PRM-50-96
(76FR26223)

Rulemaking Comments

From: Bladey, Cindy
Sent: Monday, April 09, 2012 2:43 PM
To: Rulemaking Comments
Subject: FW: Additional Information for PRM-50-96
Attachments: GMDTF IRA.pdf; Task_Force_Comparative_Analysis_of_FERC_NERC Reports_Transmitted.pdf

DOCKETED
USNRC

April 10, 2012 (11:10 am)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

From: Thomas S Popik [mailto:thomasp@resilientsocieties.org]
Sent: Monday, April 09, 2012 2:51 PM
To: Bladey, Cindy
Cc: Dudley, Richard
Subject: Additional Information for PRM-50-96

Ms. Bladey:

I ask that this email and its attachments be entered as additional information for PRM-50-96.

First, the NRC should be aware that the Federal Energy Regulatory Commission (FERC) has tentatively scheduled a Reliability Technical Conference for April 30, 2012 on Geomagnetic Disturbance (GMD) Effects. As you are aware, the initiating event for the Probabilistic Risk Assessment in PRM-50-96 is geomagnetic disturbance. We respectfully suggest that the NRC could benefit from the additional information on geomagnetic disturbance to be presented at this upcoming FERC conference. In fact, we believe that no reasonable person would come to a decision on rulemaking for PRM-50-96 before the FERC conference on geomagnetic disturbance, especially since the conference is only few weeks away and PRM-50-96 has been under consideration at the NRC for over a year now.

Second, please file the attached assessments of the recent "interim" report of the North American Electric Reliability Corporation on geomagnetic disturbance as additional information for PRM-50-96. The titles of the assessments are:

1. "GEOMAGNETIC DISTURBANCE TASKFORCE INTERIM REPORT ASSESSMENT"

2. "Comparative Analysis of *2012 Special Reliability Assessment: Effects of Geomagnetic Disturbances on The Bulk Power System* and *Electromagnetic Pulse: Effects on The U.S. Power Grid*"

Many thanks for your assistance in filing this additional information.

Thomas Popik
Foundation for Resilient Societies
(603) 321-1090

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TASK FORCE ON NATIONAL AND HOMELAND SECURITY

March 8, 2012

The Honorable Frederick Upton, Chairman
The Honorable Henry Waxman, Ranking Member
U.S. House Energy and Commerce Committee
Washington DC 20515

Dear Chairman Upton and Ranking Member Waxman:

I am writing in regard to the risk of solar storms hitting our nation's power grid and causing massive and persistent blackouts.

On February 29, 2012 the North American Electric Reliability Corporation (NERC) released a report that attempts to discount the risk of blackouts due to solar storms. The NERC report has conclusions directly opposed to numerous reports previously sponsored by U.S. Government bodies and, most recently, a report by the Defence Committee of the British Parliament.

NERC depended on subjective evaluations of industry representatives to prepare its report while the U.S. Government reports relied on scientific study. *As a result, U.S. Government-sponsored reports are recommended over the industry-sponsored NERC Report as a basis for making public policy.*

In order that staff for your committee becomes more familiar with this important and somewhat complex issue, I have attached a whitepaper authored by a member of our Task Force.

Should your staff have questions or require further information, please contact me at the number below.

Sincerely,

Dr. Peter Vincent Pry
Executive Director
Task Force on National and Homeland Security
(301) 481-4715

Attachment: Comparative Analysis of "2012 Special Reliability Assessment: Effects of Geomagnetic Disturbances on The Bulk Power System" and "Electromagnetic Pulse: Effects on The U.S. Power Grid"

Task Force on National and Homeland Security P.O. Box 191 Shelbyville, TN 37162

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Comparative Analysis of

2012 Special Reliability Assessment: Effects of Geomagnetic Disturbances on The Bulk Power System

and

Electromagnetic Pulse: Effects on The U.S. Power Grid

Thomas S. Popik
Task Force on National and Homeland Security

March 2012

Executive Summary

The North American Electric Reliability Corporation (NERC) on February 29, 2012 released a report asserting that even a worst-case geomagnetic "super storm" like the 1859 Carrington Event or 1921 Railroad Storm would likely not damage most power grid transformers, but would principally cause voltage instability and possibly result in a blackout lasting hours or days, but not months or years.

NERC's assertions are not supported by any of the official studies performed by the U.S. Congress or U.S. Government entities. Reports by the Congressional EMP Commission (2008), the National Academy of Sciences (2008), the Department of Energy and NERC itself ("2010 High-Impact, Low-Frequency Event Risk to the North American Bulk Power System"), the Federal Energy Regulatory Commission (FERC) (2010), and most recently the Defence Committee of the British Parliament (2012) all independently arrive at the scientific consensus that a great geomagnetic storm would cause widespread damage to power grid transformers, result in a protracted blackout lasting months or years, and have catastrophic consequences for society.

This paper compares the scientific methodology used in the industry-sponsored NERC report with that used in one of the official U.S. Government studies, the 2010 FERC report. It finds that the FERC Report used a more rigorous scientific methodology and arrived at better substantiated and more credible conclusions. *Therefore, the U.S. Government-sponsored FERC Report is recommended over the industry-sponsored NERC Report as a basis for making public policy:*

Below is a summary of key differences between the FERC and NERC reports:

- The FERC Report concludes that power could be interrupted to as many 130 million Americans for several years, while the NERC Report concludes that the most likely worst-case scenario is a blackout lasting hours or days. (p. 2-3)
- The FERC Report relied on a four-part quantitative model of geomagnetic disturbance effects on the U.S. power grid to develop conclusions and recommendations, while the NERC Report relied on meetings of industry experts in lieu of data collection or event investigations. (p. 21-22)
- The FERC Report was developed by a technical consultancy specializing in electromagnetic effects studies for the U. S. Department of Defense and was reviewed by multiple U.S. Government agencies, while the NERC Report was the product of a Geomagnetic Disturbance Task Force with membership consisting only of representatives of electricity generation and transmission companies. (p. 21-22)

- The FERC Report recommends installation of hardware blocking devices, while the NERC report recommends procedural actions and further study, including "Improved tools for industry planners," "Improved tools for system operators," "education and information exchanges," and review of "the need for enhanced NERC Reliability Standards." (p. 3-4)
- The FERC Report employs a computer model to predict specific geographic areas expected to experience power grid collapse during a major geomagnetic disturbance, while the NERC Report discusses how such models might be developed in the future. (p. 8-11)
- The FERC Report predicts internal heating as a likely mechanism of transformer damage during geomagnetic disturbance events, while the NERC Report predicts that likely collapse of the power grid would prevent transformer overheating and damage. (p. 11-12)
- The FERC Report presents statistical research that the U.S. transformer fleet is on average over 30 years old and therefore is at risk to damage from internal heating during geomagnetic disturbance, while the NERC Report contains no statistical data on transformer age but analyzes transformer design standards in the context of hypothetical geomagnetic disturbance factors. (p. 20-22)
- The FERC Report contains a transformer-by-transformer assessment of equipment at risk during geomagnetic disturbance, while the NERC Report discusses how such an assessment might be performed in the future using "engineering judgment" and information from equipment manufacturers. (p. 16-19)
- The FERC Report contains pictures of transformer damage at the Salem nuclear power plant in New Jersey in the aftermath of the same solar storm that caused the March 1989 Hydro-Quebec blackout, while similar pictures were removed from the released version of the NERC Report. (p. 20)

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1 Background

The conclusions of the recently released North American Electric Reliability Corporation (NERC) report, "2012 Special Reliability Assessment: Effects of Geomagnetic Disturbances on the Bulk Power System," differ significantly from the conclusions of the previous Federal Energy Regulatory Commission (FERC) report, "Electromagnetic Pulse: Effects on the U.S. Power Grid."

The FERC Report concludes that power could be interrupted to as many 130 million Americans for several years, while the NERC Report concludes that the most likely worst-case scenario is a blackout lasting hours or days.

In October 2010, the FERC produced a report, "Electromagnetic Pulse: Effects on the U.S. Power Grid," in joint sponsorship with the Department of Energy and the Department of Homeland Security (referred to as the "FERC Report" in this whitepaper). A subsection of the FERC Report was titled, "Geomagnetic Storms and Their Impacts on the U.S. Power Grid." Metatech Corporation of Goleta, CA prepared the FERC Report under the direction of Dr. Ben McConnell of the Power and Energy Systems Group at the Oak Ridge National Laboratory.

NERC's Electricity Sub-Sector Coordinating Council developed a Critical Infrastructure Strategic Roadmap to address concerns about high impact, low frequency risks to power grid reliability. As part of this roadmap, in January 2011 NERC established a Geomagnetic Disturbance (GMD) Task Force. The GMD Task Force met four times in 2011 and in February 2012 produced a report, "2012 Special Reliability Assessment: Effects of Geomagnetic Disturbances on the Bulk Power System" (referred to as the "NERC Report" in this whitepaper). NERC summarized key findings of the NERC report in a media release headlined, "Loss of Reactive Power, Voltage Instability Most Likely Outcome from GMD, NERC Report Finds," dated February 29, 2012.

FERC, comprised of five Commissioners and regulatory staff—including the Office of Electric Reliability—is the legal regulator of NERC. NERC is a private corporation with the majority of voting members representing electricity generation and transmission companies.

This whitepaper highlights key differences in conclusions, recommendations, risk assessments, and scientific methodology between the FERC and NERC reports.

