U.S. DEPARTMENT OF ENERGY

Geomagnetic Disturbance Monitoring Approach and Implementation Strategies

January 2019

United States Department of Energy
Washington, D.C. 20585

For Further Information

This document was prepared by the Infrastructure Security and Energy Restoration (ISER) division of the U.S. Department of Energy's (DOE) Office of Cybersecurity, Energy Security, and Emergency Response under the direction of Karen S. Evans, Assistant Secretary, and Adrienne Lotto, Deputy Assistant Secretary.

This report is in support of Goal 4 of the *National Space Weather Action Plan*,[1] which:

"seeks to understand vulnerabilities, increase situational awareness, and develop the capability to predict impacts on all affected critical infrastructure systems…. Real-time monitoring of effects on critical infrastructure is essential for situational awareness, enhanced preparedness, and model validation."

Please direct questions about this document to John Ostrich (john.ostrich@hq.doe.gov) or Puesh Kumar (puesh.kumar@hq.doe.gov), who lead ISER's Risk and Hazard Analysis Program.

Contributors include Idaho National Laboratory and other DOE National Laboratories, as well as government and industry partners. Special thanks to Dr. Mack Grady, Dr. George Baker, Dr. Randy Horton, Mr. Mark Olson, Mr. Richard Waggel, Dr. Luis Marti, and Dr. Christopher Balch.

[1] This report completes DOE actions 4.1.1 and 4.1.2 in the National Space Weather Action Plan, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/final_nationalspaceweatheractionplan_20151028.pdf, p. 18. These actions and others were developed to implement the National Space Weather Strategy, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/final_nationalspaceweatherstrategy_20151028.pdf.

Table of Contents

Figures

Executive Summary

Geomagnetic disturbances (GMDs) occur when Earth is subjected to changes in the energized particle streams emitted by the Sun. The solar events that cause major GMD events are coronal mass ejections (CMEs), which are eruptions of charged particle plasma from the Sun's corona that can bombard the Earth within as little as 14 hours. Near the Earth's surface, these changes induce currents, known as geomagnetically induced currents (GICs), in long electrical conductor systems such as electric power transmission and distribution lines, communication lines, rail lines, and pipelines. GMDs can have significant negative impacts on the electric grid, including electrical and electronic equipment and systems (e.g., high-frequency radio communications, global navigation satellite systems, long-haul telecommunications/internet exchange carrier lines).

In November 2014, the National Science and Technology Council within the Executive Branch formed the interagency Space Weather Operations, Research, and Mitigation Task Force (SWORM) to enhance national preparedness for space weather impacts.[2] SWORM developed a *National Space Weather Strategy*[3] and accompanying *National Space Weather Action Plan*[4] which laid out specific actions that the task force could take to enhance the nation's resilience against severe space weather events. Goal 4 of the National Space Weather Action Plan called for the U.S to "Improve Assessment, Modeling, and Prediction of Impacts on Critical Infrastructure" and more specifically for the U.S. Department of Energy (DOE) to "develop plans to provide monitoring and data collection systems." This document is responsive to that direction.

High voltage bulk power transformers, including generator step-up and major substation step-down transformers, are critical assets within the grid, because of their large area of impact, cost, and time to replace. For these systems, the GIC effects of GMDs can include:

- Harmonic currents that can cause relays to trip equipment;
- Fringing magnetic fields (i.e., flux outside the core) that can create heating in the transformer, which, if sufficiently high and of long duration, can lead to overheating and reduction of a transformer's life;
- Increased reactive power consumption that can cause the system to collapse due to voltage instability; and
- Damage and upset of customer equipment due to power quality disturbances.

There are significant gaps in in our understanding of how GMDs may affect the U.S. electric grid, and consequently also in our understanding of how to mitigate the worst of these effects. To address these gaps, an incremental and prioritized implementation of GMD monitoring approaches is recommended. The intent of this incremental implementation is to begin by using the existing industry approach of monitoring transformer operation via temperature, voltage, and current. The next step would be to correlate these data with already-collected data. Finally, data types could be expanded to improve the accuracy of GMD models and simulation, enable predictive capabilities, and ensure a more reliable, flexible, and resilient power grid for the nation.

[2] SWORM started out as a task force and later became a subcommittee of the Committee on Environment, Natural Resources, and Sustainability. Recently the National Science and Technology Council (NSTC) reorganized the Space Weather Operations, Research, and Mitigation (SWORM) activity as a *Working Group* under the Space Weather, Security and Hazards (SWSH) Subcommittee within the Committee for Homeland and National Security (CHNS). .

[3] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/final_nationalspaceweatherstrategy_20151028.pdf

[4] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/final_nationalspaceweatheractionplan_20151028.pdf

The strategy should be to:

1. Use existing data capabilities on existing individual transformers to monitor, track, and utilize temperature, voltage, and current measurements for GMD effects.
2. Increase data capabilities at substations to monitor harmonics for predictive capabilities and additional warning indicators.
3. Establish regional indicator systems through intensive monitoring of critical transformers that collect time-domain magnetic field and induced current data to support GMD effects analysis, modeling, model validation, and predictions.

This will result in:

- Increased understanding of the specific technical impacts of a GMD event on the grid to better assist the electricity sector in determining ways to mitigate or prevent widespread power outages;
- Increased accuracy and reliability of models and modeling parameters, allowing for greater reliability, optimized operations, and increased resilience against high-impact, low-frequency events;
- More accurate planning for the application of resources; and
- Assistance in addressing known gaps related to GMD events.

By improving GMD monitoring and data collection, the United States will be better positioned to protect the national electric grid through preparedness and resiliency planning.

Purpose

The U.S. Department of Energy (DOE) is part of the interagency Space Weather Operations, Research, and Mitigation Working Group (SWORM) that developed the *National Space Weather Strategy*[5] and the subsequent *National Space Weather Action Plan*[6] to implement the strategy. DOE was directed to address Goal 4 of the strategy, "Improve Assessment, Modeling, and Prediction of Impacts on Critical Infrastructure," by completing the following actions: (1) define data requirements for geomagnetic disturbance (GMD) grid monitoring, (2) complete a plan for a national geomagnetically induced current (GIC) and grid monitoring system, and delineate responsibilities for deployment of national plan. This report is a response to that directive.

Introduction – What Are GMDs?

Geomagnetic disturbances (GMDs) occur when Earth is subjected to changes in the energized particle streams emitted by the Sun. The solar events that cause major GMD events are coronal mass ejections (CMEs), which are eruptions of charged particle plasma from the Sun's corona that can bombard the Earth within as little as 14 hours. CMEs often erupt in the vicinity of an active region and are associated with large solar flares (see Figure 2).[7] However, CMEs may also arise from erupting prominences that are separate from an active region.

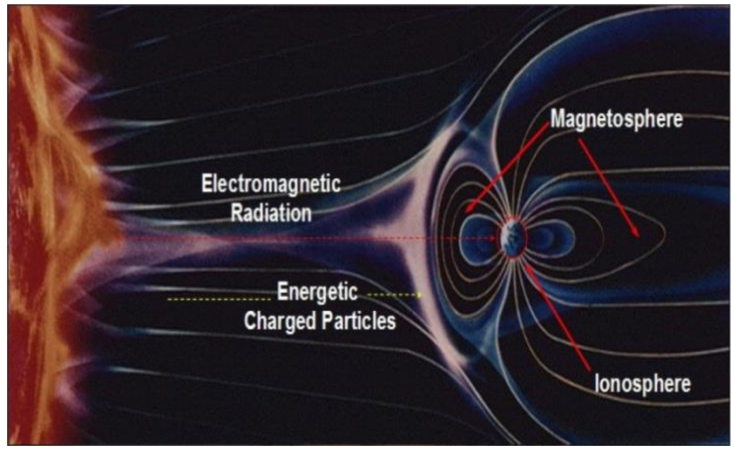

Figure 1. Geomagnetic disturbance

When in the path, CMEs deposit energy into the Earth's magnetosphere, radiation belts, and ionosphere, causing changes in the Earth's magnetic field (see Figure 1). Near the Earth's surface, these changes induce currents, known as geomagnetically induced currents (GICs), in long electrical conductor systems such as electric power transmission and distribution lines, communication lines, rail lines, and pipelines.

GMD Monitoring

Satellites monitor GMDs, and three-axis fluxgate magnetometers record the direction and total intensity of the magnetic field on the Earth's surface.[8] The United States Geological Survey (USGS) is working Earth resistivity models and providing magnetometer data to map ground-level magnetic fluctuations. The Space Weather Prediction Center (SWPC) and the National Oceanic and Atmospheric Administration (NOAA) have instrumented satellites to monitor various types of solar activity to provide early warning and for help in the study and understanding of CMEs. SWPC issues a "Watch" when a GMD event is detected on the sun that has the potential to hit the Earth within days,

[5] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/final_nationalspaceweatherstrategy_20151028.pdf

[6] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/final_nationalspaceweatheractionplan_20151028.pdf

[7] Space Weather Prediction Center, National Oceanic and Atmospheric Administration, *Coronal Mass Ejections,* n.d. Retrieved from http://www.swpc.noaa.gov/phenomena/coronal-mass-ejections.

