ELECTRIC POWER RESEARCH INSTITUTE

NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

# Geo-magnetic Disturbances (GMD): Monitoring, Mitigation, and Next Steps

## A Literature Review and Summary of the 2011 NERC GMD Workshop

2011 TECHNICAL REPORT

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*A Literature Review and Summary of the 2011 NERC GMD Workshop*

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**NOTE**

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# Report Summary

The North American power grid may be increasingly susceptible to the effects of geo-magnetic disturbances (GMDs) caused by solar storms. Without adequate steps to mitigate these effects, severe GMDs may pose a risk to power system reliability. This report summarizes information that industry experts and North American utilities presented at a recent NERC workshop on GMD mitigation and related GMD topics. It supplements this information with a review of the latest GMD literature to provide an up-to-date summary of GMD mitigation and related information for industry stakeholders.

## Background

The highly complex, interconnected North American power grid has demonstrated a long track record of reliable, secure delivery of electric power. However, solar storms or "geo-magnetic disturbances" (GMDs) have demonstrated their ability to disrupt the power grid. Caused by coronal mass ejections on the sun and better know as the cause of the strikingly beautiful northern lights, GMDs are real, and so are their consequences on the power grid. A GMD in March 1989, for example, led to the collapse of the Québec Interconnection, leaving over six million people without power for nine hours. And since that time, due to a variety of factors, the North American power grid may have become more susceptible to the effects of a severe geo-magnetic storm. History has recorded the incidence of GMDs that were much stronger than the 1989 storm (1921 and 1859). What would happen if one of those extreme storms hit today? As we approach the next peak in the 11-year cycle of solar activity in May 2013, a growing number of industry stakeholders are asking this question.

## Objectives

- To summarize and increase awareness of operational and technology-based practices and approaches that utilities can adopt to mitigate the effects on the power system of severe GMDs.
- To document related up-to-date GMD information and suggest next steps.

## Approach

The North American Electric Reliability Corporation (NERC) hosted a GMD workshop in Atlanta, Georgia, USA on April 19-20, 2011. The workshop focused on operational and planning preparations and precautionary mitigation steps that industry stakeholders can implement to mitigate severe GMDs. Representatives from NERC, EPRI, the

United States National Oceanic and Atmospheric (NOAA) Space Weather Prediction Center (SWPC), utilities, RTOs, and consultants met to share ideas on this high-impact, low-frequency (HILF) type of event. EPRI has produced this summary report to capture the insights presented at this workshop and to communicate this information to the industry. To add value to the summary report, the project team performed a literature review on the topic of GMDs, with emphasis on mitigation. This report is the result of the synthesis of the information presented at the NERC workshop and the information gained in the literature review.

## Results

As the next solar maximum approaches, this report presents a timely synthesis of information of particular immediate interest to utilities, RTOs, regulators, government officials, equipment manufacturers, and other industry stakeholders on the subject of GMDs. The report first describes the sequence of events that may lead to power grid equipment failure or damage from GMDs, summarizes past major GMD events, and outlines ongoing current work in the electric power industry related to GMDs. The report then summarizes GMD prediction, forecasting, monitoring, and alerting capabilities, including the process in place to alert utilities of impending GMDs. Known impacts of GMDs on power grids and the relative vulnerabilities of various types of grid equipment are then discussed. Perhaps the most important of these are adverse impacts on high-voltage transformers.

A summary is included of an effort to model the potential impacts to today's grid of a GMD similar to the largest historically recorded solar storms. The report then describes various operating procedures that utilities and RTOs are using to prepare for and mitigate GMDs, as well as approaches to block or reduce GIC flow in transformers and lines via retrofit of various types of equipment. The report summarizes another important mitigating component – the sharing of information on high-voltage transformer spares and development and demonstration of a Recovery Transformer that can aid rapid replacement of these devices in the event of failure due to a GMD. The report also includes a discussion of research needs and planned work in this area, along with key conclusions and recommendations.

## EPRI Perspective

EPRI has been actively involved in GMD-related research for over two decades. For example, in response to the 1989 GMD that impacted North American power systems, EPRI established a geo-magnetically-induced current (GIC) monitoring network called *Sunburst*, which is still operating today. Building on this and other important GMD research, EPRI is launching a three-year, comprehensive, multi-deliverable project to help the electric power industry prepare for and mitigate GMDs. The initial objective of this project is to determine the state of GMD knowledge, assess current capabilities, and increase industry and stakeholder awareness of the risks and mitigation procedures. The present report is the first step in this process. In a second component of this project, EPRI is addressing GMD vulnerability assessment using Sunburst and other sources and a multi-phased modeling and simulation effort. In part three of this project, EPRI will establish a Center of Expertise to test and assess mitigation technologies, perform system studies, and address member questions.

Jointly with EPRI, NASA has developed an advanced space weather forecasting system called Solar Shield. EPRI is also working with the U.S. Department of Homeland Security (DHS) and ABB to develop and demonstrate a prototype flexible high-voltage "Recovery Transformer" that can be rapidly transported, installed, and energized at a utility substation when in-place equipment fails due to a GMD or other HILF type event; the host utility of the Recovery Transformer project (CenterPoint Energy) will energize this transformer in 2011. EPRI is coordinating its initiatives closely with NERC, utilities, RTOs, and equipment manufacturers to ensure coordination and timely progress.


## Keywords

Geomagnetic disturbance
Geomagnetically Induced Current
Transformer
Vulnerability
Coronal mass ejection
GMD
GIC

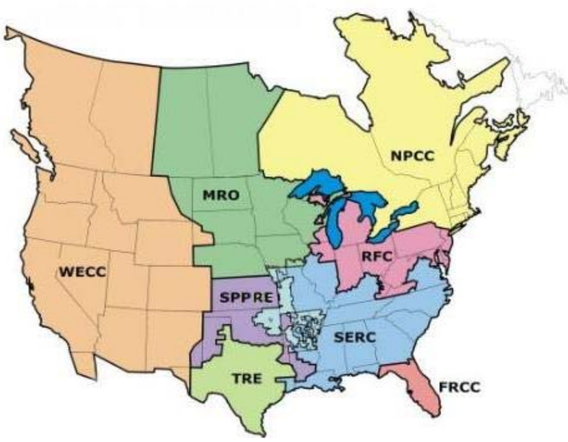
# Abstract

The highly complex, interconnected North American power grid has demonstrated a long track record of reliable, secure delivery of electric power. However, solar storms or "geo-magnetic disturbances" (GMDs) have demonstrated their ability to disrupt the power grid. A GMD in March 1989, for example, led to the collapse of the Québec Interconnection, leaving over six million people without power for nine hours. And since that time, due to a variety of factors, the North American power grid may have become more susceptible to the effects of a severe geo-magnetic storm. Without adequate steps to mitigate these effects, severe GMDs may pose a risk to power system reliability. This report summarizes information that industry experts and North American utilities presented at a recent NERC workshop on GMD mitigation and related GMD topics. It supplements this information with a review of the latest GMD literature to provide an up-to-date summary of GMD mitigation and related information for industry stakeholders. The report also includes a discussion of research needs and planned work in this area, along with key conclusions and recommendations. As the next solar maximum approaches in May 2013, this timely report is the first step in a three-year, comprehensive, multi-deliverable EPRI project to help the electric power industry prepare for and mitigate GMDs.

# NERC's Mission

The North American Electric Reliability Corporation (NERC) is an international regulatory authority established to evaluate reliability of the bulk power system in North America. NERC develops and enforces Reliability Standards; assesses adequacy annually via a ten-year forecast and winter and summer forecasts; monitors the bulk power system; and educates, trains, and certifies industry personnel. NERC is the electric reliability organization for North America, subject to oversight by the U.S. Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada.[1]

NERC assesses and reports on the reliability and adequacy of the North American bulk power system, which is divided into eight Regional areas, as shown on the map and table below. The users, owners, and operators of the bulk power system within these areas account for virtually all the electricity supplied in the U.S., Canada, and a portion of Baja California Norte, México.




**Note:** The highlighted area between SPP RE and SERC denotes overlapping Regional area boundaries. For example, some load serving entities participate in one Region and their associated transmission owner/operators in another.

| NERC Regional Entities | |
|---|---|
| **FRCC**<br>Florida Reliability Coordinating Council | **SERC**<br>SERC Reliability Corporation |
| **MRO**<br>Midwest Reliability Organization | **SPP RE**<br>Southwest Power Pool Regional Entity |
| **NPCC**<br>Northeast Power Coordinating Council | **TRE**<br>Texas Reliability Entity |
| **RFC**<br>ReliabilityFirst Corporation | **WECC**<br>Western Electricity Coordinating Council |

[1] As of June 18, 2007, the U.S. Federal Energy Regulatory Commission (FERC) granted NERC the legal authority to enforce Reliability Standards with all U.S. users, owners, and operators of the bulk power system, and made compliance with those standards mandatory and enforceable. In Canada, NERC presently has memorandums of understanding in place with provincial authorities in Ontario, New Brunswick, Nova Scotia, Québec, and Saskatchewan, and with the Canadian National Energy Board. NERC standards are mandatory and enforceable in Ontario and New Brunswick as a matter of provincial law. NERC has an agreement with Manitoba Hydro making reliability standards mandatory for that entity, and Manitoba has recently adopted legislation setting out a framework for standards to become mandatory for users, owners, and operators in the province. In addition, NERC has been designated as the "electric reliability organization" under Alberta's Transportation Regulation, and certain reliability standards have been approved in that jurisdiction; others are pending. NERC and NPCC have been recognized as standards-setting bodies by the Régie de l'énergie of Québec, and Québec has the framework in place for reliability standards to become mandatory. Nova Scotia and British Columbia also have frameworks in place for reliability standards to become mandatory and enforceable. NERC is working with the other governmental authorities in Canada to achieve equivalent recognition.

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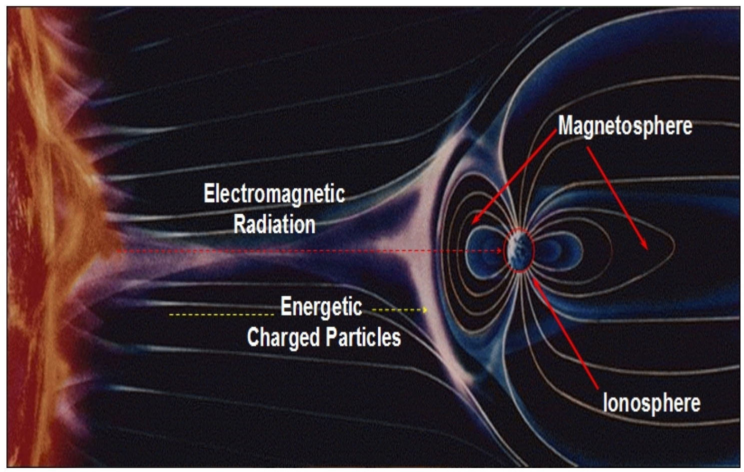
# Executive Summary

The objective of this report is to summarize the NERC Geo-Magnetic Disturbance Workshop held in April 2011[2] and provide a review of the current literature on this topic. The primary purpose of this technical report is to summarize the proceedings and increase awareness of operational and technology-based practices and approaches to mitigate the effects of severe Geo-magnetic disturbances (GMDs). This summarization provides the views of presenters, and overview of discussions. The GMD Task Force has continued its work since the Workshop and the introduction of new information and industry vetting has continued. Therefore, this report should be considered preliminary, serving as a platform from which the Task Force is building.




GMDs start with the sun. Solar coronal holes and coronal mass ejections (CMEs) are the two main categories of solar activity that drive solar magnetic disturbances on the Earth. CMEs involve the ejection of a large mass of charged solar energetic particles that escape from the sun's halo (corona), traveling to the Earth in 15 hours to 4 days (see figure to the right). Geo-magnetically induced currents (GICs) are produced only when a large CME occurs directed at the Earth. These quasi-DC currents can enter and exit the power system at transformer grounds disrupting the normal operation of the power system and can, in some cases, damage equipment. Because of their proximity to the Earth's magnetic north pole, higher latitudes typically experience greater effects of GMDs. However, a severe storm can affect equipment and systems even at lower latitudes.

The goal of NERC's Geomagnetic Disturbance (GMD) workshop was to discuss the current state of planning and operating guidance, as well as knowledge of GMD impacts. Additionally, it provided NERC staff with another opportunity to vet a draft GMD Alert[3] with industry stakeholders and subject matter experts. The GMD Alert is focused on providing advice to the industry on not only how to prepare and mitigate the impacts to operational planning and real-time operations, but also educating the industry on long-term actions that can be taken to prepare for a large event. The GMD Alert was distributed to industry early May 2011.

With over 80 attendees,[4] NERC met its targets for participation by industry members. Participants provided additional insights on the knowledge available to the industry today, the work that needs to be done, and operational procedures meant to prepare for severe GMD events. Feedback cards from attendees indicated a strong preference for NERC staff to continue educating the industry on the topic of geomagnetic disturbances. Feedback also verified that the current geomagnetic storm forecasting measures (developed by NOAA) does not necessarily correlate to disturbances that can impact the bulk

[2] http://www.nerc.com/docs/pc/gmdtf/GMD_Workshop_rev6_04.19.2011.pdf

[3] http://www.nerc.com/fileUploads/File/Events%20Analysis/A-2011-05-10-01_GMD_FINAL.pdf

[4] See Section, titled *Registrants as of March 30, 2011*

power system and confirmed a need to establish an enhanced forecasting system specifically designed for system operators.

A major outcome of the workshop was that significant work is still required by industry and governmental organizations to improve not only solar storm forecasting and but also in developing robust modeling methods to understand how GMD events impact bulk power system equipment. The primary deliverable from the workshop, the NERC ALERT on GMD, provides the industry guidance given the knowledge available today. NERC expects to provide incremental information as it become available, from the workings of the GMD Task Force. NERC actions to date on GMD include:

- Summarized industry operational measures (NERC ALERT) to help mitigate GMDs.
- Procedures to disseminate GMD information, but time to act can be short.
- Proactively addressing risks from GMD through its Critical Infrastructure Strategic Roadmap and Critical Infrastructure Protection Coordinated Action Plan.
- NERC is re-establishing the Spare Equipment Database.

The following conclusions can be drawn from the synthesis of information in this document:

- Severe GMDs are relatively rare events which could pose a credible reliability risk.
- Opinions differ on transformer and system vulnerability.
- Until now, industry efforts to analyze, synthesize, and consolidate it has been limited.
- System vulnerability to GMDs needs validation.
- Efficacy and viability of operational approaches mitigating GMD should be assessed.
- Cross-sector coordination is needed with interdependent critical infrastructures such as telecommunications and fuel supply and delivery.
- Identification, evaluation, and demonstration of equipment monitoring techniques.

# Introduction to Geomagnetic Disturbances

## Overview of Geomagnetic Disturbances (GMDs)

The North American bulk electric power system is perhaps the most critical infrastructure on the continent, for its continued reliable operation supports several other critical infrastructures, including water supply, telecommunications, food and fuel production and distribution, and others. It underpins our government, economy, and society in crucial ways. The U.S. National Academy of Engineering ranked electrification as the greatest engineering achievement of the 20$^{th}$ century, ahead of automobiles, telecommunications, computers, and even healthcare in terms of it positive impact on quality of life [1]. The North American power grid is highly complex; it is comprised of over 200,000 miles of transmission lines, thousands of generating plants, and millions of digital controls [2]. Yet, industry has demonstrated a long track record of reliable, secure delivery of power.

Without adequate steps to mitigate their effects, solar magnetic disturbances, also called geo-magnetic disturbances (GMDs), may pose a risk to reliability. Solar storms, which emanate from the sun as coronal mass ejections (CMEs), can produce an impulsive disturbance to the Earth's geo-magnetic field over wide geographic regions – a GMD. The storms are global phenomena; a single severe storm can adversely impact systems on multiple continents. The disturbance in the Earth's geo-magnetic field can cause geo-magnetically induced currents (GICs) in the ground and electrical network. Once they are introduced into the bulk power system's transmission and generation facilities, these ground-induced currents can saturate (or quasi-saturate) and may damage some equipment, which can be difficult to immediately replace, such as high voltage transformers, which require long lead times to construct and are predominantly manufactured outside North America. Spare equipment strategies and asset managers need to consider these potential impacts.

Since 1755 when recording of solar sunspot activity began, 23 solar cycles have passed, and the current solar cycle 24 began in January 2008. The sun is characterized by solar cycles of approximately 11 years in length. This means that peak solar activity, and its potential impacts on the power grid on Earth, has occurred approximately every 11 years as long as the grid has been in existence.

Power systems may be more vulnerable to the effects of a severe geo-magnetic storm than a few decades ago. Since the 1950s, the number of miles of high-voltage transmission lines has increased by about a factor of ten [3]. Hence, the number of assets that provide a conductive path for GICs has increased dramatically over the last five solar cycles. During the same period, transmission line and transformer designs have increased in voltage from 100-200 kV to 345-765 kV, which has lowered their resistance by a factor of ten and further increased their susceptibility to GMDs [4].[5] And the conducting paths are lengthening as transmission lines become interconnected (e.g., across national borders). In the last two decades, construction of new transmission lines has slowed[6] forcing some systems to operate

[5] For more information, see "How GIC Flows on the Grid" in section 3.

[6] This has occurred as a result of difficulty obtaining transmission rights of way, the high cost of EHV transmission, lack of economic and regulatory incentives in some areas to construct the lines, and technological advances that enable reliable operation closer to limits.

the bulk power system closer to operating limits more often. This increases the vulnerability to overloads caused by GMDs because the equipment may be operating closer to its nameplate thermal rating when the GIC initiates additional heating.

While the potential for adverse affects on the grid by GMDs are real, at the workshop industry experts emphasize that prudent measures are available to mitigate these potential effects. *"I am concerned that overstating the issue through hyperbole and trying to motivate action with a picture of solar disturbances causing instant devastation and the ruination of the modern world does not provide a rational catalyst for decision-making or help prioritize actions,"* cautions North American Electric Reliability Corporation (NERC) President and CEO Gerry Cauley, *"I believe the physical challenges are real and there are practical solutions available." [5]*

The primary purpose of this technical report is to summarize and increase awareness of operational and technology-based practices and approaches that utilities can adopt to mitigate the effects on the power system of severe GMDs.

## GMDs: The Sequence of Events

Geo-magnetic disturbances (GMDs) start with the sun. According to scientists, solar coronal holes and coronal mass ejections (CMEs) are the two main categories of solar activity that drive solar magnetic disturbances on the Earth. Geo-magnetically induced currents (GICs) are produced only when a large CME occurs directed at the Earth. CMEs involve the ejection of a large mass of charged solar energetic particles that escape from the sun's halo (corona), traveling to the Earth in 15 hours to 4 days (see Figure 1) [6]. These high-energy particles consist of electrons and coronal and solar wind ions [7].

At the Earth, the charged particles from the CME interact with the Earth's magnetosphere-ionosphere system in a complex process that produces ionospheric currents called electrojets. Typically millions of amperes in magnitude, these electrojets vary with both position and time (see Figure 2). Magnetic fields associated with these electrojets perturb the Earth's geo-magnetic field, inducing voltages in the transmission lines and causing GICs to flow (see Figure 3).[7] These GICs flow in the Earth and on long man-made conducting paths that act as "antennae" (depending on the impedance) such as transmission lines, metallic pipelines, tele-cables, and railways. These quasi-DC currents can disrupt the normal operation of the power system and can, in some cases, damage equipment. Because of their proximity to the Earth's magnetic north pole, higher latitudes typically experience greater effects of GMDs [9]. [8] However, a severe storm can affect equipment and systems even at lower latitudes.

[7] When magnetic fields move in the vicinity of a conductor, such as a wire, an electric current is induced in the conductor. This occurs on a grand scale in a GMD [8]. In this case, the moving magnetic field is generated by the electrojet, the electric current induced is the GIC, and the conductor is the Earth, power lines, etc.

[8] The B-H characteristic (also called the magnetization curve, BH curve, or hysteresis curve) is a graph of the magnetic field B as a function of the magnetizing field H.

