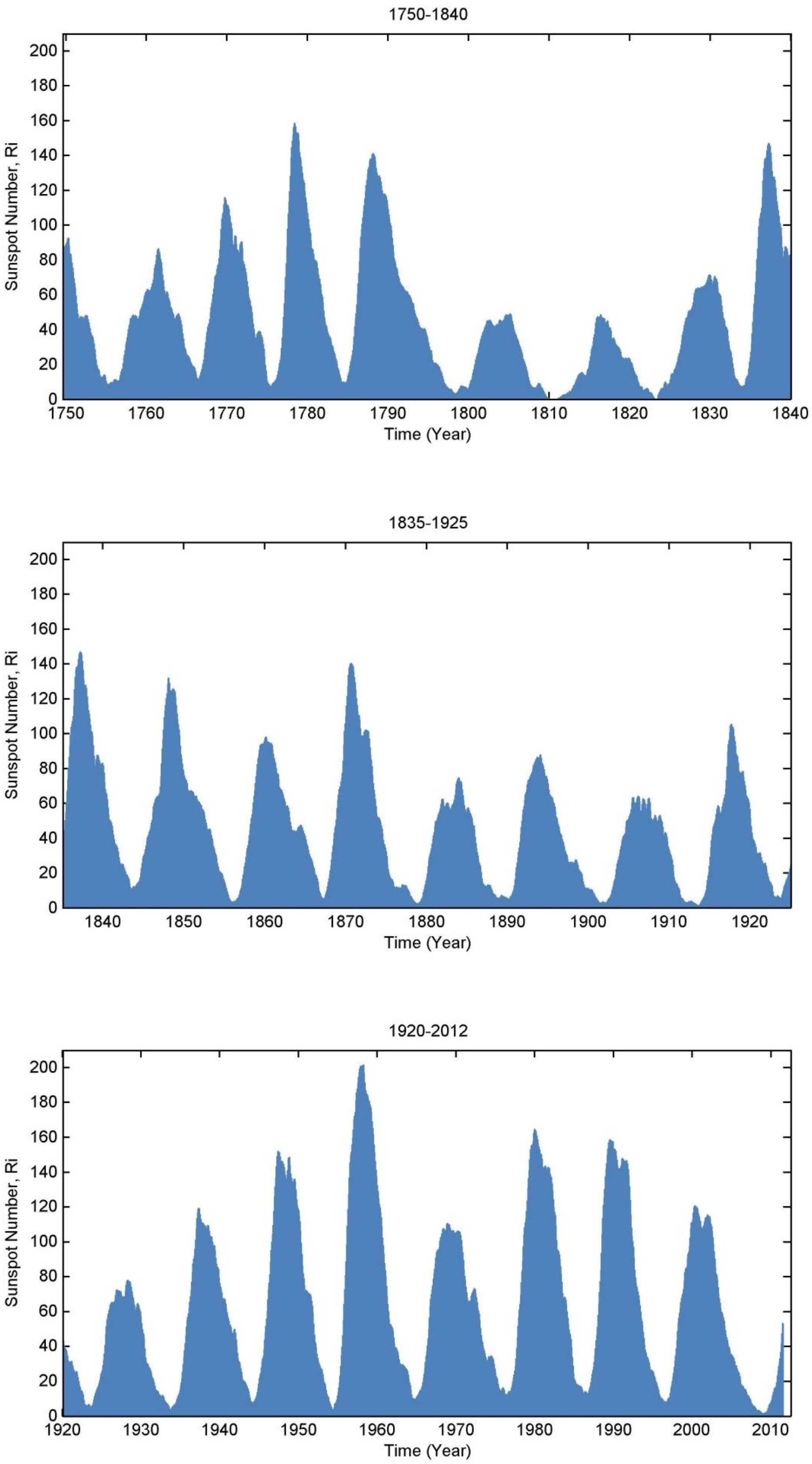

Figure 7: 262 years of sunspot data (data courtesy SIDC-team).

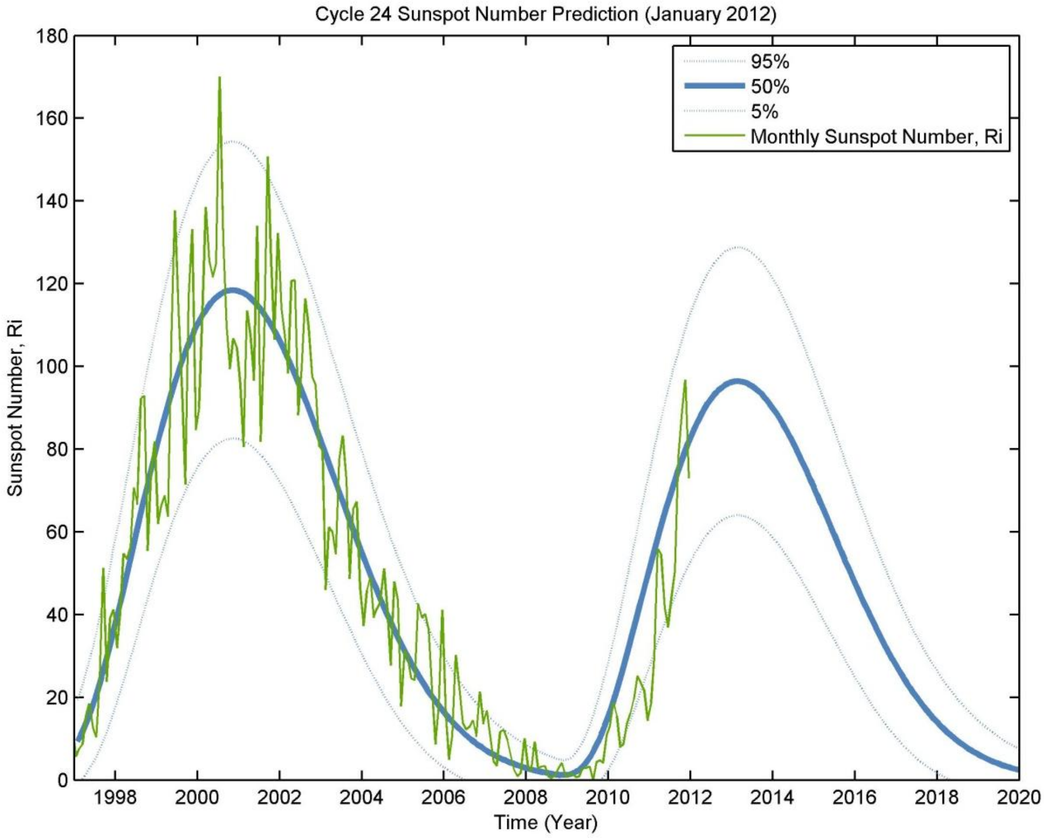

Figure 8: Cycle 24 prediction of January 2012. The 50% line indicates the predicted smoothed (over a year) sunspot number and the 5% and 95% curve indicates the expected upper and lower limit of the monthly smoothed sunspot number (prediction data courtesy of David H. Hathaway, MSFC, monthly sunspot number data courtesy SIDC-team).

4.1.3 SOLAR FLARES, CORONAL MASS EJECTIONS AND SOLAR PROTON EVENTS

Solar flares and coronal mass ejections (CMEs) often occur in close temporal proximity and have earlier been considered as being parts of the same phenomenon, but are today considered as being separate phenomena.

Solar flares are bursts of high energy electromagnetic radiation, ranging from gamma rays to extreme ultraviolet, and are seldom visible to the naked eye.

A coronal mass ejection is essentially a magnetic explosion inside the Sun that propels a massive cloud of charged particles out into interplanetary space. These plasma clouds can contain in the order of billions of tons of matter and can be accelerated to several millions of meter per second, and will typically reach Earth in the order of 20 hours to several days. During solar maxima the Sun produces 3 CMEs per day on average while only producing 1 every 5 days during a minimum (Fox, n.d.). CME are the main source of geomagnetic storms and GIC.

Larger CMEs often also produce a solar proton event (SPE) which consists of bursts of high energy protons with kinetic energy in the range of 10 MeV to 100 MeV. They can reach Earth in less than an hour. Table 1 (on page 24) lists several effects these phenomena can have on Earth and Earth's technological systems. These effects will be described in more detail in the following chapter.

4.2 EARTH AND THE MAGNETOSPHERE

When the solar wind comes into contact with Earth and the magnetosphere, the solar wind will transfer some of its energy to Earth, and this energy can affect Earth's systems in a variety of ways (see Table 1 on page 24). In the following chapter these effects and their underlying mechanisms will be discussed, with a special focus on GIC.

4.2.1 THE MAGNETOSPHERE

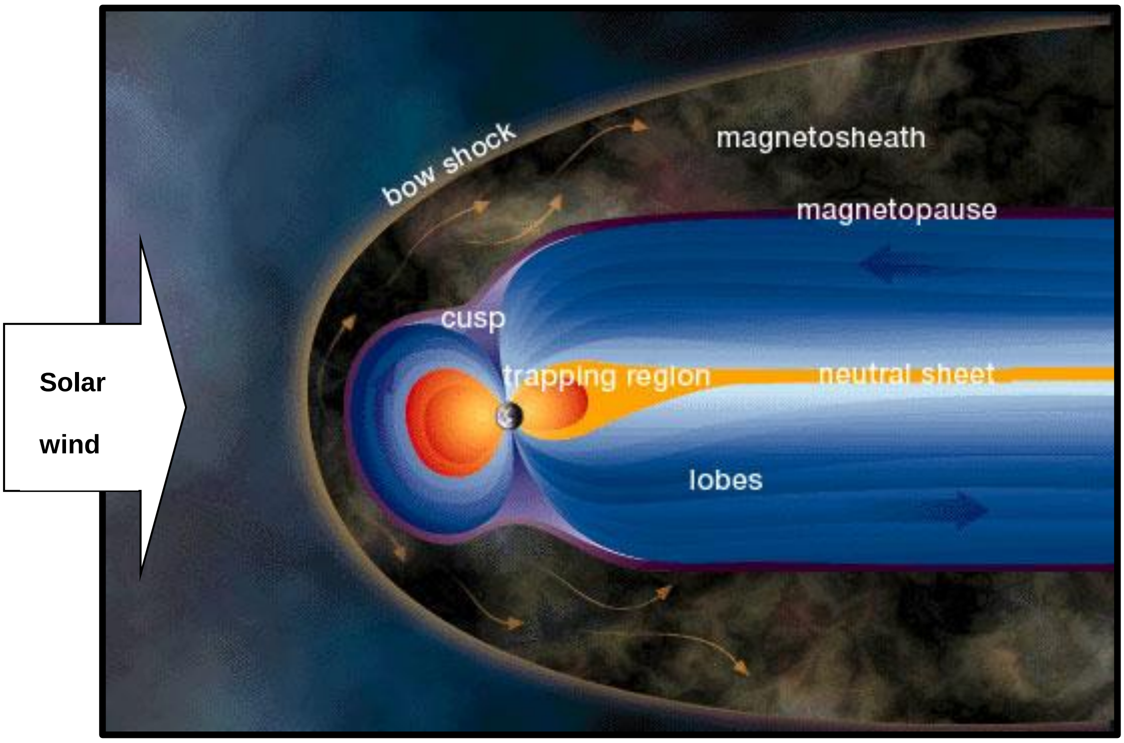

Figure 9: The Earth's magnetosphere (courtesy of NASA).