[8] USGS National Geomagnetism Program, Instrumentation, n.d. Retrieved from http://geomag.usgs.gov/monitoring/instrumentation.php.

and sometimes within as little as 14 to 16 hours. SWPC will issue a "Warning" up to an hour prior to the arrival of a GMD event, based on satellite data that provides more precise observation of the direction and magnitude of the solar wind plasma prior to the arrival on Earth. SWPC will issue an "Alert" when a GMD event has begun. System operators have operational procedures that detail what to do when SWPC makes these announcements (see Current Approach section for more information).

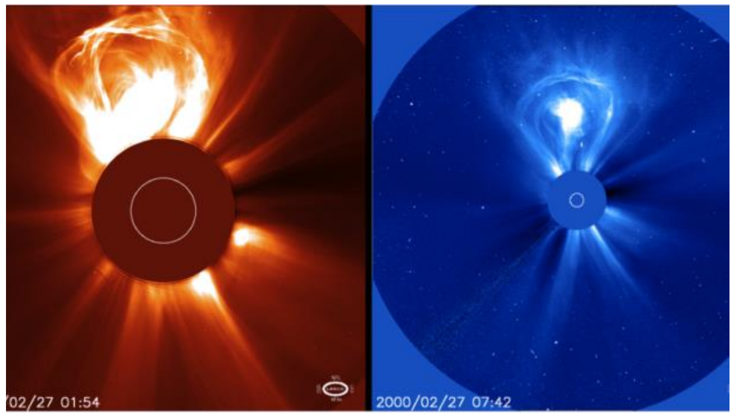

Figure 2. Coronal mass ejection (image from the National Aeronautics and Space Administration/ European Space Agency Solar and Heliospheric Observatory mission)

GMD Effects

GMDs take the form of slowly changing the Earth's magnetic fields by inducing electric fields (relative to 60 Hertz [Hz]) along the Earth's surface. For a relatively strong storm, the geoelectric field intensity might be only several volts per kilometer, but this could result in a difference of hundreds of volts between the ends of a long-distance line. The fields change so slowly that the induced voltage is practically constant from the perspective of the power grid (i.e., near-direct current [DC]). Transformers and substations require alternating current (AC) to function. When this quasi-DC current flows through this equipment, it can disrupt their operation. This could lead to customer equipment damage if, for example, a transformer was unable to step down a high voltage to the lower voltage through which the equipment was rated (see Figure 3).[9] If the quasi-DC currents are large enough, they may cause voltage collapse, leading to blackouts. DC currents that are very high, of long duration, and/or persistent can cause thermal damage to transformers.

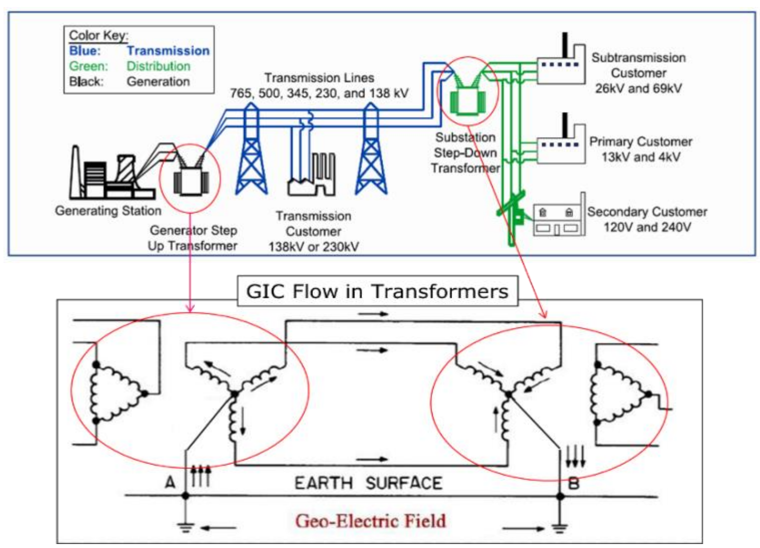

Figure 3. Geomagnetically induced currents on the grid

The quasi-DC GIC through the windings will slowly (over seconds or minutes) push a transformer into deep asymmetric saturation. Deep saturation creates severe internal thermal and mechanical stress in transformers. For grid AC voltage calculations, the saturation current is assumed to be mostly lagging; therefore, it can be approximated in a conventional AC power flow program (that utilities already have) as a very large GIC-dependent reactive power demand. The power flow program uses these reactive powers to resolve AC bus voltages and currents. Transformer saturation over a wide area can reach a point where bus voltages collapse, creating a blackout.

[9] The top portion (identified by the blue box) of the figure was retrieved from the U.S.-Canada Power System Outage Task Force, *Final Report on the August 14, 2003, Blackout in the United States and Canada: Causes and Recommendations*, April 2004. The common circuit diagram at the bottom (identified by the black box) and the overlaid circles/arrows were included to show how GIC flow occurs within the transformers.

In North America, higher latitudes typically experience greater GMD/GIC effects due to the enhanced auroral electrojet currents near the magnetic pole. However, the auroral electrojet current system in the northern hemisphere tends to expand southward during a severe storm and can affect equipment and systems, even at lower latitudes.[10]

High voltage bulk power transformers, including generator step-up and major substation step-down transformers, are critical assets because of their large area of impact, cost, and time to replace. For these systems, the GIC effects include half-cycle saturation that result in the following:

- Harmonic currents that can cause relays to trip equipment;
- Fringing magnetic fields (i.e., flux outside the core) that can create heating in the transformer, which, if sufficiently high and of long duration, can lead to overheating and reduction of a transformer's life;
- Increased reactive power consumption that can cause the system to collapse due to voltage instability; and
- Damage and upset of customer equipment due to power quality disturbances.

Historical Examples of GMDs

The history of solar storms shows that they follow a fairly regular and recurring 11-year cycle that can result in GMDs, which—if they strike the Earth and are strong enough—can impact large areas.[11] NOAA created a geomagnetic storm scale to measure their magnitude, frequency, and expected impacts.[12] Storms are categorized as minor (G 1), moderate (G 2), strong (G 3), severe (G 4), and extreme (G 5). According to the NOAA scale, G 5 storms occur about every 33 months. Although monitoring all storms is prudent, utilities only need to address the largest of the G 5 geomagnetic storms.[13]

Some significant GMD historic storms and their impacts include the following:[14]

- August 28–September 2, 1859 (known as the Carrington Event): One of the stronger storms recorded in the modern era, and one of the fastest moving, with only 17 hours in transit. Some telegraph systems were destroyed in Europe and North America.
- November 18, 1882: A GMD event caused a compass deflection of nearly two degrees.
- June 17, 1915: In the northeastern portion of North America, eastern-running telegraph lines were affected, allowing no transmissions. Northern-running lines were not affected.
- May 13–15, 1921: Railroad switching and signaling systems in New York were damaged; telephone and telegraph systems were interrupted and/or damaged across the United States and Europe; and even undersea cables were damaged.

[10] North American Electric Reliability Corporation, *Geo-Magnetic Disturbances (GMD): Monitoring, Mitigation, and Next Steps: A Literature Review and Summary of the April 2011 NERC GMD Workshop*, October 2011.

[11] Sun, R., McVey, M., Lamb, M., & Gardner, R.W., "Mitigating Geomagnetic Disturbances: A Summary of Dominion Virginia Power's Efforts," *IEEE Electrification Magazine*, Vol. 3, No. 4, December 2015, pp. 34-45. DOI: 10.1109/MELE.2015.2480636.

[12] https://www.swpc.noaa.gov/noaa-scales-explanation

[13] The North American Electric Reliability Corporation (NERC) GMD standard, TPL-007-1, requires utilities to assess the vulnerability of their system only to a 100-year GMD storm, which is a very large, extreme G 5 storm.

[14] Description taken from Newspaper Archives at SolarStorms.org.

- March 24, 1940: The Philadelphia Electric Company recorded strong reactive power swings and voltage surges throughout the electric grid. Telephone cables between Fargo, North Dakota, and Winnipeg, Canada, had wires fused together. More than 185,000 miles of telephone and telegraph lines were knocked out of service.
- August 4, 1972: Solar astronomers reported three powerful solar flares. The next day, the Pioneer 9 spacecraft detected large solar waves. AT&T reported voltage surges; Bell reported service outages from Plano, Illinois, to Cascade, Iowa; and Canadian Overseas Telecommunications Corporation reported voltage surges that damaged equipment. Transoceanic communication cables also encountered problems.
- March 13, 1989: Hydro-Quebec power grids located in Canada and supporting approximately six million customers lost power for more than nine hours. Throughout North America, there was an increased number of failed transformers in the following months.[15]
- October 29, 2003: This storm was one of the fastest moving solar storms, at only 19 hours in transit. The $450M Midori-2 research satellite was lost. South Africa experienced transformer damage and blackouts. Astronauts on the International Space Station reported radiation effects.
- July 23, 2012: A storm, at least the size of the Carrington Event and approximately twice the magnitude of the 1989 event, missed the Earth's path by one week. According to the National Academy of Sciences, the economic impact could have been in the trillions of dollars, and it would have taken years to recover from the damage.[16]

Based on these events, it is clear that specific impacts cannot be confidently modeled, predicted, or anticipated, but the overall potential impact could be catastrophic. High-voltage, bulk power transformers, including generator step-up and major substation step-down transformers, are critical assets because of the cost and time needed for replacement.

