

# EFFECTS OF GEOMAGNETIC DISTURBANCES ON THE NORTH AMERICAN BULK POWER SYSTEM

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## **Keywords**

Geomagnetic induced currents (GIC), Geomagnetic Disturbance (GMD), Bulk Power System Planning, Bulk Power System Operations, Operating Procedures

## **Abstract**

The highly complex, interconnected North American power grid has provided a long record of reliable, secure delivery of electric power. However, solar storm or geomagnetic disturbance (GMD) events have demonstrated their ability to disrupt the normal operations of the power grid. The most recent example in North America occurred in March 1989, when a GMD event led to the collapse of the Hydro-Québec system, leaving more than six million people without power for nine hours. Understanding the effects of GMD on bulk power systems and the ability of the industry to mitigate their effects are important to managing system reliability.

This paper describes the effects from Geomagnetic Disturbances (GMDs) and existing response capability available to system operators of the bulk power. Further, the major findings from the North American Electric Reliability Corporations GMD task force are provided: 1) the most likely results from a severe GMD is the need to maintain voltage stability, 2) system operators and planners need tools to maintain reactive power supply and 3) some transformers may be damaged or lose remaining live, depending on design, it's current health and geology. In addition, this paper outlines bulk power system planning and operational enhancements industry can consider to address GMD affects.

## **Introduction**

NERC conducted this assessment in response to findings in the *High Impact, Low Frequency Event Risk to the North American Bulk Power System* (March 2010) [1] report, which found the best approach to HILF events was through an organized combination of industry-led task forces and initiatives. The GMD Task Force implemented that approach for study of geomagnetic disturbances, issuing its interim report [2]. This paper provides a high level summary of the task force's findings.

## **The GMD Phenomena**

GMD emanate from the sun in Figure 1. Solar coronal holes and coronal mass ejections (CME) are the two main categories of solar activity that drive solar magnetic disturbances on Earth. CME create a large mass of charged solar energetic particles that escape from the sun's halo (corona), traveling to Earth between 14 and 96 hours [3]. These high-energy particles consist of electrons, along with coronal and solar wind ions [4]. Geomagnetic induced

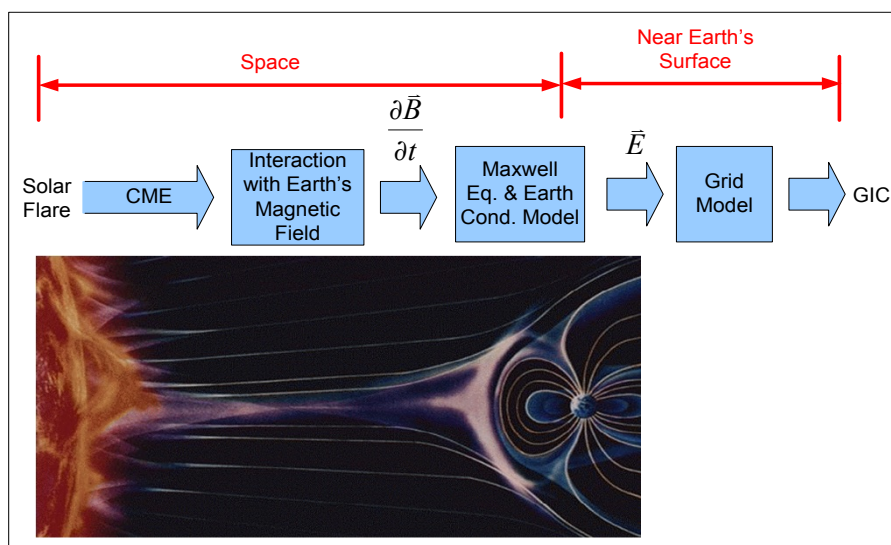
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currents (GICs) that interact with the power system appear to be produced when a large CME occurs and are directed at Earth.

Charged particles from the CME interact with Earth’s magnetosphere-ionosphere and produce ionospheric currents, called electrojets. Typically millions of amperes in magnitude, electrojets perturb Earth’s geomagnetic field, inducing voltage potential at Earth’s surface and resulting in GIC. Long man-made conducting paths, such as transmission lines, metallic pipelines, cables, and railways, can act as “antennae” (depending on the impedance), that allow the quasi-DC currents to enter and exit the power system at transformer grounds, disrupt the normal operation of the power system and, in some cases, cause damage to equipment. Current is also induced on the transmission lines through voltage induction on the loop formed by the grounded transmission line and earth. Induction can occur along a loop of transmission lines, which are connected by grounding.