The physics behind the solar wind-magnetosphere-ionosphere coupling chain is quite complex and a detailed description is out of scope for this report. Very simplified one can say that the charged particles of the solar wind are provided with a way to enter into near Earth regions through the cusps of Earth's magnetic field. This explains why high latitude areas are generally more susceptible to GIC, auroras and other space weather phenomena. Figure 9 also gives us a hint of why the Earth's axial tilt and the season of the year will have an impact on the severity of GIC events. As the solar wind interacts with the magnetosphere it causes a current to flow in the ionosphere. This current can reach several millions of Amperes and is known as an electrojet.

4.2.2 GEOMAGNETIC LATITUDE

The effects of geomagnetic storms are highly dependent on geomagnetic latitude[5], and the effects in the auroral regions are orders higher than at lower latitudes. In fact auroras are another and less adverse effect of

[5] Analogous to geographic latitude but relating to the magnetic poles instead of the geographic poles.

the electrojets. Data suggests that there is a threshold around 50-55 degrees of geomagnetic latitude that holds for most extreme geomagnetic storms. Geoelectric field amplitudes experience a drop of around a factor of 10 from 60 to 40 degrees geomagnetic latitude. It should be pointed out that there are still limited amount of data from extreme geomagnetic storms and it is hard to predict how far towards the equator a 100-year storm would reach (Pulkkinen et al., 2012).

It should also be pointed out that South Africa (around 40 degrees of geomagnetic latitude) was affected by the "Halloween storm" in spite of its sub 50 latitudes. Unfortunately the investigation of GIC in Africa is hampered by the scarcity of magnetometers on the continent (Gaunt & Coetzee, 2007).

4.2.3 GEOMAGNETIC STORMS

If the cloud from a coronal mass ejection intersects Earth, the plasma cloud and the Earth's magnetic field start to interact, causing a geomagnetic storm. Some of the energy of the CME will be transferred to the magnetosphere which in its turn may transfer the energy to the electrojets. Changes in the current of the electrojet causes fluctuations in the geomagnetic field which, in accordance with Faraday's Law of induction (see Equation 3), induces an electric field in the ground (see Equation 1) (Wik, 2008).

4.2.4 GEOMAGNETICALLY INDUCED CURRENTS

The characteristics of the geoelectric field are dependent on the fluctuations of the electrojets and the ground conductivity of the earth. Simplified one could say that the magnitude of the geoelectric field increases with increasing time derivative of the electrojets current and with decreasing ground conductivity.

The geoelectric field in its turn will drive currents within conducting structures, such as pipelines, power lines and signaling cables, at and below the surface of the earth, see Figure 2 and Figure 10 (Pulkkinen, 2003; Lindahl, 2003).

There are several variables that influence the strength of the geoelectric field during disturbed space weather and this contributes both to difficulties in accurately prognosticating the severity of a coming solar storm as well as in extreme event analysis. Some of these factors are: (a) solar activity which influences both the probability and strength of a solar storm, (b) the path, size, magnetic field-strength and -orientation of a CME cloud all have a big impact on how much energy can be transferred to the magnetosphere, and (c) the time of year and time of day when a CME hits affect which regions will be affected and how the magnetosphere is oriented with respect to the Sun. Other time varying factors that that can impact the consequences of a solar storm are (d) the load of the power system and thus how sensitive the system is to GIC at that time (see Chapter 6.3) and (e) several CMEs can also hit Earth in close temporal proximity and superimpose the effects of one storm upon another. It is hard to predict how all these factors will interact and if they will increase or decrease the consequences for the power system.

But there are other factors that are not time variant that can be taken into account when assessing a systems susceptibility to solar storms such as: (f) geomagnetic latitude, (g) ground conductivity, (h) layout and electrical properties of the power system, and (i) geographical features. These can all be taken into account and used in simulations to identify highly vulnerable areas of the power system.

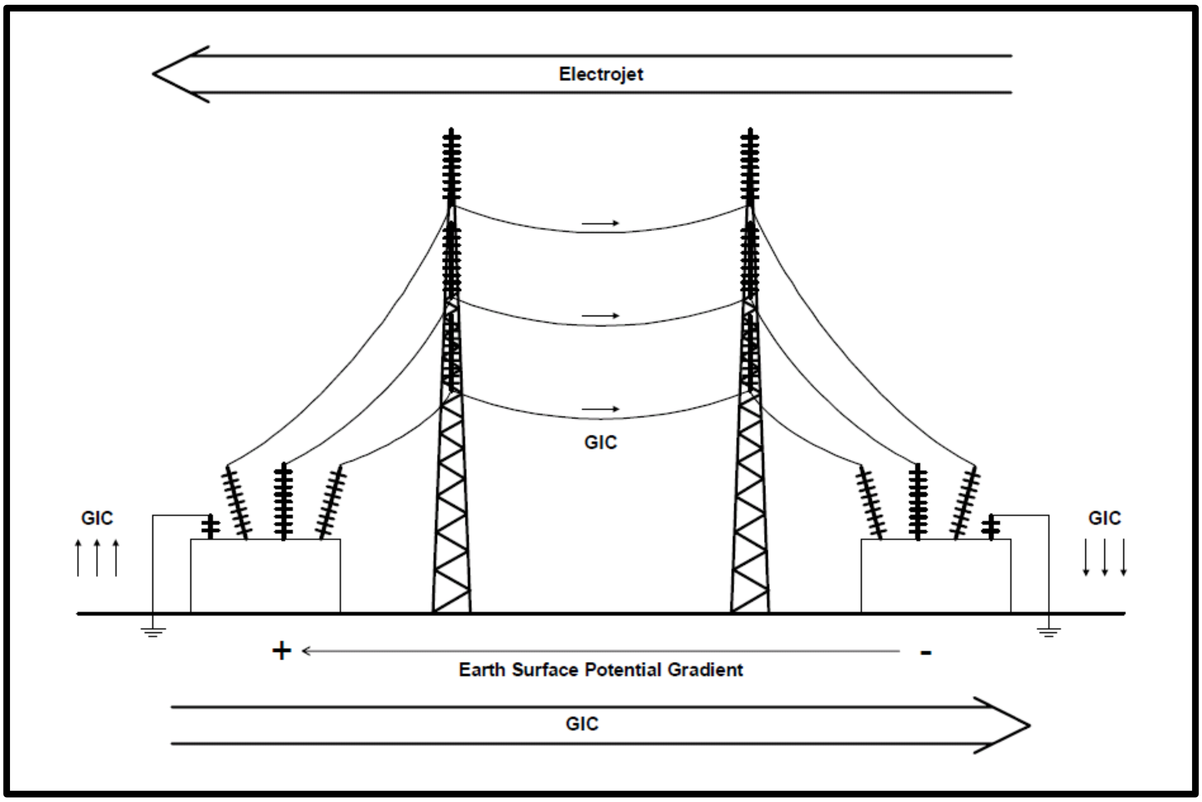

Figure 10: Illustration of GIC in power grid, fluctuations in the electrojet induces a geoelectric field on the ground, the electric field then induces a current (GIC) to enter through grounded transformers and starts to flow in the power system (Lindahl, 2003).

When simulating GIC in power systems one needs to approximate field strength of the geoelectric field at injection points, such as grounded transformers. It has been shown (Viljanen et al., 2004) that one can accurately estimate the geoelectric field components[6] (E_x, E_y) from the strength of the geomagnetic field (B_x, B_y) and knowledge of the local ground conductivity. This is of practical interest since the magnetic field fluctuations are easier to measure than the actual geoelectric field strength. Here x and y is in the horizontal plane of the ground and the x-axis is northward pointing and the y-axis is eastward pointing.

$$E_x(\omega) = \frac{Z(\omega)B_y(\omega)}{\mu_0}, -E_y(\omega) = \frac{Z(\omega)B_x(\omega)}{\mu_0}$$

Equation 1: Geoelectric field calculated from geomagnetic field.

Here $Z(\omega)$is the surface impedance, which depends on the ground conductivity, ω is the angular frequency of the fluctuating field and μ_0 is the permeability in vacuum (Viljanen et al., 2004).

A sometimes practical, but not straightforward, way of measuring the geoelectric field is by measuring earth to pipe potential in long straight sections of pipelines.

When simulations on system level GIC is impractical one can use the following linear relation (Equation 2) to calculate GIC at a single point. Several studies have shown Eq.2 to be a good approximation (Pulkkinen et al., 2012).

[6] This is derived from the plane wave relation between the electric- and magnetic-field, $\boldsymbol{B} = \frac{n}{c}\hat{\boldsymbol{k}} \times \boldsymbol{E}$ where $\hat{\boldsymbol{k}}$ is the unit vector pointing in the direction of the wave vector $\boldsymbol{k}$.

$$GIC = aE_x + bE_y$$

Equation 2: Simplified GIC calculations

Here (a, b) are system specific parameters typically in the range of 0-200 $\frac{A \cdot km}{V}$. If no transformer data is known then $a = b = 50 \frac{A \cdot km}{V}$ can give a good approximation of the sum of GIC flowing over all three phases (Pulkkinen et al., 2012).

Although the GIC is fluctuating in nature (about 0.001-0.1Hz), the frequency of the fluctuation is very low in comparison to that of the AC grid (50 or 60Hz) and thus it is often practical to think of it as a direct current or quasi direct current when looking at its effects on power applications. See Figure 11 for example of geoelectric field fluctuation and in extension GIC fluctuation (see Equation 2).

The following reading is recommended for a reader interested in performing simulations or interested in a more rigorous mathematical model of GIC ; chapter 2 of "Geomagnetic induction during highly disturbed space weather conditions: studies of ground effects" (Pulkkinen, 2003) and "Paper A" of "The Sun, Space Weather and Effects" (Wik, 2008) (which also includes examples of the (a, b) parameters for transformers in the southern part of Sweden).

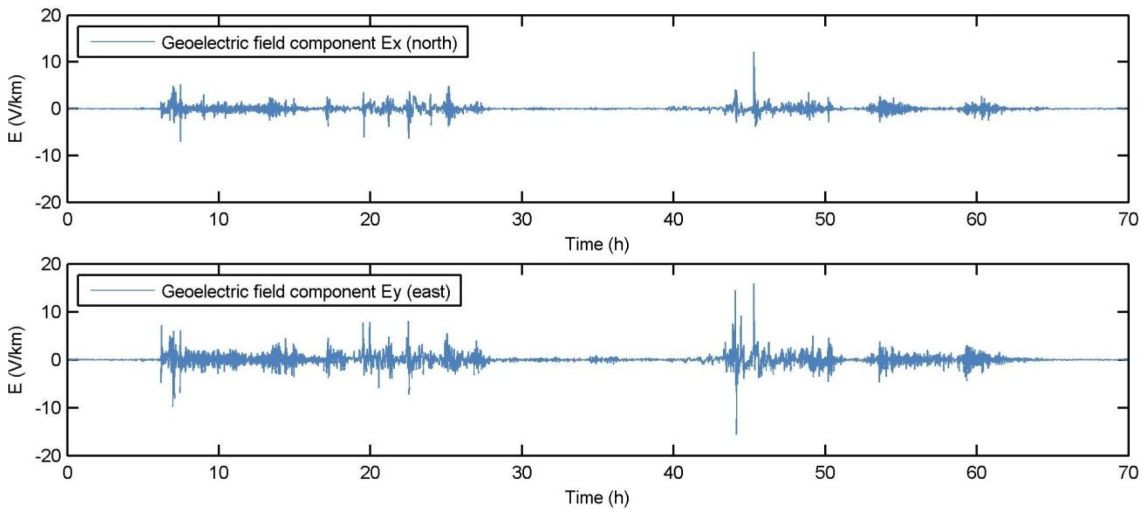

Figure 11: Example of an extreme GIC event. The data is based on the "Halloween storm" but amplitudes have been scaled to simulate a 100-year storm (see Chapter 8.1 100-year extreme GIC event). One interesting aspect to note in this diagram is the temporal properties of the event. Geoelectric field data like this can be used to evaluate a systems susceptibility to GIC (data courtesy of Antti Pulkkinen).