2 Conclusions and Recommendations

2.1 FERC Conclusions

The FERC Report, "Electromagnetic Pulse: Effects on the U.S. Power Grid," concluded in its Executive Summary that power could be interrupted to as many 130 million Americans for a period of several years:

> In 1989, an unexpected geomagnetic storm triggered an event on the Hydro-Québec power system that resulted in its complete collapse within 92 seconds, leaving six million customers without power. This same storm triggered hundreds of incidents across the United States including destroying a major transformer at an east coast nuclear generating station. Major geomagnetic storms, such as those that occurred in 1859 and 1921, are rare and occur approximately once every one hundred years. Storms of this type are global events that can last for days and will likely have an effect on electrical networks worldwide. Should a storm of this magnitude strike today, it could interrupt power to as many as 130 million people in the United States alone, requiring several years to recover. Mitigation technologies to protect the power grid against such a costly EMP event can be developed, and in some cases do exist.

2.2 NERC Conclusions

The NERC Report, "2012 Special Reliability Assessment: Effects of Geomagnetic Disturbances on the Bulk Power System" concluded in its Executive Summary that the "most likely worst-case" would be voltage instability. The NERC Report stated that its GMD Task Force does not support the findings of previous studies such as the FERC Report:

> **1.9 Conclusions**
>
> The most likely worst-case system impacts from a severe GMD event and corresponding GIC flow is voltage instability caused by a significant loss of reactive power support simultaneous to a dramatic increase in reactive power demand. Loss of reactive power support can be caused by the unavailability of shunt compensation devices (e.g., shunt capacitor banks, SVCs) due to harmonic distortions generated by transformer half-cycle saturation. Noteworthy is that the lack of sufficient reactive power support, and unexpected relay operation removing shunt compensation devices was a primary contributor to the 1989 Hydro-Quebec GMD-induced blackout.

NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. The work of the GMD Task Force documented in this report does not support this result for reasons detailed in Chapter 5 (Power Transformers), and Chapter 8 (Power System Analysis). Instead, voltage instability is the far more likely result of a severe GMD storm, although older transformers of a certain design and transformers near the end of operational life could experience damage, which is also detailed in Chapter 5 (Power Transformers).

2.3 FERC Recommendations

The government-sponsored FERC Report, "Electromagnetic Pulse: Effects on the U.S. Power Grid " recommended development and testing of blocking devices in its Executive Summary, as well as improved training and improved forecasting methods:

- Development and testing of geomagnetically induced current blocking or reduction devices is necessary to prevent or mitigate electromagnetic threats to the power grid.
- Bulk power system operators must be trained to improve their situational awareness about geomagnetic threats.
- Reporting, monitoring, and prediction and forecasting methods of geomagnetic storm and power grid events must be improved.

2.4 NERC Recommendations

The NERC Report, "2012 Special Reliability Assessment: Effects of Geomagnetic Disturbances on the Bulk Power System," recommended "vulnerability assessment tools," "notification procedures," "education and information exchanges," and review of “the need for enhanced NERC Reliability Standards” in its Executive Summary:

Improved tools for industry planners to develop GMD mitigation strategies: NERC will support the development of equipment vulnerability assessment tools, enhance the definition of the reference solar storm, and develop open source tools and methods to enhance industry response and mitigation to the threat from a solar storm.

Improved tools for system operators to manage GMD impacts: NERC will enhance the existing Reliability Coordinator notification procedures or GMD watches, alerts, and warnings. Further, NERC will work in partnership with industry to update reliability guidelines to provide stakeholders best practices to monitor and mitigate the impact of geomagnetically induced currents in real-time operations.

Develop education and information exchanges between researchers and industry: NERC will raise awareness of the impact of geomagnetic disturbances on the bulk power system by conducting focused training for industry and policy makers and by developing information exchanges between industry and GMD researchers.

Review the need for enhanced NERC Reliability Standards: NERC and the industry will investigate potential enhancements to existing NERC Reliability Standards, as well as the need for additional NERC Reliability Standards development projects, to ensure the continued reliable operation of the bulk power system in North America.

3 Power Grid Risk Assessments

3.1 Worst-Case Blackout Scenarios

3.1.1 FERC Worst-Case

The Executive Summary of the FERC Report estimates the cost of a "most extreme" or worst case scenario, as well as the cost to mitigate:

> The cost of damage from the most extreme solar event has been estimated at $1 to $2 trillion with a recovery time of four to ten years, while the average yearly cost of installing equipment to mitigate an EMP event is estimated at less than 20 cents per year for the average residential customer.

Section 4.1 of the FERC Report describes a blackout of 70% of the nation's electrical service in a "worst case" situation:

> Section 3 indicated that in worst case situations, these types of disturbances could instantly create a loss of over 70 percent of the nation's electrical service. This could be a blackout several times larger than the previously largest, the North American blackout of 14 August 2003. The most troubling aspect of the analysis is the possibility of an extremely slow pace of restoration from such a large outage and the multiplying effects that could cripple other infrastructures such as water, transportation, and communications due to the prolonged loss of the electric power grid supply. This extended recovery would be due to permanent damage to key power grid components caused by the unique nature of the electromagnetic upset. The recovery could plausibly extend into months in many parts of the impacted regions.

3.1.2 NERC Worst-Case

Section 1.3 of the NERC Report outlines two principal risks to the power grid from geomagnetic disturbance and resulting geomagnetically-induced current (GIC):

> **1.3 Two Risks**
>
> There are two risks that result from the introduction of GICs to the bulk power system:
>
> - Damage to bulk power system assets, typically associated with transformers, and
> - Loss of reactive power support, which could lead to voltage instability and power system collapse.

Section 1.3 of the NERC Report gives the most likely consequence of a strong geomagnetic disturbance event as "loss of voltage stability.":

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

Section 1.3 goes on to estimate restoration time after a system collapse due to voltage instability as only "hours to days," in contrast to a longer restoration time after transformer failures:

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

Section 5.6 of the NERC Report also describes voltage instability as the "most likely worst-case" impact of a severe geomagnetic disturbance event:

> NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. Based on the results of this chapter, the most likely worst-case system impacts from a severe GMD event and corresponding GIC flow is voltage instability caused by a significant loss of reactive power support and simultaneous to a dramatic increase in reactive power demand. Loss of reactive power support can be caused by the unavailability of shunt compensation devices (e.g., shunt capacitor banks, SVCs) due to harmonic distortions generated by transformer half-cycle saturation. Noteworthy is that the lack of sufficient reactive power support, and unexpected relay operation removing shunt compensation devices was a primary contributor to the 1989 Hydro-Quebec GMD-induced blackout.

Section 8.8 of the NERC Report reiterates the "worst case" scenario of a high magnitude geomagnetic disturbance event:

> **8.8 Conclusions**
>
> The combination of increased reactive power absorption and injected harmonics into the system by saturated transformers, changes the worst-case scenario due to a low probability, high magnitude GMD event, to one of voltage instability and subsequent voltage collapse. Reactive power absorption from saturated transformers would tend to lower system voltages. Tripping of reactive power support from capacitor banks and SVCs due to high harmonic currents at a time when the saturated transformers increases the VAr demand, creates the scenario for voltage collapse. This is exactly what triggered the 1989 Hydro-Quebec blackout.

Section 13.2, "Interim Report Conclusions," once again emphasizes that voltage instability would be the "most likely worst-case system impact" and states that system operators would attempt to maintain voltage stability even as transformers absorb reactive power (and heat) and protective systems malfunction due to harmonic distortion:

> **13.2 Interim Report Conclusions**
>
> The most likely worst-case system impacts resulting from a low probability strong GMD event and corresponding large GIC flows in the bulk power system is voltage instability, caused by a significant loss of reactive power support (VAr) and a simultaneous dramatic increase in the reactive power demand. The lack of sufficient reactive power support was a primary contributor of the 1989 Hydro-

Quebec GMD-induced blackout. NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. The work of the GMD Task Force documented does not support that result for reasons documented in this report

Therefore, the most significant issue for system operators to overcome from a strong GMD event would be to maintain voltage stability, as transformers absorb high levels of reactive power while protection and control systems may trip supportive reactive equipment due to harmonic distortion of signals. In addition, maintaining the health of operating bulk power system assets during a GMD would also be the main consideration for asset managers.

3.2 Geographic Areas at Risk for Blackout

3.2.1 FERC Analysis

The Executive Summary of the FERC Report describes geographic areas at probable risk and provides a map of affected areas:

> By simulating the effects of a 1 in 100 year geomagnetic storm centered over southern Canada, the computer models estimated the sections of the power grid expected to collapse during a major EMP event. This simulation predicts that over 300 EHV transformers would be at-risk for failure or permanent damage from the event. With a loss of this many transformers, the power system would not remain intact, leading to probable power system collapse in the Northeast, Mid-Atlantic and Pacific Northwest, affecting a population in excess of 130 million (Figure 1). Further simulation demonstrates that a storm centered over the northern region of the United States could result in extending the blackout through Southern California, Florida and parts of Texas.