**Figure 1: Coronal mass ejections observed using coronagraphs on NASA SOHO and STEREO spacecraft [10]**

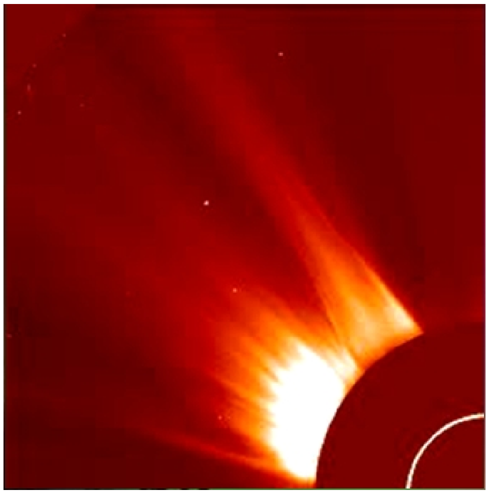


**Figure 2: Solar electromagnetic radiation and energetic particles impact Earth's magnetosphere and ionosphere, causing space weather disturbances [10]**

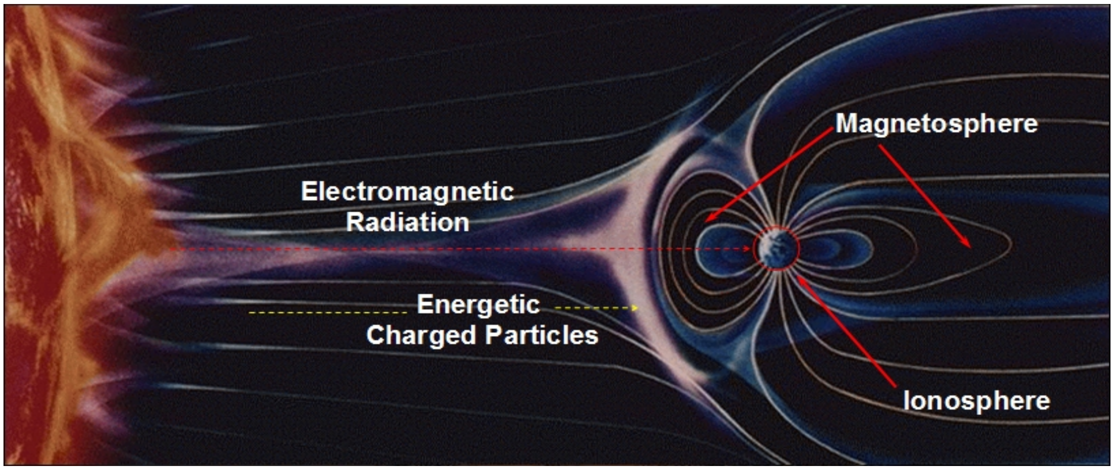
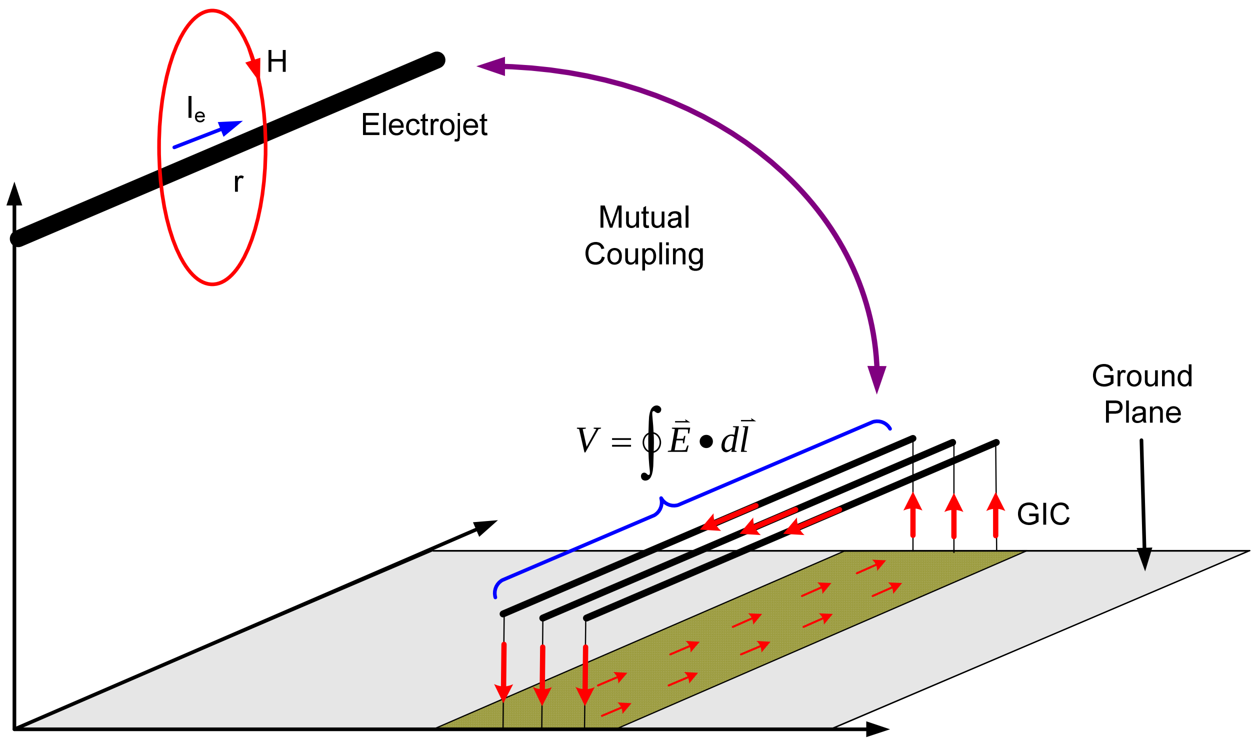


**Figure 3: Geo-magnetic effects on electric power grids [11]. Source: National Weather Service**




In summary, the chain of events that result in GICs is:

- A coronal mass ejection (CME) occurs at the sun.
- The mass of solar energetic particles travels to the Earth in 15 hours to 4 days.
- At the Earth, this mass of charged particles interacts with the Earth's magnetosphere-ionosphere system, producing varying electrojet currents above the Earth.
- Electrojet currents above the Earth produce changes in the geo-magnetic field.
- The changing geo-magnetic field induces voltage potential at the Earth's surface. The changing geo-magnetic field is measured by the amount of change in amplitude of the magnetic field and the time required making the change (dB/dt) measured in nano-Tesla per minute (nT/min).
- The voltage induced in the transmission lines drives geo-magnetically-induced currents (GICs).
- The GICs flow in the Earth and along conducting paths like power lines, potentially disrupting or damaging equipment.

On average, over an 11-year solar cycle, there are about 200 days when strong geo-magnetic storms occur, and about four days of extreme storms [12].

## Overview of Past Major GMD Impacts

The extra high voltage (EHV) portion of the grid (345-765 kV) typically experiences the highest GIC flow levels, in part because these lines and connected transformers also have lower resistance per mile than the lower voltage underlying systems and the ground impedance. The loss of these key assets due to large GIC flows on the high voltage system can rapidly widen into geographically widespread disturbances on the power grid.

The most well-known recent GMD experience in North America was the 1989 geo-magnetic storm, which led to the collapse of the Hydro Québec system in the early morning hours of March 13, 1989. About six million people were without service for nine hours or more [13]. The impact on the Hydro Québec system was estimated to cost $6 billion (6 billion Canadian dollars) [7]. Subsequent mitigation measures, such as series compensation, were installed at a cost of about $1.2 billion Canadian dollars [7]. In the USA, two phases of an older design, 3-phase 1,200-MVA, 500-kV generator step-up (GSU) transformer bank were damaged at a nuclear plant [14]; information on the health of these transformers prior to the GMD is not readily available. NERC's post-event analysis attributed over 200 significant anomalies across the continent to this single storm [4]. Two 400/275-kV transformers were damaged in the UK during this same event [15].

More recently, in late October and early November 2003, a GMD resulted in a blackout for several tens of minutes and left about 50,000 people without electricity in the city of Malmö in southern Sweden [16]. In this same event termed the "*Halloween storms of 2003,"* transformer heating and voltage fluctuations were observed in the Scottish Power network, but the effects remained at manageable levels [16]. Transformers in the Eskom network in South Africa were also significantly damaged [12]. While these storms are closely associated with the transformer and system impacts, the cause and effect relationship remains under debate.

This storm was also associated with impacts in the southern hemisphere. For example, the GMD was associated with damage and lock out of a two-year old 90-MVA, 330-kV GSU transformer in Namibia. In South Africa, on-line dissolved gas analysis (DGA) measurements on numerous GSU transformers of unspecified designs/ages, showed an increase in gassing patterns immediately after the solar storm. Failures were experienced both during and after the GMD. An inspection of the failure evidence concluded that the failures were due to damage sustained during the GMD [17].

Ninety years ago, the highest magnitude GMD of the century occurred on May 14-15, 1921. The storm disabled all telegraph service from the Atlantic coast to the Mississippi River and in major portions of the western U.S. The New York Times reported that submarine cables would need to be brought to the surface for repairs [18]. No GMD of this severity has tested the power grid since then – not even the 1989 storm. The 1921 storm may have been ten times stronger than the 1989 storm that collapsed the Hydro Québec system, according to an Oak Ridge National Laboratory analysis [19]. However, sophisticated monitoring equipment, widely deployed today, was not available at the time of the storm, making exact replication of the storm signal impossible.

The strongest ever recorded storm (estimated to be 50 percent stronger than the 1921 storm) is the ''Carrington event'' that occurred September 1-2, 1859 [20]. Scientists reached this conclusion by analyzing anomalous nitrate concentrations in polar ice core samples and estimating the fluency of protons, which are an indicator of the amount of solar energetic particles that reach the Earth. This event was named after British amateur astronomer Richard Carrington, who observed a white flare light the day before the onset of the storm – an observation independently confirmed in London, England.[9] During about six days in late August and early September, extraordinary auroral displays were observed in the night skies as far south as Hawaii, the Caribbean, and Central America. These were manifestations of two intense magnetic storms that occurred, driving magnetometer readings off their scale and disrupting telegraph communications worldwide [13]. Unfortunately none of the observations enable a direct estimation of the geo-electric field or GIC amplitudes. More specifically, large GICs were observed via their dramatic effects on telegraph equipment but the actual electric current amplitudes or geo-magnetically induced voltages were not recorded anywhere at the time [21].

GMD impacts are not limited to the electric power grid. Past storms, which have been less severe than the 1859 storm, have adversely impacted radio communications and navigation signals from Global Positioning System (GPS) satellites, affected high-frequency communications with aircraft flying over the poles (requiring flight path diversions), and impacts on spacecraft [13]. A number of these systems also depend on reliable power delivery to operate [22].

## Ongoing GMD Work in the Industry

Industry stakeholders are currently engaged in a variety of GMD research and planning activities. The summary of activities and stakeholders in this subsection is not intended to be comprehensive, but rather to illustrate the scope of efforts that are ongoing in these important subject areas.

## NERC Actions and Initiatives

NERC is conducting or involved in a number of relevant GMD activities. In July of 2009, NERC and the U.S. Department of Energy (DOE) partnered to investigate High-Impact, Low-Frequency (HILF) risks to the North American bulk power system. They formed a steering committee of experts who led a workshop in Washington DC in November 2009. Their resulting report, published in June 2010, addressed three classes of risks: 1) coordinated cyber, physical, or blended attack, 2) a pandemic, and 3) GMDs, high altitude electromagnetic pulse events, and intentional electromagnetic interference threats. The report outlines 19 proposals for action that are intended to provide input into a formal action plan [4].

In November 2010, NERC's Electricity Sub-Sector Coordinating Council (ESCC) developed and published a *"Critical Infrastructure Strategic Roadmap."*[10] The role of ESCC is "to foster and facilitate the coordination of sector-wide policy-related activities and initiatives to improve the reliability and resilience of the electricity sector, including physical and cyber security infrastructure." [23] The Roadmap that ESCC developed is a framework to address HILF-type risks. One such risk the Roadmap addressed is GMDs of intensity up to ten times greater than the 1989 storm (i.e., 4000-5000 nT/min at 50 degree latitude, or roughly equivalent to estimates of the 1921 storm). The scenario includes damage to generating station and substation equipment that is difficult to replace, leading to a cascading effect on the power system and prolonged system restoration. The scenario may cause damage to high voltage

[9] Scientists later learned that the flares Carrington and others observed were not the cause of the magnetic storms, but rather the cause was CMEs launched from or near the same sunspot region that had produced the flare [13].

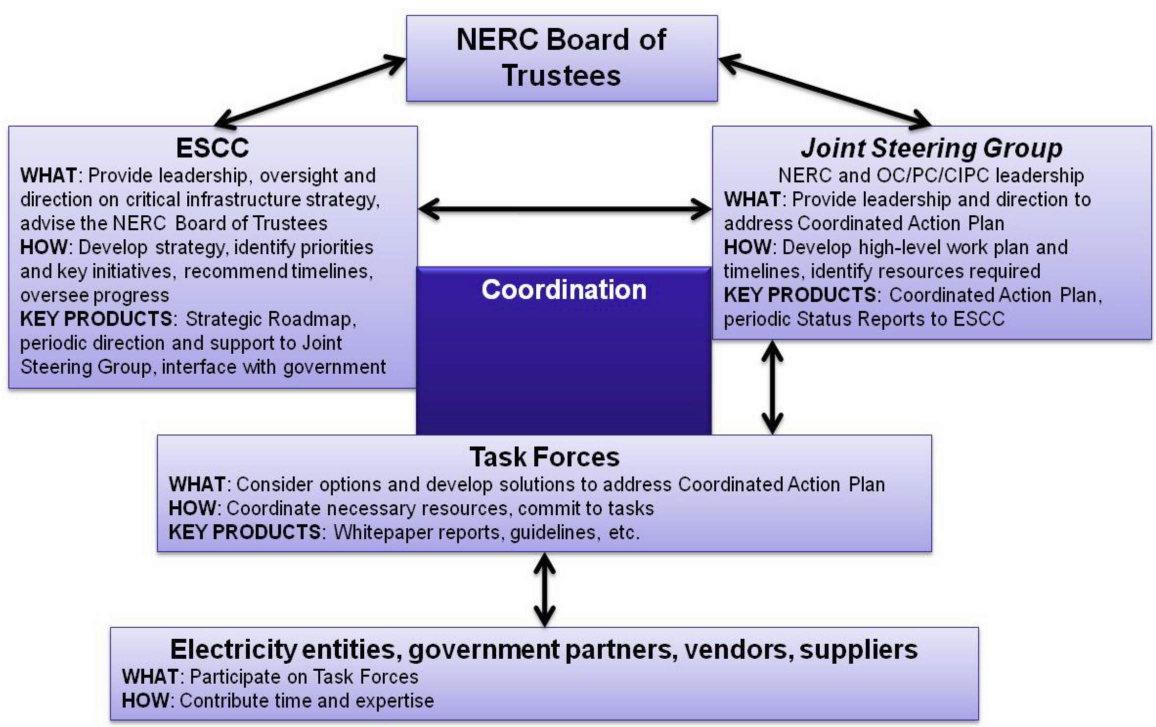
[10] http://www.nerc.com/docs/escc/ESCC_Critical_Infrastructure_Strategic_Roadmap.pdf

transformers of varying degrees in northern and southern latitudes. From an "all-threats, all-hazards perspective," the report suggests ways to enhance electricity reliability and resilience [23,24,25].[11]

Using the HILF report and ESCC Roadmap insights and recommendations, the Chair and Vice Chair of NERC's Planning, Operating, and Critical Infrastructure technical committees, along with NERC Staff, prepared and published a "*Critical Infrastructure Initiatives Coordinated Action Plan*"[12] in November 2010. For each of four severe-impact scenarios, this document presents a detailed action plan, including deliverables and milestones. For the GMD scenario, actions are grouped into current capability assessment, disturbance protection, disturbance response, and bulk power system restoration. Hence, these recommended actions are directly in line with the subject of the present report [24].

Because the recommended actions in the NERC plan cut across subjects within NERC's purview, NERC has developed a "coordinated action plan" that defines roles and responsibilities (see Figure 4). The JSG will provide leadership and direction to address the coordinated action plan. NERC will draft scope/charter documents for each of the new task forces to address the action plan, with input from JSG. Utilities, government agencies, vendors, and suppliers will contribute to the process by participating on task forces. To date, NERC has approved scopes for smart grid, spare equipment database, geo-magnetic disturbance, severe-impact resilience, and cyber attack task forces [2,24].

**Figure 4: NERC Coordinated Action Plan for Critical Infrastructure Strategic Initiatives [24]**




One of the task forces that NERC formed is the GMD Task Force (GMDTF).[13] Chaired by Bonneville Power Administration's (BPA) Mr. Donald Watkins and Vice-Chaired by PJM Interconnection's Mr. Frank Koza,

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[11] Industry may revisit "ten times 1989" scenario considering a 1-in-100 year storm. See page 7-2 of this report.

[12] http://www.nerc.com/docs/ciscap/Critical_Infrastructure_Strategic_Initiatives_Coordinated_Action_Plan_BOT_Apprd_11-2010.pdf

[13] http://www.nerc.com/docs/pc/gmdtf/PC-GMD_Sep_2010_Scope_v8.pdf

the GMDTF includes 80 people including equipment experts, utility engineers, scientists, and government representatives [26]. GMDTF Subgroup 1 is reviewing current industry capabilities to respond to GMD events and best ways to address future GMD threats. GMDTF Subgroup 2 is developing models to identify power system vulnerabilities and mitigate threats. GMDTF objectives include providing a "toolbox" of procedures and equipment adaptation to mitigate GMD impacts, and accurately simulating impacts of GMD on the power system to insulate from vulnerability. The National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and Natural Resources Canada (NRCan) are supporting this effort, with participation of the U.S. Department of Homeland Security (DHS), U.S. Department of Energy (DOE), the U.S. Department of Defense (DOD), the U.S. State Department, BPA, and the Tennessee Valley Authority. The task force plans to deliver a final report in 2011 [27].

## Spare Transformer Initiatives

Another of the task forces that the NERC Planning Committee recently established is the Spare Equipment Database Task Force (SEDTF). This Task Force recently issued an interim draft report in which it recommends establishment of a voluntary program whereby owners of long-lead time transformers would share information about their spares in a database for potential equipment sharing. Further, EPRI and the U.S. Department of Homeland Security (DHS) have embarked on a Recovery Transformer (RecX) Program to specify, design, build, and test prototypes of a new type of emergency spare extra high voltage (EHV) network transformer, discussed in Section 6.

## Electromagnetic Pulse and Electromagnetic Interference Studies

GMDs are part of a class of risks called high-impact, low-frequency (HILF) events. These events are characterized by their potential to impose very large adverse impacts on the electric power system (and other infrastructures in some cases), their rare nature, and hence, the industry's limited experience mitigating them. This group of risks includes major natural disasters such as earthquakes, tsunamis, large hurricanes, and pandemics. The group also includes deliberate attacks, such as acts of war, terrorism, coordinated criminal activity, GMDs, electromagnetic pulses (EMPs) and intentional electromagnetic interference (EMI).

In this second group, EMP and EMI attacks are sometimes studied alongside GMDs [4]. One reason is that the E3 component of the three-pronged EMP event is similar to a GMD in its effects, though its intensity is higher and duration shorter and follows on after the grid has been exposed to an E1 and E2 wave. The E3 component causes ground-induced currents that couple to transmission lines and drives high-voltage transformers to saturation [28]. Another reason is that these attacks and GMDs both have the potential to specifically disrupt and/or damage the electric power delivery system on a wide scale. There is increasing interest in Washington DC about EMP/EMI threats. In February 2011, Rep. Trent Franks (R-Arizona) introduced a new Bill in U.S. Congress (H.R.668 called the SHIELD Act) to amend the Federal Power Act to "protect the bulk-power system and electric infrastructure critical to the defense and well-being of the United States against natural and manmade electromagnetic pulse threats and vulnerabilities." [29] Some studies that group EMP, EMI, and GMD together often recommend mitigation strategies that address all three threats (e.g., the NERC HILF study [4]). Others study all three threats but report on them separately (e.g., the Oak Ridge National Laboratory study) [19]. The present report addresses only GMDs.

## EPRI Initiatives

EPRI is building on two decades of research in the GMD area to develop the knowledge and tools to understand, predict, and mitigate the impact of GMDs on power systems.

This report is the first deliverable in a three-year, comprehensive, multi-deliverable project that EPRI has recently launched to help the electric utility industry prepare for, and mitigate GMDs. Specifically, this project's objectives are to:

- Determine the likely impact of an extreme event on the North American bulk power system based on present system configuration, protection capability, and practices.
- Identify technologies available today or in the near term (especially in operations) to mitigate equipment damage, reduce the extent of the interruption, and speed recovery.
- Identify technologies that can be developed to reduce the impact of the storm as well as lower the cost of protection.

The knowledge developed in this project will help stakeholders prepare for large solar storms and to reliably operate the grid through such events. This will improve bulk power system reliability by shortening customer interruptions as well as identify the risks of equipment damage. In addition, the project may identify gaps in forecasting and mitigation solutions, and provide guidance on the economic feasibility of available mitigation technologies. EPRI plans to accomplish the project goals in three tasks, which are described in Section 7: 1) education and current capability assessment, 2) vulnerability assessment, and 3) mitigation.

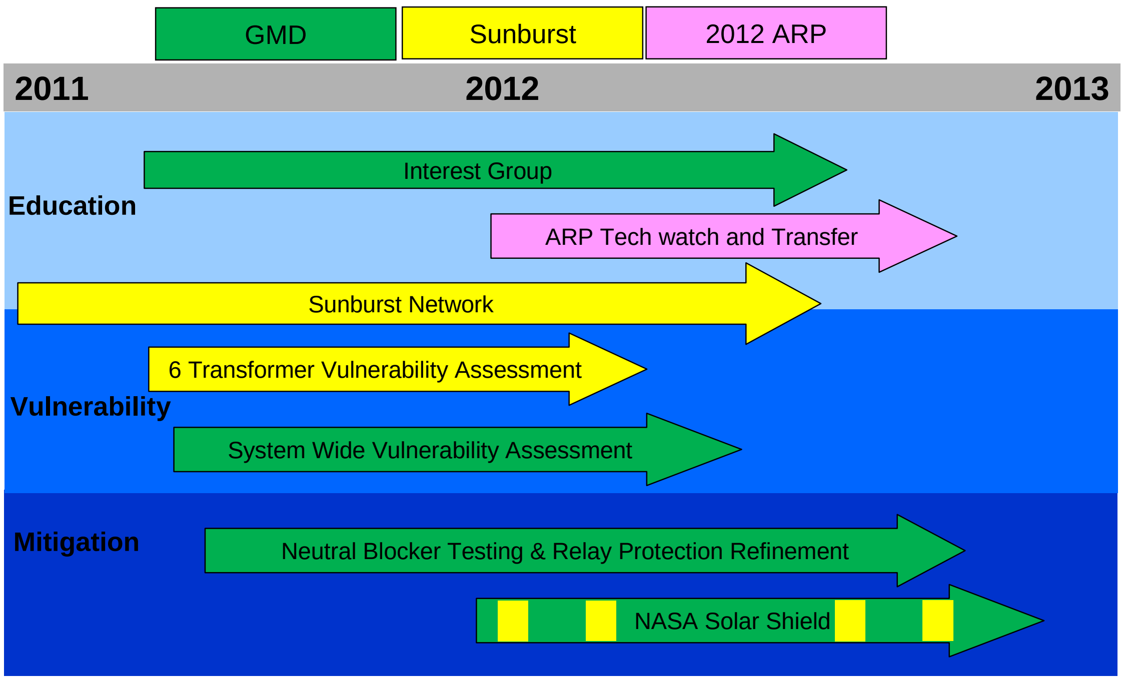
The initial objective of this project is to determine the state of GMD knowledge, assess current capabilities, and increase industry and stakeholder awareness of the risks and mitigation procedures. The present report is the first step in this process. EPRI participated in the NERC workshop on this subject in April 2011, which presented available operational approaches/procedures and available technologies aimed at limiting the impact of a severe GMD event. This workshop also covered approaches in forecasting, early warning, operations, mitigation, and restoration. The present report is a summary of that workshop, supplemented by information gathered in a literature review on GMD impacts and mitigation.