4.2.5 OTHER EFFECTS OF SOLAR STORMS

This section is included to give a more complete picture of how different forms of solar storms affect Earth and its systems. See also Table 1.

SOLAR FLARES

The effects of solar flares will reach Earth at the speed of light (approximately 8 minutes) and its effects will usually last for 1 to 2 hours. Due to ionospheric radio interference (see Table 1) solar flares can disrupt satellite communications, radar and produce shortwave radio fades and blackouts but they seldom have much effect on ground level systems (Marusek, 2007).

SOLAR PROTON EVENTS

A solar proton event (SPE) can reach Earth in between 15 minutes and up to a few hours, and its effects can last for days.

SPE causes a significant radiation hazard for astronauts and spacecrafts but there is no evidence suggesting that SPE is harmful to humans at ground level, as Earth's magnetic field will prevent the protons from reaching down to ground level. However high altitude flights, especially in the polar regions, can be affected by increased radiation during these events.

Satellites and other spacecrafts can suffer temporary or permanent damage to electrical equipment.

SPEs can also significantly contribute to depletion of the outer regions of the ozone layer (Marusek, 2007).

CORONAL MASS EJECTION

These clouds of magnetized plasma can reach Earth within 17 hours but a more typical travel time is 2 to 4 days. They can cause all of the symptoms listed below and in Table 1, with the exception of ozone layer depletion and its effects on the magnetic field can last for days (Marusek, 2007).

Effect	Coronal Mass Ejection	Solar Flare	Solar Proton Event
Geomagnetically Induced Current	X		
Geomagnetic field distortions	X		X
Ionospheric radio interference	X	X	X
Nuclear radiation	X		X
Ozone layer depletion			X
Aurora borealis	X		

Table 1: Solar storm effects (Marusek, 2007).

5 COMPONENT LEVEL CONSEQUENCES

Any grounded component of the power grid can be an injection point of GIC into the system but it is mainly iron core components that are adversely affected by DC flow. Almost all effects of GIC in the power system can be traced back to the saturation of power transformers (Lindahl, 2003), thus transformers are a good starting point for an investigation of risk for the power system.

Some readers might prefer to read Chapter 8 “The likelihood of solar storms” before reading this chapter.

5.1 POWER TRANSFORMERS

The basic principle behind all power transformers is to transfer electric energy from one AC voltage system to another via magnetic energy. This is done by taking advantage of the principles behind Faraday’s law, which states that a time varying magnetic field will induce an electromotive force, much like a voltage.

In its simplest form a transformer consists of two electrical conductors wound around a core of ferromagnetic material such as iron or steel. These two windings, called primary and secondary winding, are electrically insulated from each other and are only connected by the magnetic field in the core material.

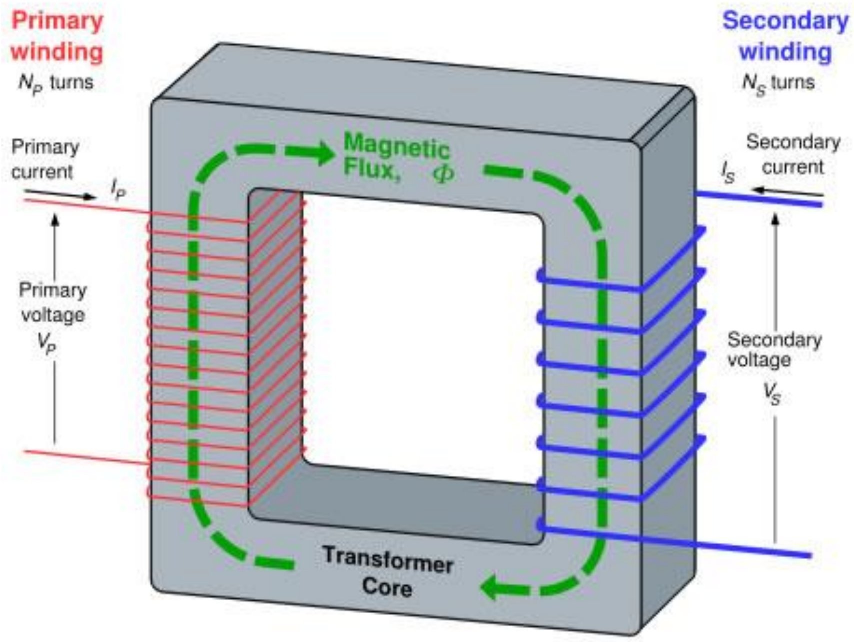

Figure 12: Idealized 1-phase transformer (BillC@Wikipedia, 2007).

Faraday's law of induction states that the electromotive force (emf) is proportional to the rate of change of the magnetic flux. This implies that when a current starts to flow through the primary winding it will induce a change in the magnetic flux in the transformer core which30

in its turn will induce an emf in the secondary winding.

If we take the ideal transformer in Figure 12 as an example, Faraday's law of induction states that

$$for\ primary\ side: V_p = -N_p \frac{d\Phi}{dt} \Leftrightarrow \Phi = -\frac{1}{N_p}\int V_p dt$$

$$for\ secondary\ side: V_s = -N_s \frac{d\Phi}{dt}$$

Equation 3: Faraday's law as applied to a transformer.

where V is the electromotive force, N is the number of windings and $\frac{d\Phi}{dt}$ is the change in magnetic flux(Φ). The magnetic flux is the sum of the magnetic B-field flowing through a cross section of the core. For an ideal transformer $\frac{d\Phi}{dt}$ will be the same at both primary and secondary side (no energy loses) which gives us the simple relation:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \Leftrightarrow V_s = V_p \frac{N_s}{N_p}$$

Equation 4: Transformer equation.

This means that the ratio of windings $\frac{N_s}{N_p}$, called turns ratio, will determine the emf ratio between primary and secondary side.

Simply put this means that an AC on the primary side, with emf V_p, will induce an alternating magnetic flux (Φ) in the core material. This flux will flow through the core and through the windings on the secondary side where it will induce the emf V_s. It is the magnetic flux in the core that may be affected by GIC. To understand this we have to know a little bit more about what happens in the core.

The core material of the transformer is chosen for its high permeability, i.e. its low resistance to magnetic flux. To better understand the concept of permeability (μ) one could make an analogy to conductivity (σ) in electrical conductors, high conductivity means it is easy for the electrical current to flow through the conductor and it is inversely proportional to resistance (R) ($\sigma \sim 1/R$). In the same way one could say that the more conductive a material is to magnetic flux, the higher its permeability. And like conductivity is the inverse of resistance, permeability is inversely proportional to magnetic reluctance ($\mathcal{R}$) ($\mu \sim 1/\mathcal{R}$). The transformer core is in other word designed to provide a path of low magnetic reluctance for the magnetic field much in the same way as an electric conductor is meant to form a low resistive path for an electric current. This analogy can be helpful for the understanding of how a transformer works even though there are important differences between the permeability and conductivity. One very important difference is that the core can become saturated with magnetic flux in a way we do not see in electric conductors (see Figure 13). Once the core has become saturated it cannot hold any higher magnetic field and additional magnetic flux will have to find other paths (e.g. through the air and transformer casing surrounding the transformer). Another important difference is a difference of scale, while the permeability of the core material is in the order of $10^3 - 10^4$ times greater than that of air the difference in conductivity between a conductor and air is in the order of 10^{22}, i.e. air acts as a very effective electric isolator while it does not form an effective barrier for magnetic flux. Leakage flux is quite common in transformers even under normal operation and affects voltage regulation and power losses. GIC risks relating to leakage flux will be discussed in more details further on in this report (see page 32)

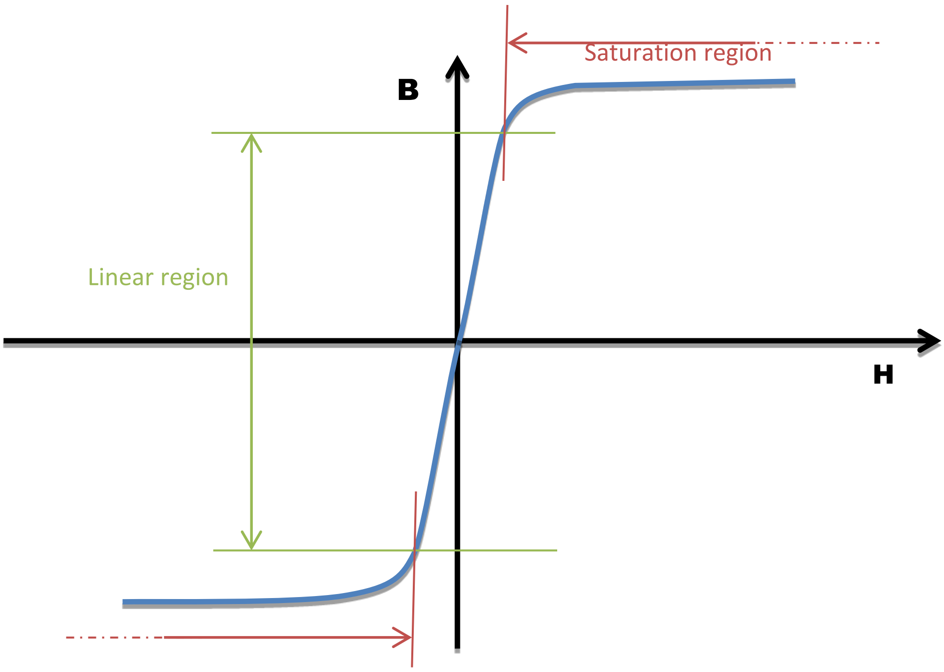

Figure 13: Saturation curve for a transformer core, $B = \mu H$. Here the B- axis can be interpreted as the internal magnetic field (the magnetic flux) in the core and the H-axis can be interpreted as the amount of magnetizing current that will flow through the primary winding needed for the induction of the B-field in the core. In the linear region the permeability (μ) can be considered constant.

Under normal operation a transformer will operate within the linear region below the core material saturation limit (see Figure 13). For reasons of economic efficiency the amount of core material in power transformers is chosen close to the specified operating limit and even under normal conditions the transformer will use the entire linear region up to the saturation threshold. As power transformers are built to operate with alternating current (AC), a direct current (DC) superimposed on the AC, which offsets the BH-curve vertically, will quickly cause the transformer core to saturate. This is in fact exactly what happens when GIC enters into the transformer through the neutral point. The consequences of this will soon be described in more detail, but first a short discussion about saturation of different cores and types of power transformers.