Figure 1: Storm interaction with Earth and transmission lines



## Monitoring and Predicting Space Weather

In the United States, the responsibility for monitoring and forecasting space weather rests with the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC). In the United States, magnetometers, which gather data on Earth’s geomagnetic field, are operated by the United States Geological Survey (USGS). In Canada, the Canadian Space Weather Forecast Centre (CSWFC) is responsible for monitoring and providing services on space weather.

Both North American space weather centers gather the available data in real time describing the state of the sun, heliosphere, magnetosphere, and ionosphere forming a picture of the environment between the sun and Earth. With this information, forecasts, watches, warnings, and alerts are prepared and issued to those impacted by space weather. Scientists and technicians use a variety of ground- and space-based sensors, as well as imaging systems, to view activity at various locations.

## Two Risks and Modeling

There are two risks that result from the introduction of GICs to the bulk power system:

- 1) Damage to bulk power system assets, typically associated with transformers, and
- 2) Loss of reactive power support, which could lead to voltage instability and power system collapse.

For extra high voltage (EHV) transformers, the effects of GIC include half-cycle saturation that results in: 1) harmonic currents, 2) fringing magnetic fields (flux that flows outside the core), and 3) increased reactive power (voltage-ampere reactive or var) consumption. Harmonic currents can cause relays to trip needed equipment; fringing fields can create heating in transformers which, if sufficiently high and sustained for a relatively long duration, can lead to their reduced life; and var consumption can cause the system to collapse due to voltage instability. Furthermore, loss-of-life to transformers results from insulation breakdown and can be detected by measuring dissolved gas in the insulating oil.

The magnitude, frequency, and duration of GICs, as well as the geology and transformer design are key considerations in determining the amount of heating that develops in the windings and structural parts of a transformer. The effect of this heating on the condition, performance, and insulation life of the transformer is also a function of a transformer's design and operational loading during a GMD event. For example, the failure of the Salem No.1 Nuclear Generator Step-Up Unit shell-type transformer attributed to the March 1989 GMD storm, was due to the development of high circulating currents in the series connections of the low-voltage windings.

Replacing failed EHV transformers is not a small undertaking, as it may require long lead-time for design, engineering, and manufacturing, unless a spare transformer is located nearby. The loss of a few EHV transformers (greater than 345 kV on the high side) – either closely located or more distant – would rarely challenge bulk power system reliability.

The most likely consequence of a strong GMD and the accompanying GIC is the increase of reactive power consumption and the loss of voltage stability. The stability of the bulk power system can be affected by changes in reactive power profiles and extensive waveform distortions from harmonics of alternating current (AC) from half-cycle saturated high voltage transformers. The potential effects include overheating of auxiliary transformers, improper operation of relays, and heating of generator stators, along with potential damage to reactive power devices and filters for high-voltage DC lines.

GIC can lead to half-cycle saturation of power transformers and generate significant amounts of odd and even harmonic distortions in the system current and voltages. When transformers are half-cycle saturated from GIC, protection and control devices may experience elevated harmonic distortion and increase the risk of current-transformer saturation, which can lead to incorrect or undesired operation of protection and control devices unintentionally isolating equipment at times when it provides critical support to the system. Isolating components, such as transmission lines, transformers, capacitor banks and static var compensators (SVCs), may reduce margins further, moving the system closer to voltage collapse. Devices such as SVCs and capacitor banks are also vulnerable to harmonics if the protection device operates on peak or root-mean-square quantities, instead of only fundamental quantities. These reactive power devices are critical to maintaining system stability during GMD events when var demand is high.