Electromagnetic Pulse: Effects on the U.S. Power Grid

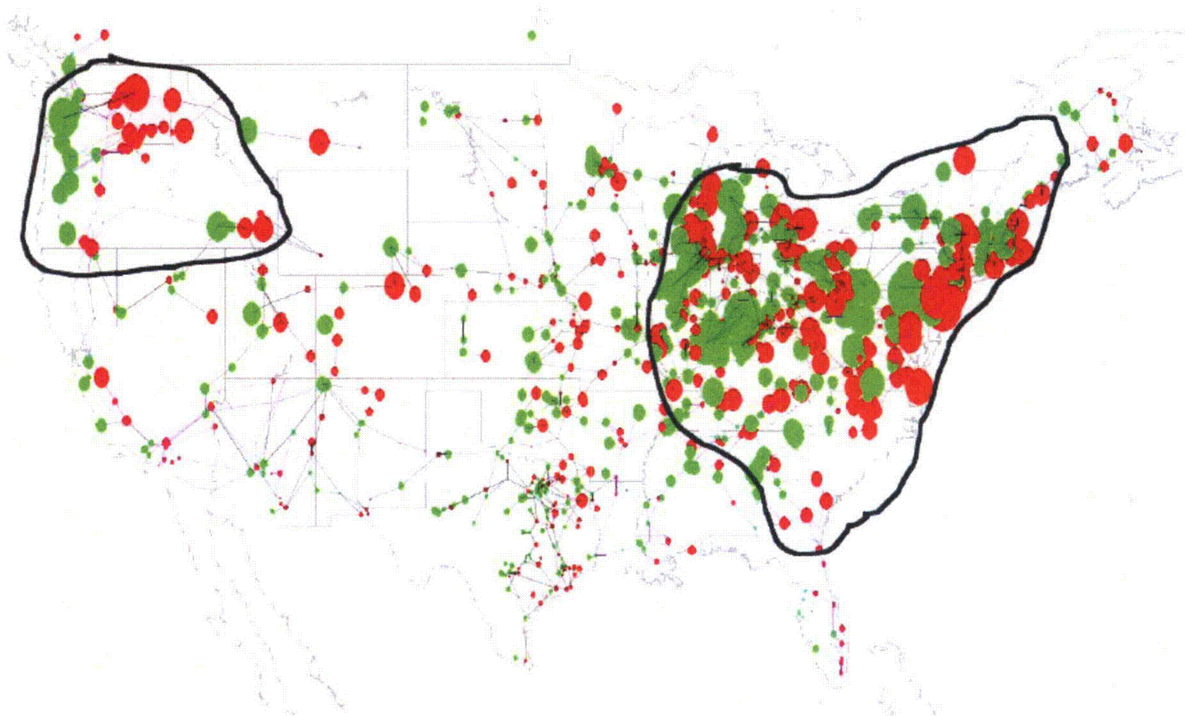

Figure 1. Areas of Probable Power System Collapse

3.2.2 NERC Analysis

The NERC Report contains no research or modeling of geographic areas most at risk for power grid collapse, but discusses how such models might be developed in the future:

> **8.1 Introduction**
>
> There has been a great deal of work during the last two decades devoted to the modeling of GIC flows in a power network. However, modeling of the effects of GIC on power apparatus and system performance during a GMD event is not as well developed. Because the most likely outcome from a large GMD event is voltage instability exacerbated protection and control failures, this area requires more work by industry to develop mitigation strategies.
>
> From the point of view of a power system engineer, what to model and how to model it depends on the intended uses of the simulation. In this chapter, modeling guidelines are organized based on how power system engineers would complete their analysis to ensure the proper operation of the bulk power system and the protection of major assets during a GMD event.

The NERC Report recommends that asset owners (electricity generation and transmission companies) perform piecemeal risk assessments of their own systems, rather than comprehensive grid-wide risk assessments performed by NERC, research organizations such as the Electric Power Research Institute (EPRI), or government bodies. While the NERC Report does recommend that risk assessment results be communicated broadly, it is important to understand that the position of NERC is that detailed risk assessments constitute "Critical Energy Infrastructure Information" that can only be disclosed among asset owners and reliability coordinators. In this context, risk assessments will be communicated "broadly" among companies that own vulnerable equipment, but may not be communicated to the public. (Emphasis in italics added.):

> **Recommendation:** Perform a risk assessment of system by asset owners for potential vulnerability to GIC.
>
> **Background:** Each asset owner should employ a set of design base criteria that addresses their GMD risk based on the characteristics and parameters of their system. *It is an imperative to communicate the criteria and results broadly as other asset owners depend upon the effectiveness of other asset owner's mitigation methods* due to the degree of interconnection and broad affects associated with space weather events. DBCT (design basis credible threat) modeling and calculations should reflect changes in system topology and new

technology. For example, equipment manufacturers need to be cognizant of the GMD threat and, when specified in equipment designs, can incorporate mitigating design features into their equipment

Lead Organization: Asset owners

3.3 Mechanism for Transformer Failures

3.3.1 FERC Analysis

The FERC Report gives internal heating and resulting transformer damage as the most likely outcome during geomagnetic disturbance events, based on experience from previous solar storms, some of which were comparatively small:

> The more difficult aspect of this threat is the determination of permanent damage to power grid assets and how that will impede the restoration process. As previously mentioned, transformer damage is the most likely outcome (although other key assets on the grid are also at risk). In particular, transformers experience excessive levels of internal heating brought on by stray flux when GICs cause the transformer's magnetic core to saturate and to spill flux outside the normal core steel magnetic circuit. Previous well-documented cases have noted heating failures that caused melting and burn-through of large-amperage copper windings and leads in these transformers. These multi-ton apparatus generally cannot be repaired in the field, and if damaged in this manner, they need to be replaced with new units, which have manufacture lead times of 12 months or more in the world market. In addition, each transformer design (even from the same manufacturer) can contain numerous subtle design variations. These variations complicate the calculation of how and at what density the stray flux can impinge on internal structures in the transformer. Therefore, the ability to assess existing transformer vulnerability or even to design new transformers to be tolerant of saturated operation is not readily achievable, except in extensive case-by-case investigations. Again, the experience from contemporary space weather events is revealing and potentially paints an ominous outcome for historically large storms that are yet to occur on today's infrastructure. As a case in point, Eskom, the power utility that operates the power grid in South Africa (geomagnetic latitudes –27° to –34°), reported damage and loss of 15 large, high-voltage transformers (400kV operating voltage) due to the geomagnetic storms of late October 2003 (Reference 4-1). This damage occurred at peak disturbance levels of less than 100 nT/min in the region.

3.3.2 NERC Analysis

The NERC Report states that older transformer designs are more at risk for damage from heating but asserts that voltage stability is still the "likely worst-case system impact" from a severe geomagnetic disturbance event. The NERC Report provides an alternative scenario to other studies that indicate a severe geomagnetic disturbance would result in the failure of a large number of Extra High Voltage (EHV) transformers:

> **5.6 Conclusion**
>
> This chapter describes the parameters that would need to be considered by entities to prepare an informed assessment of the effects of GIC flows on each power transformer within their system. The magnitude, frequency, and duration of GIC, as well as the geology and transformer design are key considerations in determining the amount of heating that will develop in the windings and structural parts of a transformer. The effect of this heating on the condition, performance, and insulation life of the transformer is also a function of a transformer's design and operational loading during a GMD event. Further, GIC measurement data shows that the change in the magnetic field (dB/dt) and corresponding GIC values vary considerably throughout the duration of a given geomagnetic storm; thus, impacts to the system and power transformers in particular, are time-dependent. This chapter also reviews past transformer failures from strong GMD events and illustrates that some older transformer designs and those that have high water content and high dissolved gasses or nearing their dielectric end-of-life are more at risk to experiencing increased heating and VAr consumption, than newer designs.
>
> NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. Based on the results of this chapter, the most likely worst-case system impacts from a severe GMD event and corresponding GIC flow is voltage instability caused by a significant loss of reactive power support and simultaneous to a dramatic increase in reactive power demand. Loss of reactive power support can be caused by the unavailability of shunt compensation devices (e.g., shunt capacitor banks, SVCs) due to harmonic distortions generated by transformer half-cycle saturation. Noteworthy is that the lack of sufficient reactive power support, and unexpected relay operation removing shunt compensation devices was a primary contributor to the 1989 Hydro-Quebec GMD-induced blackout.

3.4 Vulnerability of Transformer Fleet

3.4.1 FERC Research

The FERC Report presents research on the weighted average age of the U.S. transformer fleet, concluding that it is over 30 years old and therefore is at risk for damage, and also presents a statistical distribution of transformer ages:

> While damage assessment is important in order to evaluate the restoration of the power grid, several factors also contribute to vulnerability of the power grid to EHV transformer damage. In addition to the concern about the ability of the GIC to damage these components, the condition of this infrastructure due to advancing age may be an important compounding factor. Analysis on EHV transformer population demographics provides some details on the trend in EHV transformer condition, growth trends, age, etc. Only limited data is publicly available on the age and condition of the transmission network apparatus and infrastructure, but the data that is available also suggests looming concerns. In 1999, the ECAR Region published a report titled "How Aging of Major Equipment Impacts Reliability". From this report, Metatech has been able to assess the age statistics on EHV transformers for approximately 20% of the U.S. Grid. Figure 4-2 shows the age distribution for installed EHV transformers (345kV and above) for the ECAR region. This also indicates that weighted average age for these facilities is greater than 30 years (out of a ~40 year economic life). The age of this infrastructure is rapidly approaching old-age. As previously mentioned, these key assets are at risk due to large GIC flows caused by both the E3 and severe geomagnetic storm threats that are possible. The failure of these devices will impair the transmission network and the ability to provide rapid restoration of electric power to regions.