The Need for a GMD Monitoring System

Caused by space weather events, GMDs may have significant impacts on electrical and electronic equipment and systems, including high-frequency radio communications, global navigation satellite systems, long-haul telecommunications/internet exchange carrier lines, and electric power transmission. Further, GMDs can have various adverse effects on the electric grid, such as damaged equipment and loss of power over large areas, and they can lead to the interruption of communications and other adverse societal and economic impacts. In addition, electrification and grid expansion could increase the economic and societal impact of a GMD, especially since suppliers continue to reduce the buffer margins on equipment operating ranges that could help temper a GMD event.[17]

Significant data gaps exist that limit the ability to model effects, predict expected impacts, measure actual impacts, and evaluate potential protective measures related to GMD and the electric grid. To better understand GMDs and their interactions with the grid, the United States needs a national GMD monitoring strategy, which would include both additional data monitoring and dissemination. The

[15] Kampenman, John, Geomagnetic Storms and Their Impacts on the U.S. Power Grid, Metatech, Meta_R-319, January 2010, pp. 2–33. Retrieved from https://fas.org/irp/eprint/geomag.pdf.

[16] National Aeronautics and Space Administration (NASA), "Near Miss: The Solar Superstorm of July 2012." Retrieved from https://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm, July 23, 2014.

[17] North American Energy Reliability Corporation, *2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System*, February 2012. Retrieved from http://www.nerc.com/files/2012GMD.pdf.

increase in knowledge and understanding of how GMD events interact with the electric grid can yield increased reliability and enhanced resiliency.

Industry has developed initial benchmarks for determining the need for GMD protection, but the uncertainties associated with the following limit the ability to confidently model, predict, and anticipate system-specific impacts:

- Resultant field magnitude limits;
- Configuration of the transformer and the electric grid;
- GIC magnitude; and
- Geographic area of influence.

It is important to address these uncertainties to increase confidence that protection measures will be adequate to avoid catastrophic blackouts.

GMD event models and model validation are limited by the availability of information. Available literature regarding past GMD events typically covers relatively low-level solar storms that have occurred since increased monitoring was put in place. Further, geomagnetic observatory data are only available over the past 30 years. Historical data are also not very relevant because these data were taken at very slow sampling rates, are not correlated with GMD event and magnetometer data, and do not contain parameters that provide a complete picture, providing limited use in the study of GMD effects. Multiple predictive approaches, models, and real-time monitoring systems are in varying stages of development and implementation, with no clear direction or consensus on the data type, data format, and model applicability effectiveness/efficiency. It will be important to resolve information gaps and improve models in a coordinated manner to be able to confidently predict effects for the nation to be sufficiently prepared for high-level, wide-area GMD events.

A well-designed, real-time GMD monitoring system would provide grid operators with information on real and expected effects of specific GMD events. These effects would include changes to magnetic fields, and the location and strength of geoelectric fields and geomagnetically induced currents. Further, a successful GMD monitoring system would allow grid operators to:

- Enhance their understanding of potential, expected, and real impacts on grid components, equipment, and systems
- Improve and validate various models and simulations
- Identify areas that need more research and development
- Develop, plan, implement, and improve operational procedures to mitigate adverse impacts during specific GMDs, as well as use real-time data to take the most appropriate actions during the event and get immediate feedback on the effectiveness of their actions
- Deploy protection and/or mitigation to the appropriate location
- Evaluate the effectiveness of operational procedures, as well as mitigation and protection measures; identify any adverse (and unexpected) consequences of the procedures taken and measures implemented.

Current Approach

North American Electric Reliability Corporation (NERC) Requirements

Government, regulatory agencies, and industry have taken steps to address GMD impacts to the grid. NERC issued Emergency Preparedness and Operations (EOP) 010-1, "Geomagnetic Disturbance Operations," which requires all regional reliability coordinators and transmission operators to have procedures in place to mitigate the effects of GMD events by developing and implementing operating plans, processes, and procedures.[18] NERC's Transmission Planning standard, (TPL) 007-1, "Transmission System Planned Performance during Geomagnetic Disturbances," will be implemented over a five-year period beginning in 2017. On November 15, 2018 FERC approved NERC's Transmission Planning standard TPL-007-2 which goes into effect July 1, 2019 and has implementation dates through January 1, 2024, depending on the requirement. These standards are a good first step to ensure that GMD events, such as the 1989 event, will not have a catastrophic impact on the electric grid. However, as stated by NERC, "additional efforts are necessary to understand GMD and its impact on the bulk power system and the optimization of mitigating measures."[19]

EOP-010-1 "Geomagnetic Disturbance Operations"

EOP-010-1, which went into effect in April 2015, requires that each transmission operator have GMD operating plans in place. The transmission operator is responsible for writing and implementing these plans. Minimal guidance is given on how the operator should respond to a GMD event. Most operators adopt a safe system posture, with the intent of increasing the margins within the systems and components to allow operators to deal with current increases, excess reactive power consumption, and fluctuations caused by GMD events.

The actions that increase these margins can, but are not mandated to, include the following:[20, 21]

- Delay planned outages
- Start offline generation and synchronous condensers
- Re-dispatch generation (possibly implement autorun-back, if available)
- Manually start fans/pumps, where possible, on selected transformers to increase thermal margins
- Observe conservative operation modes, with possibly reduced transfer limits
- Discontinue maintenance work and restore out-of-service, high-voltage transmission lines to service; avoid taking long lines out of service

[18] North American Electric Reliability Corporation, *Geo-Magnetic Disturbances (GMD): Monitoring, Mitigation, and Next Steps: A Literature Review and Summary of the April 2011 NERC GMD Workshop*, October 2011.

[19] Institute of Electrical and Electronics Engineers Power & Energy Society Technical Council Task Force on Geomagnetic Disturbances, "Geomagnetic Disturbances: Their Impact on the Power Grid," *IEEE Power and Energy Magazine*, Vol. 11, No. 4, July–Aug. 2013, pp. 71–78. DOI: 10.1109/MPE.2013.2256651.

[20] Institute of Electrical and Electronics Engineers Power & Energy Society Technical Council Task Force on Geomagnetic Disturbances, "Geomagnetic Disturbances: Their Impact on the Power Grid," *IEEE Power and Energy Magazine*, Vol. 11, No. 4, July–Aug. 2013, pp. 71–78. DOI: 10.1109/MPE.2013.2256651.

[21] Northeast Power Coordinating Council, Inc., Document C-15, Procedures for Solar Magnetic Disturbances Which Affect Electric Power Systems. Retrieved from http://www.nerc.com/pa/Stand/Geomagnetic%20Disturbance%20Resources%20DL/NPCC_Procedures_for_GMD_112012.pdf.

- Maintain the system voltage within an acceptable operating range to protect against voltage swings
- Reduce loading on interconnections, critical transmission facilities, and interfaces to 90% or less of their agreed-upon limits
- Reduce loading on generators operating at full load to provide reserve power and reactive capacity
- Consider the impact of tripping large shunt capacitor banks and static reactive power compensators
- Dispatch generation to manage system voltage and tie line loading; distribute operating reserve
- Bring equipment online that is capable of dynamic reactive power support operation to provide reactive power reserve.

Federal Energy Regulatory Commission (FERC) Order No. 830 and NERC's TPL-007-1 "Transmission System Planned Performance for Geomagnetic Disturbance Events"

TPL-007-1[22], which went into effect with FERC Order No. 830 in September 2016, is being evaluated for implementation by the electric industry. FERC Order No. 830 directed NERC to collect necessary GIC and magnetometer data dating as far back as May 2013.

The standard outlines some of the key requirements for owners and operators of the bulk power system to undertake, including the following actions:

- Complete a GMD vulnerability assessment every 60 calendar months
- Develop and maintain system models and GIC system models
- Study, develop, and implement protection and/or mitigation measures, as needed
- Collect magnetometer and GIC data dating back as far as May 2013; make this information publicly available
- Provide GIC flow information and perform a transformer thermal impact assessment with this information.

Within the electric industry, established planning entities will conduct the above activities and simulations for the entire industry. A flowchart of this procedure is provided in Figure 4.

FERC Order 830 and NERC's TPL-007-1 requires analysis of the grid for GMD effects and will lead to additional insight into the strengths and weaknesses of the grid. This will lead to the identification of transformers of interest, a key element of GMD modeling.