The multi-task project described above is one of three coordinated GMD activities at EPRI. The GMD project described above is highlighted in green in Figure 5. In the education area, this project will support the GMD interest group that will be formed as new members join this project. This GMD project also supports vulnerability assessment, which will begin immediately, and mitigation, which has begun now for operations and will begin soon in hardware testing and development.

The EPRI Sunburst GIC monitoring network is highlighted in yellow. Sunburst GIC monitoring provides grid operators with real-time awareness of a GMD's intensity, aids post-storm analysis, and provides valuable input for developing improved forecasting models (including an EPRI/NASA collaboration called Solar Shield). This project also includes a vulnerability assessment of six transformers that is now underway. Sunburst and Solar Shield are explained in Section 2 of this report.

Highlighted in pink on Figure 5 is a project planned for 2012 in the EPRI annual research portfolio (ARP) that will focus on technology watch and technology transfer. This project will capture all of the activities at EPRI and elsewhere in solar activity; document how stakeholders responded and how the system responded; and document lessons learned, pending regulations, and emerging tools and approaches. This project will also track high altitude electromagnetic pulses (HEMP) and Intentional Electromagnetic Interference (IEMI). EPRI will feed back the modeling results in this vulnerability assessment project to the Solar Shield prediction models at the start of 2012.

**Figure 5: Timeline of various EPRI GMD research initiatives**



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# Prediction, Forecasting, Monitoring and Alerting

## Introduction

This section summarizes the short-term prediction activities of the Space Weather Prediction Center in Boulder, Colorado. It also summarizes existing GIC monitoring activities and how this helps to inform longer-term prediction activities. For example, historical data on GICs can be compared to sunspot activity over a solar cycle. The section then discusses a project called Solar Shield that aims to enhance space weather forecasting. The process of gathering data about impending GMDs is then described, along with the NERC process of disseminating alerts to stakeholders.

## Space Weather Prediction Center

In the United States, the main source of space weather information is the Space Weather Prediction Center (SWPC, formerly the Space Environment Center or SEC) located in Boulder, Colorado (see Figure 6). SWPC is a laboratory and service center of the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service. According to the SWPC web site, it is "the nation's official source of space weather alerts, watches, and warnings." [1] The SWPC provides both monitoring and forecasting of solar and geophysical events. To monitor events on the sun, SWPC scientists use various ground-based and space-based sensors and systems, as well as optical observatories around the world. SWPC forecasts space weather on time scales of hours to days by analyzing current conditions, comparing current conditions to past conditions, and using models [1].

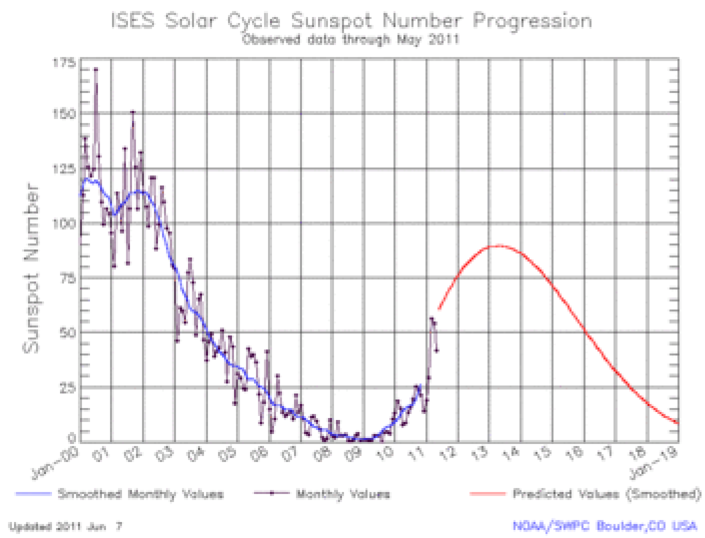
**Figure 6: Space Weather Prediction Center in Boulder, Colorado [1] Source: National Weather Service**

SWPC uses various existing satellites to monitor solar events, provide alerts, and aid forecasting. When used strictly for monitoring, they provide about a 40-60 minute warning before solar energetic particles from a CME reach Earth. These include the Solar and Heliospheric Observatory (SOHO), Advanced Composition Explorer (ACE), and Solar Terrestrial Relations Observatory (STEREO). Launched in 1995, SOHO currently operates close to the L1 Lagrange point, which is the point between the sun and the Earth where the gravitational pull from the two bodies counterbalance (about 1.5 million km or about 1 million miles from Earth). Its mission is to study the sun from its deep core to the outer corona and the solar wind. Originally intended to operate for only two years, it has greatly exceeded life expectations and is currently approved to operate through the end of 2012 [2]. Launched in 1997, ACE also currently operates close to the L1 Lagrange point. Its mission is to study energetic particles from the solar wind. It has sufficient propellant to continue to operate until approximately 2024 [3]. Both of these satellites have gathered data during most of the 11-year solar cycle #23 and the rise of solar cycle #24. Launched in 2006, STEREO uses two identical space-based observatories on opposite sides of the Earth to provide the first ever stereoscopic measurements to study the sun and its CMEs [4].

To replace the aging ACE satellite, the Obama administration is attempting to secure funding to re-purpose for solar observation a NASA satellite called the Deep Space Climate Observatory (DSCOVR), which was originally scheduled for launch in 2003 [5] The status of funding for this satellite remains uncertain [6].Examination of SWPC solar sunspot activity since the turn of the century shows the expected waxing and waning of activity over the last cycle (see Figure 7) [7]. Sunspots are dark, relatively cool areas (~4200 ºC rather than ~ 6000 ºC) on the solar surface with constantly shifting strong magnetic fields. Lasting for days or weeks, moderate sunspots are as large as the Earth and can be seen rotating as the sun spins on its axis once every 27 days. SWPC data shows that the last solar minimum (when the number of sunspots is lowest) occurred in December 2008, and that the solar cycle #24 maximum (when the number of sunspots is expected to be the highest) is forecast for May 2013 [8]. Solar cycle 24 began in January 2009.

However, the number of sunspots in a given solar cycle does not necessarily correlate to the magnitude of the solar storms. Figure 8 illustrates the solar activity over the past 23 solar cycles. The highest magnitude storm in recent memory was August 13, 1989, which occurred in a relatively active solar season. However, both the 1921 storm and the 1859 Carrington Event occurred in cycles with less than the average number of sunspots. This means that fewer sunspots in cycle #24 may not result in a quiet storm cycle. In fact, storms of high magnitude can occur anytime during the cycle [7].

**Figure 7: Sunspot activity from 2000 to February 2011 [7]**

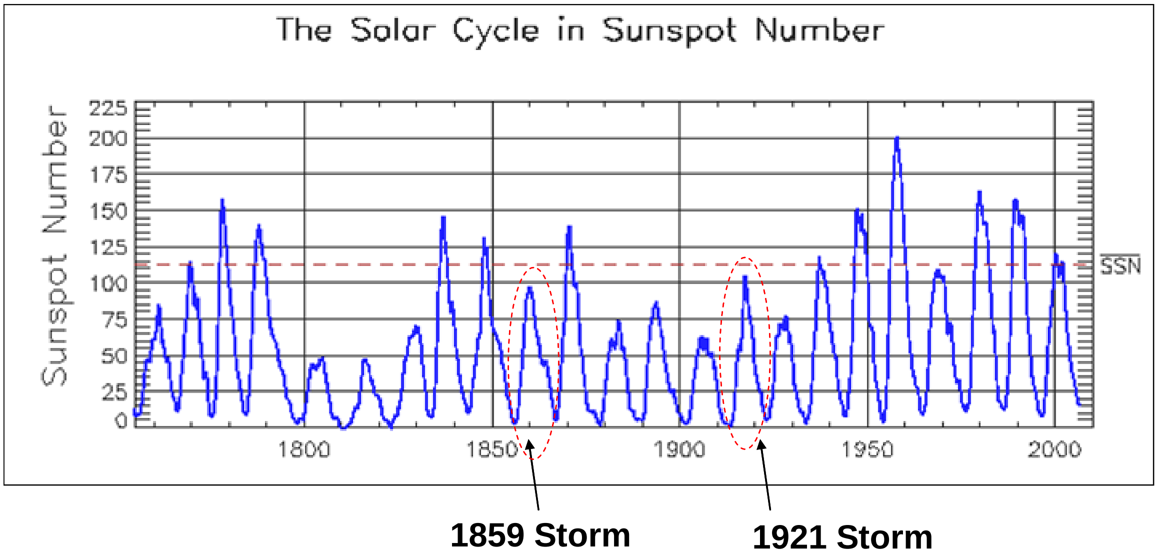



## GIC Monitoring

GIC monitoring is important to understand when and at what level GIC activity is occurring. Absent this information, implementation of GMD mitigating steps for power system operation can be based only on forecasting of solar activity along with real-time magnetometer information. Neither of these sources provides detailed information on GICs when a solar storm is occurring. Actual GIC measurements are extremely valuable because they confirm that a solar storm is occurring and provide a measure of storm severity [9].

Comprehensive GIC monitoring examines not just GICs as they occur (i.e., DC currents), but also their impact on the grid in the form of harmonics, VAR consumption, losses, and transformer heating. This provides additional information on the impacts of affected transformers and the grid. Archiving the monitored GIC data allows for evaluation of equipment susceptibility to GICs and for post-event analyses to review misoperation of system protection or equipment failures. Post-event analysis is also useful for reviewing and refining operating procedures in light of recent solar storm experience [9].

**Figure 8: Solar cycles with fewer sunspots do not necessarily result in less severe storms [7].**



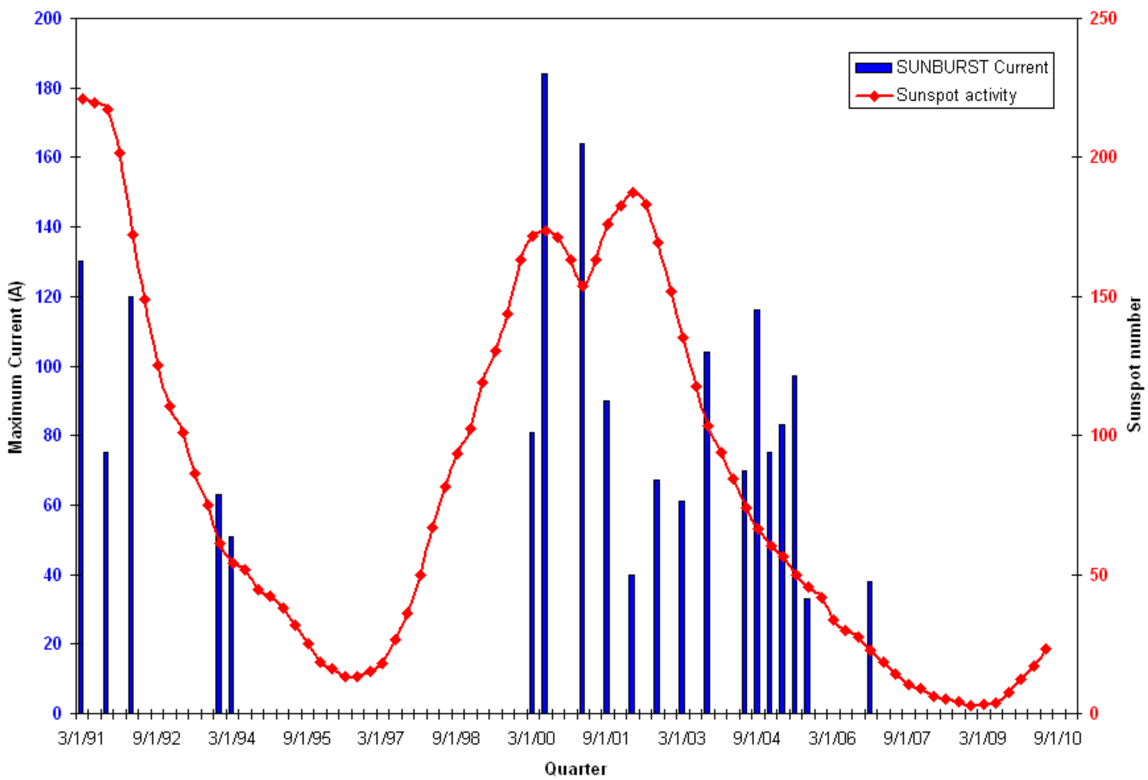

The EPRI Sunburst Network is an example of a collaborative, nearly real-time GIC monitoring system that collects data from participating utilities and then makes the GIC data available online. After the 1989 Quebec blackout, EPRI collaborated with utilities to install this small research monitoring network to collect data on GICs. Sunburst gathers data such as transformer phase currents, voltages, neutral currents, and hotspot temperatures, as well as electric and magnetic fields. Power system operators can view this GIC data during a solar storm and the sharing of GIC data provides a large area view of the storm (beyond a regional transmission system). Monitoring equipment alarms can be set for utility Supervisory Control and Data Acquisition (SCADA) systems. The Sunburst network provides automated e-mail alerts to system operators when a GIC event occurs (i.e., with more than two monitoring sites recording significant GICs on the system) [10].

Using the Sunburst network data, utilities can monitor their own GIC values in real time online and compare Earth currents for many other sites to gain a perspective concerning the magnitude and proximity of any unfolding solar storm. A utility’s own monitoring sites enable them to read real-time harmonics from its transformers. This enables the utility to determine exactly when transformer half-cycle saturation occurs and when there is danger of damage. Pooling resources in a collaborative effort creates a core team that can maintain the power system and provide updates and alerts. In addition, Sunburst generates substantial new insights into how GICs progress during a solar storm – and how this data relates to prior observations from satellites or solar observations or predictions [11].

EPRI established the Sunburst Network in 1990, and the system recorded data over a period of nine years, from late 1990 to 1999, encompassing the end of solar cycle 22 and the start of solar cycle 23. In the year 2000, the network was upgraded and new data acquisition equipment was installed to provide a near real-time, online data feed to the central server. The updated system came online in spring 2000, in time to provide warnings and record GIC activity during strong solar storms that occurred on April 6-7, 2000 [12]. The system has operated continuously since that time, capturing data for the Halloween storms of 2003 for example.

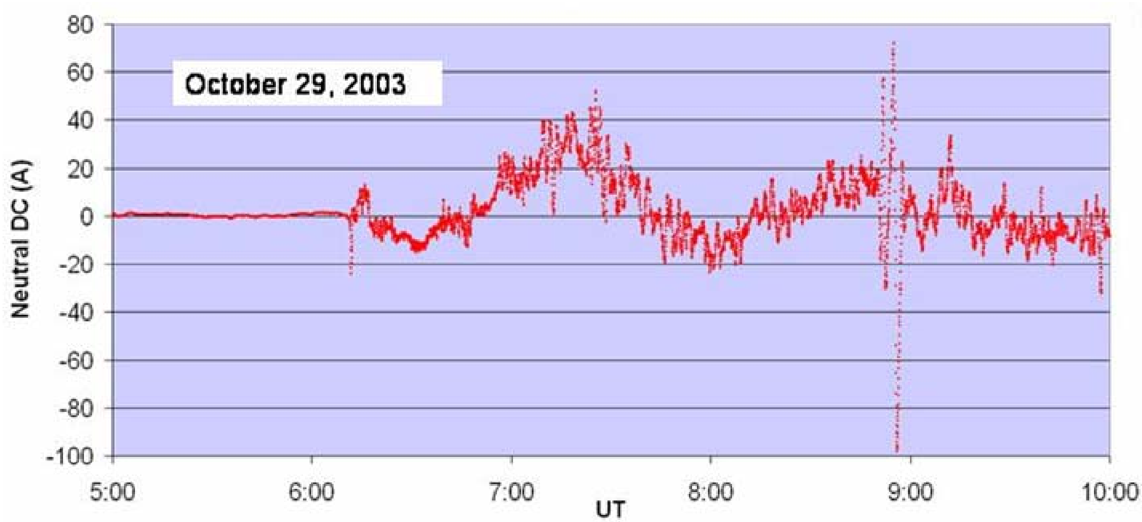
Figure 9 plots Sunburst maximum neutral currents over the last two solar cycles on top of a plot of sunspot activity during the same period. In the figure, the number of sunspots is on the right hand axis and the left hand axis is the current amplitude (the maximum measured during the event) of the storms. This plot shows that in these two recent solar cycles, the storms of any measurable magnitude *have* occurred during the storm season. The plot also shows that the major storms tend to occur on the back end, or downward slope of the storm cycle [11].

**Figure 9: Sunburst Network maximum neutral currents and sunspot activity for the last two solar cycles [11]**




Examination of a typical GIC event plot captured through Sunburst (during the Halloween storms of 2003) provides various insights (see Figure 10). For example, while the event lasts five hours or longer, the large amplitude spikes (+75 and -100 amps) are of short duration. Preliminary analysis concludes that these spikes have little impact on transformer heating due to long thermal time constants. A second observation is that there is a relatively long time period from 6:50 to 7:40 during which a modest GIC of about 15 A flows. Currents at his level add to the heating of the transformer, but probably not to overheating. Transformer overheating is a function not only of the GIC magnitude and duration, but also the type of transformer and initial loading. One goal of the industry project is to develop sets of curves for types of transformers. For each type of transformer, the project aims to determine the estimated time to overload based on initial loading and GIC characteristics. A third observation is that the current changes direction from time to time during the event. A typical GMD phenomenon, the changing polarity has no relevance to saturation or heating [11].

**Figure 10: Sunburst Network measurement of GIC during the Halloween storms of 2003 [11]**




## Enhanced Space Weather Forecasting: Solar Shield

NASA and EPRI have collaborated to advance the field of space weather forecasting. "Solar Shield" is a NASA Applied Sciences project between the NASA Goddard Space Flight Center and EPRI. The goal of the three-year project is to design and establish an experimental forecasting system that can be used to help mitigate GIC impacts on high-voltage transmission systems. Solar Shield uses large-scale models that are based on first principles and hosted at the Community Coordinated Modeling Center (CCMC), which operates at the NASA Goddard Space Flight Center [13].

The Solar Shield project identified two-level forecasting system requirements, which led to development of two partly separate experimental forecasting products. The level 2 product, which provides a 15-60 minute lead-time, is based on *in situ* Lagrangian L1 point solar wind observations and magnetospheric magnetohydrodynamic (MHD) simulations. This means that the product is completely deterministic. The level 1 product, which provides a 1-2 day lead-time, is based on remote solar observations and heliospheric MHD simulations. As a result, the level 1 forecast is partly probabilistic [13].

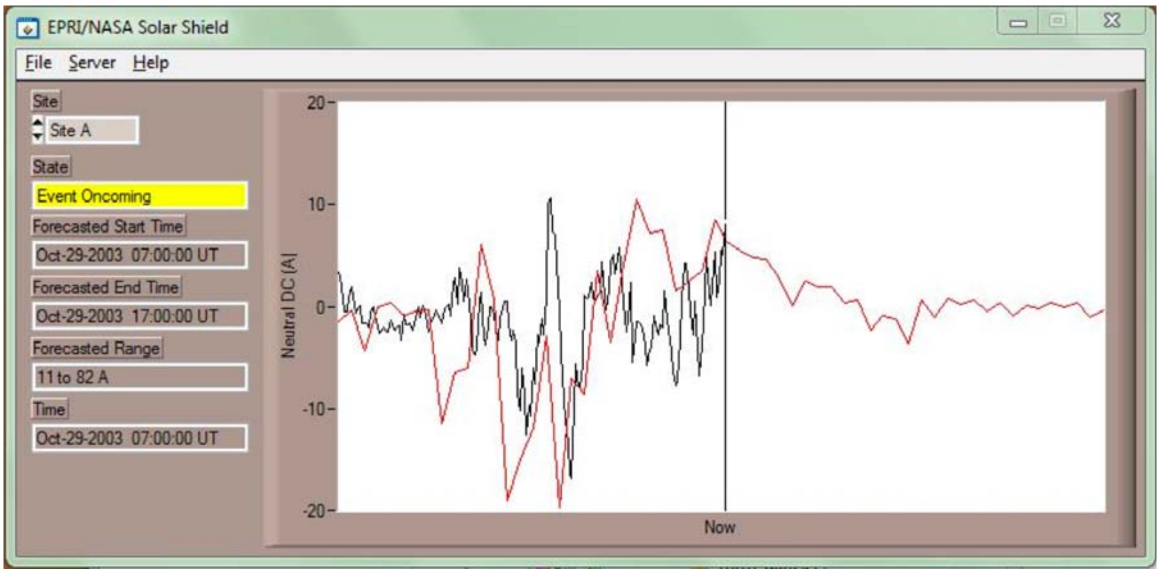
To generate level 2 GIC forecasts, Lagrangian L1 point solar wind observations from the NASA ACE spacecraft are used as inputs to a global magnetospheric MHD model. The team then uses the ionospheric current output of the MHD model to compute the GIC at individual transmission system nodes. The final output of the system is a text file of GIC forecasts, which is uploaded to the EPRI Sunburst Network. Participating utilities and other entities can access this network [13]. The level 2 part of the system is currently only applicable to high-latitude locations. The project team recommends extending the forecasting system to cover lower latitudes in order to apply this approach to the U.S. power grid [14].