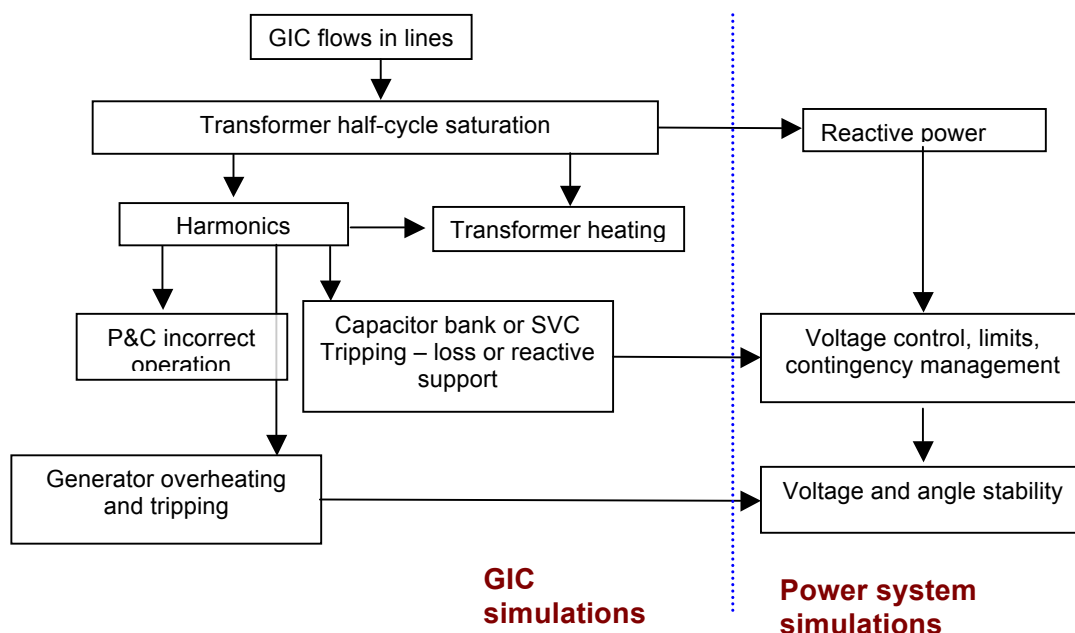
Restoration times of the power system from these two risks are significantly different. For example, restoration times from system collapse due to voltage instability would be a matter of hours to days, while replacing transformers requires long-lead times (a number of months) to replace or move spares into place, unless they are in a nearby location. Therefore, the failure of a large numbers of transformers would have considerable impacts on portions of the system.

There has been a great deal of work during the last two decades devoted to the modeling of GIC flows in a power network. However, modeling of the effects of GIC on power apparatus and system performance during a GMD event is not as well developed. Because the most

likely outcome from a large GMD event is voltage instability exacerbated protection and control failures, this area requires more work by industry to develop mitigation strategies.

From the point of view of a power system engineer, what to model and how to model it depends on the intended uses of the simulation. The diagram below summarizes the effects of GIC on the power system stemming from transformers entering half-cycle saturation. Saturation generates harmonics (including even harmonics). Both transformer half-cycle saturation and harmonics can have a negative effect on transformers causing heating and high levels of reactive absorption, while harmonics in the high-voltage (HV) network can cause problems in the performance of protective relays.

Figure 2: Effects of GIC in an HV transmission network



Harmonics can cause current overloading and tripping of capacitor banks, as well as overheating and generator tripping. In order to assess the level of saturation and, thus, harmonics, it is necessary to know the distribution of GIC flows in the bulk power system. Transformer saturation also affects the power system because the magnetizing currents of the transformer become so large (albeit very distorted) that the effective magnetizing reactance becomes very small during a fraction of cycle. In power flow terms, the effective shunt reactance of the transformer now becomes a “sink” for reactive power and its reactive power consumption increases, or alternatively, there is an effective reactive power loss in the system. The balance of reactive power in the system has a direct impact on system voltages. There are limits for maximum and minimum voltages for the reliable and secure operation of the power system, as well as limits load transmission lines and post-contingency performance (*i.e.*, the system has to be able to operate properly after an accepted contingency, such as fault and subsequent loss of a circuit takes place). These issues are normally studied with power flow simulations. To carry out these assessments, knowing the distribution of GIC flows in every line and transformer of the system under a number of different conditions is necessary.

The combination of increased reactive power absorption and injected harmonics into the system by saturated transformers, changes the worst-case scenario due to a low probability, high magnitude GMD event, to one of voltage instability and subsequent voltage collapse. Reactive power absorption from saturated transformers would tend to lower system voltages. Tripping of reactive power support from capacitor banks and SVCs due to high harmonic

currents at a time when the saturated transformers increases the var demand, creates the scenario for voltage collapse. This is exactly what triggered the 1989 Hydro-Québec blackout.