One of the most important findings made since the Hydro-Québec event is that different types of power transformers are affected to different extent. The sensitivity to GIC is very dependent on how the core is designed; it is a question of return paths for the DC induced magnetic flux (see Figure 14). Single phase transformers are more sensitive than three phase transformers. Both single phase transformers and three phase transformers come in many different core designs and they have differences in GIC susceptibility. The two most important types of three phase transformers are three legged and five legged and thus we will limit further discussions to those two.

In Figure 14, the yellow arrows symbolize the induction of magnetic flux from the windings and the smaller white arrows symbolize the possible return paths for GIC induced flux. As can be seen both the single phase transformer and the five legged tree phase transformer have two of the smaller white arrows each, giving an indication that they are more likely to saturate from a DC bias. This is in fact also the case. There will still flow the same amount of GIC through a tree legged transformers as through a five legged but the three legged will not saturate as easily (Rejminger, 1996; Andréasson, 2006; Lindahl, 2003; Fuchs & Masoum, 2008).

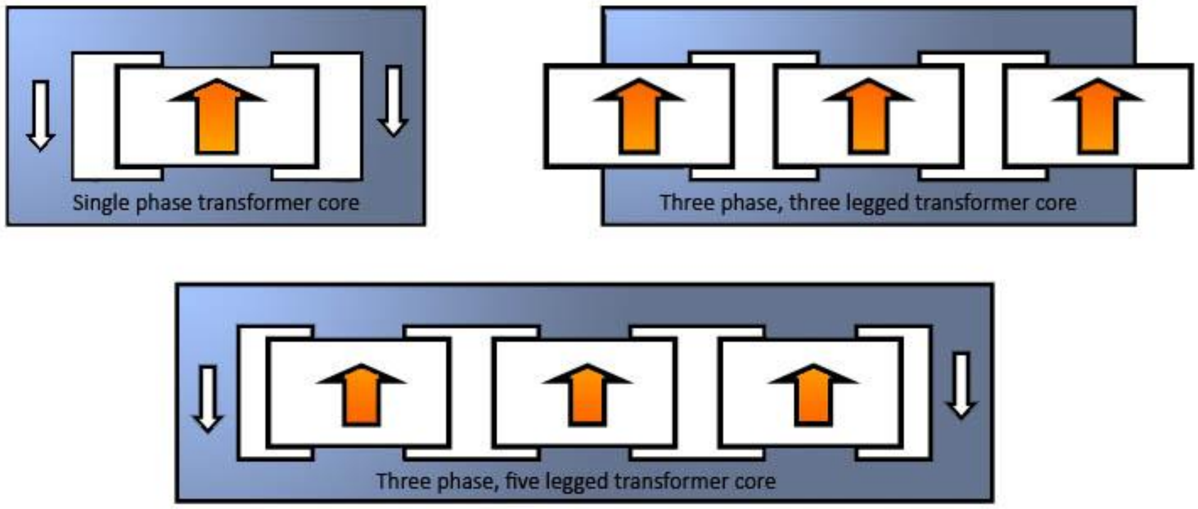

Figure 14: Transformer core types. GIC susceptibility varies between different core types. The presence of low reluctance return paths (white arrows) increases the cores tendency to saturate during GIC induced DC bias.

5.1.1 TRANSFORMER CONSEQUENCES

When GIC starts to flow through a transformer winding it will DC bias the transformer and cause the core to start to saturate (see Figure 15). This saturation will cause: (a) production of both even and odd harmonics, (b) a substantial increase in reactive power consumption and (c) increased heat production and an increase of transformer losses (efficiency declines). The severity of these effects depends on the strength of the geomagnetic disturbance. Here follows a more detailed description of each of these effects and their consequences.

One way of describing what happens when the transformer core reaches saturation is that the permeability of the core drops drastically, which means that the inductance and thus the impedance of the transformer also will drop. As the impedance drops, the magnetization current increases inversely proportional to the drop according to Ohm's law (see Figure 15 and Equation 5). This will lead to a deformation of the AC current sine wave (see Figure 16).

$$I_{magnetization} = \frac{V}{Z(\mu)}$$

Equation 5: Ohm's law.

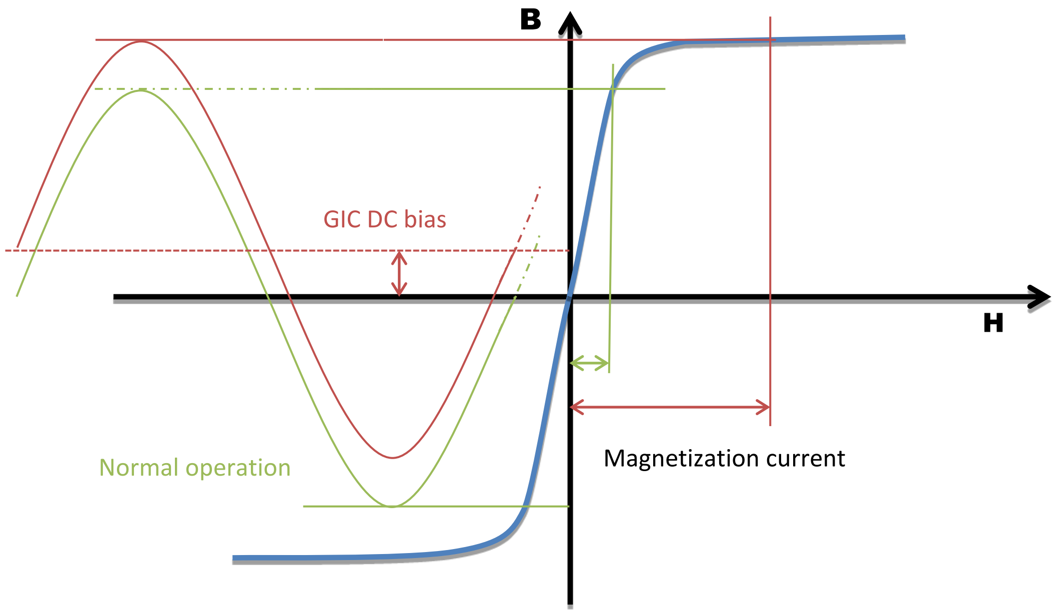

Figure 15: GIC in transformer. The green lines illustrate normal operation and red lines illustrate a situation with a DC bias. As DC bias increases, forcing the core into half cycle saturation, the magnetization current (H-axis) will increase drastically.

5.1.2 HARMONICS GENERATION AND REACTIVE POWER CONSUMPTION

The deformation of the sinusoidal current caused by the increased magnetization current has consequences to the power system. Here follows a short discussion about these.

HARMONICS GENERATION

As the transformer reaches saturation and the magnetization current increases as described above (see Figure 15), the sinusoidal current is severly deformed (see the middle graph in Figure 16). AC power systems are designed for a pure sine wave form of the current, hence deformation of the curve form will lead to a variety of problems. A common way of describing this aspect of power quality is by measuring the harmonic content of the current.

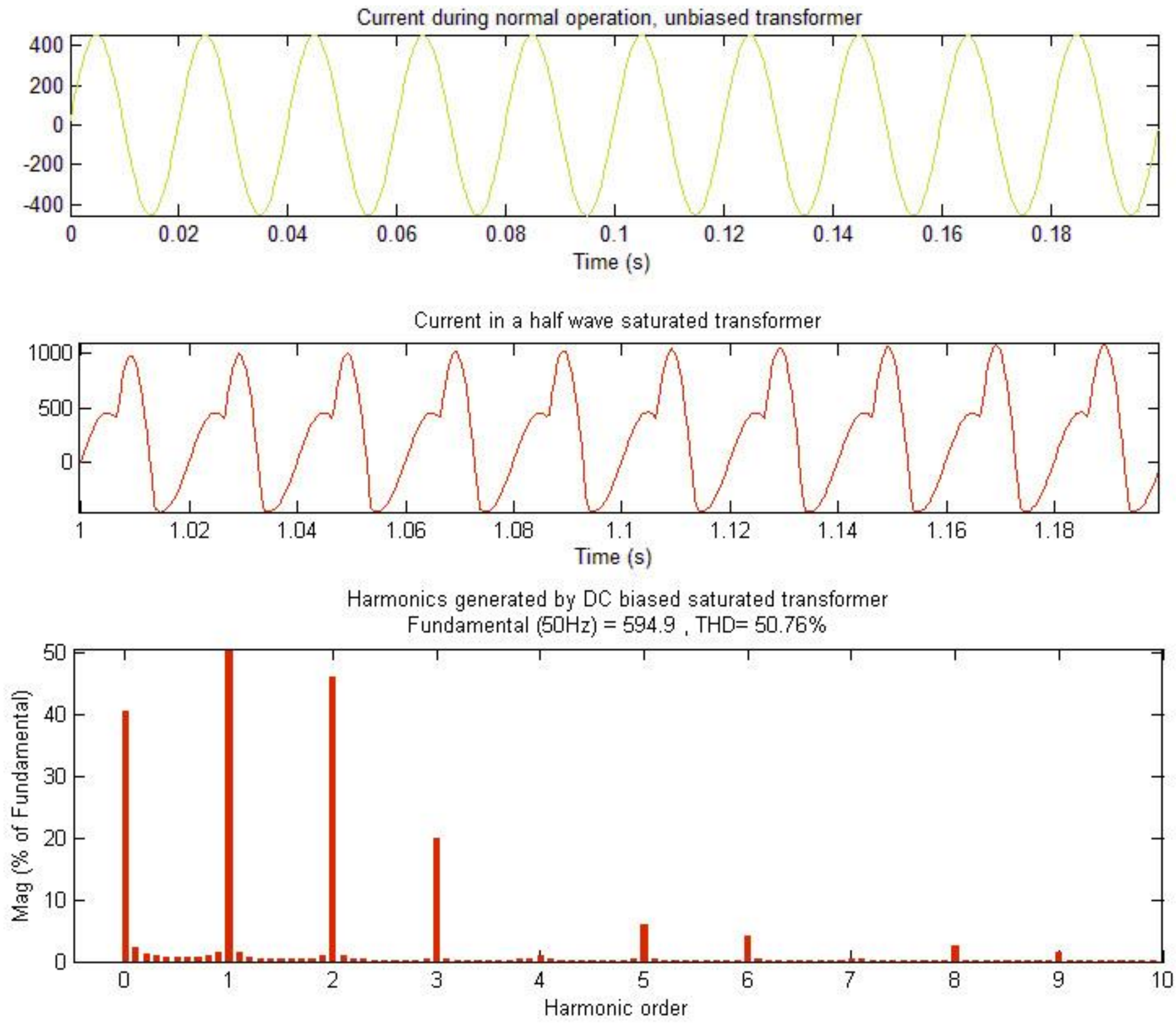

Figure 16: Example of harmonics generation due to GIC (from performed GIC simulation, see Appendix on page 53 for simulation model).
Top: Graph shows current wave form (green) during normal operation.
Mid: Current wave form (red) when the same transformer, as used in top graph, is subjected to dc-bias. Notice the strong deformation due to increased magnetization current.
Bottom: Spectrum showing harmonics contents in the dc biased current shown in the mid diagram. THD, Total Harmonic Distortion is a measurement of the harmonic distortion content.