To generate level 1 GIC forecasts, the team inputs observations of solar CMEs to a heliospheric MHD model. The model then forecasts the interplanetary conditions at the Earth's orbit as a result of the CME. The team applies a NASA algorithm to these conditions to produce GIC forecasts at individual nodes of the power grid. Like the level 2 approach, the final output is a text file of GIC forecasts. These are also uploaded to EPRI's Sunburst Network [13].

The Solar Shield system has been running in real time since February 2008 [15]. Figure 11 shows a sample screen from the Solar Shield user interface. The left-hand side shows the level 1 forecast in the form of four data fields (e.g., forecasted start time and end time, etc.). The graphic on the right of the screen shows how the level 2 forecast compares to the observed GIC up to the "now" line, and then simply shows the forecast only to the right of the "now" line.

The EPRI Sunburst GIC dataset plays a critical role in the establishment of the forecasting system. The Solar Shield project team recommends installation of new GIC monitoring sites especially. This would enable expansion and increased utility of the newly developed GIC forecasting system [14]. Further development with DHS support is now underway [15].

**Figure 11: Screen capture from EPRI/NASA Solar Shield showing level 1 forecast in data fields at left and level 2 forecast compared to observed GIC in the graphic portion [16].**




## NERC GMD Alert Dissemination

The primary source of information for space weather is NOAA's SWPC. The SWPC issues a variety of warnings, alerts, and watches (some of which are summarized below) on space weather. NERC has established an approach for disseminating information relevant to power system operation provided by the SWPC to Reliability Coordinators (RC), Balancing Authorities (BA), and Transmission Operators (TOP). This section summarizes this process.

## SWPC Alerts, Warnings, Watches

The STEREO satellite observes CMEs about eight minutes after they occur (because light travels the distance from the sun to STEREO in about eight minutes). When large solar flares are observed, SWPC issues solar flare radio blackout alerts. SWPC forecasters analyze observed CMEs to determine if they are directed toward the Earth, their speed, the anticipated strength of their impact on Earth, and the anticipated duration of the storm. The speed of the solar energetic particles (SEPs) ejected by CMEs varies, but the average speed is about one million miles per hour (1.6 million km per hour). Because the distance between the sun and the Earth is about 93 million miles (150 million km), SEPs can take about 93 hours (about four days) to reach Earth, although significantly faster SEPs have been recorded (arriving as soon as 15 hours after ejection) [17]. This travel time allows some time for a forecasting process that can be based only on visual observation of the flare [18].

The SEPs pass the SOHO and ACE satellites at the L1 Lagrange point about 1 million miles from the Earth. At a speed of 1 million miles per hour (1.6 million km per hour), this occurs about one hour or less before the SEPs reach the Earth. The SOHO and ACE satellites obtain the first actual measurements of the solar wind speed, temperature, density, and magnetic field associated with the SEPs. Based on this information, if SWPC deems that a significant geo-magnetic storm is possible, it issues a geo-magnetic storm watch and subsequently, sudden impulse warnings.

SWPC may also issue geo-magnetic Kp-index warnings, based on the expected storm strength, and Kp-index alerts as Kp-index thresholds of 6, 7, and 8 are crossed. The Kp-index ranges from 4 to 9, indicating storms of increasing intensity (see Table 1).[14] At the low end of the scale, a Kp=5 storm is characterized by a 70-120 nT intensity, and weak power grid fluctuations are expected to occur. At the high end of the scale, a Kp=9 storm is characterized by a >500 nT intensity. In this case, "widespread control problems and protective system problems can occur; some grid systems could experience complete collapse or blackouts; and transformers could experience damage." The NOAA G-scale simply assigns a convenient scale of storm strength from G1 ("minor") to G5 ("extreme") to Kp index storms of 5-9, respectively, for simplicity [18,19].

## NERC Alert Dissemination

To provide the power industry with the information needed to prepare for GMDs, NERC has established the Geo-magnetic Disturbance Alert System [23]. NERC has designated the Midwest ISO's (MISO) St. Paul, Minnesota office and Western Electricity Coordinating Council's (WECC's) Reliability Coordinators in Vancouver, WA and Loveland, CO as the focal points for information dissemination. The SWPC sends information to these offices, as well as the New York ISO, which in turn forward it to RCs, BAs, and TOPs. (The RCs can then coordinate actions between TOPs, BAs, and generator operators.) The Midwest ISO handles the Eastern and ERCOT Interconnections, and the WECC RC handles the Western Interconnection. Together, these three Interconnections cover all of the U.S. and Canada, except the Hydro-Québec TransÉnergie Interconnection (see Figure 12). The latter receives information from the Solar Terrestrial Dispatch Center (STDC) in Canada. STDC backups include the SWPC and the Geological Survey of Canada of the Department of Natural Resources Canada (NRCan) [20,24].

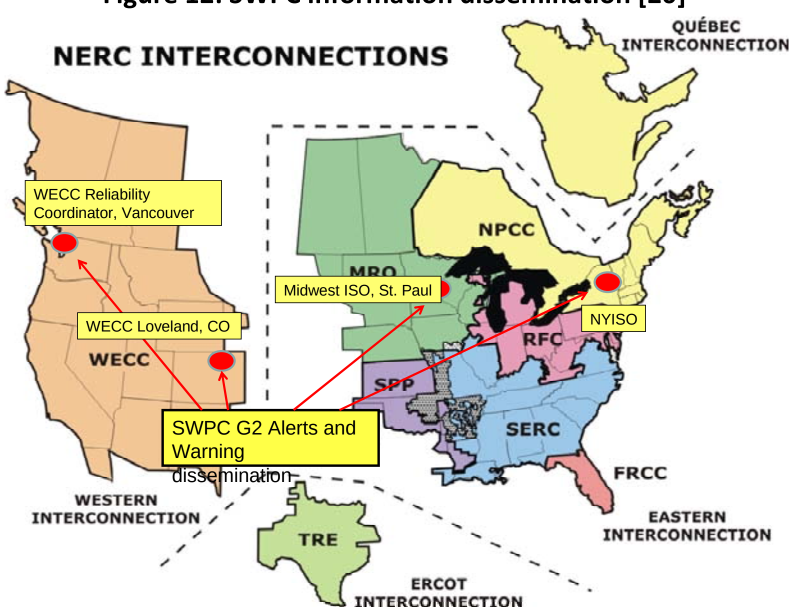
[14] The Kp index is a weighted average of K indexes from a network of geomagnetic observatories. K indexes actually range from 0 to 9, but only Kp indexes between 6 and 9 generate alerts. The K index itself is "a code that is related to the maximum fluctuations of horizontal components (nT) observed on a magnetometer relative to a quiet day, during a three-hour period." The conversion between K index and maximum fluctuation (nT) varies from observatory to observatory. The nT levels above are for the Boulder, Colorado magnetometer [19]. While the index has been in use since the 1930s, the NERC HILF report points out limitations to the K Index. These include its saturation at K9 (which corresponds to only a 500 nT variation), its determination only one in each three-hour period, and others [21]. In a recent presentation at the GMDTF meeting, SWPC indicated that its partners will be investigating alternatives to the K indexes that "extend the disturbance scale up to larger values to avoid saturation." [22]

**Table 1: K Index, G Scale, and severity of potential power system impacts [20]**

| K-Index | Severity | Power System Impacts |
|---|---|---|
| Kp=5 | G1 (minor) | Weak power grid fluctuations can occur. |
| Kp=6 | G2 (moderate) | High-latitude power systems may experience voltage alarms; long-duration storms may cause transformer damage. |
| Kp=7 | G3 (strong) | Voltage corrections may be required; false alarms triggered on some protection devices. |
| Kp=8 | G4 (severe) | Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. |
| Kp=9 | G5 (extreme) | Widespread voltage control problems and protective system problems can occur; some grid systems could experience complete collapse or blackouts. Transformers could experience damage. |

In May 2011, NERC issued an Industry Advisory on Preparing for Geo-Magnetic Disturbances, as well as a companion document that provides background on the alert [18,24]. These documents provide more information on the subject summarized above. The Industry Advisory also includes "Advisory Actions" that each entity should consider and "determine which of these actions are best suited for their system, considering their own system topology, location, ground resistivity, equipment susceptibility to GIC, and experience with past GMD events." [24] Section 4 of the present report contains more information on these Advisory Actions.

**Figure 12: SWPC information dissemination [20]**



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# Impacts and System Vulnerabilities

## Introduction

This section describes known impacts of GMDs on power grids and summarizes the relative vulnerability of various different types of grid equipment. GICs can saturate transformer cores and cause internal heating that may lead to loss of transformer life or failure during a solar storm. The impacts are not confined to the transformer itself, but can affect the stability and power quality of the grid through significant increases in reactive power demand and distortions of the alternating current. Potential effects include overheating of auxiliary transformers, misoperation of protective relays, heating of generator rotors [1], and possible damage to shunt capacitors, static VAr compensators, and harmonic filters for high-voltage DC lines. Grid operations may also be impacted by solar storm effects on GPS systems and communications [2].

## Overview of Grid Equipment Susceptibility

One of the more comprehensive, recent studies that documents computer modeling of power system susceptibility to GMDs is a 2010 series of reports prepared for Oak Ridge National Laboratory (ORNL) by the Metatech Corporation [3]. In the first report in this series, Metatech, demonstrates how geo-magnetic storms affect the power grid based on experience developing computer models over the years. This report explains that the combination of longer line lengths and lower average resistances results in higher GICs for a given geo-electric field strength. This combination of attributes occurs primarily in extra-high voltage (EHV) transmission lines, rather than high voltage (HV) or medium voltage (MV) transmission lines. Hence, these EHV assets, which play a critical in bulk power transfer across North America, are more susceptible to GICs than the HV and MV transmission and distribution system [4].

According to the report, the same trend applies to transformers. Because EHV transformers tend to exhibit lower winding resistance than HV or MV transformers, a higher GIC will result in the higher voltage transformers than the lower voltage ones, for a given geo-electric field strength. Like their transmission line cousins, these high voltage transformers are crucial to the reliable operation of the bulk power transmission system. In fact, [4] asserts that the “flow of GIC in transformers is the root cause of all power system problems, as the GIC causes half-cycle saturation to occur in the exposed transformers.”

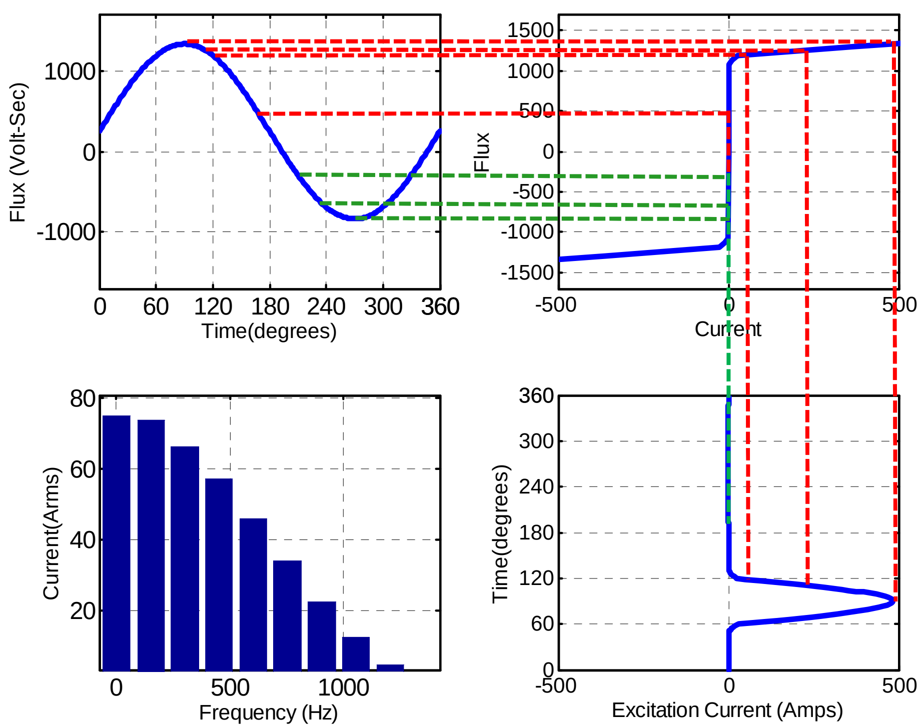
## The Root Cause: High Voltage Transformer Half-Cycle Saturation

At the most basic level, a transformer consists of primary and secondary windings coupled via a magnetic core. Currents flowing in the windings produce alternating flux in the transformer core, and this time-varying flux provides the coupling between windings that results in the transformer action – stepping voltage up or down depending on the turns ratio.

When GICs flow through the transformer windings, they create a flux offset in the core. With sufficient offset, the crests of the flux waveform can exceed the saturation level of the ferromagnetic core material. The ease with which this saturation occurs depends on the B-H[15] characteristic of the core material and, more importantly, the transformer core-winding construction.

The process of semi-saturation is illustrated in Figure 13 for a GIC level of 75 Amps. As shown in Figure 13 the GIC causes an off-set in the flux waveform, thereby increasing the flux waveform in the positive half cycle and decreasing the waveform in the negative half cycle. The resulting excitation current can be constructed by mapping the resulting flux waveform to the saturation characteristic of the transformer. In the positive half cycle there is a significant increase in excitation current which corresponds to the point at which semi-saturation occurs. Due to the flux being offset, the exciting current during the negative half cycle is negligible. Semi-saturation results in a significant increase in 60 Hz and harmonic components of the exciting current. The 60 Hz component of the exciting current results in an increase in the VAr demand of the transformer.

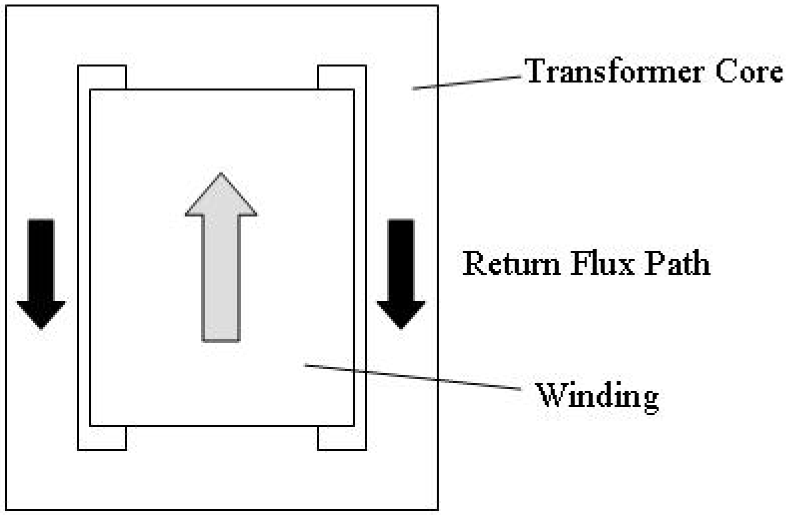
**Figure 13: Transformer Semi-saturation Caused by a GIC**




Single-phase transformers are the most vulnerable to semi-saturation because the DC flux has a low reluctance path through the core, as shown in Figure 14. Thus, semi-saturation can occur for relatively low levels of GIC.

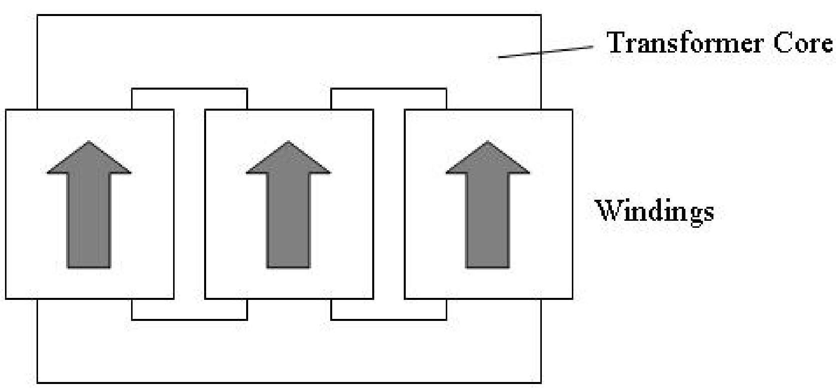
[15] The B-H characteristic (also called the magnetization curve, BH curve, or hysteresis curve) is a graph of the magnetic field B as a function of the magnetizing field H.

**Figure 14: Single-phase shell or core form transformers are most susceptible to Saturation from GICs due to the low reluctance return path for DC flux [4].**




The transformer type that is the least susceptible to semi-cycle saturation from GIC is the three-legged core-form transformer, as shown in Figure 15. With equal GIC on each phase winding, the DC flux is all in the same direction, and there is no low reluctance return path in the core – the flux must return in air. Hence, a large GIC magnitude is needed to saturate the core in the winding area for this type of transformer construction.

**Figure 15: Three-leg, three-phase, core-form transformer type is least susceptible to saturation from GICs [5]**




Depending on the return flux paths that the core construction provides, other transformer types are between the single-phase transformer and the three-legged three-phase core-form transformer in terms of vulnerability to GIC-caused semi-cycle saturation. In order of decreasing susceptibility to saturation, the other transformer types are seven-leg shell-form, three-phase conventional, and five-leg core-form (All of these are three-phase transformers). In a bank of single-phase transformers, saturation occurs in each phase independently. Saturation effects are more complicated in three-phase transformers due to the common flux paths in the core. For certain three-phase core-types, it is possible for the individual phase waveforms to be distorted differently.

When semi-cycle saturation occurs in a transformer, there are three main negative impacts: harmonics, heating, and increased VAr consumption (see Figure 15).

***Harmonics*****:** Semi-cycle saturation of the core produces all harmonics with magnitudes decreasing with harmonic order. These harmonics can cause mis-operation of protective relays, overloading of capacitor banks, and heating in generator rotors.

***Heating*****:** During semi-saturation, magnetic flux extends out beyond the core into parts of the transformer where it would normally be negligible. The fringing fields can produce eddy current heating and magnetization losses, potentially causing localized hot spots in a transformer. The localized heating may cause damage to insulation, windings, leads, bracing, and tank walls. The heating may also cause gassing of the transformer oil. At the least, the localized heating causes accelerated aging of the transformer.

***Increased VAr consumption*****:** Semi-cycle saturation in effect reduces the magnetizing reactance of the transformer thereby significantly increasing the 60 Hz component of the exciting current. This causes the transformer to appear as an inductive load on the transmission system. The resulting MVAr demand is dependent on the level of GIC and transformer type. During a solar storm, this increase in reactive loading can lead to voltage depression and in the worst case scenario, can disconnect transmission lines, initiate load shedding, or lead to system voltage collapse.

Generally, measured DC neutral current and the key indicators of saturation –harmonics and changes in transformer VArs – go hand in hand. Monitoring of DC neutral current provides a direct measure of GIC (except for autotransformers), but utilities can also monitor the impact of GICs by measuring at least the second harmonic of one phase on each side of a transformer.

The preferred method is to measure all phase currents and voltages with sufficient phase accuracy to calculate real and reactive power (VArs) for the transformer. Not only does this level of monitoring provide a view of the GIC impact during a solar magnetic disturbance, but it also provides information on transformer vulnerability. For example, this level of monitoring can help answer questions such as the following:

- At what level of GIC does saturation start?
- Is the transformer being heated?
- What is the transformer VAr consumption as a function of GIC?
- What level of harmonics is created as a function of GIC?

## How GIC Flows on the Grid

GICs are the result of magnetic field induction in the transmission lines. Time varying magnetic fields induces an electric field. The magnitude of the electric field is a function of the earth conductivity structure of the earth, with lower conductivity resulting in higher electric fields. The resulting field induces a voltage in the transmission line via Faraday's Law [7],

$$V = \oint \vec{E} \bullet d\vec{l} \tag{1}$$

where E is a vector representing the electric field, and dl is a vector representing the incremental length and direction of the transmission line. For most transmission lines, (1) can be estimated with reasonable accuracy using (2) [8],

$$V = \vec{E} \bullet \left\{ \vec{P}_2 - \vec{P}_1 \right\} \tag{2}$$

where, $\vec{P}_1$ and $\vec{P}_2$ are vectors corresponding to the positions, with respect to a fixed reference, of each end of the line. For GICs to flow in a transmission line, both ends of the transmission line must be connected to grounded transformers as shown in Figure 16.