Planners and operators require the technical tools to model GIC flows and develop mitigating solutions, as necessary. The development of these tools includes a combination of GIC flow calculations for a variety of system conditions and configurations, test wave-fronts representative of GMD events for a variety of latitudes and ground conductivity structures, and suitable thermal equipment models.

### Existing Response Capability and Monitoring Device Assessment

A number of systems in North America have GMD event operating procedures that are triggered by forecast information and/or field GIC sensors. However, NERC’s May 2011 background document, *Preparing for Geomagnetic Disturbances* alert, indicates “severe GMD events present risks and vulnerabilities that may not be fully addressed in conventional bulk power system planning, design, and operating processes.”[5] Existing operating procedures generally focus on adding more reactive power capability and unloading key equipment at the onset of a GMD event. However, more tools are needed for planners and operators to determine the best operating procedures to address specific system configurations.

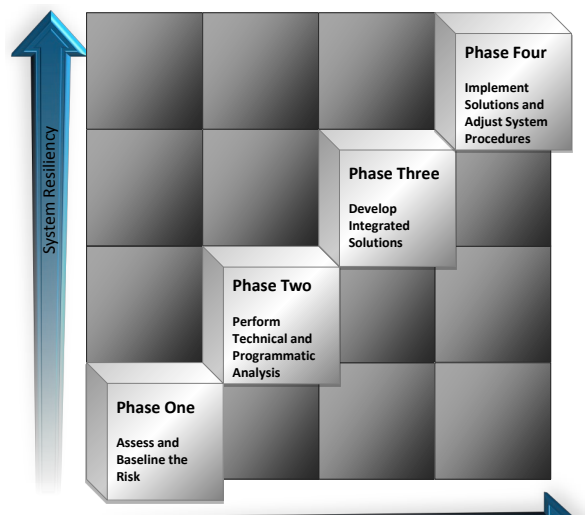
Harmonic overloading of SVCs and capacitor banks, at a time when reactive compensation needs are high due to reactive power absorption from transformer half-cycle saturation, can make maintaining system voltage problematic. Extensive monitoring and simulation models are not widely available, and therefore, the existing operating procedures may not be sufficient to respond to large GMD events.

An essential part of a GIC mitigation program is the installation of monitors to measure GICs and harmonic currents on a continuing basis. Monitors are a key source of real-time information that can guide system operators in determining real-time response. Additionally, monitors can provide valuable historical records that can be evaluated and factored into power system planning and analysis. Coupled with alerts and warnings issued by the SWPC or CSWFC, monitors can provide the reinforcing information that a GMD event is imminent or in progress and can support operational decisions and actions. One potential mitigation approach is to reduce GIC flow through the use of series compensation on the line, and/or placing blocking capacitors or neutral resistors in the transformer’s neutral-to-ground connection. This report describes how such devices function, summarizes considerations for their appropriate placement, discusses their failure modes, and summarizes general functional requirements.

### Risk Management Approach

Figure 3 shows a phased approach to GMD risk mitigation. The first step in risk management for GMD is to develop a number of credible scenarios and the associated probability of occurrence (e.g., severe storm – once in 100 years; serious storm – once in 10 years). Next, determine each scenario’s effects on the bulk power system (e.g., loss of equipment, number of customers impacted, and duration of storm). Alternative approaches can be developed to eliminate or ameliorate the effects, and

Figure 3: Phased approach to GMD risk mitigation



selections made for appropriate combinations of mitigation to minimize the total cost of mitigation and storm impact. The final step is to implement the solutions, adjust system procedures, track performance, and update the process as new information becomes available.

## **Conclusions**

The most likely worst-case system impacts from a severe GMD event and corresponding GIC flow is voltage instability caused by a significant loss of reactive power support simultaneous to a dramatic increase in reactive power demand. Loss of reactive power support can be caused by the unavailability of shunt compensation devices (e.g., shunt capacitor banks, SVCs) due to harmonic distortions generated by transformer half-cycle saturation. Noteworthy is that the lack of sufficient reactive power support, and unexpected relay operation removing shunt compensation devices was a primary contributor to the 1989 Hydro-Québec GMD-induced blackout.

NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. The work of the GMD Task Force does not support this result. Instead, voltage instability is the far more likely result of a severe GMD storm, although older transformers of a certain design and transformers near the end of operational life could experience damage.

There are options available for system operators and asset managers to mitigate the impact from geomagnetic disturbances. These strategies provide industry participants with procedures and methods that should be implemented now to better manage the risks from geomagnetic disturbances. However, the margin gained by using these system operating procedures is dependent on number of factors, including (but not limited to) equipment characteristics, system design, geology and operating philosophy of the asset manager.

The following conclusions are drawn:

1. The most significant issue for system operators to overcome a severe GMD event is to maintain voltage stability. As transformers absorb high levels of reactive power, protection and control systems may trip supporting reactive equipment due to the harmonic distortion of waveforms. In addition, maintaining the health of operating bulk power system assets during a geomagnetic storm is a key consideration for asset managers.
2. The magnitude, frequency, and duration of GIC, as well as the geology and transformer design are key considerations in determining the amount of heating that develops in the windings and structural parts of a transformer. The effect of this heating on the condition, performance, and insulation life of the transformer is also a function of a transformer's design and operational loading during a GMD event. Further, some older transformer designs are more at risk for experiencing increased heating and var consumption than newer designs. Additionally, transformers that have high water content and high dissolved gasses and those nearing their dielectric end-of-life may also have a risk of failure.
3. Planners and operators require the technical tools to model GIC flows and subsequent reactive power losses to develop mitigating solutions, as necessary. This tool development includes publically available GIC flow calculations for a variety of system conditions and configurations, test waveforms representative of GMD for a variety of latitudes, and suitable transient and thermal equipment models.

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## Biographies

**Mark G. Lauby** earned both his Bachelor of Electrical Engineering and Master of Science in Electrical Engineering from the University of Minnesota. He is the author of more than 100 papers on the subjects of power system reliability, expert systems, transmission system planning, and power system numerical analysis techniques. He was selected as the 1992 IEEE Walter Fee Young Engineer of the Year, has served as Chair of a number of IEEE working groups and was elevated to an IEEE Fellow in 2012. Following his work at the Mid-Continent Area Power Pool (MAPP) and Electric Power Research Institute (EPRI), Mr. Lauby joined NERC and is currently the Vice President and Director of Reliability Assessments and Performance Analysis where he leads the electric reliability organization’s efforts to independently assess and report on the overall reliability, adequacy, and associated risks of the interconnected North American bulk power system.

**John N. Moura** is the Associate Director of Reliability Assessments for the North American Electric Reliability Corporation (NERC), where he joined in 2008. Mr. Moura now leads the electric reliability organization’s efforts to independently assess and report on the overall reliability, adequacy, and associated risks of the interconnected North American bulk power system. He is the co-author of numerous NERC special reports including Accommodating High-Levels of Variable Generation, Reliability Impacts of Climate Change Initiatives, and Effects of Geomagnetic Disturbances on the Bulk Power System. John is actively engaged in multiple technical groups across North America focused on the reliable integration of variable generation, demand response performance, smart grid initiatives, environmental regulations, and power system risk and vulnerability analyses. John is currently a member of Institute of Electrical and Electronics Engineers (IEEE). John also directs the advancement of NERC’s Geomagnetic Disturbance Task Force, with a primary focus on understanding the effects of GMD on bulk power systems. Mr. Moura earned his BS from Rutgers University.

**Eric Rollison** is the Engineer of Reliability Assessments at the North American Electric Reliability Corporation. Eric began working at NERC in April 2009 and joined the Reliability Assessments and Performance Metrics Group in July 2010. He previously was an Engineer in the Compliance Enforcement group within NERC. Eric is currently a member of Institute of Electrical and Electronics Engineers (IEEE) and the American Society of Mechanical Engineers (ASME). Prior to joining NERC, Eric worked for five years as both an Engineer and Project Manager in the Aerospace Industry working on sensor manufacturing and development for a mid-sized manufacturing firm that worked directly with General Electric and Pratt & Whitney on Military, Aerospace, and Industrial projects. Eric has a Master’s of Science in Finance from Temple University, which he received in January 2009, and he holds a Bachelors of Science in Mechanical Engineering degree from Villanova University, which he received in 2001. Eric’s research interests are in applying brute force computation analysis to large, complex datasets.