[22] https://www.nerc.com/_layouts/15/PrintStandard.aspx?standardnumber=TPL-007-1&title=Transmission%20System%20Planned%20Performance%20for%20Geomagnetic%20Disturbance%20Events&jurisdiction=United%20States

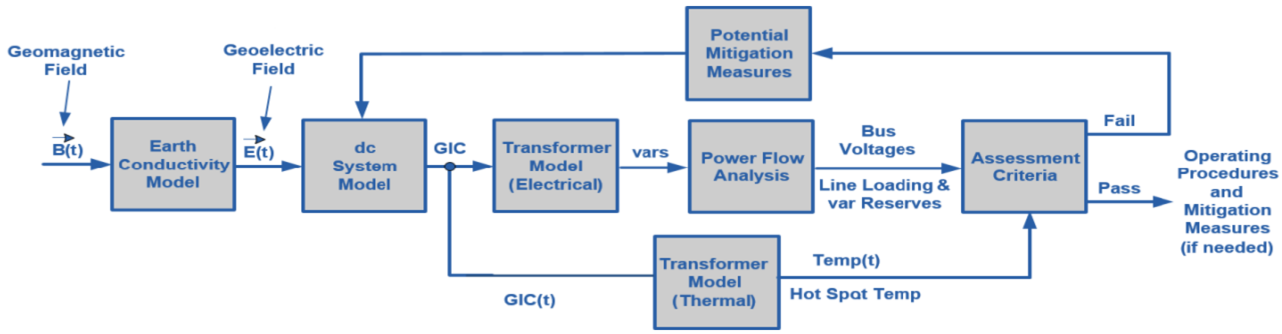

Figure 4. NERC GMD Vulnerability Assessment Process (TPL-007-1)

FERC Order No. 851 and NERC's TPL-007-2 "Transmission System Planned Performance for Geomagnetic Disturbance Events"

FERC Order No. 851[23] approved NERC's proposed Reliability Standard TPL-007-2[24]. According to NERC[25]:

> Reliability Standard TPL-007-2 provides enhanced requirements to address reliability risks arising from geomagnetic disturbances (GMDs), including the risks posed by severe, localized events. The standard also establishes deadlines for entities to develop and implement corrective action plans to address identified GMD vulnerabilities and contains requirements intended to expand the collection of GMD data. In the final rule, FERC directed NERC to revise provisions related to corrective action plans. Specifically, FERC directed NERC to revise the standard to: (i) require the development and implementation of corrective action plans for vulnerabilities identified through the supplemental GMD vulnerability assessment; and (ii) include a process for considering, on a case-by-case basis, requests for extending the time to implement corrective actions. NERC is to submit a revised standard within 12 months of the effective date of TPL-007-2. FERC also directed NERC to submit a report discussing the circumstances under which entities extend corrective action plan deadlines and the disposition of any requests. In the final rule, FERC also accepted the revised GMD research work plan submitted by NERC on April 19, 2018. The revised work plan provides an expansive and detailed framework for conducting research into the GMD-related research areas identified by FERC in Order No. 830. The revised work plan was submitted in response to a FERC order issued on October 19, 2017.

[23] https://www.nerc.com/FilingsOrders/us/FERCOrdersRules/E-3_Order%20No%20851.pdf

[24] https://www.nerc.com/_layouts/15/PrintStandard.aspx?standardnumber=TPL-007-2&title=Transmission%20System%20Planned%20Performance%20for%20Geomagnetic%20Disturbance%20Events&jurisdiction=United%20States

[25] https://www.nerc.com/news/Pages/Summary-of-November-FERC-Open-Meeting-Action.aspx

Rudimentary Technology and Modeling Approaches

For industry, transformer temperature is the most important parameter to monitor because transformer damage is the most costly and devastating outcome. GMD is closely linked to increases in transformer temperature, which could impact grid reliability. All large transformers are monitored for some temperature parameter in areas such as the tank, top oil, or windings. The concern associated with using only this monitoring capability is that when extreme temperatures are seen, damage has already started to occur within the internal insulation materials of the transformers. Further, these measurements may not reveal small hot spots that reach damage thresholds for transformer insulation.[26] Analysis is needed to develop decision processes that allow for early warning and prediction capabilities of an impending or just initiated temperature rise caused by GMD events; such analysis would be based on the data collected during grid monitoring. Improved GIC-caused heat sensing can also provide benefits for detecting temperature rise for other effects/problems.

The normal response of transmission operators to rising transformer temperature is to reduce the demand on the transformer. During a GMD event, the standard approach is to “redirect” GIC flow from overheated transformers; this usually means changing generation profiles and opening transmission lines. However, taking a transformer out of service due to rising temperatures during a GMD event typically increases GIC—and its associated impacts—in neighboring transformers.

The capacity of a transformer is not a strong factor in GIC flow. Considerations such as geologic location, configuration of transmission lines, transformer winding configurations, and other factors are keys to determining a transformer’s susceptibility to GMD events. Transformer connectivity is a major factor, as transformers having long line length connections with low resistances per mile are more susceptible to GIC. Transformers on the geographical edge of the system often experience elevated levels of GIC due to the long lines to connect them to the rest of the system. For that reason, 230-kilovolt (kV) and above transformers tend to be of greater concern than lower kV transformers. In addition, lower voltage transformers connected to transmission lines that are long and have three or four bundled conductors per phase (especially if they are in regions where there are no higher voltage candidates) may also be susceptible to GIC. Generally, the 345-kV and above transformers are costlier and have longer replacement times (more than 18 months for some). Ultimately, understanding a transformer’s susceptibility to a GMD event will require comprehensive analysis that includes a complete network model and factors in large area impacts and near simultaneous effects on multiple transformers.

Today, transformer protective relays routinely sample each voltage and current at the rate of 128 samples per cycle of 60 Hz (i.e., 7,680 samples/second); therefore, common harmonics through at least the 16th harmonic can be accurately computed (i.e., magnitude and angle). Also, dedicated power monitors routinely monitor at 25 kilohertz (kHz). Utilities use these data and models for to operate their systems. Supervisory control and data acquisition measurements of transmission line power flows and voltages are continually compared with simulations conducted every minute or every few seconds by their state estimator power flow models to identify discrepancies between measurements and simulations. Most of these data are used as reactionary indicators for operations; very little are correlated to GMD events and used for analysis or study.

[26] A common practice in the industry is to measure the dissolved gases in the transformer oil, which results from the breakdown of electrical equipment and insulating material. These gases are an indicator of damage that has occurred inside a transformer and are considered an essential indicator for transformer maintenance.

GMD Modeling and Simulation Standards

Current GMD standards define preliminary methods for estimating magnetic strength versus time, as well as latitude scaling factors and Earth conductivity scaling factors.[27] Given the magnetic field and scaling factors, utilities can estimate the strength and direction of the surface electric field at any point in their system. The induced currents that result, in addition to their own electric power flow data, will support calculation of the potential impact of GIC on the electric system.

GIC impacts are seen in a transformer as it is driven into an abnormal operating region, termed *half-cycle saturation*. The saturation operational region for a transformer depends on a number of factors, including the internal configuration, materials of construction, cooling, insulation, and loads. The main objective of the power flow simulation is to compute AC voltages and currents, real and reactive power flows, and transformer losses.

Once a simulation has been performed, the utilities need to identify overheated transformers and propose and simulate possible mitigation strategies. For example, once a transformer reaches a ceiling temperature, it could be tripped offline. Unfortunately, this will likely increase the impact on neighboring transformers. With additional data about GMD effects on the grid, these models and simulations will improve—strengthening knowledge of the power system and enabling identification of other actions that could be taken before transformers reach the point of damage.

GIC Uncertainties in the Existing Models

Transformer models and modeling programs are essential industry capabilities. Transformers are modeled, designed, and tested to meet specifications supplied by the planners and operators. As essential as these models and modeling programs are, they have many limitations regarding GMD interactions that can introduce major errors, mainly because of the lack of empirical data and understanding of actual GMD effects.

GMD Field Data: The modeling difficulty for GIC flow and transformer core saturation is different from those for normal operation. Saturation effects are highly non-linear, and uncertainties28 can be at least an order of magnitude greater for GIC flow models, through which accuracy depends on the grounding resistance estimates and (to a much greater extent) the estimated GIC values used to represent the GMD event. Based on the limitations of GIC modeling and simulations in use today, larger numbers of monitors, sensors, or monitoring systems specifically for GIC are needed so that data can be collected and analyzed. Field data and/or experimental data for a GMD event are required to develop and calibrate realistic power system models.

Power System Configuration Data: Because of the geographic and directional changes of GMD fields, the configuration and geographic location of the power grid has a bearing on GMD interaction with the grid. Presently, power grid simulation programs do not include information such as latitude/longitude of buses or the predominant power line orientation, such as north-south or east-west, and their respective transformer connections.

[27] In Docket No. RM15-11-000, Order No. 830 of 22 September 2016, the Federal Energy Regulatory Commission has directed NERC to perform additional studies to improve the latitude scaling specification of GMD and "determine whether new analyses and observations support modifying the use of single station readings around the Earth to adjust the spatially averaged benchmark for latitude."

[28] Perhaps the greatest unknown in transformer core modeling is transformer hysteresis and how it varies with disturbances and interactions caused by GMD events. Even if the normal operation and performance of the transformer are well understood, the hysteresis curve needed to describe magnetic field behavior with quasi-DC GIC stress and determine transformer core losses can only be crudely estimated.

GIC calculation and power flow software that can incorporate field data and power system configuration data will allow more accurate GMD models to be developed.