**Figure 16: Conducting path for GICs due to grounded wye connections at both ends of a transmission**

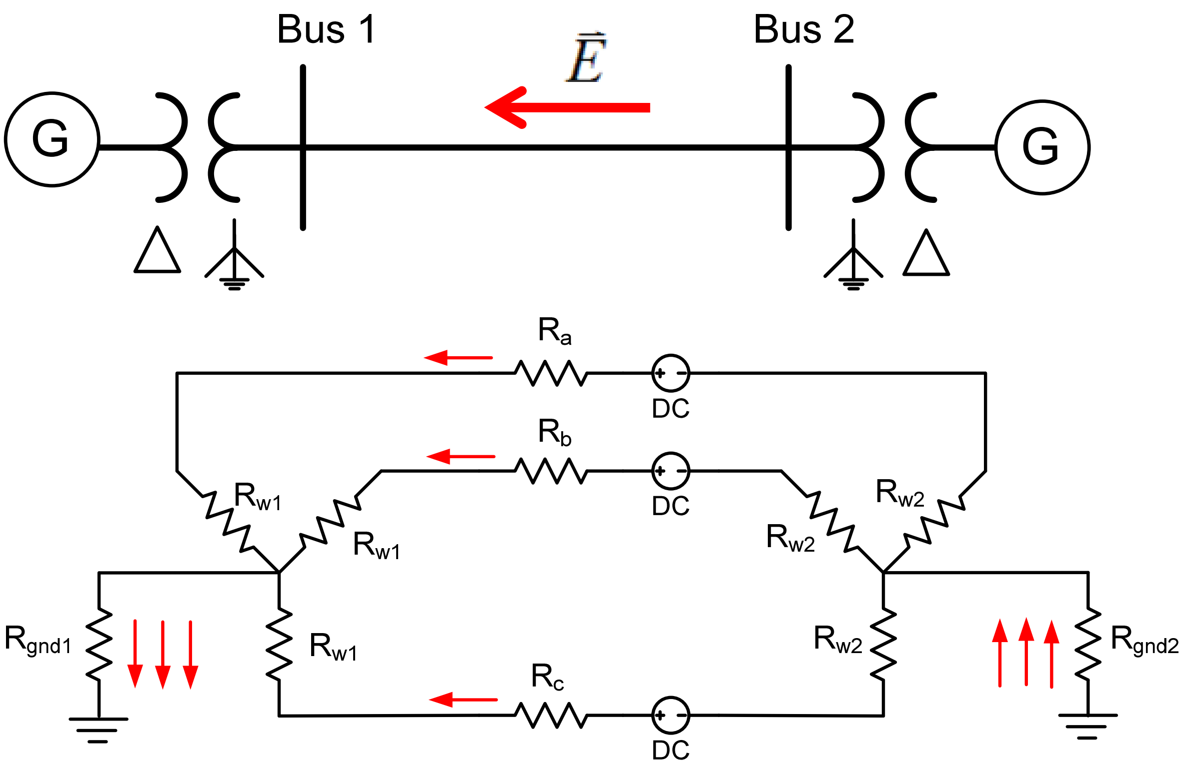
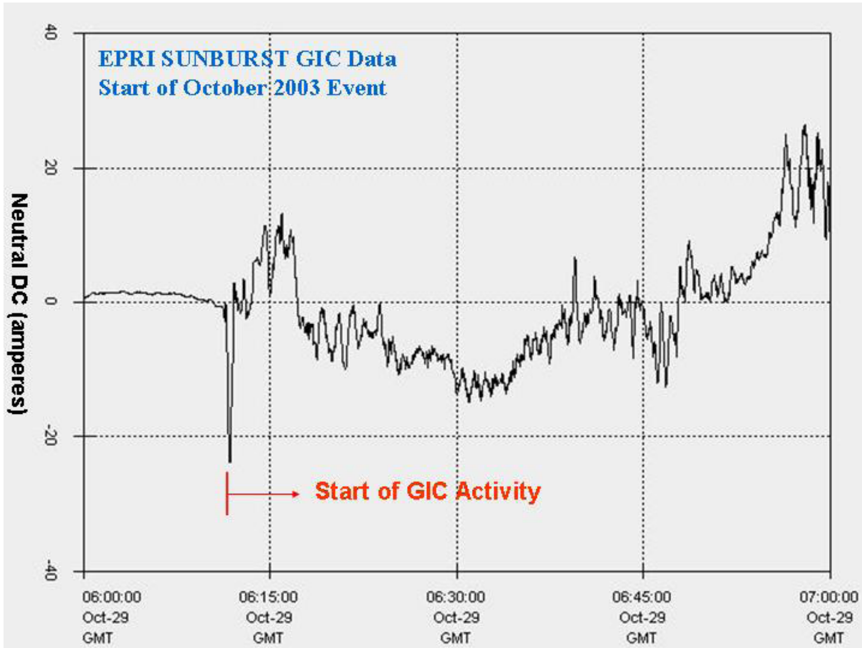



Figure 17 is a time plot showing measured GIC from the Sunburst network recorded during the start of a solar storm that occurred at the end of October 2003 (called the "Halloween storms"). Grid lines are at 15 minute intervals. The illustration shows that the GIC phenomenon is transient; albeit quite slow, with time scales on the order of tens of seconds to minutes. The plot also shows that GIC levels can swing dramatically from a peak in one direction to a peak in the opposite direction within tens of seconds.

**Figure 17: Time plot showing start of GIC activity during the Halloween Storms of 2003 [4]**




From a DC circuit standpoint, the magnitude of GIC current that flows is the induced voltage in the transmission line, divided by the total resistance. With a large interconnected transmission system, how GICs flow becomes a network problem, i.e. one cannot consider each transmission line independently. During a solar storm, the electric field is continuously changing, and hence, not only does the GIC magnitude change continuously, but the direction changes as well. This changing magnitude and direction of GIC is visible in Figure 17.

For a short transmission line, the total resistance of the GIC path is typically dominated by the winding and ground resistances of the transformers. When the line is short, there may be little induced voltage.

Conversely, with a long transmission line, the resistance of the phase conductors becomes the dominant resistance, and the induced voltage may be significant. For example, a 100-km/62-mile transmission line in the direction of a 1-V/km electric field would have an induced voltage of 100-V to drive GIC. Electric field magnitudes during a GIC event typically range from 1 to 6 volts per kilometer (V/km) with continuously varying magnitude and direction.

The Earth's geology plays a significant role in the magnitude of GICs. Electric fields, and hence induced voltages, are largest where the Earth conductivity is lowest, which is typically regions dominated by igneous rock. GIC flow may also be impacted by large bodies of water and the Earth's conductivity at the water boundaries.

To summarize, GICs are quasi-DC (i.e., slow transients with time constants on the order of tens of seconds or minutes) that are driven by induced voltages in the lines and typically change magnitude and direction throughout the duration of the storm. Depending on a transformer's construction, GICs flowing through the windings produce a flux offset that may cause semi-cycle saturation of the transformer core and disrupt normal transformer operation [6].

## Relay Vulnerability

Relay malfunctions are also an area of susceptibility to GMDs.

Some older static or electromechanical relays that protect shunt capacitors and static var compensators operate on *rms* quantities, and do not distinguish between fundamental and harmonic frequencies. Thus, harmonics generated from nearby semi-saturated transformers may cause these relays to misoperate. This removes from the system the valuable contribution of these capacitive devices; they are no longer able to compensate for the increased reactive power demand caused by the GICs. During solar cycle #22, these relay failures contributed to power system problems [4]. Microprocessor based relays utilize signal processing techniques that remove unwanted harmonic content, and; therefore capacitor banks and harmonic filter bank protection schemes that utilize these relays are not susceptible to misoperations caused by harmonics.

Transformer differential relays are vulnerable regardless of relay type. Harmonic restraint is often employed to protect against relay misoperation due to transient inrush currents. The scheme restrains the differential element whenever a particular level of 2nd or 5th harmonic current is measured by the relay. In the case of transformer inrush, this condition is temporary. However, in the case of a GMD event, the situation could last for a considerable period of time, e.g. hours. Depending on how the relay is set and the level of harmonic current, the differential element could be restrained throughout the GMD event. It is important for the relay engineer to evaluate the sensitivity of harmonic restraint settings to GMD events.

## Increasing Vulnerability to Reliability

Early in Section 1, the present report summarized some reasons why the North American power system may be becoming more vulnerable to GMDs. These include the ten-fold increase in EHV transmission miles, higher transmission voltages, longer interconnected lines (e.g., across national borders), and the more recent slowing of transmission expansion, pushing these systems to operate closer to their limits. A closer look at this concept reveals more insights into why today's power system may be more vulnerable than the system of even two or three solar cycles ago.

As explained in the ORNL report, voltage regulation plays a key role in assessing increasing vulnerability of the EHV transmission systems to GMDs. Increasing power transfers on the transmission network in recent decades have reduced reactive power reserves. To address this, power systems have added voltage regulation resources (e.g., shunt compensation) locally. In some cases, the margin of stability has been reduced, according to the ORNL report authors. This means that a relatively minor voltage disturbance, if not identified and mitigated appropriately, could cause instability not only locally but could propagate across wide area power systems [4]. While procedures are in place to mitigate voltage disturbances that occur periodically on power systems from a variety of sources, GMDs pose another potential source of voltage disturbance.

## Timing of Vulnerability

Would a GMD of given severity produce more severe impacts when power systems are operating at peak load or at light load? While one might think the answer is the former, at least one industry expert believes it is the latter. At a workshop in 2008, Executive Director of Systems Operations at PJM Interconnection Mr. Frank Koza opined that a period of light load with high power transfer patterns is when the power system is most susceptible to GMDs. The reason is that failure of multiple facilities in this scenario would leave few mitigation options. Conversely, failure of the same number of facilities at peak load would be less impactful because almost all generators are running, and the contingencies could be mitigated using various emergency procedures and well-established practices [10].

This light load scenario tends to occur in the middle of the night in the spring and fall. This is of concern because evidence shows that GMDs are more likely to occur in the spring and fall than the summer or winter [11].

## Potential Impacts if the 1921 GMD Occurred Today

Modeling of power grids and the impacts of GICs on power grid equipment has advanced to the point that analysts may be able to estimate the potential impact on the present power grid if a storm the likes of the 1921 GMD were to occur today. As related previously, estimation of the 1921 and 1859 storm activity, the resultant surface gradient, and GIC impact is difficult due to inadequate monitoring at the time of the older storms.

In the ORNL report, Metatech performed a modeling analysis of EHV transformers based on their understanding of historical storm magnitudes. The authors assumed a 4800 nT/min storm at a 50-degree latitude with a homogeneous east-west direction and all lines in service. The minimum GIC amount that causes transformers to fail or incur damage is uncertain. According to the Metatech authors, older transformers may be vulnerable at 30 amps per phase or higher; modern transformers may be vulnerable at 90 amps per phase or higher. To address this uncertainty, Metatech ran analyses at each level. Only the more conservative 90 amps per phase amount are examined here [12].

This particular study concluded that about 20 percent of 345-kV transformers (214 transformers), 28 percent of 500-kV transformers (137 transformers), and 32 percent of 765-kV transformers (17 transformers) were likely to fail or be damaged under this storm scenario. This represents a total of over 350 failed or damaged high-voltage transformers across North America in a short period of time (e.g., a few hours or days). Of these, the study estimated that a total of 94 generator step-up transformers in the northeastern region of the U.S. would be at risk of failure or damage. This is significant because loss of these transformers would not only impair transmission in this region, but also deprive the region of base-load power generation from large power stations in the area. In addition, the study estimated that such as a storm could place an additional almost simultaneous demand of over 100,000 MVArs on the power system [12].

The thermal response of the transformers was not evaluated as part of the study. Additionally, the system response and potential operator intervention was not considered. Further research is warranted.

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# Mitigation: Operating Procedures

## Introduction

This section summarizes Advisory Actions relevant to operating procedures that NERC released in May 2011. This section also summarizes operational procedures that NERC GMD Workshop participants described in April 2011. These included primarily large utilities (BPA, Con Edison, and Hydro One Networks), one Interconnection (Hydro-Québec TransÉnergie Interconnection), and one Regional Transmission Organization (RTO) – the PJM Interconnection). In addition, this section summarizes the results of a preliminary literature review on operating procedures to mitigate GMDs (New York ISO and New England ISO). A brief profile of the geographic location and scope of operations is provided for each of these stakeholders. Together, they represent a cross-section of organizations responsible for operation of large portions of the high-voltage transmission systems in the Northern United States and Canada – geographic areas that are particularly vulnerable to GMDs.

## NERC Advisory Actions

NERC's May 2011 background document for its Geo-Magnetic Disturbance Alert states that "severe GMD events present risks and vulnerabilities that may not be fully addressed in conventional bulk power system planning, design, and operating processes." [1] To help stakeholders address these risks and vulnerabilities, NERC issued one of its Industry Advisories, which are designed "to improve reliability by disseminating critical reliability information and are made available pursuant to Rule 810 of NERC's Rules of Procedure, for such use as your organization deems appropriate." [2] The Advisory contains Advisory Actions that NERC suggests entities consider implementing, "considering their own system topology, location, ground resistivity, equipment susceptibility to GIC, and experience with past GMD events."

The actions are divided into three categories: 1) operations planning actions, 2) real-time operations actions, and 3) long term stakeholder actions. The operations planning actions are intended for the time period after SWPC or STDC *predicts* a severe GMD event (K>6) but before it issues a severe GMD *warning*. The real-time operations actions are the next step in the process. They are intended for the time period after receiving a severe GMD warning (K>6, about 30-60 minutes before storm impact) but before detection of increased GIC levels. The long term actions are intended to prepare for *future* occurrences of severe GMDs. The first two types are summarized in this section of this report; the latter type is addressed in appropriate portions of Sections 3, 5, and 6 [2].

## Operational Planning Timeframe

The NERC Advisory Actions for GMDs in the operations planning timeframe consist of increasing import capability, increasing real and reactive reserves, and increasing attention to situational awareness. Another procedure to consider in this timeframe is suspension of major switching operations [2].

To increase import capability, NERC recommends discontinuing non-critical maintenance work and evaluating postponing/rescheduling planned outage and maintenance. To increase real and reactive reserves, NERC recommends reducing generator loading, and bringing equipment online that can provide reactive power. To increase attention to situational awareness, NERC recommends increasing vigilance for unusual voltage or MVAr variations; monitoring transformers and GSUs for temperature, noise, or dissolved gas increases; and monitoring trips in shunt capacitors and static VAR compensators [2].

## Real-Time Operation Timeframe

The NERC Advisory Actions for GMDs in the real-time operations timeframe consist of increasing reactive reserves and decreasing loading on susceptible equipment; and increasing attention to situation awareness [2].

To increase reactive reserves and decrease loading, NERC recommends bringing additional reactive reserves online, adjusting voltage schedules, reducing power transfers, reconfiguring transmission, and re-dispatching generation. To increase situational awareness, NERC recommends reducing power output at susceptible generator stations with erratic reactive power output, and removing transmission equipment from service if unusual equipment behavior is experienced (assuming the system impacts of removing this equipment have been evaluated).

## Stakeholder Experience: Operating Procedures to Mitigate GMDs

At the April 2011 NERC GMD workshop, various entities described planned or ongoing operating procedures for mitigating GMDs. Some of these actions are consistent with NERC's Advisory Actions, while others represent additional steps that are appropriate for the particular utility. The remainder of this section summarizes operating procedures described at the April 2011 NERC GMD workshop from utilities and power pools (in alphabetical order), as well as the operating procedures identified in the literature review.

### Bonneville Power Administration

Bonneville Power Administration (BPA) is a federal nonprofit agency that markets wholesale electric power from 31 federal hydro projects in the Columbia River Basin, representing about one-third of the electric power used in the Pacific Northwestern U.S. BPA also operates about three-fourths of the high-voltage transmission in its service territory (about 15,200 miles/24,500 km and 260 substations) [3]. As described by Bonneville Power Administration's Don Watkins at the April 2011 NERC workshop, BPA monitors GICs on 12 transformers (primarily 500 kV and 230 kV on the BPA transmission network). The utility measures the DC GIC at the neutral connection, standard hot-spot temperature, and VAR flow through the transformer. System operators can view these parameters on their SCADA displays. BPA is beginning the process of upgrading its monitoring to include harmonic levels [4].

BPA manages GMDs and GICs under existing operating instructions for unusual conditions. When the utility receives a GMD forecast for a major storm (K7 to K9) from the reliability coordinator, BPA reviews operations for vulnerability and implements appropriate actions. Some of these actions involve reducing limits to 90 percent of their normal rating. BPA adjusts the loading on HVDC circuits, for example, to be no larger than the 90 percent range of their nominal rating. Similarly, BPA reduces the loading on interconnections, critical transmission facilities, and critical transmission interfaces to 90 percent or less of their operating security limit [4].

BPA discontinues maintenance work or outages. For example, the utility avoids taking long lines out of service and considers discontinuing maintenance work and restoring out-of-service high voltage transmission lines to service as necessary. BPA also avoids series capacitor outages, because series capacitors block the GIC in compensated lines. The utility ensures that the GIC monitoring equipment is in service [4].

BPA voltage-related actions can include dispatching generation to manage system voltage (as well as tie line loading and to distributed operating reserves). Other voltage-related actions can include reducing the loading on generators operating at full load to provide reserve power and reactive capability. BPA also can bring equipment capable of synchronous condenser operation online to provide reactive power reserve if needed. The utility can consider the impact of tripping large shunt capacitor banks and static VAR compensators, and maintaining dynamic reactive reserves [4].

### Consolidated Edison (NY)

Consolidated Edison Company of New York (Con Edison) provides electric service in New York City and most of Westchester County, and provides natural gas in parts of New York City and Westchester. As described by Con Edison's Sean Eagleton at the April 2011 NERC workshop, Con Edison monitors GIC activity with the EPRI Sunburst GIC severity map and an independent GIC sensor at its Goethals Substation. When the K index is 7 or greater and the utility observes significant GIC activity, Con Edison takes three types of actions to sustain reliability: 1) actions to provide additional operating margin for transformers, 2) actions to provide greater voltage control stability, and 3) actions to maximize system resilience with available resources. To increase operational margin for transformers, Con Edison reduces the normal limits on inter-area and critical transmission lines to a maximum of 90 percent of the normal rating [5].

To increase the margin of stability for voltage control, the utility initiates a variety of actions. It monitors Energy Management System (EMS) MVAR displays for unusual deviations. When appropriate, Con Edison dispatches generation to manage system voltage and tie line loading, and to distribute operating reserve. It places capacitor banks in service, where possible, and evaluates the impact of the loss of transmission shunt capacitor banks. Con Edison also adjusts MVAR dispatch of generators to maintain acceptable voltage levels [5].

To increase the resilience of the system, Con Edison discontinues maintenance work and restores out-of-service high voltage transmission lines to service, where possible. The utility also staffs all major 345-kV transmission substations and stations needed to support in-city (New York City) generation [5].

In the future, Con Edison plans to use active strategies such as using GIC detector and magnetometers to provide reliable alarms and indications for operator use in GMD response procedures. The utility also plans passive strategies for the future, including use of neutral resistor/blocking devices to reduce GIC flow through power transformers. Section 5 of this report provides more information on this mitigation technology [5].

## Hydro One Networks

Hydro One Networks is the largest electricity transmission and distribution company in Ontario, Canada, accounting for about 96 percent of Ontario's transmission capacity (about 29,000 km/18,000 miles) [6]. At the NERC GMD Workshop, Hydro One's Luis Marti described their operational planning approach for GMDs in the form of three levels of response. In each scenario, the company defines an envelope of operation and defines a visual picture of maximum GIC flows. In general, key needs are operator training and real-time simulation. Many of the needed activities can be cost justified through other business drivers besides GMD mitigation. These can include the need for online dissolved gas analysis (DGA) monitoring of assets nearing end of life [7].

Level 1 is standard operational response under a safe posture. Actions in this scenario include managing reactive power fluctuations, increasing spinning reactive reserve, and increasing transmission capacity. The level 2 scenario consists of loss of reactive compensation by protection. Actions in this scenario include determining the sequence of equipment trips and establishing the best configuration/mitigation alternatives. The company would adjust flows according to the location of capacitor banks and SVCs in relation to harmonic sources and the prevailing e-field direction. Hydro One would determine if loss of reactive compensation needs to be predictive or reactive. The level 3 scenario is characterized by imminent equipment loss and relay misoperation. Potential actions include load and generation shedding, artificial islanding, arming special protection systems, and short-term line overloading [7].