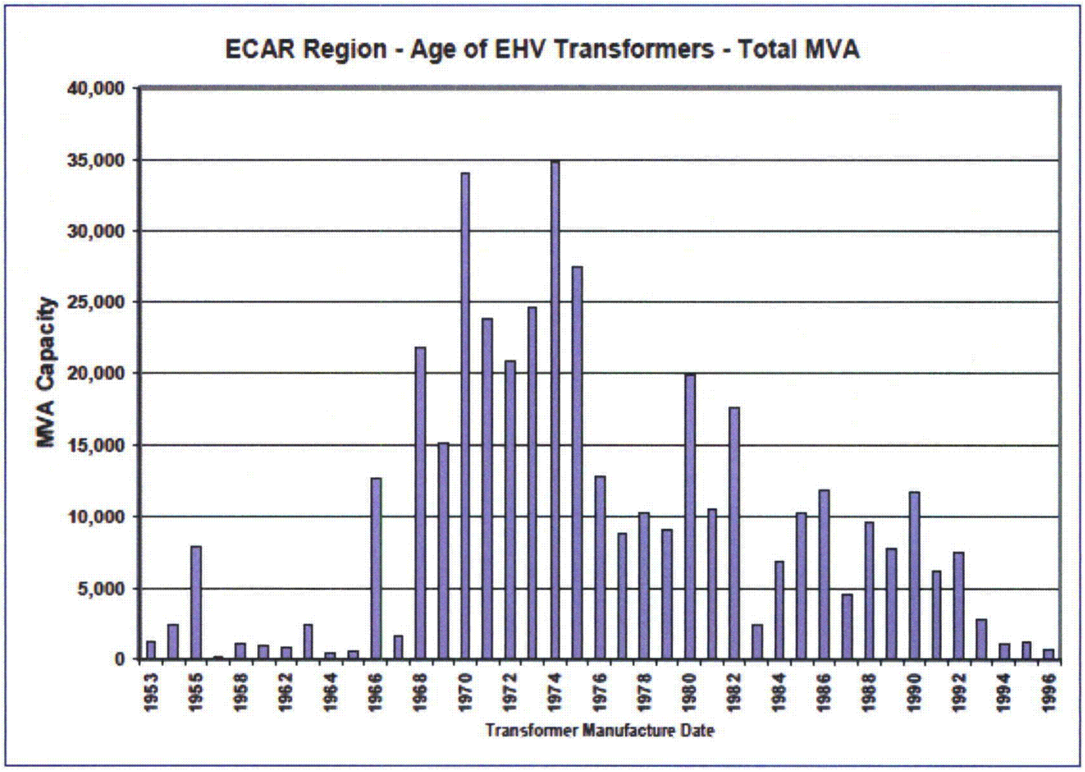

Figure 4-2. Age/manufacture dates of extra high voltage transformers in ECAR.

3.4.2 NERC Research

The NERC Report presents no data on average age of transformers. Instead, the NERC Report presents an analysis of transformer design standards in the context of hypothetical geomagnetic disturbance factors:

> **5.5 Transformer Vulnerability Assessment**
>
> Section 9.2.3 of IEEE C57.91 — 1995 summarizes what is currently known in terms of the vulnerability of transformer winding insulation from the perspective of normal and emergency operation winding and other metallic hot spot temperatures:
>
> > 9.2.3 Risk considerations
> >
> > Normal life expectancy loading is considered to be risk free; however, the remaining three types of loading (planned overloading, long-term emergency, and short-term emergency) have associated with them some indeterminate level of risk. Specifically, the level of risk is based on the quantity of free gas, moisture content of oil and insulation, and voltage.

> The presence of free gas as discussed in annex A may cause dielectric failure during an overvoltage condition and possibly at rated power frequency voltage. The temperatures shown in table 8 for each type of loading are believed to result in an acceptable degree of risk for the special circumstances that require loading beyond nameplate rating. A scientific basis for the user's evaluation of the degree of risk is not available at this time. Current research in the area of model testing has not established sufficient quantitative data relationships between conductor temperature, length of time at that temperature, and reduction in winding dielectric strength. Additionally, there are other important factors that may affect any reduction, such as moisture content of the winding insulation and rate of rise of conductor temperature.

Placed in context of overheating caused by half-cycle saturation, it is only possible to say that if the winding and other metallic part, hot-spot temperatures remain below 180 degrees Celsius and 200 degrees Celsius, respectively, during the short-term emergency loading timeframe of 15 minutes, it would result in an acceptable degree of risk. Exceeding these suggested temperatures would result in additional, but indeterminate risk. The magnitude, frequency, and duration of GIC flows, as well as the geology and transformer design are key considerations in determining the amount of heating that develops in the windings and structural parts of a transformer and the potential for insulation damage.

With the current state of knowledge, the best vulnerability assessment option is to use transformer thermal models to determine the appropriate risk-free temperatures that specific transformers may reach when subjected to GIC. Thermal models can take many forms, such as the detailed finite element method (FEM) models used by manufacturers or the transfer function models presented in Simulation of Transformer Hot-Spot Heating due to Geomagnetically Induced Currents.

If the short-term emergency temperatures suggested in IEEE C57.91-1995 are exceeded, a transformer can be flagged as being exposed to a higher degree of risk and deserving of a closer look in the context of its condition (e.g., age, moisture, dissolved gasses). Whether a given transformer can be expected to see such temperatures during a severe GMD event can only be estimated when all relevant factors are considered:

- Local ground resistivity and network configuration.
- Loading and availability of reactive support.
- Voltage and loading limits.

3.5 Assessment of Specific Transformers at Risk

3.5.1 FERC Analysis

The FERC Report contains a transformer-by-transformer assessment of equipment at risk from geomagnetic disturbance. Below is an example of the FERC Report risk assessment for commonly used 345kV transformers:

> Table 4-1 provides a summary for both a 90 amp (left hand side) and 30 amp at-risk thresholds. The left hand side of Table 4-1 provides a summary of the at-risk 345kV transformers for each state using a 90 amps/phase GIC threshold. The quantities provided are the at-risk MVA of 345kV transformer capacity for each state, the at-risk number 345kV transformers and the percent of the total 345kV transformer capacity at risk for each state. The right hand side of Table 4-1 provides a similar summary for each state of the at-risk 345kV transformers only using a lower 30 amps/phase GIC damage threshold.

Table 4-1. Comparison of 345kV at-risk transformers for 90 amp/phase and 30 amp/phase GIC levels

90 Amp GIC At-Risk Threshold

345kV At-Risk Transformers (90 Amp/phase GIC Level)

State	345kV MVA	# of At-Risk 345kV	% of MVA Capacity
AR	600	1	30.1%
CO	2,430	6	29.6%
CT	1,376	5	15.8%
IA	1,060	2	8.6%
ID	2,750	4	38.2%
IL	5,540	20	9.4%
IN	10,896	21	26.5%
KS	4,401	8	27.5%
KY	1,467	4	10.6%
MA	5,764	12	33.3%
ME	2,332	4	45.3%
MI	63,485	27	35.4%
MN	5,342	9	27.0%
MO	4,241	7	17.1%
ND	400	1	7.4%
NE	1,408	4	10.6%
NH	930	4	100.0%
NJ	1,385	2	38.1%
NM	235	1	1.7%
NV	680	2	11.3%
NY	12,274	20	29.0%
OH	8,555	15	15.0%
OK	1,049	3	6.3%
PA	2,234	4	14.7%
SD	400	1	11.5%
UT	3,638	6	23.4%
VT	448	1	29.6%
WA	3,944	6	86.8%
WI	6,459	13	35.6%
WY	690	1	24.6%
345kV Total	156,423	214	20.0%

30 Amp GIC At-Risk Threshold

345kV At-Risk Transformers (30 Amp/phase GIC Level)

State	345kV MVA	# of At-Risk 345kV	% of MVA Capacity
AR	1,400	3	70.2%
AZ	625	1	5.9%
CA	600	2	100.0%
CO	6,800	15	82.7%
CT	2,991	10	34.3%
IA	3,908	9	31.9%
ID	3,698	7	51.4%
IL	27,702	87	46.8%
IN	25,590	62	62.2%
KS	9,851	19	61.5%
KY	5,848	12	42.2%
MA	13,256	27	76.5%
ME	4,232	8	82.2%
MI	125,374	56	70.0%
MN	12,552	23	63.4%
MO	15,160	28	61.2%
ND	3,598	10	66.9%
NE	6,491	15	49.0%
NH	930	6	100.0%
NJ	1,385	2	38.1%
NM	3,547	9	25.3%
NV	3,300	12	54.8%
NY	25,530	55	60.4%
OH	32,500	69	56.9%
OK	10,800	21	64.7%
OR	554	1	100.0%
PA	9,049	18	59.5%
RI	479	1	24.6%
SD	1,000	3	28.7%
TX	7,620	13	6.4%
UT	10,721	25	69.1%
VA	732	1	32.9%
VT	1,512	3	100.0%
WA	4,544	7	100.0%
WI	10,620	27	58.5%
WV	3,277	6	39.9%
WY	2,700	4	96.4%
345kV Total	400,476	677	51.2%
Increase %	156.0%	216.4%	

Of particular concern would be the permanent loss of large GSU (generator step-up) transformers at power plants in the northeastern region of the U.S. (i.e. NE Quad). The loss of these transformers causes a compounding of difficulties, in that the EHV transmission network is impaired along with the loss of output of vital and usually baseload nuclear, coal, and hydro-electric generation resources for the power grid. There are a considerable number of the large GSU transformers "at-risk" due to GICs of at least 30 amps per phase in these units. Approximately 128,000 MVA of GSU transformer capacity would be at-risk, which is ~63% of all large power plant GSU's in the NE Quad. In total there is ~430,000 MVA of generation capacity in the NE Quad, which means that nearly 50% of the generating capacity in the NE Quad are numerous smaller capacity units which connect into the power grid at 161kV and lower operating voltage levels. In general, it is likely that most of these smaller generating units would not be baseload, but would more likely be peaking units that would typically operate for a limited number of hours on an annual basis. It is also possible that these smaller generators may not be fully staffed or have sufficient fuel resources available to provide meaningful continuous operation during an emergency. From this larger base of generation, the large-size at-risk GSUs and associated generators constitute ~30% of all NE Quad generation resources. It would also be expected that these are predominantly baseload generators which are vital to operation of a stable interconnected grid. Figure 4-13 provides a graphic summary of the fuel types for the generators that are associated with the at-risk GSU transformers. As shown in this summary, ~82% of the generators at-risk are the large nuclear and coal fired power plants. The loss is particularly important for the nuclear capacity since ~92% of all nuclear generation in the NE Quad would be out of service long-term.