Hydro One Approach: An Example of Evolution in Modeling Approaches

The Hydro One transformer approach provides valuable insights that can be implemented in the United States. This approach provides representative regional data, while reducing the required number of sensors and data analysis systems. It provides the ability to accurately capture the GMD impact on the grid to improve existing models and simulations, and it increases the ability to use these models and simulations as predictive tools, instead of merely response triggers.

Because of its geographic location and experience with a major GMD event, Hydro One in Canada has been very proactive in developing GMD monitoring systems, as well as protection and mitigation approaches. Many within the electric industry identify Hydro One's approach as the "baseline" for a GMD monitoring system.

The current Hydro One GMD approach is based on using models of transformer heating due to GICs.

- **Post-Event Response Analysis:** Each transformer has had an in-depth response analysis to enable modeling of its specific behavior under GIC stress, including the effects of surrounding systems at its substation.
- **Identifying "Canary" Transformers**: A model of the grid interconnected to the transformer was developed, including the response to various GMD events, allowing Hydro One to identify susceptible substations and representative transformers based on age, configuration, and/or location. These key transformers have been identified as "canary transformers" and are considered representative of a specific region or area(s).
- **Strategic Sensor Placement:** Hydro One installed magnetometers and GIC monitors in support of these canary transformers. Operators in different regions look to these canary transformers to identify and apply GMD protection and mitigation procedures.

Hydro One is working on the next generation of operator interfaces, decision algorithms, models, and expansion of its phasor measurement unit (PMU) network to support GMD analysis. Hydro One's goals are to continue increasing the amount and type of data obtained, increasing its PMU network, and obtaining time-domain data to support GMD analysis.

In the following section, one recommendation builds on the Hydro One example. In the section titled "Regional Data Collection," the Hydro One transformer was the basis for the recommended approach described.

Recommended GMD Monitoring Approach

The below recommendations aim to address Goal 4 of the SWORM action plan. Specifically, this section:

1. Defines data requirements for geomagnetic disturbance (GMD) grid monitoring
2. Describes a plan for a national geomagnetically induced current (GIC) and grid monitoring system and delineate responsibilities for deployment.

FERC's Order No. 830 and NERC's TPL-007-2 (as described in the "Current Approach" section) drive the electric industry to increase their modeling and analysis to specifically focus on GMD events. The unified approach outlined below is essential to provide nationwide information in support of overall industry needs.

Although DOE and others have supported and funded the collection of both GIC and magnetometer data, neither a consistent approach nor data-gathering requirements for GMD monitoring have been developed or accepted within the industry. For the data that are being collected, there is limited correlation to GMD events and no standardization in data and format. Plus, the data are not generally available outside of the individual utility. Across industry, there is a consensus that GMD event data for analysis and model validation are lacking; however, given the limited acceptance of the need for additional GMD monitoring, industry adoption and implementation have been slow.

This section of the report outlines a more robust monitoring approach that builds on existing knowledge and methods and their known limitations. It is recommended that DOE and industry adopt an incremental and prioritized implementation of this GMD monitoring approach that has four main areas of focus, with each one covering a larger geographic envelope. The first area of focus is the transformer, the second is the substation, the third is the region, and the fourth is nationwide data dissemination.

The areas of focus are presented below (Appendix A provides more details on many of the focus areas):

1. **Transformers:** Collect individual transformer data on temperature, voltage, and current measurements above what is presently done in control systems for the operation and protection of transformers.
    a. Take advantage of the existing transformer monitoring and control data, such as differential relays, and use the data for GMD monitoring, as well as operations. These data might be internal to the control system for operation and protection of the transformer. Inclusion of operational and environmental data, such as transformer loading and environmental temperatures, is important.
2. **Substations:** Outfit substations for additional monitoring of harmonics for predictive capabilities and additional warning indicators specific to GMD.
    a. Use data-gathering systems to collect, time-stamp, and correlate the data with GMD events.
    b. Use synchrophasor networks to obtain the harmonics measurements, plus phasor form (magnitude and angle), at an appropriate sampling rate for GMD monitoring and analysis of key transformers.
3. **Regional Data Collection:** Establish regional indicator systems through intensive monitoring of critical transformers and more fully equip them with data-gathering systems focused on GMD monitoring.
    a. Monitor both DC and AC, as well as the harmonics of the AC.
    b. Utilize magnetic field fluctuation monitors to understand local GMD effects and the resulting GIC effects. Encourage real-time external distribution of geomagnetic measurements, which can then be incorporated into more accurate nationwide space weather specifications (i.e., a national electric field map) and databases.

c. Use GIC monitors paired with magnetic field monitors, and correlate this data relating GICs to changes in the magnetic field caused by GMD events.

d. Record time-domain voltage and current waveforms to ensure confidence that all measurements agree.

4. **Data Dissemination:** Encourage real-time external distribution of geomagnetic measurements, which can then be incorporated into more accurate and comprehensive nationwide databases.

Hardware or firmware updates may be needed for these data to be available outside the current control systems and architecture. Models that utilize the data collected in accordance with NERC's TPL-007-1 and the data recommended under these approaches can:

- Determine optimum locations for GMD-specific sensors, such as magnetometers, GIC sensors, and PMU systems
- Help determine the type and amount of GMD-specific data needed for a location
- Establish a correlation among grid- and GMD-specific sensor data.

This monitoring approach allows for tailored application and implementation to meet the needs of industry, regulatory agencies, and the research community.

Conclusion

GMD monitoring is an area of growing acceptance within the electric industry. NERC and the utility industry have developed systems and approaches that will help the nation understand GMD effects and protect the electric system from a major GMD event.

Although steps have been taken to mitigate the effects of GMD hazards on the electric grid, gaps remain concerning the accuracy and the ability of predictive capabilities to model and simulate GMD impacts on the electric grid, including the following:

- Unknowns on how GIC interact with the electric grid or its specific components
- Unintended consequences of protection device installation
- Uncertainties in DC flow and core saturation models
- Adequacy of procedure-based protection schemes and warning times
- Lack of consensus within the industry on how to approach GMD monitoring.

To address these gaps, an incremental and prioritized implementation of GMD monitoring approaches is recommended. The intent of this incremental implementation is to begin by using the existing industry approach of monitoring transformer operation via temperature, voltage, and current. The next step will be to correlate these data with already-collected data. Finally, data types would be expanded to improve the accuracy of GMD models and simulation, enable predictive capabilities, and ensure a more reliable, flexible, and resilient power grid for the nation.

The following steps are recommended:

5. Use existing data capabilities on existing individual transformers to monitor, track, and utilize temperature, voltage, and current measurements for GMD effects.
6. Increase data capabilities at substations to monitor harmonics for predictive capabilities and additional warning indicators.
7. Establish regional indicator systems through intensive monitoring of critical transformers that collect time-domain magnetic field and induced current data to support GMD effects analysis, modeling, model validation, and predictions.

With the implementation of NERC's TPL-007-2, more analysis and modeling of the grid will take place. An essential result of TPL-007-2 can be the identification of transformers of highest interest based on age, model, configuration, location, or failure consequences—the transformers that will be of most interest and concern for a GMD event. The logical next step for these high-interest transformers will be to begin monitoring and collecting data that can be used for predictions and operational warning.

The predictive data—whether for individual transformers, substations, or transformers of interest—need to be gathered and used when considering and evaluating GMD protection. The goal for GMD monitoring is for operators to receive data that are timely and useful, in addition to having data available for confident GMD analysis, modeling, and validation. Considerations such as implementation cost to individual companies and the sharing of sensitive information are driving factors for gaining complete acceptance by industry. The graduated implementation of monitoring approaches will expedite the data collection required for a confident GMD effects assessment and effective protection of the national electric grid.

Glossary/Acronyms

AC	Alternating current
CME	Coronal mass ejection
dB	Change in the amplitude of the magnetic field
DC	Direct current
DOE	U.S. Department of Energy
dt	Time it takes to make the change in amplitude of a magnetic field
EOP	Emergency Preparedness and Operations
FERC	Federal Energy Regulatory Commission
GIC	Geomagnetically induced current
GMD	Geomagnetic disturbance
Hz	Hertz
I	Current
IP	Internet protocol
ISER	Infrastructure Security and Energy Restoration Division
kHz	kilohertz
kV	kilovolt
NERC	North American Electric Reliability Corporation
NOAA	National Oceanic and Atmospheric Administration
OE	Office of Electricity Delivery & Energy Reliability
P_{avg}	Active power (average)
P_{loss}	Active power loss
PMU	Phasor measurement unit
Q_{avg}	Reactive power (average)
Q_{loss}	Reactive power loss
R&D	Research and development
RMS	Root mean square
SCADA	Supervisory control and data acquisition
SWORM	Space Weather Operations, Research, and Mitigation Working Group
SWPC	Space Weather Prediction Center
TPL	Transmission planning
USGS	United States Geological Survey
V	Voltage

Appendix A: Technical Recommendations: GMD Monitoring Approaches

The below recommendations aim to address Goal 4 of the SWORM action plan.