When subjected to the DC bias of GIC a transformer becomes a rich source of both even and odd harmonics (see the bottom diagram of Figure 16) (Lu et al., 1993; Ma et al., 2010). This has been confirmed by transformer simulations in SimPowerSystems, a module in Simulink and Matlab. This simulation model can provide realistic quantitative data (see Figure 16 and Figure 17) and the model is presented in Appendix.

The increased harmonics contents in the current can lead to a number of problems in the power system, among them:

- Mis-operation of protective relays;
- Overheating of capacitor banks;
- Overloading of harmonic filters of HVDC;
- Increased reactive power consumption;

(Fuchs & Masoum, 2008).

Both the mis-operation of protective relays and increased reactive power consumption will be discussed in more detail below.

REACTIVE POWER CONSUMPTION

Another result of increased magnetisation current is a substantial increase of reactive power consumption (see Figure 17). This can lead to instability in the power system and thus risk of voltage colapse. This has also been shown through the simulations mentioned above.

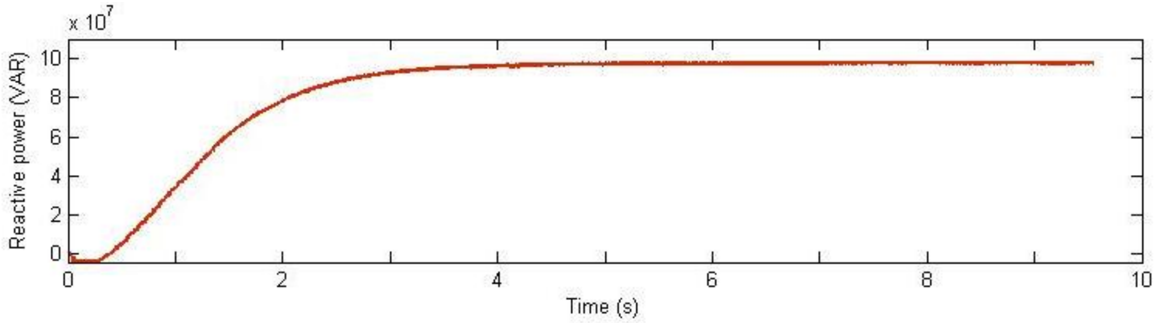

Figure 17: Reactive power consumption in simulated transformer (see Appendix on page 53 for simulation model). At time zero a constant GIC starts to flow through the transformer and the core starts to saturate. Once the core is satureted (about time 4s) the reactive power consumtion remains constant.

5.1.3 HEATING AND CATASTROPHIC FAILURE OF TRANSFORMER

Heating of the transformer is another risk relating to the presence of GIC in the transformer. There are two separate mechanisms that lead to increased heating of a transformer during GIC induced half-wave core saturation. The first relates to heating of the windings and the second relates to magnetic flux leakage.

HEATING OF THE WINDINGS AND FAILURE OF TRANSFORMER

Heating of windings is arguably the greatest GIC related risk as it can lead to catastrophic failure of the transformer. In this event repairs will be difficult, if at all possible, and spare parts or replacement unit can have lead-times exceeding 18 months during normal market-conditions (see Supply risk on page 35).

The current flowing through a transformer winding follows Ohm's law as described in Equation 5. The impedance (Z) of the transformer winding has two components, a resistive and an inductive part where the inductive part is dominant. When the core saturates the inductance drops dramatically and thus the current increases, as discussed above. The increase in current flowing over the resistive part of Z leads to an increased generation of heat in the windings.

$$P_{heat} = I^2 R$$

Equation 6: Heat generation in transformer windings.

If allowed to continue, the increased heat generation in the windings can lead to permanent damage to the windings (see Figure 5) and possibly fire, resulting in a catastrophic failure of the transformer.

HEATING DUE TO MAGNETIC FLUX LEAKAGE

As the transformer core saturates it will no longer provide the induced magnetic flux from the primary winding with a path of low magnetic reluctance. The magnetic flux will find new return paths of relatively low reluctance, such as structural components of the transformer made of ferromagnetic material. As these parts, such as pull rods etc., are not designed to minimize eddy current[7] induction from the leakage flux they will start to heat up. This heating will be localized to high flux regions of the new return paths. This can lead to damage of structural parts, general rise in temperature of the transformer and gassing (gas generation) of the tank oil. A general temperature increase in the transformer oil will also lessen its ability to dissipate heat from the transformer windings making permanent winding damage more likely.

Permanent transformer damage has been documented both from the 1989 storm at the Salem Nuclear Power Plant (see Figure 5 on page 14) in USA and from the “Halloween storm” of 2003 in South Africa. Also during the Halloween storm, a transformer at a Swedish nuclear power plant experienced a 13˚C increase in top oil temperature in a transformer containing 69 tons of oil before mitigating action were taken to allow the transformer to cool down. Gassing in transformer oil and burnt paint on transformers tanks casing are other observed GIC- related incidents (Gaunt & Coetzee, 2007; Baker et al., 2008; Marusek, 2007; H. Swahn, personal communication, September 15, 2011).

CUMULATIVE DAMAGE TO TRANSFORMERS

It is reasonable to assume that there are transformers in operation that have up until now undiscovered GIC related damages that might be more susceptible to further GIC damage. This could hypothetically be due to increased resistance at the site of damage and thus it would be prone to additional heat generation at that site. There are indications that this kind of cumulative effect exists but there is yet not enough data to support this hypothesis.

5.1.4 INCREASE OF TRANSFORMER LOSSES

An overall loss of transformer efficiency has been observed during experiments. The losses seem to depend linearly on GIC, thus in extension on the geomagnetically induced electric- and magnetic-field (Lahtinen & Elovaara, 2002).

5.2 MIS-OPERATION OF PROTECTIVE RELAYS

Mis-operation of protective relays is a common failure mode during geomagnetic storms.

A protective relay is a device meant to disconnect any element of a power system that experiences a fault or operates in an abnormal manner. There are two principal ways a protective relay can be unreliable, they can fail to operate when expected to or they can operate when not expected to. Thus when setting these relays there are two reliability factors to take into consideration, namely dependability and security. Dependability is a measure of the likelihood that the protective relay will operate correctly for all faults that they are expected to operate for. Security is a measure of likelihood that the protective relay will not operate incorrectly for any

[7] Eddy current is circular currents induced in conductors when they are exposed to a changing magnetic field (magnetic flux). In accordance with Ohm’s law this causes heat generation and transformer losses.

fault. These two factors are opposed and finding the right balance between the two can sometimes be hard (Horowitz, 2003).

In this GIC related context it is the security of protective relays that is of most interest, i.e. during geomagnetic storms there is a likelihood of protective relays misinterpreting the harmonics content in the AC and sense false fault conditions. Without going into details about the inner workings of protective relays, one can summarize that protective relays are sensitive to the harmonic content in the current and particularly to the third harmonics of the fundamental frequency. During geomagnetic storms transformers can produce large amounts of harmonics as described above; if this harmonic content is high enough it can cause the protective relay to erroneously sense a fault and trip (T. Johannesson, personal communication, November 22, 2011).

The consequences at system level of incorrect tripping of lines and equipment will be discussed in more detail in the following chapter. When analyzing the consequences at system level due to the mis-operation of protective relays, one should take the possibility of several simultaneous trips into consideration since they are usually set to trip under similar circumstances and a very severe storm can reasonably be expected to cause these circumstances over a large area simultaneously.

Erroneous protective relay tripping is what lead to the power outage in Malmö 2003 and also played a key role in the events that led to the province wide power outage in Québec 1989 (Malmgren, 2003; Hydro-Québec, n.d.).

6 CONSEQUENCES AT SYSTEM LEVEL

Depending on the severity of a geomagnetic disturbance, the consequences at power systems component level, detailed in the previous chapter, can have a series of consequences at the system level, ranging from no system impact at all to widespread voltage collapse significantly disrupting critical infrastructure.

6.1 LOCAL POWER OUTAGE

The power system has several different voltage levels where the highest voltage systems are used for long distance transmission of electricity. The lower voltage levels are used for distribution to consumers. The highest voltage levels, in Sweden 400kV and 130kV, are set up in a mesh configuration while the lower voltage levels, 50kV and lower in the Swedish power system, are set up in a radial configuration, much like a tree with stem and branches. The mesh configuration provides redundancy, and if a protective relay trips a single line in the transmission system this would normally not cause a power outage, but it would increase the strain on the remainder of the system. If the protective relay on the other hand disconnects a part of a radial distribution system, then any point downstream from the tripped relay would be temporarily out of power until that relay has been reset. This is exactly what happened in Malmö on October 30th 2003 when 50 000 customers where disconnected (Malmgren, 2003, T. Johannesson, personal communication, November 22, 2011).

This loss of power consumption could be expected to have a strengthening effect on the rest of the system, since a severe geomagnetic storm will strain the power system due to increased transformer losses, increased reactive power demand and the possible loss of production or import, etc.

Local power outage could also have damaged transformers as root cause and in that case it could take a substantial time to return the system to normal operation downstream of that point.

6.2 LOSS OF PRODUCTION

A power production unit or import/export unit is connected to the distribution system at a single point, and if a protective relay trips a line or disconnects a transformer at that point then all of that production is temporarily lost. Short term this increases the strain on the power system and can be part of a chain of events that leads to voltage collapse. This is part of the course of events that led to voltage collapse in Québec 1989.

If the disconnection is due to damaged equipment this can be a long term issue and substantial values can be lost in addition to repair cost.

Thus it can sometimes be a rational mitigation strategy to temporarily decrease load or disconnect transformers, at danger of permanent damage, during GIC events (H. Swahn, personal communication, September 15, 2011).

6.3 VOLTAGE COLLAPSE

High load in the transmission system can cause a variety of problems, voltage regulation is one among them.

During geomagnetic storms reactive power consumption in transformers will increase radically leading to an increased strain on the power system. This can by itself lead to a voltage collapse especially during periods of high consumption and high utilization of transmission capacity such as during cold periods. Unfortunately the reactive power consumption covariates with harmonics production, heating of transformers and other GIC related risks (see Chapter 5) which can lead to situations where production and transmission capacity are lost which drastically can increase the likelihood of a system wide voltage collapse. This is what happened 1989 during the Hydro-Québec event (see Chapter 3.2).

Simulations performed by Svenska Kraftnät in 2003 (Kielén, 2004) concluded that the Swedish transmission system, at that time, would normally have the capacity to handle the increased reactive power consumption during a geomagnetic storm as long as the system was intact. They also concluded that the following situations could lead to an increased risk of voltage collapse:

- High consumption;
- High transmission, with one or more generators, transmission lines, transformers or shunt capacitor banks out of service;
- Extreme geoelectric field amplitudes $\left(|\boldsymbol{E}| \geq 20\frac{V}{km}\right)$.

Unfortunately it is likely that the system will not be intact during extreme storms such as a 100-year storm. To further investigate the consequences of extreme GIC levels on the power system system-wide simulations needs to be performed. These simulations needs to that take both component and system effects into account, in order to simulate the covariance and interdependencies factors of GIC in the power system.

A selective shutdown of parts of the net is a possible but not very attractive mitigation strategy during severe geomagnetic storms.

6.4 SUPPLY RISK

Transformers and transformer spare parts can have lead-times in the range of one to two years under normal market conditions. It is reasonable to assume that geomagnetic storms strong enough to damage a transformer to the extent that it needs repair or replacement could also have damaged other transformers, this increased demand for spare parts or replacement units could create a worldwide shortage of transformer production capability.