4.5.2 NERC Analysis

The NERC Report contains no specific risk assessment of major power apparatus such as transformers under geomagnetic disturbance conditions. Instead, the NERC Report discusses how such assessments might be performed in the future using "engineering judgment" along with information provided by equipment manufacturers:

> **8.6 Assessment of Equipment Performance**
>
> In order to assess the performance of major power apparatus under GIC, it is necessary to know the stresses imposed on equipment and their withstand characteristics when exposed to those stresses.
>
> The determination of stresses, namely GIC during a GMD event, can be calculated using the guidelines discussed in this chapter and Attachment 8, using the maximum credible scenarios discussed in Chapter 4 or variations based on the simulations of the power network discussed in the next section. However, such maximum credible threats are not yet an industry standard for use by equipment manufacturer to test the performance under credible and reproducible GIC stresses. That said, these hazard levels can be used by planners to determine impacts and take mitigating actions, balanced against the risk to reliability and overall organizational goals.
>
> As discussed, GIC capability vs. load of major equipment, such as transformers, cannot be generalized because the effects are dependent on design and construction details of the transformer and will be different depending on the duration of the GIC pulses. GIC withstand characteristics of major equipment, such as transformers, cannot be generalized because the effects are dependent

of design and construction details. Another difficulty is that there are no testing standards against which to assess equipment withstand. This is an area that still requires much work. Industry transformer standards associations (IEEE/IEC) are encouraged to develop such standards.

Therefore, in terms of equipment performance, conservative use of engineering judgment in combination with information equipment manufacturers provide to support that judgment, should be used to assess the effects from GMD events.

3.6 Photographic Evidence of Transformer Failure

3.6.1 FERC Report Pictures

The FERC Report contains pictures of a failed transformer at the Salem nuclear power plant in New Jersey, in the aftermath of the same solar storm that caused the March 1989 Hydro-Quebec blackout:

> Figure 2-33 provides a picture of one-phase of the transformer and several pictures of the extensive internal damage done to the 22kV low-voltage windings of the transformer. In spite of these core and windings being immersed in oil for insulation and cooling, the heating was so intense that it not only burned away all the paper tape winding insulation, but caused extensive melting of the windings, which are normally rated for ~3000 amps.

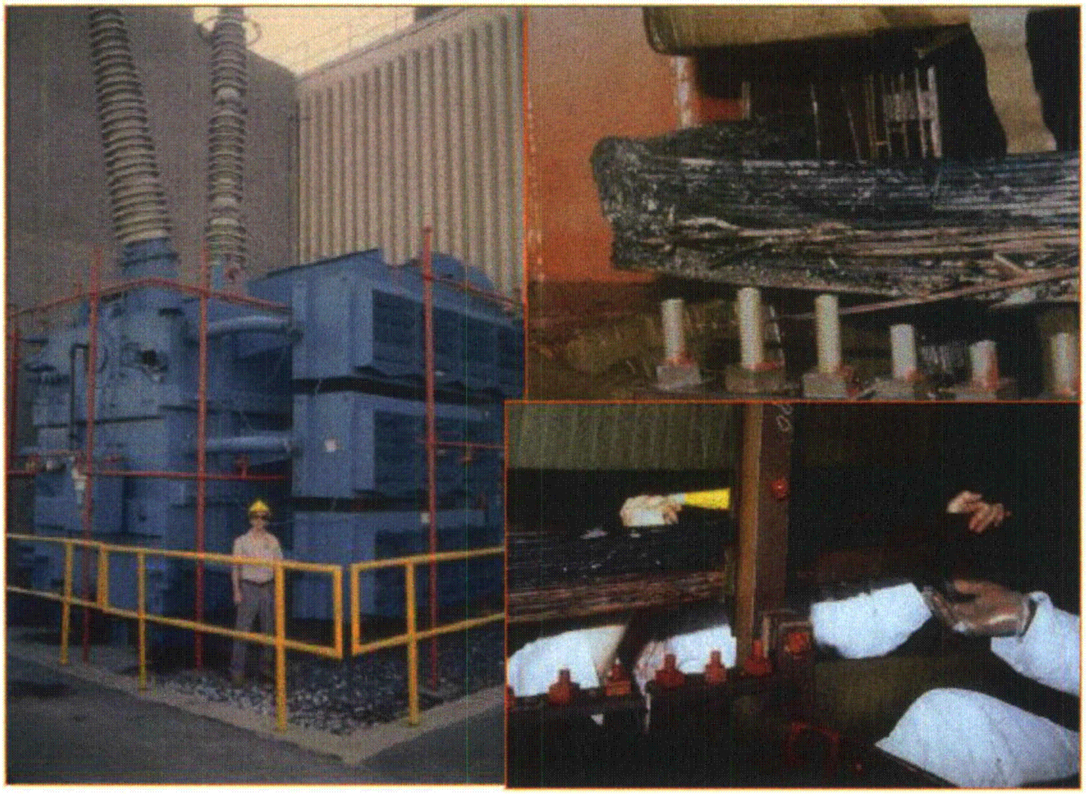

Figure 2-33. Damaged transformer at the Salem Nuclear Plant.

3.6.2 NERC Report Pictures

The NERC Report contains no photographic evidence. Pictures of failed transformers in prior drafts have been removed from the final report.

4 Report Methodologies

4.1 FERC Report Methodology

Metatech Corporation of Goleta, CA prepared the FERC Report under the direction of the Power and Energy Systems Group at the Oak Ridge National Laboratory. Metatech is a private contractor specializing in electromagnetic interference analysis for the U.S. Department of Defense, electric utilities, and other private corporations. Drafts of the FERC Report were reviewed and approved by technical experts at the Oak Ridge National Laboratory and the FERC Office of Electric Reliability.

While the FERC Report did reference published research on geomagnetic disturbance, the primary methodology of the FERC Report was to build a four-part model of the U.S. power grid under geomagnetic disturbance conditions. The model components are:

- Geomagnetic Storm Environment Model
- Ground Models and Electric Field Calculation
- U.S. Electric Power Grid Circuit Model
- Transformer and AC Power Grid Performance Model

The results of this four-part U.S. Power Grid Model inform the conclusions and recommendations of the FERC Report.

The methodology and assumptions for the four-part U.S. Power Grid Model are explained in the FERC Report. However, the software code for the four-part U.S. Power Grid Model is proprietary, much like the software code for other commercially-available modeling tools. The proprietary nature of the software code for the four-part U.S. Power Grid Model has been a point of controversy.

4.2 NERC Report Methodology

NERC convened a GMD Task Force with members consisting of electric utility representatives, observed by other stakeholders. The NERC Report was the work product of the GMD Task Force. The GMD Task Force convened in four face-to-face meetings during 2011, conducted several telephonic meetings, and commented on report drafts. The report drafting team consisted of NERC staff, technical experts from the Electric Power Research Institute, a representative from the U.S. Department of Energy, a technical consultant, and several representatives of electric utilities. Formal "membership" and voting rights for the GMD Task Force were limited to representatives of electricity generation and transmission companies.

In preparation of the NERC Report, relevant technical literature on geomagnetic disturbance was reviewed. In addition, GMD Task Force participants contributed their real-world experience with power grid operations and effects of geomagnetic disturbance.

The NERC Report did not employ modeling of geomagnetic disturbance effects on the U.S. power grid; instead such modeling was recommended as a future step. However, transformer manufacturers contributed modeling of heating effects on power transformers, including research submitted for publication but not yet published.

NERC has data for past transformer failures contained in its Generating Availability Data System (GADS). GADS is a mandatory reporting system for conventional generators. NERC also has data for past transformer failures contained in its Transmission Availability Data System (TADS). TADS collects data for transformers with 200 kV or more on the low-side. EPRI has collected data on transformer exposure to geomagnetically-induced currents (GIC) as part of its Sunburst program for over 20 years. EPRI did not contribute any location-specific GIC data to the GMD Task Force and, as a result, the task force was unable to perform statistical correlations between GIC and transformer failures.

Despite suggestions from GMD Task Force participants, NERC management declined to perform root cause or event investigations of incidents where transformer damage might have resulted from geomagnetic disturbance. Instead, NERC management was a strong proponent of its system of "vetting" by industry experts. NERC management stated in an email to GMD Task Force participants:

> In any event, NERC is assessing the landscape of risks to the bulk power system, specific to solar storms. However, we do not complete this assessment by performing root-cause or event investigations. Rather industry engineering experts' review and vet information using engineering concepts to determine the state of potential vulnerabilities as well as develop recommendations and conclusions.

GEOMAGNETIC DISTURBANCE TASKFORCE

INTERIM REPORT ASSESSMENT

Status review and process assessment of the GMDTF Interim Report

March 21, 2012

INTRODUCTION

BACKGROUND AND OVERVIEW

In early 2011, NERC formed the Geomagnetic Disturbance Task Force (GMDTF) with the goal of reaching scientific consensus on risks and mitigation options for the US-Canadian Bulk Electric System (BES) from a large coronal mass ejection from the Sun. Task force participants – electric sector representatives, scientists and engineers, NERC staff, government representatives and other stakeholder organizations – held several meetings and conference calls to discuss the several technical issues involved.

The Task Force made progress, and an interim report has been in the works for several months with participation and iteration by task force participants. A draft version circulated to task force participants a short time ago (January 9, 2012) correctly indicated that while progress has been made, the findings so far are preliminary, and specific, unambiguous conclusions or recommendations have not yet been developed or adopted by the task force. For this reason the report to be issued in early March was expected to be an interim version. Generally speaking, previous drafts included several key points: (a) reaching broad, generalizable conclusions for the highly varied transformer types and ages in the U.S. fleet will be difficult to impossible, (b) much more data should be gathered on transformer status, (c) no definitive conclusions on transformers' ability to withstand geomagnetically induced currents (GIC withstand) can be reached at this time, and (d) more research, modeling and data collection and sharing were needed to resolve outstanding scientific and technical questions.