Transformers

To fully monitor and utilize transformers identified through Federal Energy Regulatory Commission (FERC) Order No. 830 and North American Electric Reliability Corporation (NERC) Transmission Planning (TPL) 007-1 as indicators of events, industry must embrace a net-centric approach that allows entities to view and correlate real-time data. Data should be time-stamped and correlated with geomagnetic disturbance (GMD) warnings and magnetometer data.

Temperature Measurements

Internal temperature is almost universally monitored in all large transformers. A rise in transformer temperature, regardless of where readings are obtained within the transformer, is a proven protection parameter used by industry as a guide for operations and a trigger for emergency procedures. However, temperature rise is slow and is not an accurate predictive indicator of a GMD event. Further, temperature rise is not a purely GMD-driven parameter. There are concerns that once significant temperature increases are seen, some damage, even if small, has already occurred within the transformer. For these reasons, factors such as load, ambient temperature, and other operational factors need to be collected. In that way, the actual impact of geomagnetically induced current (GIC) itself on transformer temperature can be known.

To increase the applicability of temperature measurements in support of GMD effect studies, warnings about space weather events and any magnetometer data with time stamps need to be correlated with any GMD indicators.

Conventional Voltage and Current Root Mean Square Measurements

Root mean square (RMS) voltage and current measurements are the most fundamental electrical measurements for detecting transformer stress and overload. In power systems, RMS voltages are dominated by the 60-hertz (Hz) component. High-voltage RMS (such as 120% over standard operating conditions) can result in damage to insulators and high transformer saturation losses. Low-voltage RMS also can stress downstream systems and equipment, and it can increase the risk of cascading outages from voltage collapse. Transformers have maximum current ratings. High currents produce excess losses and heating. Imbalance between phases indicates abnormal behavior. In circuit analysis, RMS values are the equivalent power average magnitudes of voltage and current phasors; they contain no phase angle information.

All large power transformers use RMS voltage readings on both high- and low-voltage sides as part of normal operations. They also have RMS current measurements on either or both sides. Most transformers have built-in current monitoring transformers that feed a stepped-down version of transformer currents in each phase to a protective relay in the substation. Voltage measurements are taken with capacitor-divider devices on the high-voltage side and small instrumentation transformers on the low side. Active and reactive power (P_{avg} and Q_{avg}, respectively) are calculated using voltage and current measurements inside protective relays. The fact that these data are being used by control and protection systems does not mean that the data are being collected, are correlated with GMD events, or are available for use outside the relays.

Most large transformers read the following values for normal operations and warning indicators:

- RMS AC phase voltages (i.e., V_{an}, V_{bn}, and V_{cn}) and line currents (i.e., I_a, I_b, and I_c) on the high-voltage side
- RMS AC phase voltages and line currents on the low-voltage side
- Transformer temperature(s) sufficient to estimate hot spot temperature
- Overpressure conditions.

Presently, these data are not fully used or tracked for GMD effects. By correlating this information with GMD indicators (such as space weather warning, magnetometer data, or calculated geoelectric fields), these values will increase our understanding of the interactions of a GMD on the grid and improve modeling accuracy. Additional data that could be developed using the RMS parameters are as follows:

- P_{avg} and Q_{avg} on the high-voltage side
- P_{avg} and Q_{avg} on the low-voltage side
- RMS AC in a transformer neutral-to-ground connection.

GIC Mitigation Device Data

After performing the vulnerability assessments required under NERC's TPL-007-1 standard, some utilities will likely install devices on their transformers to mitigate or block GICs. There are a number of GIC filter systems available from various suppliers. So far, the existing systems have a number of limitations—they are large, expensive, and do not have total acceptance across industry for their ability to eliminate the GIC effects. Additional testing and development have been emphasized by Executive Order 13744 on Coordinating Efforts to Prepare the Nation for Space Weather Events (October 13, 2016).

The Executive Order directed the U.S. Department of Energy (DOE) to develop a plan to test and evaluate available devices that could mitigate the effects of GMD on the electrical power grid. DOE will focus its activities on the capabilities of these systems to restrict GIC flow into the electric power grid. DOE will also focus on areas and activities that will help the electric industry mutually accept GIC blockers/filters; this work will include research to verify that no unintended harmful consequences will result from the use of such blockers/filters. Data indicating how well the devices filtered and/or blocked the GICs during storms, and if any unintended consequences occurred, would be valuable to others contemplating installation.

Substations

Substations are terminations for transmission lines, which serve large industrial and commercial loads and feed distribution systems that, in turn, feed smaller customer loads. Transmission systems have large transformers that connect medium-voltage generators to high-voltage lines and high-voltage transmission lines to lower voltage lines (e.g., 20-kilovolt (kV) generator stepped up to 345 kV, which is stepped down to 138 kV or even lower to distribution levels such as 12.5 kV or 25 kV). Substations contain the large transformers that are most likely to be affected by GMD damage. They also house the monitoring and protection devices that quickly detect problems and open circuit breakers. Substations usually have a collection of transformers, some of different sizes and/or line orientation (i.e., north-south versus east-west). By implementing certain measuring approaches on a transformer or a set of transformers with complementary size and orientation, additional information can be obtained that will supplement GMD monitoring.

Root Mean Square Harmonics

The standard measures of harmonic voltage and currents are RMS volts and amps, respectively. Unlike standard RMS (which is mostly 60 Hz), harmonic percentages of the fundamental values are computed by sampling voltage or current waveforms and decomposing the waveforms into their Fourier harmonic components (i.e., harmonics 2, 3, 4, 5, and 6, which are 120, 180, 240, 300, and 360 Hz, respectively). As an example, these are described as "the third harmonic magnitude, which is 5% of the fundamental 60 Hz magnitude."

Harmonic calculations for voltage and current are performed by some conventional protection relays and, if needed, by more specialized equipment—all of which are familiar to and used by electric utilities. Harmonic information describes the multiples of 60-Hz components of voltage and current waveforms. Harmonics are like the "tones" of a musical instrument in that the harmonics of the fundamental frequency are what separate the sound of one instrument from another. "Tones" change when the power system has abnormalities, just as a transformer's audible noise can change. However, electrical harmonics are extremely sensitive to changes; events such as asymmetric transformer saturation caused by GIC are clearly visible. In fact, the second and third harmonics in a transformer have been used in system protection schemes for at least 50 years. While modern relays can compute harmonics, the information typically is used only within a respective control system. For the purposes of grid GMD effects monitoring, harmonic information that is already available needs to be sent securely to a central location.

Regional Data Collection

Regional Indicator Transformers

The regional indicator transformer concept is extrapolated from Hydro One's approach with its "canary transformers." By identifying the regional transformers of interest (or transformers that can be used as representatives) and applying more complete GMD monitoring systems, the electric industry will cost-effectively provide early warning indicators and data sets that can be used to strengthen the knowledge of GMD effects on the power system, as well as improve and validate current models.

Transformers that should be considered in regional sampling have one or more of the following attributes:

- Only grounded-wye connections on the high-voltage side
- Connected miles of transmission lines (i.e., antennas) that are mostly capable of carrying DC current ("DC capable" means that both ends of a line have grounded-wye connections)
- Transformers that are on the geographical edge of a system (i.e., end-of-line enhancement effect and coastal enhancement effect)
- GIC-susceptible lines that cover possible GMD orientations
- Systems that are susceptible to GIC perturbations and systems that are 345 kV and above (lower-voltage transformers (e.g., 138 kV) may be appropriate in regions where they are critical or the backbone transmission voltage)
- High consequence areas or regions

- Single point-of-failure locations, where transformer failure will affect a high number of other critical, dependent systems.

In addition, these systems must allow for data to be supplied to other stations and/or operators in their area of influence. It should be noted that under the requirements of NERC's TPL-007-1, "transformers that are determined by analysis and modeling to not be susceptible to GMD effects will not be required to comply with GMD monitoring and analysis requirements." Essential to a true nationwide GMD monitoring system will be the need for regional indicator transformers to be identified in all areas, even those regions deemed not to be susceptible to GMD events.

GIC Measurement Systems

Some of the larger and newer transformer monitoring systems have embedded GIC measurements. If not already embedded, a GIC sensor can be installed on a transformer neutral and the data output routed through a Supervisory control and data acquisition (SCADA) system. For optimal data collection, sensors should be able to measure currents in the range of 1000 amps, and should respond to frequencies in the sub-Hz range. The split-core (i.e., clamp-on) option is recommended to avoid taking the transformer out of service to temporarily disconnect the transformer ground connection.

GIC sensor data should correlate with magnetometer data and calculated geoelectric fields (i.e., GIC/geomagnetic field measurement systems in the same vicinity are needed).

Three-Axis Magnetometer

FERC Order No. 830 directed NERC to collect necessary GIC and magnetometer data dating as far back as May 2013. This is a significant step in beginning to establish GMD correlated data; however, there is concern that the available data might not contain the necessary information or pedigree to support GMD analysis and may not be applicable to the location of the transformer. The electric industry has expressed concerns about being responsible for magnetometer installation, calibration, maintenance, and data development. Industry needs to investigate areas or regions that can be represented by a single magnetometer to support GMD monitoring systems; these analyses can be representative of a full region and provide indications throughout. Industry must also establish standards that identify the data to be collected, support the information, and dictate the format. Issues such as data distribution, collection, and management need to be addressed in support of FERC Order No. 830 and NERC's TPL-007-1, as well.