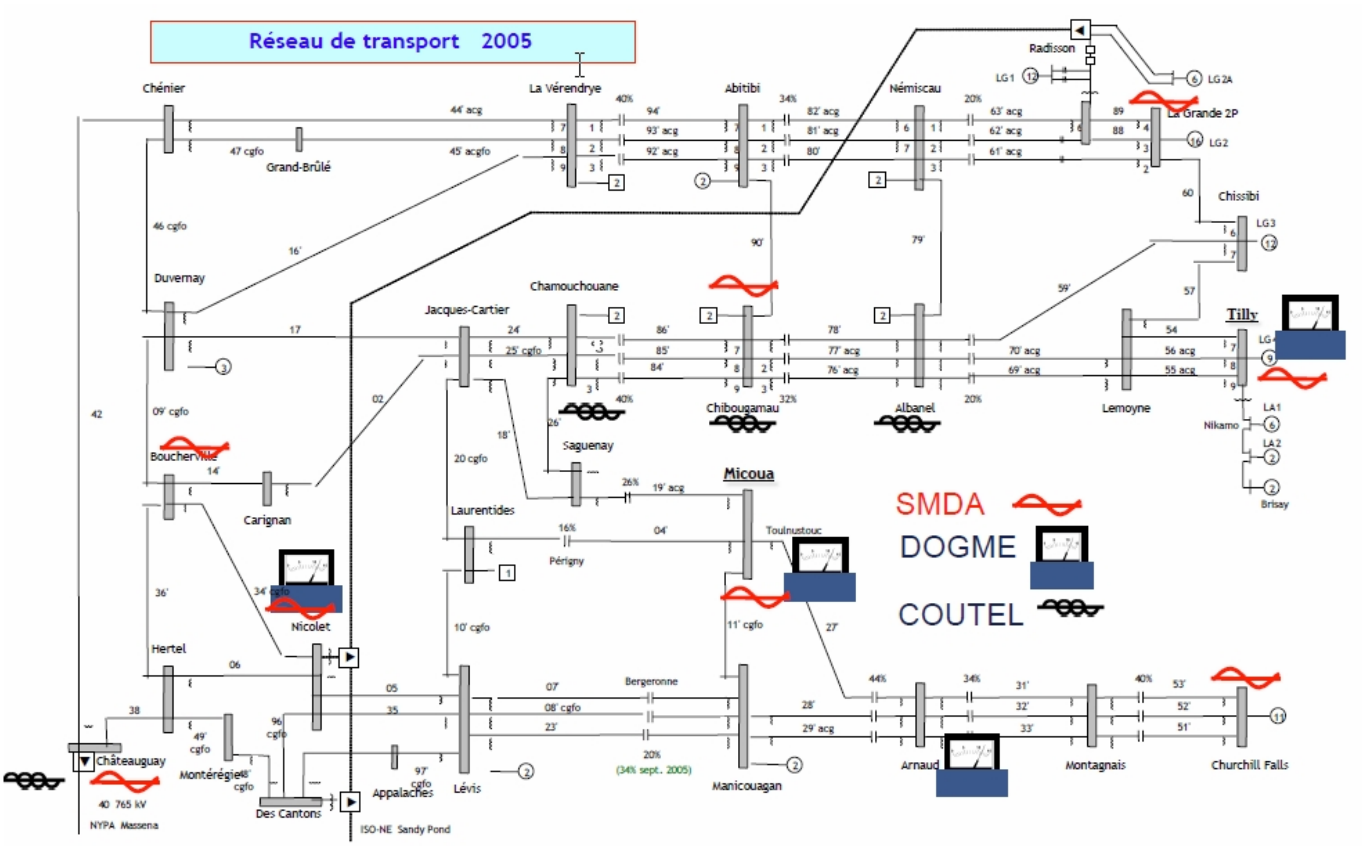
## Hydro-Québec TransÉnergie

Since the voltage collapse of the Hydro-Québec system during the 400-500 nT/minute, K9 storm of 1989, Hydro-Québec TransÉnergie Interconnection's (HQ-TE) Sébastien Guillon explained at the April 2011 NERC workshop that HQ-TE has implemented significant steps to enhance preparation for future GMDs. These have included measures to block or reduce GIC flow; these are described in Section 5 of this report. This section focuses on HQ-TE's GIC measurements and operational procedures [8].

HQ-TE's primary generation (about 95 percent hydroelectric) in the northern end of the service territory serves a peak load of about 40,000 MW that is mainly in the south end of the service territory – about 1000 km/600 miles away. HQ-TE operates the most extensive transmission system in North America (about 32,200 km/20,000 miles and 515 substations). Much of this long distance transmission is 735 kV or higher (about 11,400 km/7100 miles), and voltage control is crucial. HQ-TE measures GIC impacts in various locations. Using a COUTEL measurement system, HQ-TE measures real DC neutral currents and 2$^{nd}$, 3$^{rd}$, and 4$^{th}$ harmonics in transformers at four substations. Using a Solar Magnetic Disturbance Asymmetry- (SMDA) phasor measurement system, HQ-TE measures real voltage fluctuations (voltage asymmetry and harmonics) due to GIC at eight substations. Using a geo-magnetic storm detection system called DOGME, HQ-TE measures even voltage harmonics at four 735-kV substations. Figure 18 shows the locations of these measurement systems in the HQ-TE service territory [8,9].

HQ-TE initiates operator actions if the Kp value is greater than or equal to 8, SMDA measures voltage asymmetry of greater than 2.2 percent, or DOGME measures even voltage harmonics of greater than 2.6 percent. Operator actions include putting series capacitors back online (if they were off-line), and operating Static VAR Compensators (SVC) and Series Compensation (SC) at +/- 50 MVARs. The Interconnection also reduces operating limits based on the grid pattern and reactive sources, and reduces transit in some areas. HQ-TE limits the HVDC link with the Eastern Interconnection to between 40-90 percent with specified configurations [8]

**Figure 18: Locations of three types of GMD-related measurement systems on the Hydro-Québec TransÉnergie Interconnection [8]**




## ISO New England

ISO New England is an RTO that serves six states in the Northeastern U.S. and operates a high-voltage transmission system of about 8000-mile/12,900 km [10]. ISO New England devotes 13 pages of its System Operating Procedures, updated recently (February 2011) to GMD procedures. ISO New England, as part of the Northeast Power Coordinating Council (NPCC), receives GMD status information from the Solar Terrestrial Dispatch Center (STDC) via a notification system called the STD Geo-magnetic Storm Mitigation System (GSMS). This communications software package installed in the RTO control room activates automatically when receiving a GMD storm alert of Kp6 or higher. When STDC predicts at least a 40 percent chance of GMD activity at levels of Kp7 or greater, the Operations Shift Supervisor reviews existing and planned operations for vulnerability [11].

GMD operational mitigation actions include ensuring that GMD monitoring equipment is in service and discontinuing maintenance and restoring out-of-service high-voltage transmission lines. The RTO reduces loading on inter-area ties and other critical lines to at most 90 percent of their nominal ratings. Similarly, the RTO adjusts the loading on the HVDC ties to within 40-90 percent of nominal ratings. The supervisor reviews the availability of static VAR compensators (SVC) and capacitor banks, and considers the impact of tripping large shunt and series capacitors and SVCs. To protect against voltage swings, the RTO maintains system voltages in acceptable ranges, and considers posturing generators to provide additional reserves and reactive capacity. The supervisor can also dispatch generation to manage system voltage and tie line loading, and to distribute operating reserve. The RTO can also bring online equipment that can provide synchronous condenser operation [11].

### New York ISO

The New York Independent System Operator (NYISO) operates almost 10,900 miles/17,500 km of high-voltage transmission lines in New York State [12]. According to the NYISO Transmission and Dispatching Operation Manual, after receiving an alert of K7 or greater, the NYISO implements a variety of actions. These actions include informing transmission owners that they should reduce normal limits to 90 percent of nominal ratings. This applies to both inter-area and internal transmission lines and transformers in the system. The system also reduces real-time commitment/real-time dispatch (RTC/RTD) stability transfer limits and RTC/RTD central east voltage contingency limits to 90 percent of their normal values. Similarly, the NYISO reduces flows on inter-area and internal Secured Transmission System transmission lines to 90 percent of their normal rating. Further, the RTO requests that generators in their system adjust machine excitation to help maintain system voltages in acceptable ranges. When a contingency occurs, the RTO requests its transmission owners to implement appropriate emergency procedures. When the RTO receives an alert of K9 and observes significant GIC activity, the RTO activates its thunderstorm warning cases [13].

The NYISO also requests that its transmission owners implement various actions, including restoring out-of-service transmission facilities, evaluating the impact of loss of facilities, and monitoring SCADA MVAr and voltage displays for unusual variations. The RTO also asks that its transmission owners keep substation capacitor banks in service and evaluate the loss of transmission shunt capacitor banks [13].

### PJM Interconnection

The PJM Interconnection is an RTO that coordinates the movement of wholesale power over about 61,200 miles/98,500 km of transmission lines in all or parts of 13 states and the District of Columbia, ensuring service for more than 58 million people [14]. At the April 2011 NERC workshop, Frank Koza of the PJM Interconnection explained that operators monitor DC current at Missouri Avenue in Atlantic City and Meadow Brook Station near Winchester, Virginia. According to the PJM Interconnection Emergency Operations Manual, if the DC measurement at either station is greater than 10 amperes and operators confirm that this is due to geo-magnetic storm activity by verifying a measurement at a minimum of one other key 500-kV transformer in its service territory, then GMD procedures are initiated. PJM monitors reports received from the SWPC, but receipt of a certain level of storm prediction or warning is not required for PJM to initiate its GMD procedures (see Figure 19) [15,16].

The crux of PJM's GMD procedures is operation of the system to "GMD transfer limits." To determine these limits, PJM's operations planning department group performs studies that model various scenarios. PJM updates these studies seasonally, and PJM operators update them to accommodate current conditions when implemented. The scenarios modeled in the studies include partial or total loss of the Hydro-Québec TransÉnergie (HQ-TE) Phase 2 HVDC line to Sandy Pond, reduction or complete loss of generation at the Artificial Island shown in Figure 20, and tripping of certain EHV capacitors [16].

PJM's actions when a GMD has been confirmed include notification of various members and operation to the reset GMD transfer limits. Dispatchers re-dispatch generation as needed to meet these revised limits, reduce transformer loading, and raise voltage in anticipation of the possibility of capacitor tripping [15]. PJM member actions include providing GIC measurement confirmation, providing advance warning of any necessary restrictive plant procedures, verifying that GIC measurement devices are operating properly, and reporting all actions to PJM dispatchers [16].

## Stakeholder Experience: Common Themes in Operating Procedures

The operational procedures reported by various utilities and RTOs are generally consistent with the Advisory Actions that NERC distributed in May 2011. While specific operations procedures vary considerably, most entities engage in some sort of the following operations with regard to GMD detection and operational mitigation:

- Operators monitor GMD forecasts and alerts from various entities. They also engage in varying amounts of GIC monitoring on their own systems.
- Operators establish criteria in advance for the circumstances in which GMD operational procedures should be implemented.
- Upon receiving forecasts, alerts, or measurements indicating GIC activity, operators ensure that remaining GIC monitoring equipment on their systems is online and functioning properly.
- As their procedures specify and as circumstances warrant, operators then typically perform a combination of actions that include curtailing maintenance on critical assets and returning them to service; reducing operating limits to more conservative levels (usually to 90 percent of normal limits) and re-dispatching; implement various volt/VAR-related actions; and implementing other actions they deem appropriate and necessary.

**Figure 19: PJM Interconnection combines SWPC and system measurements to determine whether to initiate GMD procedures [15]**

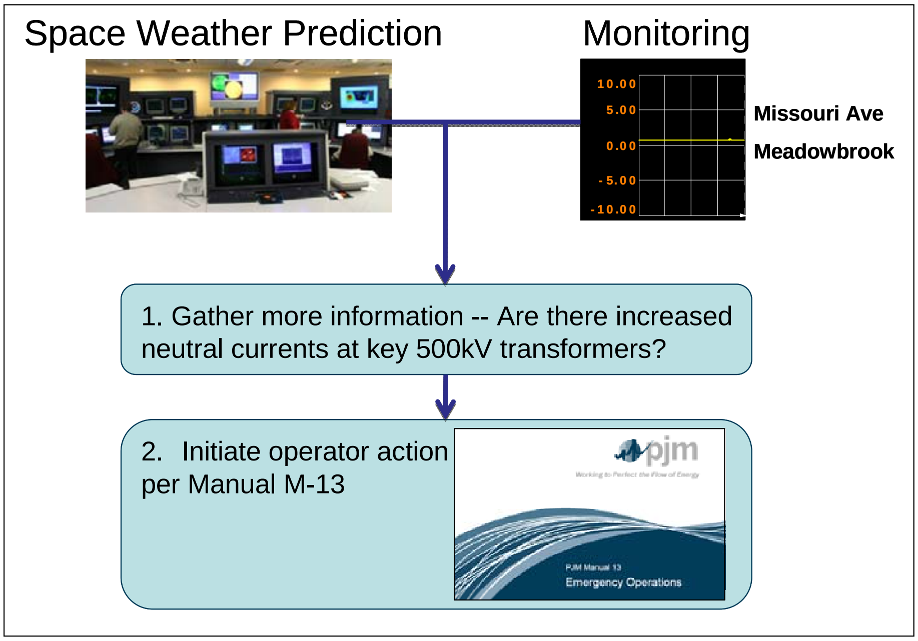
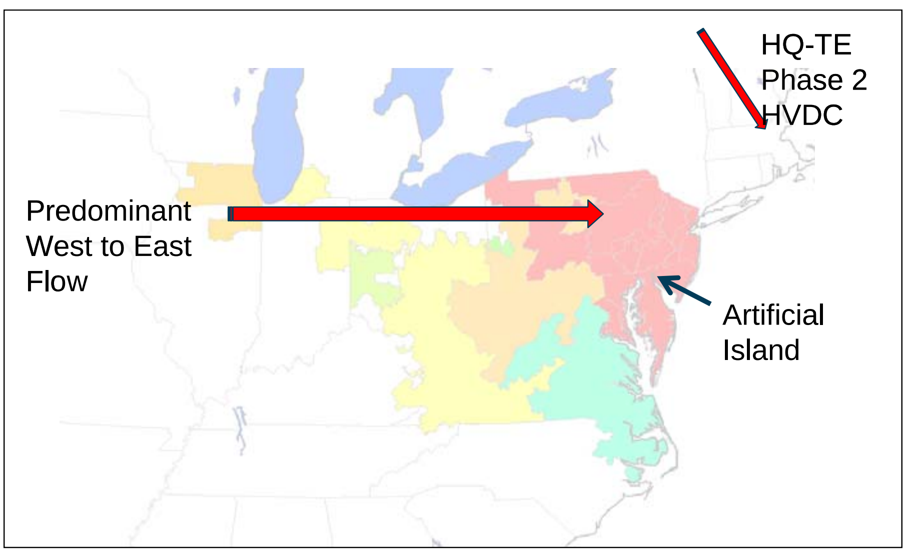


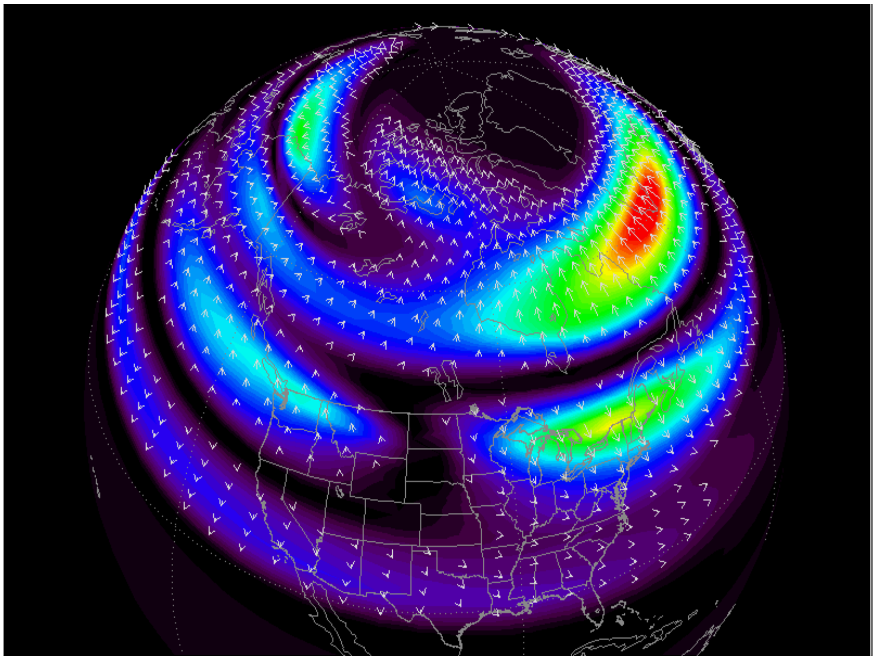

**Figure 20: PJM Interconnection runs studies modeling various scenarios, including loss of the shown HVDC line or loss of generation in the Artificial Island shown, to determine GMD transfer**




**limits [15].**

Another common theme in these operational procedures to mitigate GMDs is situational awareness. A key aspect of improved situational awareness is the availability of proper visualization tools to help operators understand the current GMD situation. Figure -21 shows a synoptic condition map that enables operators to quickly make situational assessments. This map is based on an assimilative model of the storm environment on May 4, 1998. It provides a situational assessment of ground-level GMD conditions [17].

**Figure 21: Synoptic condition map provides situational assessment of ground-level GMD conditions (shown here based on a model of the May 4, 1998 storm) [17]**



## The Process: Implementing New Procedures

The process of implementing mitigation procedures involves work in advance of GMDs, during GMDs, and after GMDs. Basically, it involves a five-step process.

- Determine which procedures suit the particular needs of the service territory.
- Develop detailed system-specific procedures as a function of SWPC alert levels.
- Document these in an easy-to-use form, including operating guidebooks, for energy control center operators and supervisors.
- Train operators on these procedures (and conduct periodic follow refresher training as needed).
- Implement the procedures as appropriate during GMDs
- For major events, perform post-event analysis and refine procedures as needed.

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# Mitigation: Blocking or Reducing GIC

## Introduction

As a complement to operational procedures, this section summarizes approaches to block or reduce GIC flow in transformers and lines to mitigate GMDs. These include series compensation, use of blocking capacitors in the neutral ground, and use of neutral resistors to reduce GIC flow. Experience at an Interconnection is illustrated, and the latest recommendations for optimal methods are summarized.

## Methods of Blocking GIC Flow

A 2008 EPRI report summarizes methods of blocking GIC flow in transformers [1]. The most fundamental approach, though not necessarily practical based on system considerations, is to block the path of GICs. This would involve either the elimination of one of the two neutral ground connections at either end of a transmission line, inserting series compensation on the connected transmission lines, or use of a blocking capacitor in the neutral-ground connection. With any of these options, GICs cannot flow through the transformer windings, and the problems caused by semi-cycle saturation – namely harmonics, heating, and VAR consumption – are eliminated. Implementation of any blocking solution should be accompanied by a system study, since elimination of GICs on one transmission line may significantly change the GIC impact to other parts of the system and can influence system operations. In other words, GICs should be viewed as a network problem.

Figure 22 shows a transmission line that is wye-connected at the left, and delta connected at the right. Because the transmission line is only grounded at one end, there is no path for GICs to flow. The most significant difficulty with this potential countermeasure is that single-phase autotransformers are the transformer of choice for bulk transmission at high-voltages due their high efficiency and low construction cost (with the shared winding). Autotransformers are nearly always neutral-grounded to limit over-voltage problems. Thus, not only do they provide a ground connection for GICs, they also provide a through-path for GICs to flow from the high-side transmission line to the low-side transmission line, or vice versa.

Even if autotransformers are not used, a topology for always connecting a transmission line in the manner shown in Figure 22 – wye-connected on one side and delta-connected on the other side – is not always possible or practical based on system considerations. For example, a delta-wye connection introduces a specific phase shift, and the transformer connections must be made according to standard design to keep phasing consistent between the different voltages on the system (for interconnections).

Because GICs are quasi-DC, capacitors are essentially an open circuit. Thus, two other blocking approaches involve the use of capacitors (see Figures 22 and 23). In Figure 23, series compensation (capacitors) on the center transmission line phases blocks the flow of GICs. Note that in Figure 22, GICs are still shown flowing onto the autotransformer at the right and continuing on the transmission line to the right. For series capacitors, primary issues are line impedance, load impedance, and system stability (due to resonance) [1].

**Figure 22: Schematic showing that GICs have no path if one end of transmission line has a delta-connected Transformer [1]**

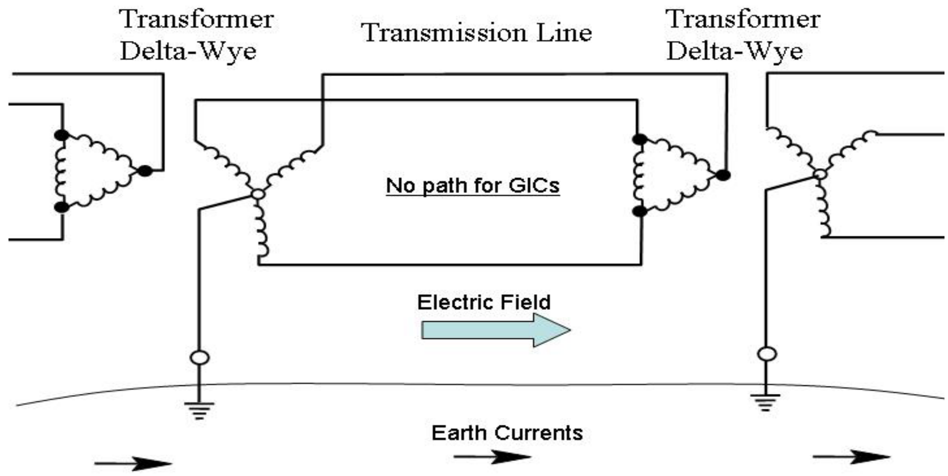
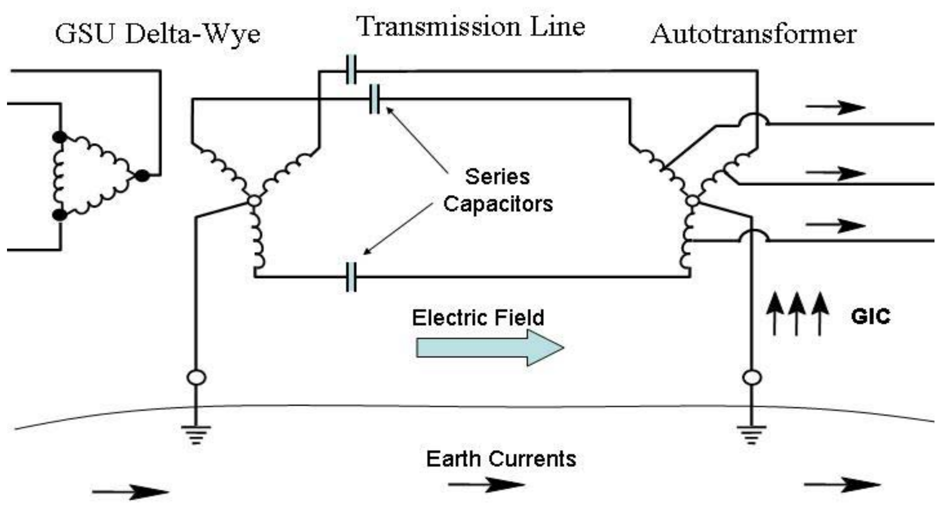


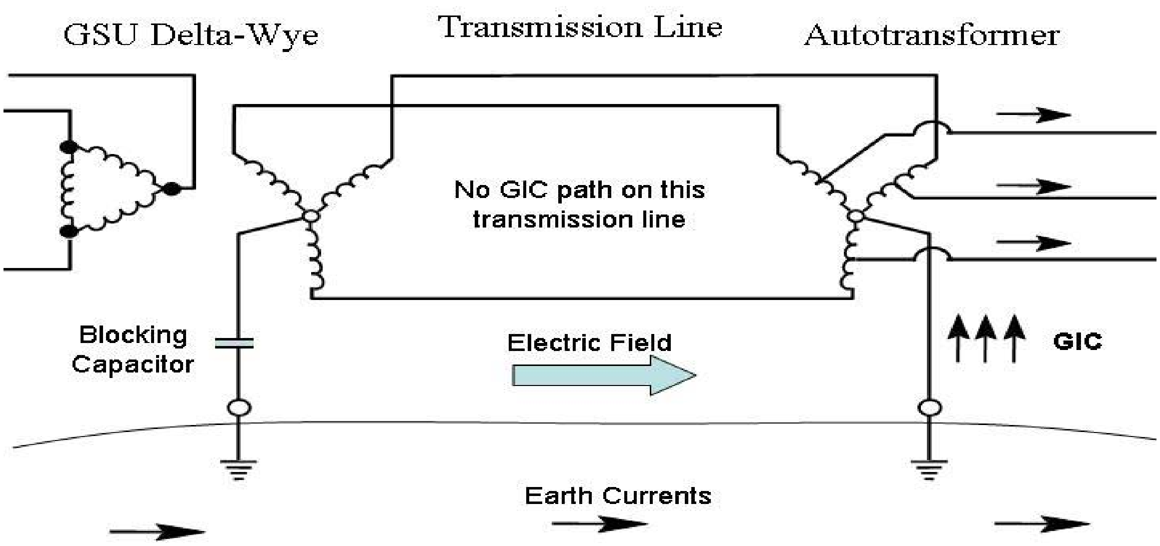

**Figure 23: Series compensation (capacitors) interrupts the GIC path [1]**




In the Oak Ridge National Laboratory report, Metatech points out that the Western Electricity Coordinating Council (WECC) uses series compensation on about 55 percent of the miles of its 500-kV lines. Yet, a Metatech analysis shows that this region remains vulnerable to GMDs. The Metatech analysis of the WECC system showed that series capacitors there reduced overall GIC levels by 12-22 percent. Hence, Metatech concludes that “transmission line series capacitors applied on a limited and targeted basis do not appear to be an effective or likely economical choice for the reduction of GIC across the U.S. power grid, especially in the tightly interconnected eastern portions of the grid.” Metatech further points out that implementation of series compensation on all three phases of all transmission miles would be exceedingly expensive [2,3].