GENERAL CONCERNS WITH THE NERC GMD TASK FORCE REPORT[1]

We were surprised, therefore, to read the recently published NERC GMD Task Force Report, which does not reflect the above key points. The report includes valuable material, and the bulk of the report still points out that there is much work to be done in arriving at scientifically supported and unambiguous conclusions. However, surprisingly, the published version of the report includes an important, broad and apparently unsupported assertion, copied here verbatim from the Conclusion section of the Executive Summary:

> "The most likely worst-case system impacts from a severe GMD event and corresponding GIC flow is voltage instability caused by a significant loss of reactive power support simultaneous to a dramatic increase in reactive power demand. Loss of reactive power support can be caused by the unavailability of shunt compensation devices (e.g., shunt capacitor banks, SVCs) due to harmonic distortions generated by transformer half-cycle saturation. Noteworthy is that the lack of sufficient reactive power support, and unexpected relay operation removing shunt compensation devices was a primary contributor to the 1989 Hydro-Québec GMD-induced blackout.
>
> NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. The work of the GMD Task Force documented in this report does not support this result for reasons detailed in Chapter 5 (Power Transformers), and Chapter 8 (Power System Analysis). Instead, voltage instability is the far more likely result of a severe GMD storm, although older transformers of a certain design and transformers near the end of operational life could experience damage, which is also detailed in Chapter 5 (Power Transformers)."

And,

> "What transformers are at risk from a GMD?
>
> The magnitude, frequency, and duration of GIC, as well as the geology and transformer design are key considerations in determining the amount of heating that develops in the windings and structural parts of a transformer. The effect of this heating on the condition, performance, and insulation life of the transformer is also a function of a transformer's design and operational loading during a GMD event. This report reviews past transformer failures from strong GMD events and illustrates that some older transformer designs are more at risk for experiencing increased heating and VAr consumption than newer designs. Additionally, transformers that have high water content and high dissolved gasses and those nearing their dielectric end-of-life may also have a risk of failure."

---

1. The full name of the report, as published, is "2012 Special Reliability Assessment: Effects of Geomagnetic Disturbances on the Bulk Power System." For convenience, it is referred to in this document as the NERC GMD Task Force Report.

Finally, the title from the press release that accompanied the report unambiguously highlights this conclusion as the most important finding of the report:

> "Loss of Reactive Power, Voltage Instability Most Likely Outcome from GMD, NERC Report Finds"

Upon careful review of the report, we were unable to find any supporting material for such a definitive claim, which appears to be a significant departure from all previous report drafts[2] and, indeed, from all previous U.S. Government studies[3]. We were disturbed to find that relevant data that could conflict with this conclusion has apparently been removed from the report, including photographs and other evidence of GMD transformer damage that appeared in previous report drafts.

Since the report's definitive, positive claim could discourage efforts to protect the U.S. from possible severe GMD-related grid damage, it must, of course, be backed up by extensive transformer data collection, review and corresponding detailed electrical and thermal modeling. While such data collection and analysis were identified as urgent needs in the deliberations of the task force, this effort has not yet taken place, or even initiated, to our knowledge. In fact, the above, definitive assertion in the report is likely to discourage any such effort.

Based on discussions with a number of GMD Task Force participants, including corporate members, these and similar concerns were shared by many, who encouraged us to provide this assessment. In view of this and in order to help improve a prospective re-issue of a revised GMD Task Force Report, we provide below an initial assessment of apparent technical and associated process errors.

Two areas of concern

There are two major areas of concern regarding the contents of the report: the relationship of the report to the task force process, and technical content.

1. Process assessment

Given the societal importance of risks with potential for grid-wide vulnerability, NERC's establishment of a GMD Task Force was an important and positive decision. For this, as for other areas falling within NERC's mandate, the credibility as well as the federal mandate for the FERC-NERC process requires "reasonable notice and opportunity for public comment, due process, openness, and a balance of interests in developing reliability standards and otherwise

2. A government task force observer, for example, commented: "This published NERC report is quite different from the last draft sent to the task force in January."

3. Previous related studies include: DOE – NERC HILF Report, the NASA/ NAS Study, and the Oak Ridge National Laboratory FERC-DOE-DHS Study.

exercising its duties." After its startup, the GMD Task Force met these criteria for months, with broad and open participation by experts from throughout the energy sector.

After the January 19th call for comments, this open scientific process was replaced by a closed report-writing effort, which may, perhaps, explain how the published report came to include broad assertions that do not reflect the task force process or previously vetted data and modeling. As a result of this change, many task force participants who could have contributed to a better work product were left out of the discussion during the final period leading up to report publication. In fact, given this change in process, the report cannot properly be represented as a product of the Task Force, but rather as a document drafted by a subset of the Task Force and separately edited by other NERC personnel, without open review by the full Task Force. The report, therefore, seems to represent a departure from NERC's normal, acceptable standards for open scientific modeling, data gathering and peer-reviewed assessment.

Time pressures and other factors may sometimes cause inadvertent process errors leading to premature conclusions. However, when addressing risks with a potential for serious damage to critical societal infrastructures, such a process error becomes a grave and dangerous matter. Indeed, if a legitimate, devastating societal risk were dismissed due to mischaracterization of an inadequate or incomplete process, it could undercut the most fundamental purpose of the FERC-NERC regulatory process, putting the health and security of our nation at risk. In the case of the NERC GMD Task Force Report, with global, optimistic assertions of robustness and survivability of the entire age and design-variant U.S. EHV transformer fleet, minimal process standards would seem to include both an aggressively open, peer-reviewed assessment process, and diligent and comprehensive transformer fleet data collection, review and corresponding modeling. Regrettably, the published report appears to meet neither of these process standards.

2. Technical assessment

Specific conclusions for the robustness and survivability of the entire highly age and design-variant U.S. transformer fleet can only be responsibly made if based at least on the minimal scientific requirements that would warrant such assertions. These minimal requirements would include:

a. **Extensive transformer data collection (type, age, voltage).** No such data collection effort is referenced in this report or has yet been undertaken by the GMDTF.

b. **Full review and understanding of all currently available, publicly reported GIC-related transformer problems.** The GMDTF has not yet requested this information from owner/operators.

c. **In the absence of a thorough, comprehensive data base, extensive detailed modeling of many transformer types.**

Lacking a broad data base to generate heuristic conclusions (i.e., 2 (a) and (b)), presumably such conclusions must be based on extensive electromagnetic and thermal finite element modeling of hundreds of different transformers. Modeling of only one type of transformer (single phase), however, is referenced in this report (See Chapter 5, figs 24, 25, 27, and 28). In addition, the modeling referenced is limited to an as yet unpublished IEEE presentation (Figs 24 and 25) and an unpublished paper (figs 27 and 28) that has had neither peer review nor review by the full GMD Task Force. At the last full, open meeting of the task force (November 9-10, 2011), there was unanimous agreement that a model of one specific transformer cannot be properly utilized to make general and far-reaching conclusions for the entire widely varying population of transformers that would be exposed to a severe GIC event.

In Summary

As indicated in several major government studies, many of the nation's best scientists and multiple federal departments and agencies have concluded this issue could cause serious damage to the U.S. power grid, and could potentially have an impact on the continuity of the United States as we know it. Any recommendation that such a profound risk need not be robustly addressed must meet the highest standards of rigorous, open scientific inquiry.

Organizations making definitive, positive assertions that could lead to such recommendations may fairly be asked to recognize that they have taken on their shoulders, individually and collectively, the responsibility for risking the health, security and potentially even survival of future generations of Americans, and must therefore meet the highest standards of careful, comprehensive, unbiased and peer-reviewed assessment.

Regrettably, perhaps due to procedural flaws and internally driven schedule constraints, this new report does not appear to meet these standards.

NERC's formation of the GMD Task Force was an important and positive step. We strongly support the GMD Task Force, and we hope this interim report assessment will help get the process back on track. The work is of great importance, both to the electric sector and to the nation.

NERC GMD TASKFORCE REPORT
DETAILED ASSESSMENT

PREVIOUS STUDIES

The work of the GMDTF follows several studies, reports and initiatives on Severe Space Weather (and related EMP studies) by a wide array of U.S. government departments and agencies, including:

- Congressional EMP Commission
- Congressional Strategic Posture Commission
- NASA / National Academy of Sciences
- DOE / NERC
- FEMA
- FERC / DOE / DHS / Oak Ridge National Laboratory
- White House OSTP

The recently released GMD Task Force Report properly highlights the efforts begun last year in undertaking another review of the important GMD issue. However the report, surprisingly, includes positive assertions for the robustness of the U.S. EHV transformer fleet that are not based on existing transformer GIC impact data or detailed modeling of most transformer types. In fact, the report itself, while making such assertions, includes virtually no technical basis for this remarkable departure from the conclusions of all the above reports, which were authored, reviewed, and put forth by a cross-section of America's most respected scientists. In most cases, reaching definitive conclusions on an area of such profound importance to the energy sector and the public depends on basic data gathering and detailed modeling. Although future plans for such efforts were discussed in task force meetings and called for in the Interim Report recommendations, the task force has not yet gathered such data or performed such detailed modeling.

Under these circumstances, it would be quite helpful if a revised report could be prepared with proper adherence to the GMD Task Force's usual practices for previewing, review and comment / iteration by task force participants, and without assertions that do not include requisite technical substantiation.

To assist NERC management in producing a revised, interim report with the broadest possible task force review and participation, utilizing a process that can yield well-founded technical conclusions, concerns with the findings as well as recommended changes in the current version of the report are summarized below.

MAJOR PROCESS AND TECHNICAL CONCERNS WITH THE CURRENT NERC GMD REPORT

1. GIC Impact limited to voltage instability: Unsubstantiated assertions suggesting that the worst case GMD impact would be voltage instability.

From the GMD Task Force Interim Report:

- "The most likely worst-case system impacts from a severe GMD event and corresponding GIC flow is voltage instability caused by a significant loss of reactive power support simultaneous to a dramatic increase in reactive power demand."
- "NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. The work of the GMD Task Force documented in this report does not support this result for reasons detailed in Chapter 5 (Power Transformers), and Chapter 8 (Power System Analysis). Instead, voltage instability is the far more likely result of a severe GMD storm, although older transformers of a certain design and transformers near the end of operational life could experience damage, which is also detailed in Chapter 5 (Power Transformers)."
- "Restoration times of the power system from these two risks [damage to transformers and voltage instability] are significantly different. For example, restoration times from system collapse due to voltage instability would be a matter of hours to days, while replacing transformers requires long-lead times (a number of months) to replace or move spares into place, unless they are in a nearby location. Therefore, the failure of a large number of transformers would have considerable impacts on large portions of the system."