7 CONSEQUENCE FOR OTHER TYPES OF SYSTEMS

Due to increased interconnectedness and interdependencies, the effects of solar storms on other types of systems can have direct or indirect consequences for the power supply system. In this chapter the consequences for communication and control systems will be discussed followed by a discussion about how pipelines are affected.

7.1 COMMUNICATIONS AND CONTROL SYSTEMS

Communication systems today are quite complex and their different parts are subject to certain solar storm related risks.

Today much of communication infrastructures for critical infrastructures are based on optical fibers which are not directly susceptible to GIC. However, there is still a substantial part of communications routed through copper wire and thus susceptible to GIC, which could lead to both temporary disruption of service and permanent damage to equipment. Signal repeaters have been known to fail due to GIC, and thus even optical fiber systems are not immune (Medford et al., 1989). This is true for telecommunications and other communications systems such as those used for monitoring and control of power systems and train signaling (see Appendix for a case study of disturbance of train-signaling in southern Sweden). There are many other GIC related incidents for communication systems, the trans-Atlantic cable between Newfoundland and Scotland February 1958 being the best known (Pulkkinen, 2003).

Satellites and spacecrafts are especially sensitive to disturbed space weather since they cannot take advantage of the protection from Earth's magnetosphere. There is both a likelihood of equipment damage to the satellites and a likelihood of disruption of their communication due to disturbances in the ionosphere. The latter is particularly true for communication satellites and GPS signaling (Baker et al., 2008). Furthermore the amount of radio interference increases markedly due to the above mentioned ionospheric disturbances. Disruption of communication can range from induced noise to complete signal loss. Shortwave radio is especially afflicted by these disturbances.

The communication systems are also dependent on power supply to run and battery backups will start to run out after 15 minutes without power in the Swedish 3G system (E. Andersson MSB, personal communication, November 16, 2011).

Today there are many systems relying on GPS navigation and timing signals to sequence and control processes. These systems can be directly or indirectly affected. The use of GPS in this context can often be unknown to the operator and thus this risk is in danger of not being identified until after an event.

Short term this can complicate control and repair of power systems as well as any other function relying on communication during and after a severe solar storm. Long term it could cause problems for any control system without redundancy that relies on a single form of communication, especially if this system relies on a single satellite to function.

7.1.1 AIR TRAFFIC

Air traffic will likely suffer delays due to rerouting and possibly cancelation of flights, especially intercontinental flights routed over the northern polar regions due to increased radiation at high altitudes there, and due to communication and navigation interference (see above and Chapter 3.3).

7.2 CORROSION ON GAS PIPELINES

As mentioned above GIC flows through all long conducting structures. The cathodic protection of pipelines can temporarily be rendered inoperative during disturbed space weather resulting in increased corrosion rate of the pipeline.

To counter the corrosive environment of the earth in which the pipe is buried a combination of insulating coating and cathodic protection (CP) are often used. The pipe is made the cathode of an electrochemical cell either by attaching a sacrificial cathode (galvanic CP) or by applying a negative pipe-to-earth voltage of about 1V (impressed current CP/ active CP). Due to the size of pipeline structures active cathodic protection is routinely used in combination with coating of mechanically protective polyethylene insulation (Edwall & Boteler, 2001).

When a geoelectric field acts on a pipeline, GIC starts flowing in the pipeline. This would not be a problem if the GIC only flowed in the pipe, but due to inhomogeneities of the pipeline and surrounding earth GIC can flow from the pipe to the surrounding earth, especially near ends or bends of the pipeline. This can easily result in pipe-to-soil voltages of a few volts which is several times greater than that of the active cathodic protection (-1.0 V) and thus GIC can temporarily make the active CP inoperative and possibly also contribute to corrosion of the pipeline (Pirjola, 1999; Gummow et al., 2002). The increase in corrosion rate has proven to be hard to quantify.

During geomagnetic storms there is a high probability of increase in the corrosion rate of pipelines. It has been estimated that the active cathodic protection could be inoperative in the order of two weeks on a yearly basis during periods of high solar activity (H-E Edwall, personal communication, June 22, 2011).

The conductivity through the insulating coating of the pipe varies linearly with the length of the pipe. Also the voltage difference for the endpoints of the pipe is linearly length dependent. According to Ohm’s law a 50% reduction of the length of conducting pipe will thus lead to 75% reduction of GIC (see Equation 7). This is of course quite simplistic but helps to understand the mechanism.

$$Ohm´s\ law\ I = \frac{V}{R}$$

$$The\ voltage\ dependence\ on\ length\ V \sim l \cdot \mathbf{E}$$

$$The\ resistans\ dependence\ on\ length\ R \sim \frac{1}{l\sigma}$$

$$The\ above\ eqations\ combined\ gives\ us:$$

$$I \sim l^2$$

Equation 7: GIC in pipelines as a function of length.

Thus an electric sectioning of the pipe with the use of insulating joints can drastically decrease the influence of GIC on pipelines.

The Swedish gas-pipelines, including E.ON owned parts, are already today sectioned off with insulating joints and the longest section is less than 50km (H-E Edwall, personal communication, June 22, 2011).

8 THE LIKELIHOOD OF SOLAR STORMS

Geomagnetic storms are fairly uncommon phenomena, and when they occur it is only some of the strongest that have any consequence for power systems. Most geomagnetic storms will go unnoticed since they do not have any observable properties except for auroras and some increase in radio noise. Thus the majority of people will not have any intuitions about the frequency of solar storms of different strengths. Only the strongest geomagnetic storms pose a threat to power systems, but once part of a system is affected by a solar storm the effects can quickly cascade through the power system and give rise to large scale consequences.

The likelihood of solar storms does not follow a uniform probability distribution curve but rater it varies with the solar cycle. This is especially true for coronal mass ejections, which are the main source of risk for power systems. As mentioned previously the likelihood of a CME is roughly 15 times greater during solar maxima compared to solar minima (page 19). 1 to 15 is also roughly the difference in sunspot activity between solar minimum and maximum (see Figure 18). It is not an unreasonable approximation that the likelihood of a CME has a roughly linear relation with the number of sunspots.

In Figure 18, GIC related incidents in Swedish technological systems are plotted over a sunspot activity graph, giving a picture of the frequency of storms strong enough to generate disturbances. The plotted events are limited to documented events known to the author and it is likely that several relevant events have been left out, which could explain the apparent calm during the sixties and seventies.

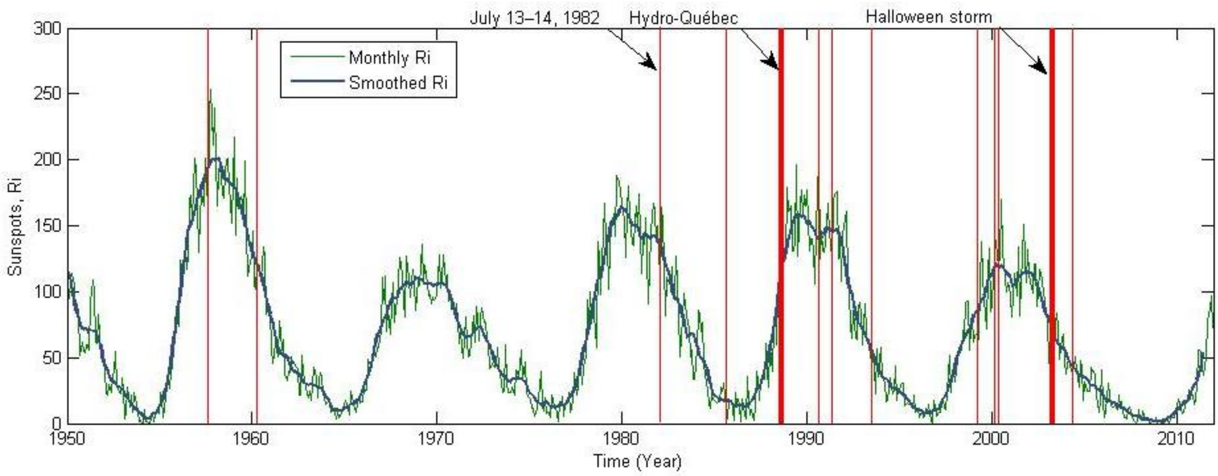

Figure 18: Documented GIC events (red vertical lines) in Sweden overlaid on a solar activity digram. The Hydro-Québec event (wich also had effect in Sweden) and the Halloween storm are marked with thick lines. A short case study of the events of July 13-14 1982 is available in the Appendix. A list of the all the marked events is also availible in the Appendix (solar activity data courtesy of SIDC (SIDC-team, 2012)).

8.1 100-YEAR EXTREME GIC EVENT

There are several difficulties in estimating reasonable values for 100-year extreme GIC events. There are many variables that influences the likelihood of high values of the geoelectric field (see Geomagnetically induced currents on page 21). To come up with a useful 100-year GIC event scenario one will have to make generalizations and make allowances for variation in the geographic location, i.e. take geomagnetic latitude and ground conductivity into account. It is practical to build such a scenario around geoelectric field strength since it has a linear relationship with GIC (see Equation 2).

Recent statistical analysis of geomagnetic data shows that a 100-year storm would have 10 s geoelectrical field peak values around 20 V/km in an area with low ground conductivity and high geomagnetic latitude, such as the Québec area in Canada (Pulkkinen et al., 2012). Very simplified one could set up the following relationship between the geoelectrical field strength, ground conductivity and geomagnetic latitude.

$$\boldsymbol{E} = c(Z) * d(\varphi) * \boldsymbol{E}_{base}$$

Equation 8: This equation shows the relation between geographical factors and the geoelectric field.

Here $c(Z)$ is a ground conductivity factor typically in the range of 1-4, 1 for high conductivity and 4 for low conductivity, $d(\varphi)$is a geomagnetic latitude factor typically in the range of 1-10, 1 for sub 40° geomagnetic latitude and 10 for super 60° geomagnetic latitude (Pulkkinen et al., 2012). For the 100-year storm scenario $\boldsymbol{E}_{base}$ would have a 10 s peak value of 0.5 V/km and represent the geoelectric field at a sub 40° geomagnetic latitude area with high ground conductivity.

8.2 LIKELIHOOD OF EXTREME EVENTS

The concept of a 100-year storm normally implies a uniform probability distribution, i.e. the probability of occurrence is the same from one year to another. Assuming this we get the following expression for the probability of at least one 100-year storm:

$$P = 1 - \left(1 - \frac{1}{T}\right)^n \Leftrightarrow P = 1 - \prod_{i=1}^{n} \left(1 - \frac{1}{T}\right)$$

Equation 9: The exceedance probability of T-year extreme event.

where *T* is the storm threshold (100 year in our case) and *n* is the number of years we are interested in. One can calculate that the probability of at least one 100-year extreme event occurring during any one given year (*T*=100, *n*=1) would be 1%, and the probability of at least one 100-year event over a period of 11 year (*T*=100, *n*=11) is 10.5%. Since the probability of solar storms occurrence are not a uniform probability distribution Equation 9 only holds true when *n* is a full multiple of a 11-year cycle ($n = i * 11, i \in \mathbb{Z}$).