Magnetometers are small devices that detect the magnitudes of the three vector components of the Earth's local magnetic field—north-south, east-west, and up-down. Space weather warnings and data provide general indications of a GMD's magnitude and direction. GMD effects can have different orientations and magnitudes, and they are not homogeneous across time or regions. GMD-inducing currents in the Earth's magnetosphere are analogous to currents in a river; there are ebbs and flows that are separate and distinct to a particular region. There are both large- and small-scale characteristics of the various current systems of concern. However, current sources are at a minimum distance of about 100 kilometers from the ground, so there is a corresponding lower limit to the resolution required for ground-level specification. Nonetheless, localized magnetometer readings are the best option for understanding the geomagnetic regional profile. A magnetometer should be mounted at least 100 meters from steel structures, either on a short pole or less than a meter below ground. The readings are made at several kHz, and can be sent via fiber optics or radio links to a nearby data-gathering center, such as a substation.

A three-axis magnetometer sensor should be paired with GIC monitors at indicator transformers. Monitored geomagnetic fields near a transformer location provides actual magnetic field parameters and can be used as inputs to electric field calculations to predict local GIC. These can be used to develop transfer functions from dB/dt[29] to GIC that can be used to predict future GIC or validate models directly from any known or benchmarked GMD threat. Also, local magnetometer data can be compared with space weather warning values to the extent possible, allowing for direct correlation of predicted GIC values and actual measurements, as well as predicted GMD magnetic fields to those actually experienced. This correlation subsequently offers more accurate information to the operator on actions to take and a more accurate model validation without the need for detailed data on deep Earth conductivity. Local magnetic field measurements can be convolved with the best available Earth transfer functions to calculate geoelectric fields in the region of interest. Recent activities in the research community are resulting in improved specification of these transfer functions over a significant portion of the country, although some critical gaps still exist at this time.

A magnetometer must be installed in a low magnetic noise area. Hydro One reported a significant amount of testing before determining the location for their magnetometers. Because of this requirement, magnetometers may not be installed in the most optimum location for pairing with GIC transformer sensors. Hydro One also reported significant lessons learned from using fiber optics to transfer data from magnetometers to data acquisition systems to avoid ground voltage potential problems.[30]

Synchrophasor Network

Most electric utilities have, or are working toward installing, synchrophasor equipment in many of their major installations. Synchrophasor systems operate independently from SCADA control systems and serve to observe grid oscillations and abnormalities, which is distinct from the purpose of SCADA control systems. RMS measurements of voltage, frequency, and sometimes current are taken 30 times per second and sent back to a concentrator station via ethernet. Because the readings are time-stamped using global positioning system clocks, the voltages and current measurements indicate both magnitude and phase angle (phasors). The angles are very sensitive to low-frequency oscillations (0.4 to 10 Hz) and give clear indications of grid instabilities and potential problems. The electric industry and research community have investigated a variety of systems—from transformer-specific systems, to small in-home sensors and applications. The synchrophasor network is an ideal way to send, receive, and share data in real time. GIC and saturation-related measurements are ideal candidates for sending via synchrophasor networks because grid and transformer abnormalities can be flagged and verified within seconds.

Utilizing the RMS values discussed above and sampling at the higher rates that the synchrophasor systems/network support, data measurements are approaching rates that support predictive capabilities for GMD monitoring. The synchrophasor network utilizes a global positioning system, time-aligned network and private internet channels to send back electric system measurements—or any other type of measurements (such as temperature, magnetic, and acoustic)—to centralized "concentrators." One concentrator can handle about 30 remote stations, where one station takes care of an entire substation. Concentrators can be programmed to forward data to other concentrators through public or private internet using static internet protocol (IP) addresses, firewalls, and

[29] The rate of change of a magnetic field, given by the ratio between the amount of change in the amplitude of the magnetic field (dB) and the time it takes to make that change (dt).

[30] A DOE program is collaborating with the Electric Power Research Institute and industry to deploy 12 inexpensive magnetometers (called *variometers*) along the East Coast of the United States near substations to provide more localized data on the changes in magnetic fields during GMDs.

encryption.[31] This time-stamping of data allows for precise time correlation of GMD event parameters. Further, by gathering and sharing these data for large areas, the range, strength, and impact of a GMD event can be more completely analyzed.

Time Domain

RMS and phasors are descriptors of the actual time-domain voltage and current waveforms. Modern power system relays sample actual time-domain waveforms and then mathematically compute their DC, 60 Hz, and harmonic component magnitudes and phase angles. Time-domain waveforms are the "real thing," while other calculations are simple summary descriptors of the waveforms. Therefore, it is recommended to occasionally include sampled waveform data and compare it to RMS and phasor calculations to ensure confidence that the measurements all agree.

Sampled waveform data are used by protection relays and control systems; however, the data are logged for a short time and then discarded. For the purpose of GMD monitoring and analysis, the waveform data need to be collected and archived. Grid operators need to evaluate and determine the optimal data volume and how to manage the information over time. Real-time data for a large number of systems that are taken continuously will equate to extremely large data sets. As high GICs and GMD storm warnings are received, data collection could be increased to cover the event.

Data Dissemination

Widespread sharing of data is important to better understand the actual impacts of space weather on equipment and on the electric grid system, which will allow owners and operators to validate models that help determine expected impacts when and where actual data are not available. A greater level of modeling and analysis of data (e.g., RMS, harmonics, time domain) and the correlating impact on grid equipment (e.g., transformers, relays, generators) are needed. Testing is essential for correlating system response and validating models. The scientific community is desperate for additional data to study the effects of GMD, validate models, create new models, and perform system and material testing. Industry concerns that these data are either business sensitive and/or may identify critical assets to malevolent actors need to be addressed before providing these data to researchers.

There are a number of parameters that could be developed and collected to support GMD monitoring. Specific data have been recommended as part of this report to help establish GMD interactions with the grid. A thorough investigation is needed to determine (1) what data are needed and why, (2) what data will be business sensitive for the industry, (3) the frequency of data collection, and (4) establishment of the reason for and location of data collection, including database management. Approaches and standards for data format and management, durations for which data are kept, and recognizing and archiving data will need to be investigated.

A key part of the GMD analysis process will be the estimation of GIC due to GMD effects. GIC is a direct result of the GMD-imposed electric field and the ground resistivity. Gaining a better understanding of the ground resistivity at a particular transformer and for a region of interest surrounding a transformer is needed. The uncertainties in Earth conductivity topology are extensive and can introduce order of magnitude uncertainties for induced current predictions. These data should not be sensitive and can be shared.

[31] Currently, synchrophasor data transmission is unencrypted. Thus, these networks could be used by hackers to confuse system operators. It will be important to ensure data security in the future.

With the release of NERC's TPL-007-2 and FERC Order No. 830, FERC tasked NERC with a number of actions that could be augmented by incorporating the recommendations provided in this report. Some of those actions relate to collection and dissemination of data. NERC would be a logical entity to collect, store, and disseminate some of these data to owners and operators, as well as researchers. For effective approaches for GMD protection, a national strategy that encompasses multi-agency and industry collaboration on the sharing of data should be undertaken.

With the addition of predictive parameters, the levels of automation that could be used should be investigated. Operator interfaces will be required and also must be developed to allow for the increased amount of data that will be available. Operator interfaces determine the parameters of interest and representations that are of most use to operators.

The instrumentation and data collected for grid GMD effects also could be useful in case of an EMP because the late-time E3 component is similar (although it will be shorter in duration and could be higher in field strength) to the GICs from a GMD. This correlation is important, and the sharing of findings with organizations concerned about nuclear detonation effects (e.g., U.S. Department of Defense, long-haul communication carriers, pipeline industry) will be important for an all-hazards approach to the resilience and protection of the electric grid.

Data Requirements

The recommended datasets for GMD monitoring are listed below with details provided regarding their description and importance, collection, and usage.

GMD Monitoring Data Requirements	Description and Importance to GMD Monitoring, Modeling, and Alerts [32]	Data Collection and Usage
Individual Transformers		
Transformer temperature	• Temperature measurement is the most basic approach for most monitoring or protection schemes on all large transformers. Further, utilities use temperature measurement to assess the severity of GMD events. • Temperature measurements are made in the tank, top oil, and/or winding hot spot. • Temperature monitoring systems are applied almost universally in all large transformers. • Due to the large thermal mass of transformers, integral temperature measurements may not detect the presence of local hot spots. By the time critical conditions are apparent, hot spot damage may have already occurred. • Data cannot be conclusively equated to a GMD event due to other events that also cause increased temperatures.	The most common temperature-related measurements taken for large transformers are as follows: • High-voltage and low-voltage winding temperatures (for one-phase) • Top oil temperature • Ambient temperature • Status and stage of cooling fans • High-voltage, low-voltage, and tertiary winding amps (for one-phase). These readings are typically taken every second. While not telemetered to central locations, one-second readings are used locally, and they trigger alarms that are immediately telemetered. The winding hot spot temperature is estimated from the above readings and has a thermal time constant of 7–8 minutes. Transformer core thermal time constants are much longer (in the range of 30 minutes).