In Figure 24, a blocking capacitor is applied to the neutral ground connection of a transformer. Note that the blocking capacitor is required only at one end of the transmission line to fully block GIC flow on that line. Again, however, GICs must be considered at the system level. Considerable efforts since the 1990s studied and demonstrated neutral ground blocking capacitors. The approach at that time was to implement the devices on a limited number of particularly vulnerable transformers, rather than more broadly as may be needed. In the Oak Ridge National Laboratory study, Metatech concluded that "Widespread application of neutral capacitor devices would bring considerable uncertainty and risk of impedance changes and ferroresonance concerns on the network. Limited application of neutral capacitors would not be effective in mitigation concerns of wide spread catastrophic damage to key EHV transformers." [2,3]

**Figure 24: Blocking capacitor inserted in the neutral-ground connection to block GICs [1]**




As one component in a broad strategy to mitigate GMDs, Hydro-Québec TransÉnergie Interconnection's (HQ-TE) has installed series compensation, neutral capacitors on transformers, and blocking capacitors on transmission lines. Its series compensation improves the robustness of its lines, reduces DC current, and reduces voltage variations (see Figure 24). Figure 25 illustrates its use of neutral blocking capacitors on transformers, and Figure 26 shows its use of blocking capacitors on AC transmission lines [4].

**Figure 25: Series compensation at the Hydro-Québec TransÉnergie Interconnection [4]**

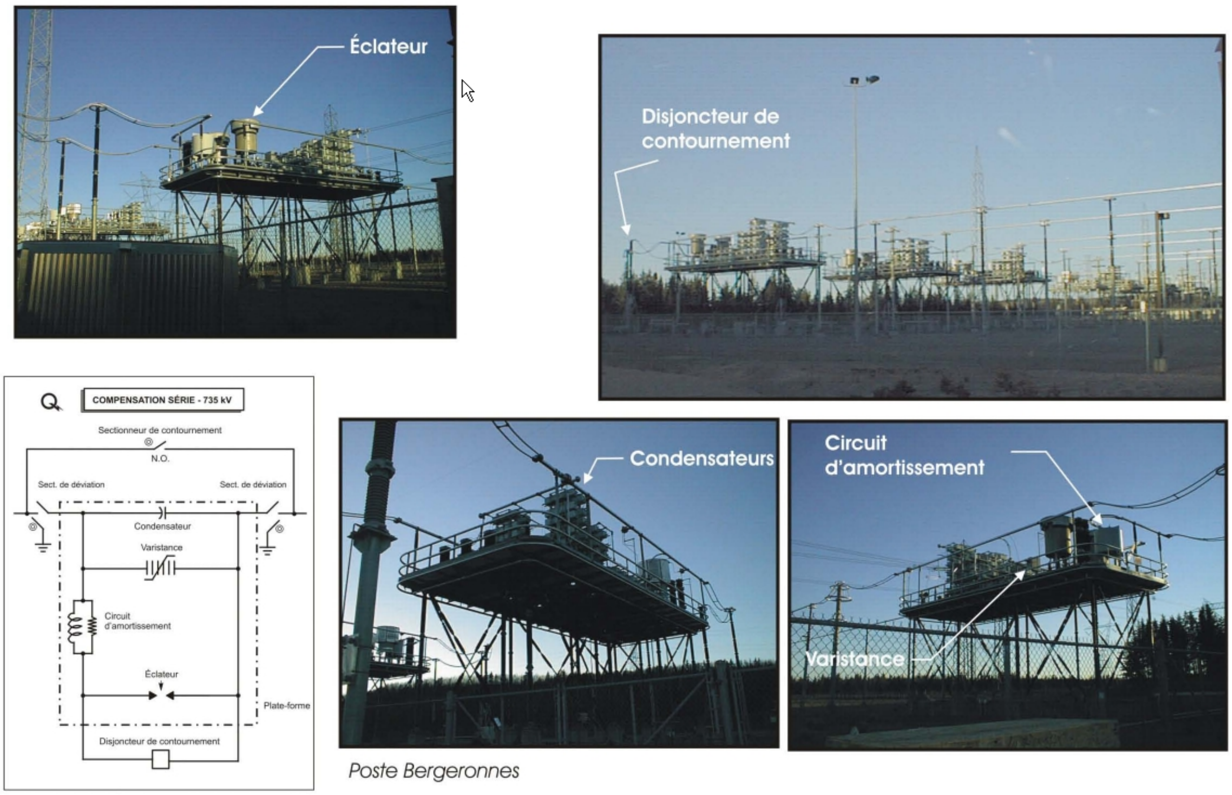



**Figure 26: Neutral blocking capacitors on transformers at the Hydro-Québec TransÉnergie Interconnection [4]**

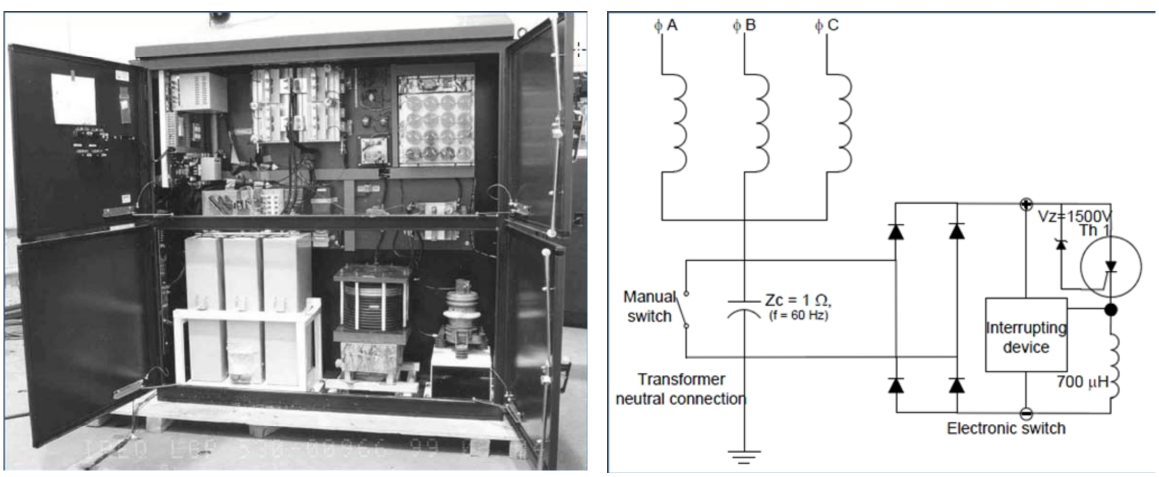
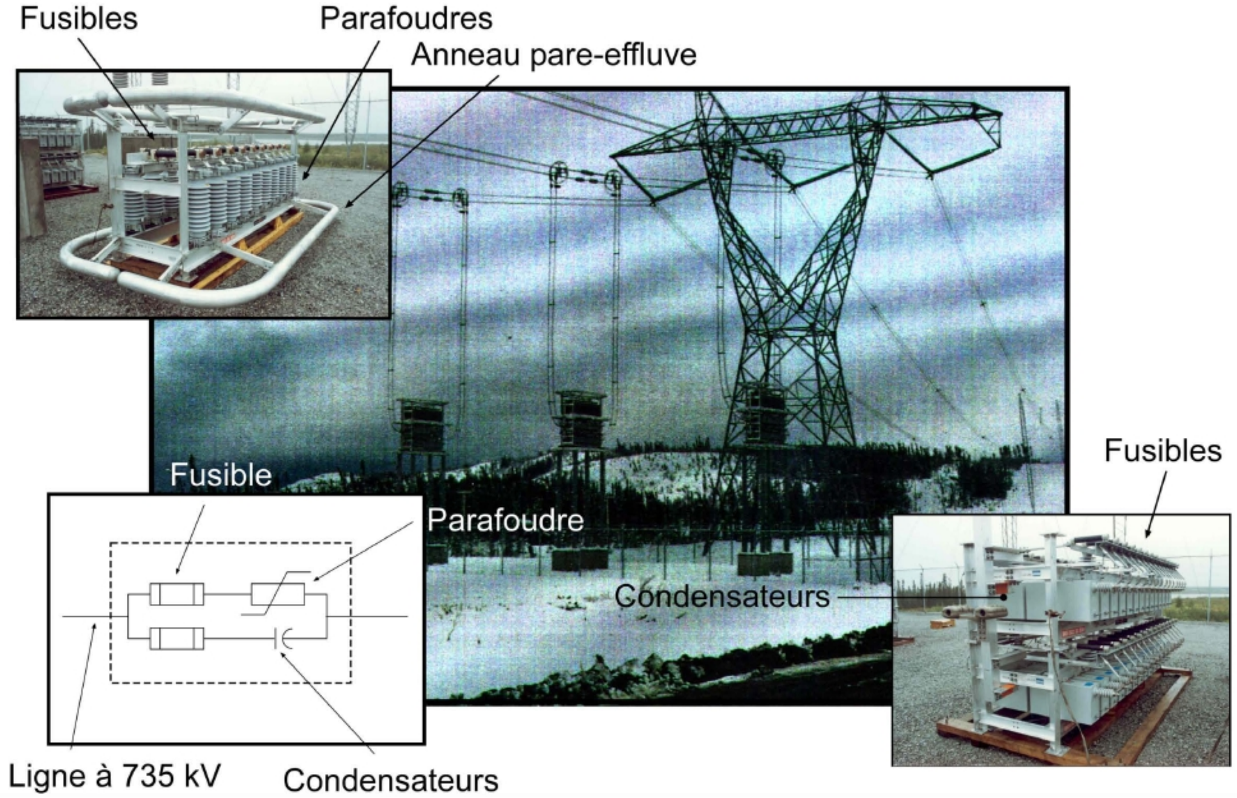


**Figure 27: Blocking capacitors on AC transmission lines at the Hydro-Québec TransÉnergie Interconnection [4]**




## Methods of Reducing GIC Flow

One additional approach that reduces GICs is the use of a 2.5 to 7.5 ohm resistance in the ground connection (at the same location as the capacitor in Figure 24). This has been called a neutral grounding resistor or a neutral resistor/blocking device (NRBD), even though, strictly speaking, it does not fully block current flow. Con Edison, among others, has expressed interest in installing and testing these devices in selected locations to reduce GIC flow through transformers [5]. The reduction in GIC levels depends on the resistances – ground resistance, transformer winding resistances, and transmission line phase resistance – for the specific situation where it is applied, but typical levels that can be achieved are 60-70 percent reduction. The issues associated with this approach are identical to all of the issues that come with resistance grounding, namely selecting a ground resistance value based on fault current and relaying requirements [1].

Metatech examined IEEE guidelines to determine whether these resistors would alter grid grounding effectiveness. They concluded that use of low-ohmic resistors would probably not alter the grounding coefficients beyond these guidelines. In fact, Metatech concluded that “the approach of using neutral resistors for GIC reduction does not appear to pose significant or insurmountable impediments.” [2]

Based on a preliminary cost estimate to retrofit EHV transformers in the U.S., Metatech recommended to the House Subcommittee on Emerging Threats, Cybersecurity, and Science and Technology that “the analysis performed to date for the EMP Commission by Metatech indicates that the conceptual design of installing neutral resistors on the transformer neutral-to-ground connections is the preferred option of protection” Metatech recommended further studies to determine the number and location of transformers that should be retrofitted, cost refinement, and finalize design requirements for the protection system [6]. The impact on system protection schemes is also warranted.

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# Mitigation: Inventory, Spares, and Recovery Transformers

## Introduction

This section describes initiatives in the industry that address the urgent need for spare high-voltage transformers. Because these transformers are the most critical power system equipment that can be potentially damaged or destroyed by a large GMD, addressing the need for equipment spares is an important complement to operational procedures and other GMD mitigating measures.

This section examines this issue from various perspectives. First, the need to perform an inventory of available spares is described. Then, the section summarizes the NERC Spare Equipment Database (SED) effort – an important initiative now underway to share high-voltage transformers in the event of a High Impact Low Frequency (HILF) event such as a GMD. (It is important to note that SED does not replace or supersede the Edison Electric Institute's Spare Transformer Equipment Program (STEP), which addresses replacement of transformers under terrorist attack scenarios only.) The section then summarizes the EPRI/U.S. Department of Homeland Security program to develop and demonstrate Recovery Transformers – high-voltage transformers that can be rapidly transported, installed, and energized where needed in response to a variety of HILF events.

## Inventory Assessment and Spare Equipment Databases

Large transformers are highly reliable. However, in the event of a failure due to man-made or natural cause (e.g., a GMD), six months or in some cases a longer period of time is required to procure, transport, install, and energize a replacement transformer. Due to the very high capital cost of these devices (e.g., $1-$5 million each), each utility owns a limited number of spare transformers.

As a first step to address this issue, in its Industry Advisory on GMDs issued in May 2011, one of NERC's Advisory Actions is to identify high-voltage transformers that could be damaged by GICs and conduct an inventory of company-wide spare transformers [1].

As a further step, if utilities could pool together all of the spares regionally or nationally, a larger number would be available for replacement in the event of a significant GMD. The goal of a NERC GMD Spare Equipment Database (SED) program is to provide a means to securely connect entities that need replacement transformers with entities that have such spares available. In the event of a HILF-type event, such as a significant GMD, access to information about available spares to match particular needs at a specific substation location would help speed power restoration. NERC's GMD Spare Equipment Database Task Force (SEDTF) is spearheading this effort [2].

Participants can include transmission owners, generator owners, original equipment manufacturers, and after-market sellers. The program will initially include long-lead time transformers with a low side rating of 100-kV or higher and a maximum rating of 100 MVA or higher. SED will be an online computer application that is available 24x7 and managed by NERC staff. The secure database will incorporate safeguards to assure data confidentiality. Initial rollout of this program is planned for January 2012. This program is not intended to replace or supersede any existing transformer sharing programs, such as the

Edison Electric Institute (EEI) Spare Transformer Equipment Program (STEP) summarized below, or other regional or neighboring utility sharing arrangements [2].

EEI's STEP Program, launched in 2006 in response to the 9/11 terrorist attacks, addresses the need to pool resources in response to a terrorist attack. About 50 transmission providers that represent about 70 percent of the U.S. transmission grid currently participate in this program. Program participants agree to a binding obligation to provide a transformer if requested by another participant. To do this, each participant signs a Spare Transformer Sharing Agreement that requires a participant to make the transformer available if a terrorist attack occurs and the President of the United States declares a state of emergency [3].

## EPRI / DHS Recovery Transformer Initiative

High-voltage transformers installed around North America vary significantly in their design, site-specific installation, and compatibility with ancillary equipment. Many are in most respects custom built for a particular installation. As a result, the SED program, assuming very large participation, is useful for a utility if it can identify a spare that is available, identical in design, compatible with site-specific requirements, compatible with site ancillary equipment, and meets other requirements. While this matchup of a spare with requirements may occur in some instances, a more comprehensive solution is needed to more broadly meet the need of spare transformers in the event of a HILF-type event.

Another limitation is that only about 1 percent of the current in-place stock (about 2000) of high-voltage transformers is currently replaced each year in North America (i.e., about 20 transformers). Worldwide production capacity is less than 100 units per year [4]. Hence, if a large number of high-voltage transformers were damaged in a short period of time, obtaining adequate replacements quickly would be challenging.

To address this need, EPRI and the U.S. Department of Homeland Security (DHS) have embarked on a project called the Recovery Transformer (RecX) Program. The mission of this program is to specify, design, build, and test prototypes (designated Phase 1 and Phase 2) of a new type of emergency spare extra high voltage (EHV) network transformer (i.e., equal to or greater than 345 kV). These transformers will be rapidly transported to, and energized at, US electric grid substations during the recovery time period after high voltage transformer outages occur due to equipment failure (see Figure 28). The equipment failure may be man-made (e.g., from a terrorist attack) or due to natural events (e.g., an earthquake, hurricane, or GMD).

The first three prototype single phase recovery transformers have been constructed and completed full factory testing at its manufacturer (ABB) in Phase 1 of this project. Incorporating current state-of-the-art technologies, it will be demonstrated on the grid at a live substation owned and operated by CenterPoint Energy in Houston, Texas. This demonstration will include performance and reliability monitoring. The second recovery transformer prototype built during Phase 2 of this project is planned to be significantly smaller, lighter, and easier to deploy than the recovery transformer in Phase 1. Ultimately, the recovery transformer must be capable, when built at different scale sizes, to replace the majority of the more than 1000 extra high-voltage transmission transformers in service in the U.S., which have different power ratings, voltages, impedances, taps, and physical arrangements.

**Figure 28: The EPRI/DHS Recovery Transformer will be quickly transportable to a substation for rapid installation and energization.**

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# Research Needs and Planned Work

## Introduction

This section provides an overview of research needs and planned work in the GMD area. Some of this information was presented at the NERC GMD Workshop in April 2011, while other information is described in the literature.

## Education and Current Capability Assessment

Utilities and RTOs have been monitoring GMD activity for a number of years, and many have established procedures to implement when GMD activity exceeds defined thresholds. But not until the NERC publication in May 2011 of its list of Advisory Actions for operations planning and real-time operations did a centralized set of such actions exist. NERC also published its background on this alert, which concluded with a table characterizing power system impacts for each level of Kp index. NERC's Industry Advisory and Background for Alert documents are extremely helpful to the industry, and illustrate the value of assimilating useful information in an organized fashion for industry use.

More information like this is needed. The industry needs a clearer understanding of the potential system impacts of defined levels of storm activity based on fact-based analysis to develop appropriate mitigation solutions. Industry stakeholders need to better understand the advantages and disadvantages, along with the trade-offs for relative success when implemented, and other aspects of a broad range of operational planning and real-time operations procedures to mitigate GMDs. In addition, the industry needs to better understand available technologies and approaches to limit the extent and duration of GIC events, including installation of neutral grounding resistors to reduce the flow of GICs in transmission systems.

At the same time, a large audience of stakeholders that are not industry insiders has less awareness and understanding of GMDs. Legislators, regulators, other government officials, business leaders outside of the electric power industry, the press, and the public are in this group. They need information in various forms to help them make informed decisions.

A large amount of information has been documented in various forms around the world over approximately the last two solar cycles in response to the GMD of 1989 that affected Hydro Québec and others 22 years ago. Yet prior to the development of the present report, few significant efforts have been mounted to review, analyze, synthesize, and consolidate a broad range of useful information to both aid present GMD mitigation efforts and guide future work.

As a result, EPRI recommends that a project team update this report periodically to collect, synthesize, document, and disseminate useful GMD information for both the industry and other stakeholders. Of special importance will be further documentation of operational practices to prepare for the approaching solar maximum and lessen storm impact. Feedback on the present report by the industry can help guide the organization, emphasis, content, and form of future synthesized information in future reports. In addition, as other specific GMD efforts underway by NERC, EPRI, various utilities, and other organizations bear fruit, the results and insights from these reports can be integrated into periodic updated versions of the synthesis reports. In addition to technical reports, the form of future deliverables can include white papers, operator action plans, guidebooks, trade articles, web site content, PowerPoint presentations, and others to suit particular audiences and needs. Given the timely nature of this situation, the project team can also distribute quarterly updates of information in the form of newsletters and webcasts open to various stakeholders. The goal of this collaborative process is to unearth new insights from the industry, scientific community, government sector, and others that will provide further informed actions to minimize future GMD impacts.