Thus one needs to take solar activity into account if one is interested in the exceedance probability for a period shorter than one solar cycle. As stated above one can approximate a linear relationship between the probability of a CME and the sunspot index. In the interest of finding a rough method of calculating the probability of solar storms one could make the following additional assumptions; (a) that all CME stands an equal chance of travelling earthwards, (b) that the CME giving rise to an extreme GIC event can erupt at any time during the solar cycle, (c) that the peak value of the geoelectric field will be caused by a single CME. Having made these assumptions one could add a solar activity factor $\frac{R_i}{\bar{R}}$ to Equation 9 and get the following expression for exceedance probability:

$$P = 1 - \prod_{i=1}^{n} \left(1 - \frac{R_i}{\bar{R}} \frac{1}{T}\right)$$

Equation 10: Solar activity corrected exceedance probability of *T*-year extrem solar storm.

where R_i is the sunspot numbers of year i and $\bar{R}$ is the mean sunspot number. Even if the assumptions above is a simplification and not entirely true Equation 10 gives us a better tool to estimate probability than the uniform distribution assumption of Equation 9. The value of $\bar{R}$ will have a significant impact on the calculated probability and thus it is important to carefully consider the data set that is used.

To calculate $\bar{R}$ (over full cycles, i.e. between two minimum) one could for example, either choose (a) the period for the data that the calculation of the 100-year peak value is based on, see above (1993-2006), (b) a period dating back to the Carrington event 1859 or (c) a period dating back to the start of reliable sunspot data records (i.e. back to the oldest minimum April 1754), see Figure 7.

Alternative	Period	Mean value $\bar{R}$
a	March 1996 to November 2008	64
b	December 1855 to November 2008	56
c	April 1754 to November 2008	52

Table 2: Sunspot mean values. Data used is monthly smoothed sunspot numbers (SIDC-team, 2012).

Alternative (a) only includes one solar cycle and even though the 100-year extreme value data is gathered during this period, earlier data have been taken into account in its validation. Alternative (b) stretches over 15 cycles and covers almost all available GIC data and should give a better estimate of sunspot mean value, than alternative (a). Alternative (c) covers 23 cycles and should provide an even better estimate of mean value but since we do not have any reliable solar storm data prior to the period around the Carrington event this mean value does not have as good correlation to the data set used for estimating the 100-year extreme events as (a) and (b). Thus alternative (b) $\bar{R} = 56$ seems to be the most reasonable value to use.

Since good prediction of sunspot numbers is only available a couple of years ahead and since Equation 10 is a rough estimate any probability estimate for longer periods is probably best done in terms of full cycles.

If one is interested in estimating the exceedance probability of other field strengths than the 100-year extreme one can use Equation 10 and insert values from Table 3 or by getting data from Figure 2 in “Statistics of extreme geomagnetically induced current events” paper (Pulkkinen et al., 2008).

T (*T*-year extreme event)	10 s peak value $\|\boldsymbol{E}_{Base}\|$ (see Equation 10)	10 s peak value $\|\boldsymbol{E}_{high\ lat,low\ \sigma}\|$
100	0.50 V/km	20 V/km
11 (one cycle)	0.32 V/km	13 V/km

Table 3: Table of geoelectric field values for statistical extreme events (Pulkkinen et al., 2008).

Now using this data and the estimation of cycle 24 (see Figure 8) one can now estimate the probability of a 100-year storm during 2013 to 1.7% and for the period 2012-2014 the corresponding probability is 4.7%. The probability of a 11-year extreme event during the period 2012-2014 is 41%.

9 RISK TREATMENT

The main focus of this report is risk analysis and not risk treatment. Thus it will not discuss risk treatment methodology and only briefly touch upon different possible risk treatment alternatives.

9.1 SPACE WEATHER FORECASTING

It is important to accurately predict solar storms in order to be prepared to implement mitigating actions in a timely manner and minimize the economic impact for both the society and the owners of affected infrastructure. There are a lot of very interesting ongoing research in this area and the prognostication capabilities are likely to increase in the future.

Today there is a worldwide network of 13 regional warning centers[8] (RWC) dedicated to provide forecasts and warnings of disturbances to the solar terrestrial environment which is organized by the International Space Environmental Service (ISES). The current forecasting capabilities allows for predictions of solar activity up to a month in advance, but it does not provide information about the exact time of the expected disturbance or if a CME will travel earthwards. A CME will be detected at the moment of eruption, but it will take longer before its travel path and other attributes can be determined and one can predict if it will affect Earth and its severity. With the aid of the ACE and SOHO spacecraft among others, located at the L1[9] point between the Earth and the sun, it is possible to receive up to half an hour of advance warning before a CME hits Earth.

Solar shield is a collaborative project between NASA, Catholic University of America (CUA) and the Electric Power Research Institute (EPRI) aimed at forecasting space weather effects on power transmission systems. The project shows great potential for forecasting GIC in power systems (Pulkkinen et al., 2010).

9.2 POSSIBLE RISK TREATMENT STRATEGIES

There are many viable risk treatment alternatives for GIC related risk.

TRANSFORMER RISK TREATMENT

There are several technical solutions for stopping GIC from flowing through transformers and thus drastically decreasing the risk for a single or a group of transformers and in extension also lessening the system related risks (Metatech, 2010; Andréasson, 2006; H. Swahn, personal communication, June 20, 2011).

- GIC blocking devices:
    - Neutral blocking device (insulation strength of winding neutral);
    - Series capacitors compensation of transmission lines;
    - Neutral capacitor blocking device;
    - Impedance grounding through resistor or reactor;
    - Polarization cells with electrolyte or solid state;
    - Active cancelation through auxiliary winding.
- Real-time measuring and alerts of GIC through transformer neutral and transformer temperatures.
- Active cooling of transformers to increase thermal convection.
- Temporary disconnection of transformers operating close to sustaining permanent damage.

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[8] One of these regional warning centers is located in Lund, Sweden.

[9] The L1 libration point which is a point of Earth-Sun gravitational equilibrium, about 1.5 million km from Earth and 148.5 million km from the Sun.

PROTECTIVE RELAY RISK TREATMENT

One of the most important lessons learned from both the Hydro-Québec event in 1989 and the blackout in Malmö during the Halloween storm in 2003 was the importance of the setting of correct trip levels to avoid unwarranted trips due to GIC generated harmonics. A review of existing relay settings and revision of guidelines relating to protective relays with GIC in mind have proven to be one of the most cost effective ways to lessen system wide GIC related risk (Malmgren, 2003; Hydro-Québec, n.d.).

SYSTEM LEVEL RISK TREATMENT

- Perform simulation of power system to: (a) find high risk transformers, (b) identify acceptable threshold levels for $\boldsymbol{E}$-field, $\boldsymbol{B}$-field and GIC, and (c) to calculate system wide reactive power consumption.
- Take GIC into account when defining new transformer specifications.
- Implementation of voltage collapse avoidance and mitigation strategies such as selective shutdown of parts of the net to lower the consumption and increase stability in the system.
- GIC related education of relevant operations personal.
- Continuity planning for GIC related risks.

COMMUNICATION RISK TREATMENT

- Beforehand analyze communication needs during and after storm to gain a better understanding of risk exposure.
- Implement communication and control backup systems where needed.
- Investigate control systems´ GPS (navigation and timing) dependency to identify potential risks.

10 SUMMARY

Solar storms have many things in common with other kinds of natural phenomena such as storms, earthquakes and tsunamis. They are all risks that have the potential for disaster if not properly managed. But while man has had thousands of years of experience of the very tangible effects of the latter three examples and time to develop risk treatment strategies, solar storms are abstract and its effects are next to invisible unless you know what to look for. We cannot trust our intuition to guide us when assessing solar storm risk and the need for a structured risk management process is important for a rational response. The benefits of a structured risk management method is substantial for all low frequency /high impact risks, but for solar storms it is indispensible since there is no other mechanism in an organization or in society at large that will prompt mitigating actions.

GIC and geomagnetic storms is the result of a very complex chain of events, originating from magnetic energy buildup in the interior of the sun. This energy is transferred through interplanetary space, the magnetosphere, the ionosphere, the ground to finally end up as a quasi-DC current flowing through transformers in the power system. Since transformers are not normally designed to handle DC current flowing through the neutral point this causes problems. It causes the transformer core to saturate which in its turn causes several additional undesirable phenomena. It is this saturation of the transformer core that is the source of all primary risks to the power system.

Disturbance in the space weather is a fairly uncommon phenomenon and furthermore the Swedish power system is thought to be robust enough to handle even quite severe space weather without catastrophic failures. Even so solar storms are a very real and physical threat that have the potential to cause substantial damage both to the power system and to other critical infrastructures. If not properly handled the socioeconomic consequences can be severe. The major consequences to the power system are local or nationwide power outages, catastrophic failure of transformers and long term loss of production.

Even though prognostication of space weather is possible today, the high complexity of these phenomena will limit the amount of information that will be available ahead of time.

SUMMARY OF RISK FACTORS FOR TRANSFORMERS

Geographical factors

- High latitudes;
- High ground resistivity.

Geometric factors

- Long transmission lines;
- Corners in power systems.

Equipment factors

- 1-phase transformers are more sensitive than 3-phase;
- For 3-phase transformers, 5 legged are more sensitive than 3 legged.

SUMMARY OF RISK FACTORS FOR THE POWER SYSTEM

- High consumption;
- High transmission, with one or more generators, transmission lines, transformers or shunt capacitor banks out of service;
- Extreme geoelectric field amplitudes $\left(|\boldsymbol{E}| \geq 20\,\frac{V}{km}\right)$.

11 CONCLUSIONS

This report has given an overview of, the source, likelihood, and possible consequences of solar storm events that are strong enough to results in extreme GIC levels in the power systems, in short the necessary parts of a risk analysis. This is the first time this has been done in a structured way with risk management methodology, to the knowledge of the author, and as such it should add value and facilitate GIC related risk management for power systems.

11.1 A GUIDE TO RISK EVALUATION OF SOLAR STORMS

A risk value is often defined as the product of consequence and probability of occurrence. The goal of this report is in part to enable the reader to calculate a quantitative risk value for GIC risk scenarios, by aiding in consequence assessments, and to enable a reasonable estimation of probability of occurrence.

If one for example is planning the installation of a new transformer, with an expected lifetime of 50 years, the probability for a 100-year extreme event to occur during its lifetime is somewhere in the range of 36-42%[10], depending on when, during the solar cycle, it is planned to be installed. It is harder to make general statements of quantitative consequence values since it will vary greatly from transformer to transformer, partly due to the transformer risk factors (listed on page 43) and partly due to other factors such as where it is installed, the value of the equipment, value of lost production, value of lost distribution, availability of replacement units, and other risk scenario specific details.

Due to the comparatively greater complexity of a system compared to its components it will necessarily be a more complex task to estimate risk values for the system. On a system level it is important to take the interdependencies of the different risks detailed in this report into account. Previous studies of the Swedish power systems GIC susceptibility have not taken this into account which to some extent reduces their value for risk evaluation at system level. Thus it is recommended that simulations on system level that can take these interdependencies into account be performed in order to achieve an accurate risk evaluation.

