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"

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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

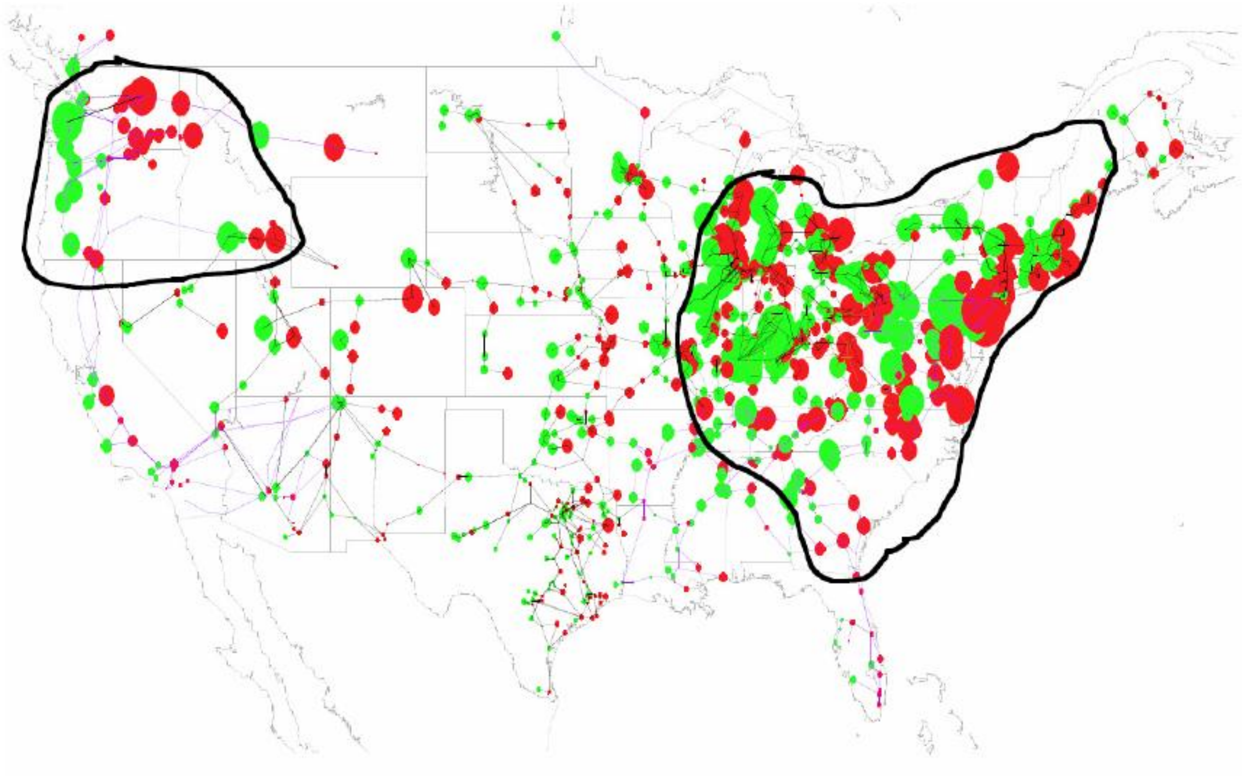


**Figure 1. Areas of Probable Power System Collapse**

### 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.

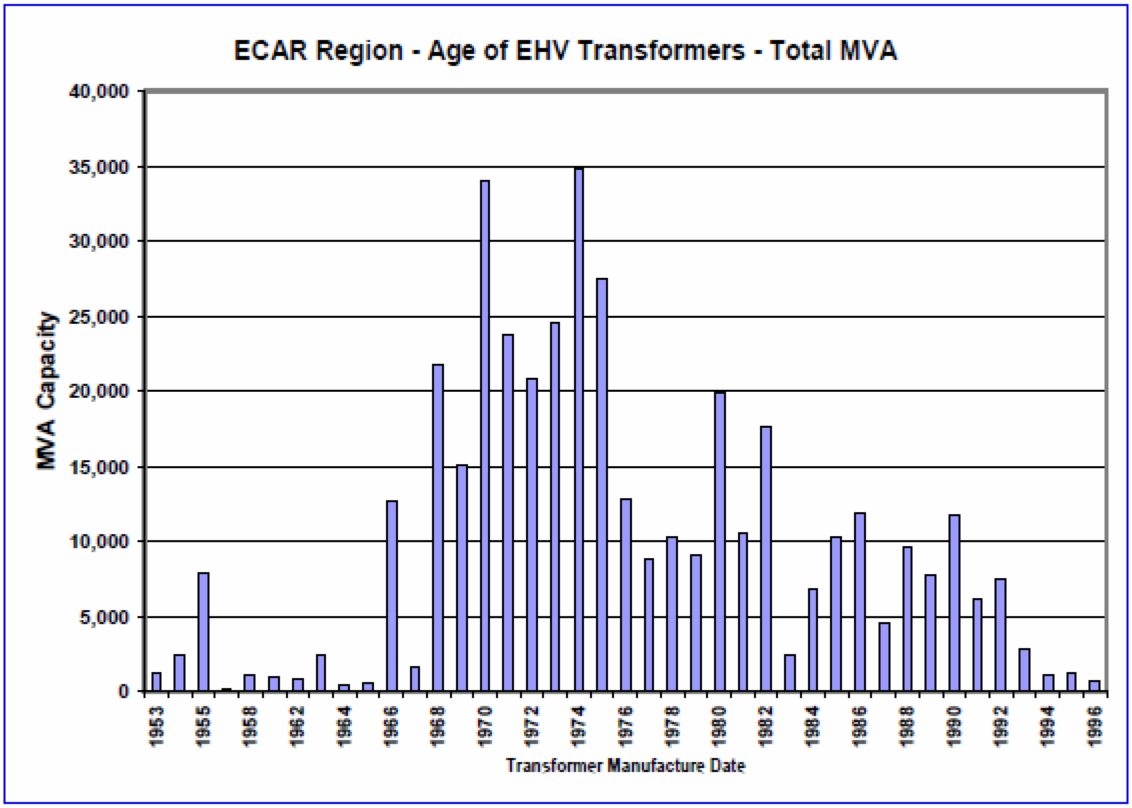