## Enhanced Forecasting, Monitoring, and Prediction

Analysis from NASA Goddard Space Flight Center has provided a preliminary assessment of the probability of extreme solar storms and their requisite surface gradient in high latitude regions [1]. This work can lead to a recommendation to the NERC Electricity Subsector Coordinating Council (ESCC) that the industry revisit the “ten times 1989” storm scenario. A more reasonable, 1-in-100 year storm scenario would provide a more realistic input function. Additional research is required to calculate the 100-year scenarios as a function of latitude as well as geology (ground conductivity). With location-specific extreme scenarios, electricity providers could be better armed to develop cost-effective solutions to the GMD threat.

In the area of GMD monitoring, EPRI’s Sunburst Network has demonstrated its value over the last two solar cycles as a centralized monitoring system of GICs. Gathering actual data on GICs, and comparing GIC data across geographic areas for different storm orientations and magnitudes is helpful for both system operators and researchers/scientists enhancing mitigating technologies. More utilities are encouraged to participate in the Sunburst Network and begin realizing the benefits of this continent-wide system.

Increased participation in the Sunburst Network also enhances the value of the recently completed EPRI/NASA Solar Shield advanced GMD forecasting system. Specific recommendations for enhancement of the Solar Shield include extension of the level 2 forecasting to lower-latitude locations.

## Enhanced Mitigation Procedures and Technologies

EPRI is initiating a project to focus on mitigation of GMD impacts. Numerous technologies and approaches are available that may lessen the impact of solar storms. EPRI will establish a Center of Expertise to test and assess mitigation technologies, perform system studies, and address member questions. Due to the urgency of action, the team will not be able to fully vet and deploy hardware solutions. However, transparency and open vetting is a key attribute of this activity.

The team will focus special attention on operational preparations in the near term that can help reduce impacts. Therefore, EPRI will prepare a guidebook on current capabilities to support industry action.

The team will test existing technologies, such as neutral blockers, and operational strategies such as transformer loading. EPRI will assess emerging mitigation concepts and equipment, such as protection relays and advanced ideas in operations given advanced forecasting. Mitigation will include technologies that can reduce the extent of the impact or reduce the duration of outages. The team will evaluate the impact on the protected equipment, along with the possible impact on adjacent lines, transformers, and mitigation equipment, and approximate cost.

Given sufficient resources and member interest, EPRI may also explore functional specifications for new transformers and or handling of spares. Additionally, the team will focus on products and solutions that may help individual entities to comply with emerging standards. EPRI will produce a guidebook of mitigation and recovery operational procedures. A second guidebook will investigate the ability of existing and emerging technologies to manage the impacts of GMD. Further, EPRI will investigate interconnection-wide planning and operating approaches, with recommendations for changes required to maintain and improve bulk power system reliability. This guide will cover forecasting, early warning, operations, and restoration practices, as well as mitigation equipment, and planning approaches. This project will also strive to develop a technology roadmap, based on a gap analysis, of needed technologies.

Part of this effort may include further evaluation and testing, pilot demonstration, and ultimately expanded installation of neutral resistor blocking capacitors. In light of the advantages described in section 5 of these devices, utilities and others should give serious consideration to installation of this mitigation approach. Utilities are encouraged to participate as host sites and demonstration sponsors for this activity.

## Modeling and Simulation Efforts and Approaches

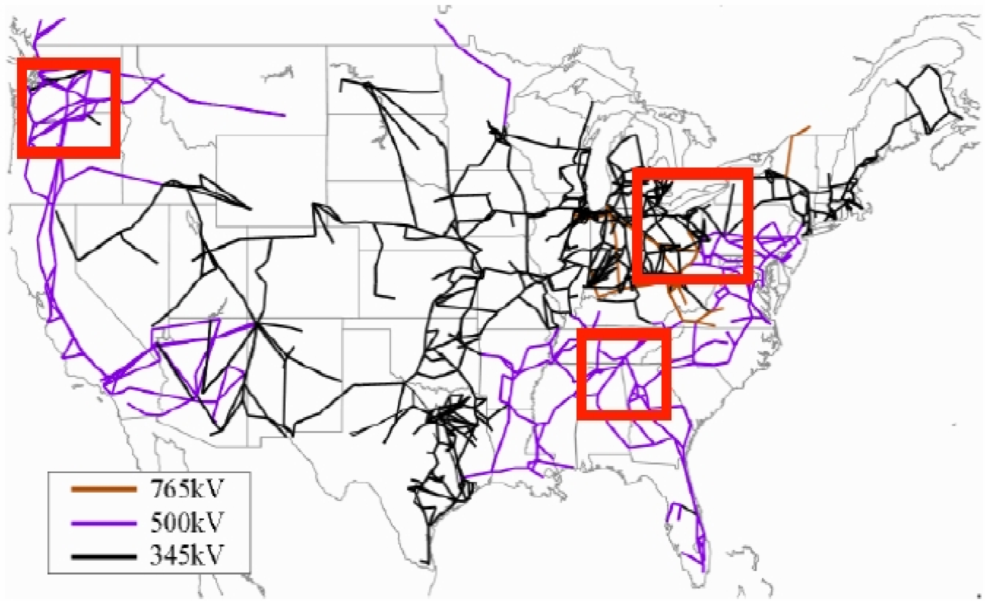
### EPRI Initiated Efforts

As part of its planned GMD activities, EPRI is embarking on a significant project to address GMD vulnerability assessment. The research question is to assess potential impacts to the grid and to determine influencing factors. EPRI's strategy will be to measure induced GICs using the Sunburst Network and other sources, assess the vulnerability of transformers, and conduct system-wide modeling [2].

The project team will develop system models of representative regions of the North American grid in cooperation with NERC staff and EPRI's Grid Operations and Planning research areas. The objective is to select three regions to verify the efficacy of the models. EPRI will select regions that are large enough to capture the influences of the storm input, yet small enough to enable detailed modeling. The plan is to select regions of the size of a utility or an operating region in different areas of the system (see Figure 30) [3]. Particular emphasis will be placed on:

- Potential transformer experience resulting from heating due to GICs, including failure primarily, but also degradation
- Increased VAR consumption and voltage stability
- Harmonic generation and effects on equipment (capacitor banks, harmonic filters, etc.)
- GIC effects on protection and control systems [3]

**Figure 30: EPRI will perform detailed system modeling in three regions of the EHV grid to assess GMD vulnerability [3]**




To do this, EPRI will determine GIC flows in the network using available data and assumptions. This will involve developing an open source software program that is capable of performing multiple cases (contingency analysis). The next step is to perform an AC load flow that accounts for additional VAR demand caused by transformer semi-cycle saturation. Using EPRI's Electromagnetic Transients Program (EMTP-RV), EPRI will then perform a more detailed analysis. These time-domain simulations require a more sophisticated system model than the GIC flow or AC load flow analysis. The simulations will help determine possible harmonic generation due to the semi-cycle saturation, as well as potential impacts on power quality and equipment such as capacitor banks, harmonic filters, and transformers. Using information from this time-domain analysis (COMTRADE files), EPRI will then determine potential impacts on system protection and control. EPRI will also develop a screening methodology and perform simulations to analyze the impacts of GIC on transformers. In close coordination with original equipment manufacturers, this requires testing of select transformers to validate the model [3].

Both the approach and the assumptions must be transparent to scientists and regulators. A technical team comprised of NERC, utility, and EPRI staff will analyze all results to ensure process veracity. Project participants and others may use the models and analysis to determine how the system and associated components will respond to a given storm or to evaluate candidate mitigation devices and strategies. The entire Interconnection will not be modeled, even at 230 kV and above. Instead, local level modeling of representative subsystems will provide the necessary granularity. The local systems can then be scaled up to determine system response. The models will provide a virtual playground for assessing new storm scenarios and mitigation approaches.

## NERC Initiated Efforts (GMDTF) and Advisory Actions for Stakeholders

In its May 2011 Industry Advisory, NERC included a section of its Advisory Actions devoted to modeling and simulation. In the portion of the Advisory Actions called long-term stakeholder actions, NERC described actions to simulate GIC effects on the power system to identify assets that could be damaged. Simulation is recommended for various geo-magnetic storm orientations and intensities. Damage mechanisms that can be examined include semi-cycle saturation, increased system reactive requirements, and harmonics. The goal here is to determine how different types of transformers will react, and how mitigation techniques will work. As a complement to this work, stakeholders can use simulation models from transformer manufacturers to identify GIC heating effects and to determine the performance of cooling systems. Stakeholders can then review operating practices in areas susceptible to GMDs to ensure that voltages do not approach operating range limits [4].

One of the objectives of NERC's GMD Task Force (GMDTF) is to accurately simulating impacts of GMD on the power system to insulate from vulnerability. Hence, Subgroup 2 of the GMDTF is developing models to identify power system vulnerabilities and mitigate threats. The National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and National Resources Canada (NRCan) are supporting this effort, with participation of the U.S. Department of Homeland Security (DHS), DOE, the U.S. Department of Defense (DOD), the U.S. State Department, BPA, and the Tennessee Valley Authority. The task force plans to deliver a series of white papers and a report in 2011 [5].

To do this, NERC will assess existing modeling capability, validate GMD and equipment models to understand their strengths and weaknesses, and work with IEEE to ensure that models are available to industry planners. NERC will gain industry agreement on design targets, and document existing equipment tests for both blocking techniques (described in Section 5 of this report) and impacts on relaying (described in section 3). NERC will then develop a coordinated Interconnection-wide study and methods that simulate GIC injections, reactive and harmonic impacts, and system dynamics. Staff will simulate potential solutions to increase resiliency, including equipment hardening and operating procedures. Documentation will include a primer for planners, models and methods, and input into NERC's standards process [6].

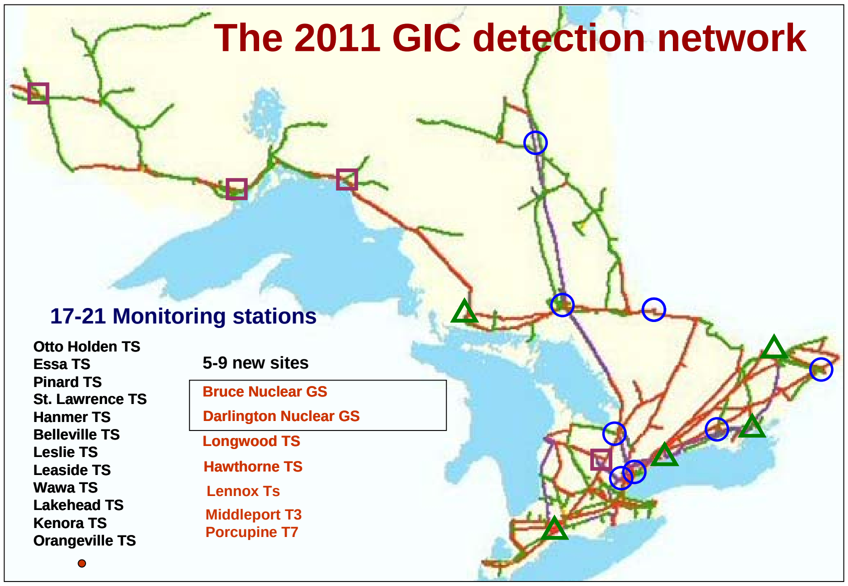
### Hydro One Ongoing Activities

With regard to modeling and simulation, Luis Marti of Hydro One Networks of Ontario, Canada pointed out at the April NERC GMD workshop that comprehensive modeling tools do not exist, but that a single simulator cannot meet all GIC modeling needs. For their purposes, they recommend [7]:

- Using existing commercial software to solve DC networks
- Obtaining forcing functions from historical records (from NRCAN) and measurements on their GIC detection network
- Calculating harmonics from measured GICs on their system (see Figure 31), analytical calculations, and use of EMTP, and then determining their impact on transformers, capacitor banks, protection and control, and reactive power loss and voltage stability
- Modeling loss of reactive power as a reactor in a load flow program

They recommend that GIC withstand be a part of standard transformer testing, and that a standard for GIC testing is needed [7].

**Figure 31: Hydro One Network's 2011 GIC detection network [7]**




## Spare Transformers

NERC's Spare Equipment Database, now being developed specifically to address transformer sharing for a large catastrophic event that causes damage to numerous pieces of equipment, is a primary example of how industry cooperation and collaboration can yield significant benefits. The advance work to populate this database will certainly be highly useful if a significant number of transformers are damaged in a GMD. Hence, transmission owners, generator owners, transformer original equipment manufacturers, and third-party transformer owners are encouraged to enter their information in this database as soon as it is launched.

The EPRI/DHS Recovery Transformer project, now underway, provides another means to reduce the risk of long-term transformer outages in the event of a large GMD as well as for other high impact events. Additional utilities are encouraged to join CenterPoint Energy as hosts and sponsors of this important initiative. Successful implementation of the first three Phase 1 single-phase Recovery Transformers at CenterPoint Energy should lead quickly to expansion of the program to more demonstration sites. The Phase 2 (advanced technology) Recovery Transformer effort is likely to yield high-voltage transformer designs that will meet this need even more effectively.

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# Conclusions

The following conclusions can be drawn from the synthesis of information in this document:

- Severe GMDs are relatively rare events. However, due to the growth in high voltage transmission systems over the last few decades that are now operating close to their limits, GMDs could pose a credible reliability risk. The greatest risk scenario involves widespread damage to high-voltage transformers and long recovery times.
- Procedures are in place to observe solar activity, measure the severity of Earth-directed solar activity at the L1 Lagrange point, and relay this information rapidly to interested parties (via the SWPC and STDC). Capabilities are also in place to provide forecasts of potential GMDs in the form of warnings, alerts, and watches.
- NERC has established procedures that are now in place to disseminate reliable impending GMD information to Reliability Coordinators, Balancing Authorities, and Transmission Operators across North America, but the time window to act to mitigate GMDs can be short. Improvements in forecasting are ongoing and are boosted by recent NASA/EPRI work on the Solar Shield. Large-scale forecasting improvements will require significant investments by government organizations.
- NERC has summarized operational measures to help mitigate GMDs and has provided them to the industry in summary form. Measures of this type documented in May 2011 are consistent with reported measures implemented and planned for implementation at various utilities and RTOs across North America.
- A system of monitoring actual GICs (the EPRI Sunburst Network) has been in place for two full solar cycles and continues to provide useful information to the industry. Some individual utilities also monitor GICs.
- NERC has adopted a proactive role in addressing severe impact risks, including GMDs, by developing a Critical Infrastructure Strategic Roadmap and Critical Infrastructure Protection Coordinated Action Plan.
- NERC is re-establishing an important program (the NERC GMD Spare Equipment Database) that enables utilities and others to share high-voltage transformers in the event of GMD-caused transformer damage.
- An EPRI/DHS project is developing and demonstrating a Recovery Transformer that will be quickly transported, installed, and energized as needed to fill the need for replacement high-voltage transformers that are damaged due to GMDs.
- Technologies exist that can be retrofitted to transmission equipment to reduce vulnerability to GMDs. One leading candidate, for example, is a neutral grounding resistor to reduce GIC flow in high-voltage transmission lines.
- One modeling analysis commissioned by the Oak Ridge National Laboratory concluded that if a GMD of severity similar to the 1921 storm occurred today at 50-degree latitude, then over 350 high voltage transformers may fail or incur damage (assuming a failure/damage threshold of 90 amps per

phase) and could impose an almost simultaneous burden of over 100,000 MVARs on the power system. However, opinions differ on transformer and system vulnerability.

- A large amount of information has been documented in various forms around the world over approximately the last two solar cycles in response to the GMD of 1989 that affected Hydro Québec and others 22 years ago. Yet prior to the development of the present preliminary report, few significant efforts have been mounted to review, analyze, synthesize, and consolidate a broad range of useful information to both aid present GMD mitigation efforts and guide future work.
- Industry needs to identify and assess the efficacy and economic viability of operational approaches for mitigating GMDs.
- When considering mitigation identification, assessment, and prioritization, cross-sector coordination with interdependent critical infrastructures such as telecommunications and fuel supply and delivery.
- Identification, evaluation, and demonstration of additional equipment monitoring techniques (e.g., real-time transformer temperature monitoring, etc.).
- Further evaluation, demonstration, and ultimately widespread implementation of technologies to harden the bulk power system to GMDs are needed.
- Vulnerability assessment is needed to better assess the susceptibility of the power system to GMDs and the effectiveness of various mitigating procedures and technologies.

# Acronyms

| Acronym | Expansion |
| --- | --- |
| AC | alternating current |
| ACE | Advanced Composition Explorer (satellite) |
| BA | Balancing Authority |
| BPA | Bonneville Power Administration |
| CCMC | Community Coordinated Modeling Center (NASA) |
| CME | coronal mass ejection |
| DC | direct current |
| DGA | dissolved gas analysis |
| DHS | U.S. Department of Homeland Security |
| DOD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DSCOVR | Deep Space Climate Observatory (satellite) |
| EEI | Edison Electric Institute |
| EHV | extra high voltage |
| EMI | electromagnetic interference |
| EMP | electromagnetic pulse |
| EMS | energy management system |
| EMTP | Electromagnetic Transients Program |
| EPRI | Electric Power Research Institute |
| ERCOT | Electric Reliability Council of Texas |
| ESCC | Electricity Sub-Sector Coordinating Council (NERC) |
| GIC | geo-magnetically induced current |
| GMD | geo-magnetic disturbance |
| GMDTF | Geo-Magnetic Disturbance Task Force (NERC) |
| GPS | global positioning satellite |
| GSU | generator step-up (transformer) |
| HEMP | high-altitude electromagnetic pulse |
| HILF | high-impact, low-frequency |
| HQ-TE | Hydro-Québec TransÉnergie (Interconnection) |
| HVDC | high voltage direct current |
| IEMI | intentional electromagnetic interference |
| ISO | independent system operator |
| JSG | Joint Steering Group (NERC) |
| MHD | magnetohydrodynamic |
| MISO | Midwest ISO |
| MVA | million volt-amperes |
| NERC | North American Electric Reliability Corporation |
| NASA | National Aeronautics and Space Administration |
| NOAA | National Oceanic and Atmospheric Administration |
| NPCC | Northeast Power Coordinating Council |
| NRCan | Natural Resources Canada |
| nT/min | nanoTesla per minute |
| NYISO | New York Independent System Operator |
| RC | Reliability Coordinator |

| Acronym | Expansion |
|---|---|
| RecX | Recovery Transformer |
| RTC/RTD | real-time commitment/real-time dispatch |
| RTO | regional transmission organization |
| SC | series compensation |
| SCADA | supervisory control and data acquisition |
| SED | Spare Equipment Database (NERC) |
| SEP | solar energetic particle |
| SOHO | Solar and Heliospheric Observatory (satellite) |
| STDC | Solar Terrestrial Dispatch Center (Canada) |
| STEP | Spare Transformer Equipment Program (EEI) |
| STEREO | Solar Terrestrial Relations Observatory (satellite) |
| SVC | static VAR compensator |
| SWPC | Space Weather Prediction Center (NOAA, National Weather Service) |
| TOP | Transmission Operator |
| VAR | voltage-ampere reactive |
| WECC | Western Electricity Coordinating Council |

# Registrants as of March 30, 2011

| First Name | Last Name | Company |
|---|---|---|
| Mohammed | Alfayyoumi | Dominion |
| Jane Ann | Verner | Pepco |
| Keenan | Atkinson | The Energy Group |
| Victoria | Bannon | Duke Energy |
| Dave | Baumken | Public Safety Canada |
| Emanuel | Bernabeu | Dominion Technical Solutions |
| Chris | Bolick | Associated Electric Inc. Co-op. |
| Jim | Brenton | ERCOT |
| Bob | Canada | NERC |
| Robert | Casey | Georgia Transmission Corporation |
| Heide | Caswell | Pacificorp |
| Gerry | Cauley | NERC |
| Chuck | Chakravarthi | Southern Company |
| John Chan | Chang | Manitoba Hydro |
| Alton | Comans | Southern Company |
| Ray | Connolly | Exelon |
| Michael | Cooper | National Grid |
| Robert | Cummings | NERC |
| James | Danburg | Situationally Aware Association |
| Thomas | David | AEGIS |
| Mohamed | Diaby | EFACEC Power Transformer |
| Binh | Dinh | Dayton Power and Light |
| Stacy | Dochoda | Southwest Power Pool Regional Entity |
| Sean | Eagleton | Consolidated Edison of New York |
| Dan | Evans | Westar Energy |
| Adam | Flink | Midwest Reliability Organization |
| Peter | Galligan | VELCO |
| Gary | Gazankas | Great Lakes Power Transmission, LP |
| Brian | Gooder | OPG, Inc. |
| Ian | Grant | Tennessee Valley Authority |
| Sebastien | Guillon | Hydro-Quebec |
| Jose | Guzman | Schweitzer Engineering Laboratories, Inc. |
| Jeff | Hackman | Ameren Corp. |
| Ken | Hall | Hall Energy Consulting |
| Tim | Hattaway | PowerSouth |
| Eric | Hatter | American Electric Power |
| Trevor | Hutchins | U of Illinois |
| Linda | Jacobson | City of Farmington |
| Wally | Jensen | Emprimus |

| First Name | Last Name | Company |
| --- | --- | --- |
| Daniel | Jesberg | Midwest Reliability Organization |
| Paul | Kaminski | We-energies |
| John | Kappenman | Storm Analysis Consultants |
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