[32] Detailed comments regarding the data and their usage were taken from IEEE Standard C57.163-2015, "IEEE Guide for Establishing Power Transformer Capability While Under Geomagnetic Disturbances," and from discussions with power system protection engineers.

GMD Monitoring Data Requirements	Description and Importance to GMD Monitoring, Modeling, and Alerts [32]	Data Collection and Usage
Conventional voltage and current root mean square (RMS) measurements (RMS AC V_{an}, V_{bn}, V_{cn}, I_a, I_b, and I_c, plus P_{avg} and Q_{avg}, on transformer high-voltage side and low-voltage side)	Many existing transformers have systems that are or could be tracking RMS measurement data. However, the data are not being utilized for GMD monitoring and protection. • Data could be used for predictive measurements and assist in GMD understanding, analysis, and protective procedure triggering. • Power losses cause transformer heating, and conventional voltage and RMS measurement are much faster than temperature when it comes to quickly identifying abnormal conditions. • Some software and/or hardware upgrades may be required to utilize the data outside local systems.	RMS voltages and currents for each winding, as well as phase for important transformers, are already taken for the purpose of transformer and system protection. P_{avg} and Q_{avg} in and out of transformers may or may not be computed. It is important to consider the following: • Having P_{avg} and Q_{avg} readings on both sides of a transformer is important to this approach because it will permit quick and accurate measurement of P_{loss} and Q_{loss} in a transformer. • P_{loss} increases considerably with geomagnetically induced current (GIC), thus creating heating and high temperatures. • It is commonly believed that Q_{avg} flowing into a transformer subjected to GIC increases even more significantly. Thus, P_{loss} and Q_{loss} will provide early warning of transformer stress, as do GIC measurements, for several minutes prior to significant transformer temperature increases.
Substations (monitor at least one transformer in the substation). Note: north-south and east-west susceptibility to GMD need to be considered in the choice of a transformer.		
RMS harmonic current magnitudes for high-voltage side I_a, I_b, and I_c, for harmonics 1, 2, 4, and 5	Many existing transformers have systems that are or could be tracking RMS harmonic data. However, the data are not being used for GMD protection. • Data can be used for predictive measurements and better understanding of GMD events. • Harmonics allow for greater predictive capabilities and indication of transformer saturation with sufficient time to react before damage occurs. • Some software and/or hardware upgrades may be required. • The third harmonic is excluded due to current hardware capabilities. • Generally, only harmonics from one phase are available; data from all three phases would provide better data sets.	Measuring both GIC and harmonics provides awareness that the transformer may be experiencing difficulty handling the GIC flow. • Core saturation of a transformer generates harmonics that will increase heating within the transformer. • Measured magnitudes of current harmonics can give a rough indication of the additional eddy current losses in windings and metallic structural components. • The harmonics associated with part-cycle core saturation have a unique signature, which along with the presence of direct current (DC) from GIC, can indicate that the core is undergoing saturation. • The signature is a pattern of harmonics where the majority of current from even-ordered harmonics is greater than the odd-ordered harmonics. • It is recommended to compute the total even-ordered harmonic distortion and compare it against computed total odd-ordered harmonic distortion to detect GIC-related saturation.

GMD Monitoring Data Requirements	Description and Importance to GMD Monitoring, Modeling, and Alerts [32]	Data Collection and Usage
Synchrophasor network	Synchrophasor data obtains key information for GMD monitoring and analysis at an appropriate sampling rate and utilizes phasor measurement units (PMUs) that are implemented throughout the industry. • Phasor form of 60 hertz (Hz) components, magnitudes, and angles for high-voltage side and low-voltage side. • V_a, V_b, V_c, I_a, I_b, and I_c, plus neutral current—include harmonics 2, 3, 4, 5, and 6 (magnitude and phase angle). • PMUs require a global positioning system time stamp that may be impacted by a GMD event. Data will continue to be stamped based on the control system clock; however, time drift will occur.	Phase angles are essential to perform calculations of real and reactive power, for both fundamental frequency and harmonics. Power from individual harmonics has the potential to be a key indicator of GIC saturation. • Utilities already use phase angle in 60 Hz measurements. • The magnitude of harmonics, by itself, does not provide a full understanding of a waveform. • To properly reconstruct time-domain waveforms using a Fourier series, 60 Hz and harmonics of 60 Hz phase angles are needed. While harmonic phase angles are not yet directly mentioned in transformer standards, it is known from U.S. Department of Defense, Defense Threat Reduction Agency tests that the angles do vary considerably during GIC-related saturation. Using synchrophasor networks to time-stamp and send GIC-related data back to central locations for archiving and study is a logical way to proceed. It also permits global positioning system time-stamping and synchronization so that data from all locations can be analyzed with perfect time alignment.
Regional Indicator Transformers (based on models of GMD events and transformer characteristics). Regional transformers can be instrumented to a higher degree and then used as an indicator for a region.		
GIC measurement systems (sensor to measure DC or quasi-DC in transformer neutral-to-ground connection)	• GIC DC sensors can be fairly easily installed and used to measure DC in transformer neutral-to-ground connections. • GIC measurement systems are widely known, understood, and used throughout the industry. • GIC can be a good indicator that DC is affecting the transformer and that potential problems could occur. • When used in conjunction with GMD indicators, DC provides advance alert regarding the severity of a GMD event because it is a time-leading indicator of potential transformer saturation. • Transformer models may not accurately represent the true impacts of DC. • Supervisory control and data acquisition system upgrades may be needed to deal with higher sampling rates.	GIC is typically measured by extracting the amount of DC flowing through the grounded neutrals of power transformers. • GIC is quasi-DC and requires filtering to reduce 50–60 Hz and higher frequencies by at least 40 decibel in relation to DC magnitudes of interest. • Devices employed are Hall-effect sensors or series resistors. • A Hall-effect current transducer can be solid core or split core. • High fault currents may cause a Hall-effect current transducer to magnetize, in which case it must be demagnetized. • The measurement range can be as high as ±500 amps, with the resolution to detect 0.1 amps DC.

GMD Monitoring Data Requirements	Description and Importance to GMD Monitoring, Modeling, and Alerts [32]	Data Collection and Usage
	• Systems may not be sensitive enough to capture spikes and long-term effects.	
Three-axis magnetometer	Three-axis magnetometers are sensors used to detect magnetic field fluctuations in a region. The sensor tracks the time-domain magnetic field vector in all three directions and provides indications of local magnetic fields that produce GICs, which are essential for understanding field strength and the direction to analyze and understand GIC development and coupling. • Good models are needed to analyze impacts; having actual magnetometer readings is important in calibrating models. • Systems may not be sensitive enough to capture spikes and long-term effects. • Systems need to be away from magnetic noise and transformers. It may take time and effort to evaluate location sites. • In order to develop *dB(t)/dt* → *I(t)* transfer functions, magnetometers should be proximal to transformer GIC sensors but not close enough to be affected by the transformers' magnetic fields.	The Earth's magnetic field varies considerably over hundreds of miles during a GMD event. The nearest reporting magnetometer to an affected transformer may not represent the local situation. For the purposes of creating and calibrating GIC models for large power grids as a GMD occurs (even at low levels throughout the year) it will be essential to have magnetometer readings relatively close to instrumented transformers to develop *dB(t)/dt* → *I(t)* transfer functions. In that way, the existing methods to predict GIC for actual disturbances can be compared to actual measurements, and thus improve and validate models.
Magneto-telluric surveys	Magneto-telluric surveys can be used to calculate GIC based on a DC model for the power grid and proposed GMD event. • Magneto-telluric surveys are used to develop the Earth-transfer function used to calculate the geoelectric field. • An Earth-response tensor that accurately incorporates full 3D Earth conductivity effects and allows a relatively accurate calculation of the geoelectric field. • Those calculations, in turn, can be used to calculate GIC based on a DC model for the power grid.	Alternately, by utilizing the Earth-response tensor and GIC monitors, the GMD magnitude or geoelectric field can be developed for other areas.
Time domain samples (time-domain waveforms sampled at the top of each minute)	The inclusion of time domain provides a complete data set for GMD analysis. Specifically, checking the measurements' actual sampled time-domain data is the best method to ensure that reported summary measurements—such as RMS, harmonic magnitudes and phase angles, and active and reactive power—are properly computed. Furthermore, periodically, there may be events that have frequency content above the harmonic measurements proposed in this	The time domain for data sampling should be three-cycles of 60 Hz–128 samples per cycle. • High-voltage side and low-voltage side V_a, V_b, V_c, I_a, I_b, I_c, GIC, three-dimensional magnetometer readings, and transformer temperature. The redundancy of having both calculations and sampled waveforms is important to periodically confirm RMS, power, and harmonic measurements develop and calibrate models,

GMD Monitoring Data Requirements	Description and Importance to GMD Monitoring, Modeling, and Alerts [32]	Data Collection and Usage
	document. One time-domain set of waveforms per minute would help avoid any measurement errors.	identifying errors and raising confidence levels in detecting events. Sampling helps address the following: • Extremely large data sets • Data analysis and management However, operator interfaces will need to be developed to present data to operators.