The message implied by this assertion: There is little to no risk of serious power grid damage, and we need be concerned only about power instability. Power outages caused by GMD, therefore, would be short term only.

Analysis

This claim did not appear in previous iterations of the report, and it may be that severe time pressures mandating the release of the report resulted in inclusion of novel, non-vetted ideas of this type.

Nothing cited in the report supports the claim that voltage instability is "most likely".

The executive summary points to Chapters 5 and 8 to support the claim that voltage instability, rather than failure of a large number of transformers, represents the "most likely system impacts from a severe GMD event." Support for such a claim would seem to be very straightforward. If it could be clearly demonstrated that voltage instability large enough to cause power system collapse occurs at a GIC at or above X Amps, while damage to transformers is not a concern until a GIC level of 2X, 5X, or 10X is reached, this assertion would be better supported. However, chapters 5 and 8 offer no such comparison; or even a rough quantitative measure of levels of GIC that are of concern to cause either phenomena.

Chapter 5 focuses mostly on transformer heating due to GIC. While there are no general conclusions, one or two test cases are presented. Measured data from a limited selection of locations on one particular single-phase transformer appears in Figure 26, showing a temperature rise in "tie plate points" of ~15 C with 5 amps GIC applied for 2 hours, with most of the temperature rise occurring in the first 30 minutes. In addition, a one-minute spike of 16.67 Amps raises the temperature another 5 degrees, with the indication that it would have climbed more had the GIC pulse been longer. A model calculation in reasonable agreement with this measurement (Figure 28) shows heating of 48 C associated with two GIC current spikes of 70 Amps/phase lasting roughly 3 and two minutes, respectively, using the "5 V/km, high-conductivity 100-year scenario" developed and discussed in Chapter 4. A discussion of a calculation of temperature rise using the same GIC waveform but the "20 V/km, low-conductivity 100-year scenario" also cited in Chapter 4, a temperature rise of over 200 C is calculated. Figure 29 shows measured temperature and GIC levels, which are highly correlated, that resulted in external tank temperatures of 173 C from a short burst of 60 Amps GIC in a three-phase transformer (20 Amps/phase). In addition, the report also cites tank temperatures of over 400 C in a transformer during the 1989 storm.

Chapter 8 focuses on the question of voltage instability and reactive power loss in the power system due to GIC. Figure 33 is a reactive power loss model of the same transformer under the same conditions as the heating calculated in Figure 28. The results indicate a reactive power loss of 116 MVAr during a 2 minute GIC spike of 120 Amps/phase in the 5 V/km scenario and a reactive power loss of 143 MVAr during the same 2 minute spike of 370 Amps/phase in the 20 V/km scenario.[4] 120 Amps/phase, and undoubtedly 370 Amps/phase, are enough to cause severe transformer heating.[5]

There is, again as in Chapter 5, no specific threshold GIC level that is asserted to cause voltage instability. Rather, Chapter 8 states,

> "At this time, the tools to calculate harmonics as a function of GIC flows are relatively limited to transient analysis simulations with one of the family of electromagnetic transients programs with approximation techniques. Electromagnetic transient simulations tend to be complex and not well-suited to simulate full-scale interaction of GIC and transformer saturation,"

and,

> "As discussed, GIC capability vs. load of major equipment, such as transformers, cannot be generalized because the effects are dependent on design and construction

4. Note that these reactive power loss levels seem anomalous. While details of the transformer model are not sufficiently provided in the report, nevertheless a much higher MVAr should have resulted from the 370 amps spike compared to the 120 amps spike. This point may bear further investigation in a prospective report reissue.

5. Note: The time axis in figure 33 is mislabeled. It should read "hours" instead of "min" consistent with figures 27 and 28.

> details for the transformer and will be different depending on the duration for the GIC pulses. GIC withstand characteristics of major equipment, such as transformers, cannot be generalized because the effects are dependent of design and construction details. Another difficulty is that there are not testing standards against which to assess equipment withstand. This is an area that still requires much work. Industry transformer standards associations (IEEE/IEC) are encouraged to develop such standards."

These statements do, in fact, accurately represent the present thinking and supportable conclusions of the full GMD Task Force, making it clear that this very model, addressing a single transformer design, cannot be generalized to characterize the entire, highly variable, aging U.S. transformer fleet. It cannot, of course, be used as a basis for the apparently unsupported claim found anomalously at the end of the chapter.

> "The combination of increased reactive power absorption and injected harmonics into the system by saturated transformers, changes the worst-case scenario due to a low probability, high magnitude GMD event, to one of voltage instability and subsequent voltage collapse." –

While there is individual discussion of transformer damage and voltage instability, there is simply no comparison of damage versus instability in the report to support the definitive, positive conclusion that one (relatively benign) failure mode is more likely than another.

There is no known evidence that voltage instability would be a worst case scenario

While there was broad agreement among GMD Task Force members that GICs would give rise to harmonic generation in transformers and increased reactive power losses, leading to voltage instability, there appears to be no basis for asserting that voltage instability is therefore the "worst case." The embedded implication seems to be that the grid would "self-protect" during a GMD event, with voltage instability causing a blackout before serious equipment damage occurs. This, however, is better described as a "best case" scenario compared to the actual "worst case" scenario where many transformers are damaged or destroyed.

There is no evidence of grid "self-protection" in previous GMD events.

In fact, among the GMD events cited within the report, there is no evidence of blackouts resulting in transformer protection. In the 1989 Storm, for example, the entire Quebec grid blacked out within 90 seconds due mostly to system instability. But even with a collapse this sudden, two transformers were still damaged. In the U.S. during the same storm, a transformer in New Jersey was destroyed with no accompanying voltage instability-induced blackout. During the 2003 Halloween storm in South Africa 14 transformers were damaged, with no blackout occurring during the storm itself.

Even theoretical "self-protection" scenarios would require very specific, "tailor-made" GMD events

The South African failure mode is actually an example of a likely scenario for a very dangerous severe GIC event. With EHV transformer damage that could yield failures distributed over many minutes, days or weeks, as in the South Africa scenario, transformer replacement times would turn such a situation into an (eventual) catastrophic grid failure, with no immediate grid-wide blackout.

A "self-protect" scenario, if it would work at all, would require an extremely high level GMD event, causing self-protecting failures rapid enough to protect neighboring transformers. However, even this scenario is not without unique equipment damage risks posed by severe geomagnetic storms. During collapse of the grid, circuit breakers would be called upon to interrupt large DC currents (GIC) which they are simply not rated to do, this could lead to other forms of damage than to just transformers on the grid.

Hoping for mutually compensating failures in a severe GMD event is not sound engineering practice

It is, in any case, not normal engineering practice to count on mutually compensating accidents in the midst of a massive failure mode to compensate for known system vulnerabilities. Responsible engineering practice is to ensure critical systems have no single-point failures, and are inherently robust against known, severe risks.

Recommendation: The GMD Task Force should insist, on all future claims of modeling, on a detailed description of the modeling, and should document any available simple validation techniques. Where this is deemed an important issue, since the physics involved in grid modeling of this type is quite simple, if GMDTF feels further anchoring is essential they should develop their own, open source grid model and attempt to do comparison studies with past-used models. In fact, the Kappenman GIC-Power Grid software has already been made open-source since EPRI reports that Kappenman authored have been provided to the GMD Task Force. However, in the technical community, since private models are usually proprietary and source codes are not available, government or other decision making bodies may commonly develop their own models and spend effort comparing the predictions of the two models under known conditions to co-validate both.

2. Severe, damaging GIC levels and durations are not expected

From the GMD Task Force Report:

> "In the case of the 20 V/km, low-conductivity, 100-year scenario, and 400 MVA, 500/16.5 kV transformer, the maximum calculated metallic part temperature exceeds 200 degrees Celsius for 14 minutes, therefor IEEE C57.91-1995 thresholds would be exceeded. To place this scenario in perspective, this level of GIC represents more than 10 times what was experienced by Hydro-Quebec and Public Service Electric and Gas (PSE&G) on March 13, 1989. Also, the 14-minute duration is greater than the duration of the highest peaks experienced by the same systems in 1989."

The message apparently implied by this assertion: We need not expect, or be concerned about, very severe GIC levels for long durations, which have no scientific basis.

Analysis

Minimizing or ignoring the 20 V/km, low-conductivity scenario developed by the GMDTF is unwarranted and irresponsible. There are two very well supported scientific bases for this severe storm scenario. As indicated in the report, a very similar storm scenario was used in the "series of studies" listed above under "Previous Studies." It was not, as some seem to have misinterpreted, arrived at by "multiplying the effects of the 1989 storm by a factor of ten" as a way to generate a model of a powerful GMD event. The severe GMD event used in previous studies is in fact the best available model of a storm that occurred in 1921 and is referenced in chapter 1 of the interim report. The scientific, peer-reviewed, publication of analysis of the 1989 and 1921 Storms[6] shows that the geomagnetic field disturbance of the 1989 Storm was:

$$\frac{dB}{dt} = 480 \ \text{nT/min}$$

while the for the 1921 Storm it was

$$\frac{dB}{dt} = 5000 \ \text{nT/min}$$

ten times as large.

While the overall effects of such a disturbance depend on a number of factors (ground conductivity, operating voltage, transmission line and magnetic field orientation, etc) there is, according to

6. J. Kappenman, "Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events - An analysis of observational evidence including the great storm of May 1921", Advances In Space Research, 88 (2006), 188-199.