Figure 4-2. Age/manufacture dates of extra high voltage transformers in ECAR.

## 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.

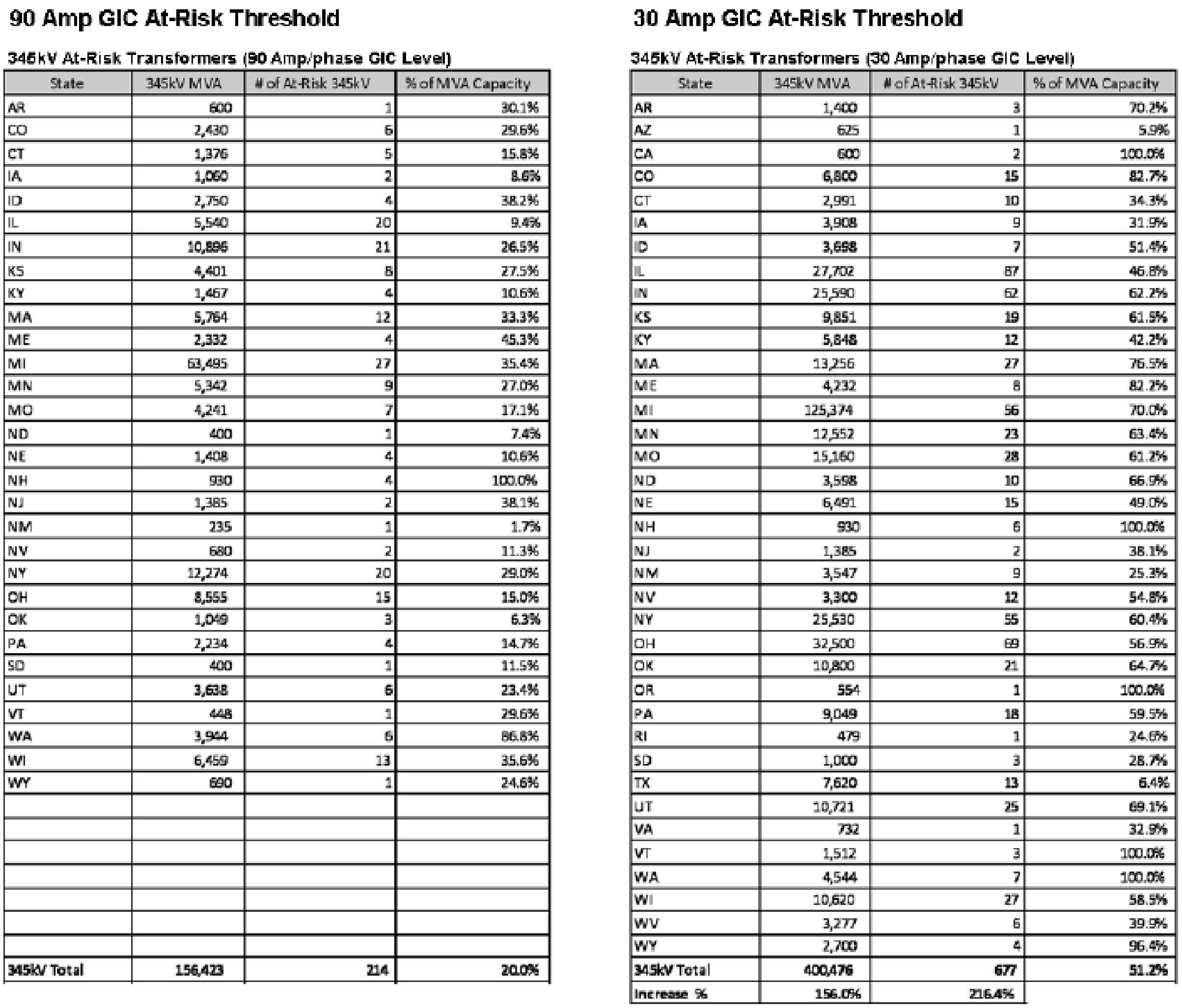
## 3.5 Assessment of Specific Transformers at Risk

### 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 | 63,495 | 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 | 82.7% |
| 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.