Due to the long implementation times for many of the risk treatments mentioned in Chapter 9 it can be advisable to take these mitigating actions under consideration well ahead of solar maxima. During times of high solar activity and increased likelihood of geomagnetic storms, time restrictions will lessen the freedom of actions and in extension opportunity for risk treatment. It is also worth pointing out that severe space weather is not limited to solar maxima, disturbances may also occur during solar minima. There are no safe periods, only relatively safer ones.

11.2 INTERDEPENDENCY, COVARIANCE AND UNCERTAINTY

Society's infrastructure is increasingly complex with ever growing levels of dependencies and interdependencies. This growing complexity in combination with early adaptation of new technology complicates any attempt to understand the full socioeconomic impact of severe space weather. A solar storm severe enough to damage the power distribution system will likely have a wide array of consequences also for other types of infrastructures, many of which have not been discussed in this report. In other words there will likely be a covariance between solar storm related failures both on component and system level, i.e. several failures will occur in close temporal proximity.

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[10] 36% is the exceedance probability for a 100-year extreme storm over 4 cycles (approximately 44 years) and 42% is the corresponding value for 5 cycles (approximately 55 years), see Chapter 8.

The history of solar storms are likely as old as the solar system, but our first experience of the consequences they can give rise to is limited to only a century and a half and our accumulated data and knowledge of the Sun is far from enough to truly understand all the consequences of the phenomena.

Both the complexity of society and our lack of knowledge of solar storms contribute to the uncertainty factor and thus increase the risk. The suggested further studied as mentioned in below would therefore potentially decrease the GIC related risk for both power systems and for society.

11.3 SUGGESTIONS FOR FURTHER STUDIES

This research has brought up some issues that need further investigation in order to increase the understanding of the risk of geomagnetically induced currents in power systems. These items are not listed in any prioritized order.

Simulation of GIC in the power system. There have been some simulations performed on the Swedish power systems (Kielén, 2004; Wik, 2008) but these have been based on a single aspect of geomagnetic storm risk (reactive power and GIC, respectively) and they have not taken the full system dynamics and interdependencies of harmonics production, reactive power consumption and transformer damage into account. The power system has also changed since these simulations were made and new changes are planned. These changes have not been taken into consideration in previous simulations.

Development of better **simulation models of different transformer core types** for use in above simulations and for use in transformer risk evaluation. The currently available simulation models have not been developed with GIC generation in mind, thus better transformer models would better approximate differences in GIC response.

Further **statistical analysis of geomagnetic storms** with respect to strength, duration and frequency of occurrence would lessen the uncertainty factor and increase the accuracy of probability predictions, which would lead to more accurate risk evaluation.

Documentation of **new knowledge of transformer design principles** to decrease GIC risk during transformer planning and production. Development of suitable transformer specification requirements with respect to GIC.

Further studies into the **effect of GIC in HVDC systems**.

11.4 FINAL WORDS

Going back to the question of how well we are equipped to handle severe space weather, the answer will unfortunately not be a straightforward one. The Swedish power system is fairly well equipped to handle storms of strengths similar to those that we have come to expect during the last couple of decades. However, the same cannot be said for a once in a hundred year storm or stronger without further analysis of the power system. Thus it is the consequences of these the very strongest storms that need to be further studied. This should not be taken to mean, that storms of lesser strengths does not pose a threat on component level. Transformers with high risk values should not be overlooked during risk assessment.

Due to the low frequency high impact nature of severe solar storm related risk it is of importance to consider this risk thoroughly and on a regular basis, failing to do so will not make the risk go away.

As our knowledge of geomagnetic storm risks increases, so does our opportunities to implement effective risk management solutions.

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APPENDIX

ADDITIONAL CASE STUDY

SOUTHERN SWEDEN, JULY 13 AND 14, 1982

In the night between July 13 and 14, 1982, the traffic lights turned red for a railway section without any obvious reason. The railway section was about 45 km in length and situated in the southern part of Sweden. After a while the lights turned green and later red again. The reason was that the geoelectric field affected the relays. In normal conditions there is a DC voltage of 2.5 to 6 V over the relays, which drives a current pulling the relay when the rails are free of trains. When a train comes there will be a short-circuit and the relay switches. In the night between July 13 and 14, a negative voltage was induced that was opposite to the abovementioned voltage of 2.5-6 V. The relay reacted as if the rails were blocked and caused the traffic lights to turn red. When the induced voltage became positive the lights turned green again (Wik, 2008).

GIC EVENTS IN SWEDEN

(Boteler, et.al, 1998; Wik, 2008; Messing, 1986; Messing, 1994; Malmgren, 2003)

DATE	EFFECTS
Sept 2, 1859	Problems with the telegraph system in Gothenburg.
May 13–15, 1921	Fires in telegraph equipment.
Feb 11, 1958	Fires with severe damage in telegraph equipment.
Nov 13, 1960	30 line circuit breakers tripped in the high-voltage power network.
July 13–14, 1982	4 transformers and 15 lines tripped in the high-voltage power system. Railway traffic lights turned erroneously to red. Telecommunications were also affected.
Feb 8–9, 1986	5 events in the high-voltage power system, 1-3 lines tripped per event.
March 13–14, 1989	5, 130 kV, lines tripped, 5-degree temperature increase in a generator.
March 24, 1991	9, 220 kV, lines and a transformer tripped.
Nov 9, 1991	1, 220 kV, line tripped. Large pipe-to-soil voltages in a pipeline.
Feb 21, 94	2, 130 kV, lines tripped.
1999	Radio communication for protection lost in the power system.
2000	Voltage drop in the 400 kV system.
April 6, 2000	Largest ever GIC measured in a transformer (about 300 A).
Oct 30, 2003	Power blackout in Malmö, excess heating in a transformer.
Nov 8, 2004	GIC of over 100 A measured in a transformer in southern Sweden.

A MORE DETAILED LIST OF EVENTS IN SWEDEN DURING THE "HALLOWEEN STORM" OF 2003

(Kielén, 2004)

DATE	EFFECTS
2003-10-29 07:11:42	220 kV line from the power station in Härjedalen tripped, resulting in 140 MW of production stopped.
2003-10-29 07:12:29	130 kV line in Östergötland tripped. The same line trips again at 08:04:10.
2003-10-29 07:46	400 kV line from SwePol Link at Karlshamn tripped. Import from Poland on 300 MW disrupted.
2003-10-30 20:55	400/220 kV transformer in the vicinity of Östersund tripped.
2003-10-30 21:03:43	400/130 kV transformer in Örebro tripped. Overload in 130 kV net.
2003-10-30 21:03:44	130/10 kV transformer in the vicinity of Norrköping tripped.
2003-10-30 21:07:15	130 kV line in Malmö tripped. 50 000 customer without electricity in between 20 and 50 minutes.
2003-10-30 21:08:00	130 kV line from Örebro in the southwest direction tripped.
2003-10-30 21:08:32	130 kV line close to Boden tripped.
2003-11-20 18:04	400 kV line from SwePol Link at Karlshamn tripped. Import from Poland off 400 MW disrupted.

TRANSFORMER SIMULATION MODEL

Matlab and Simulink module SimPowerSystems was used to simulate the effects of GIC for this thesis. The model in Figure 19 was used for Figure 16 and Figure 17. This model simulates the effects of GIC flowing through a transformer. GIC is injected to the system through the controlled voltage sources and exits through the neutral points of the transformer. THD is measured in the THD block and reactive power consumption is measured through a PQ block. Here the ramp block has been used as a convenient way of providing the controlled voltage sources with input. Scopes were used to study various outputs from the model.

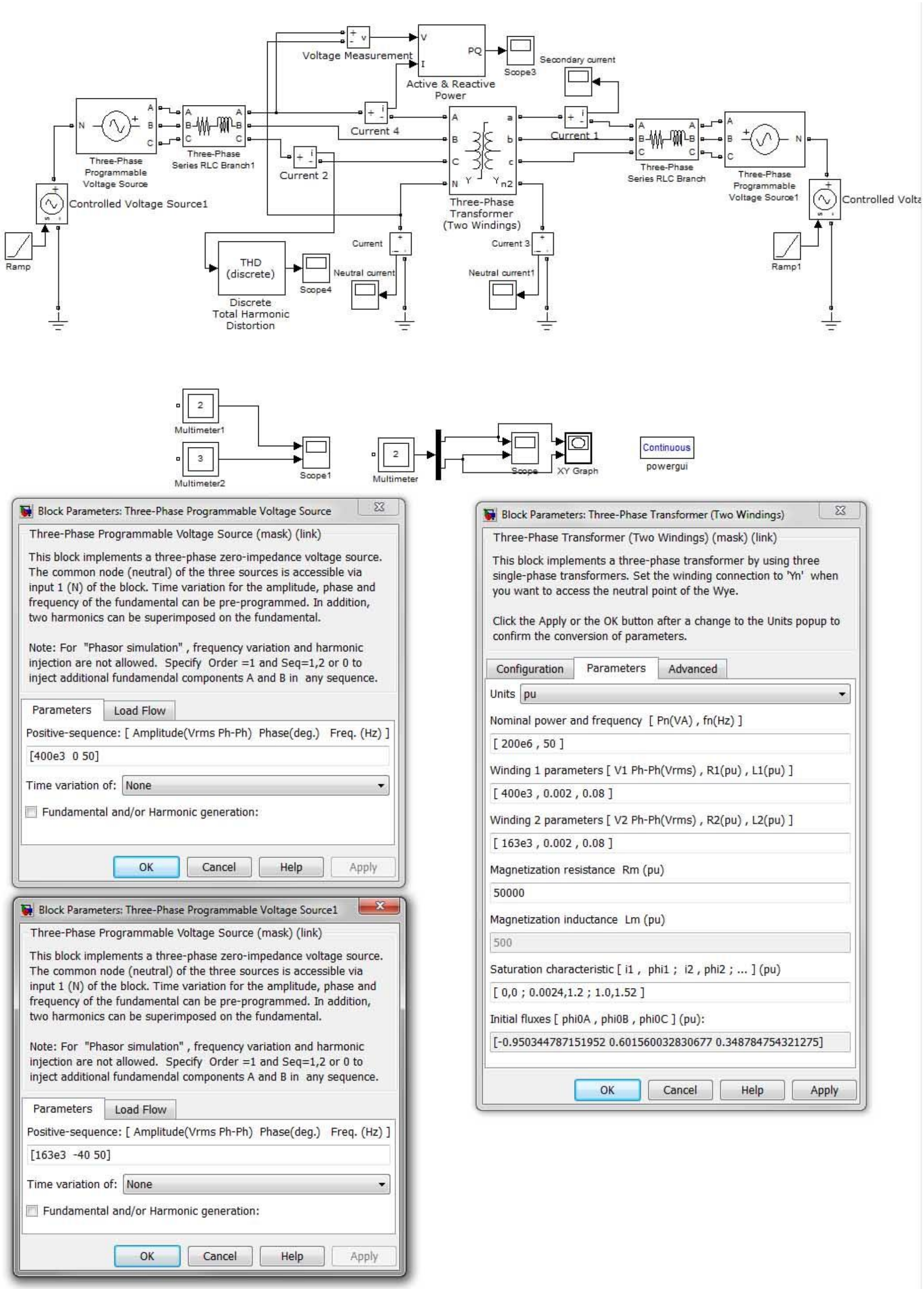

Figure 19: SimPowerSystems GIC simulation model.

EQUATIONS, FIGURES AND TABLES

EQUATIONS

FIGURES

TABLES