Maxwell's Equations and Kirchoff's Laws a linear relationship between the dB/dt, the electric field E and the induced GIC. This does in fact represent a "supportable scientific basis" for looking at a storm with an intensity of ten times the 1989 storm. Further, the peak electric fields during the 1989 storm is cited on page 65 of the report to be 1.7 V/km (dependent on time and location within North America). The GMDTF was also presented information on prior observations for storms less intense than the 1921 storm of geo-electric field intensities that ranged from 5 V/km to 11 V/km within mid-latitude portions of the U.S.

In chapter 4 of the interim report, new analysis led by Antti Pukkinen and Emanuel Bernabeu, both GMDTF participants, has preliminary findings indicating that the 100-year storm intensity for "high-latitude, low-conductivity" regions such as the Northeastern U.S. would have electric fields averaging 20 V/km and with a range of 10 - 50 V/km. This value was derived independently by a statistical data extrapolation methodology rather than the phenomenological modeling used by Kappenman in the earlier study. Nonetheless, we see the same factor of ten difference in intensity. Therefore it is certainly a scientifically defensible basis for the task force to use as the basis for a 100-year storm event dB/dt values of 5000 nT/min and electric field strengths of 20 V/km and as large as 50 V/km as our scenario of interest. Finally, although there is not enough data to do a similar analysis for the 1859 Carrington event, it is believed by most (though due mostly to anecdotal evidence and observational reporting) to have been even more powerful than the 1921 storm.

Contrary to the GMD interim report's assertion, there is an excellent basis for the use of a GMD level of ten times the 1989 Quebec storm.

The basis for the downplaying of a GMD of this magnitude – a result put forth in the report itself – remains unknown at this time. Both the 100-year scenario developed in Chapter 4 and the above-indicated 1921 Storm Scenario conclusions are in fact anchored by showing that the detailed model conclusions were well supported by simple extrapolation methods and other techniques, commonly used by phenomenologists to check that detailed models are providing answers that meet reasonable approximations and other forms of testing of their conclusions.

Even had this anchoring not been done, the scenario used by the other reputable studies could not, of course, be ignored. Having gone through over 12 years of vetting, reviewed by some of the nation's most reputable sources, there has been no finding of error in the scientific methodology used to arrive at this conclusion. The scenario, therefore, remains far more credible than optimistic assumptions to the contrary.

3. GIC-Withstand Assertion: Unsubstantiated assertions relating to ability of transformers to withstand Geomagnetically Induced Currents (GIC-withstand).

From the GMD Task Force Report:

- "This report reviews past transformer failures from strong GMD events and illustrates that some older transformer designs are more at risk for experiencing increased heating and VAr consumption than newer designs. Additionally, transformers that have high water content and high dissolved gasses and those nearing their dielectric end-of-life may also have a risk of failure."
- ". . . although older transformers of a certain design and transformers near the end of operational life could experience damage, which is also detailed in Chapter 5 (Power Transformers)."

The message apparently implied by this assertion: There is little to no risk to transformers, except for a few very old transformers of a certain type. Any severe grid outage would result from an unlikely simultaneous catastrophic failure of multiple transformers. Therefore, there is no risk of catastrophic damage to the grid.

Analysis

This assertion is unsupported in the report. There is no discussion, in Chapter 5 or elsewhere, of the transformer GMD impact data that would be necessary to support such an assertion. In fact, the report includes no data regarding transformer loss of life, damage, or failure due to GMD events, except one vague statement that transformers damaged in New Jersey in 1989 were an "old" design.

In the iteration of the report last shared with GMDTF participants on January 9, 2012, a fuller, more nuanced version of this conclusion was included:

"Some types of transformers will be at risk during a geomagnetic storm. Older, shell-type transformer designs are at the greatest risk for potential failure. Additionally, transformers with high water content and high proportion of dissolved gasses in the oil, and transformers nearing their dielectric end-of-life, might potentially be at risk from a strong geomagnetic storm. Would transformers with these characteristics catastrophically fail during a severe event? More study and analysis is needed, but the increasing rate of dielectric degradation increases the probability of failure for transformers. It is not known how many transformers could fail, as the results are based on a number of characteristic assumptions including (but not limited to) GIC flows into the transformer, transformer design, number of transformer limbs, transformer loading history, age of transformer, and number of other characteristics. All Assumptions and methods used for planning and operating studies with regards to geomagnetic storms need to be transparent, and validated through existing Interconnection Reliability Modeling groups."

In addition, we find it remarkable and surprising that all photographs of transformer GMD damage – included in all previous drafts -- were removed from the published version of the report. Such photographs, when coupled with more complete conclusions, as in the draft quote immediately above, tend to give an accurate sense of our current inability to make robust, positive conclusions about the security of the U.S. aging transformer fleet. Their removal, coupled with the shift to such positive, definitive conclusions, seems both anomalous and surprising.

Task Force assessment of insufficient data not included in published report

The shortening of this conclusion between the January 9 draft and the recently published report gives the incorrect impression that only pre-1972 shell type transformers are at significant risk. As is clear from the January 9 version, no strong conclusion / assertion was yet reached by the GMD Task Force participants. It was apparently inserted into the report after all regular comments on the previous draft had been submitted on January 19, 2012. There was discussion and wide agreement that shell-form transformers represent the core configuration with the lowest magnetic reluctance, and therefore highest likelihood of stray flux under GIC conditions. It was never the GMD Task Force's conclusion, however, that other core types are immune to GIC, as the above assertion might indicate. Indeed, specific data referencing broad failures of other core types were in fact presented and discussed.

Available data suggests failure modes in multiple transformer types

For example, when examining reporting from the only U.S. utility that made data on transformer incidents for the March 1989 storm publicly available, task force participants learned that eight transformers of different design suffered deleterious effects from this one storm, more than one-third of the utility's entire EHV transformer fleet. Larger storms would, of course, result in greater impacts to these transformers and would likely affect an even greater proportion of EHV transformers.[7] Indeed, it was an essentially unanimous conclusion of GMDTF participants during the November meeting that generalizing results about GIC withstand capabilities of transformers may be impossible because of the near-uniqueness of each design.

From the only data made available to the public from the March 13, 1989 storm of the experience of transformer problems across an entire power company (APS paper), there was specific evidence that 3 legged core form transformers suffered deleterious effects. This experience shared by APS also noted that high percentages of their network transformers were impacted by this historically weak storm.

As mentioned above, they noted eight transformers that suffered deleterious effects, more than one-third of their entire EHV transformer fleet, from this one storm. Larger storms are quite certain to produce larger impacts to these transformers and likely affect an even greater proportion

7. P.R. Gattens, R. M. Waggel, Ramsis Girgus, Robert Nevins, "Investigations of Transformer Overheating Due To Solar Magnetic Disturbances", IEEE Special Publication 90TH0291-5 PWR, Effects of Solar-Geomagnetic Disturbances on Power Systems, July 12, 1989.].

of EHV transformers. Unfortunately, no other power company has voluntarily reported to the public their experience or analysis of this or other more recent storms and transformer problems, nor are they required to under the existing NERC process.

"Simultaneous, catastrophic" failure mode assumption is invalid

The GMD Task Force Interim Report might imply that a key concern for EHV transformers is "simultaneous, catastrophic failure." This, however, is not a proper characterization of the concern. It is a well-known and agreed upon fact by all GMDTF members that the mean replacement time for new extra high voltage transformers is between 12 - 18 months, when requested in conventional, small numbers. At this replacement rate, "simultaneous" failure – and potentially catastrophic problems for the power grid – effectively occurs if transformers are damaged to a degree where significant numbers fail within days, weeks, or even several months of a GMD event.

More study and analysis needed

As the January 9 GMD Task Force Interim Report draft stated (see above), "more study and analysis is needed." To the best of our knowledge however, in the time between the above draft and the now-published report, no more study and analysis has been conducted and, if it should become available, as the draft report recommended "it needs[s] to be transparent, and validated," so that peer review can build confidence in any conclusion. Lacking this, in the words of the January 9 draft of the report, "It is not known how many transformers could fail." At this time, there is simply no well-supported basis for the report's implication that the number of failures would be minimal following a GMD event.

Concluding remarks:

New concerns over Severe Space Weather and associated Geomagnetic Disturbances have been studied recently by multiple government agencies, including some of the nation's best scientists and engineers. With reports from all of these studies projecting the potential for catastrophic consequences for the nation, any credible organization undertaking to minimize these concerns must subject itself – and be subjected by others – to the highest possible standards of scientific scrutiny and thorough peer review.

When evaluating an issue projected by the Oak Ridge National Laboratory DOE/FERC/DHS study, by NASA and the National Academy of Sciences, the previous DOE / NERC HILF study and others to be a potential existential risk for tens of millions of Americans, the implied personal and organizational responsibilities far surpass normal technical and scientific standards. The recently published GMD Task Force Report does not appear, however, to meet NERC's standards of self-scrutiny and peer review, and certainly does not rise to the level of especially diligent, cautious and comprehensive data and modeling review required for an issue of such unique importance. Along with many other participants and members of the task force, we hope that this report will be retracted, and a suitable due diligence process review initiated to ensure that procedural flaws are not repeated, and an unimpeachable, careful revised process is put in place, designed to include the broadest possible scrutiny.

We urge the report's authors to recognize that their report, unique among all others in its optimistic assertions, could contribute to a possible failure to harden the U.S. grid against severe GMD events. If such an event proves to be catastrophic, as all previous government studies have warned could be the case, the NERC GMD Task Force Report could be viewed as a key contributor to an unprecedented national catastrophe. The organizational and personal responsibilities involved appear to be unprecedented, and should be given the most careful consideration.

Once again, as stated above, NERC provides an important public service, and its processes normally meet the high standards expected for an organization with federally mandated responsibilities. We strongly support the GMD Task Force, and we hope this GMD Task Force Interim Report Assessment will help get the process back on track. The work is of great importance, both to the electric sector and to the nation.