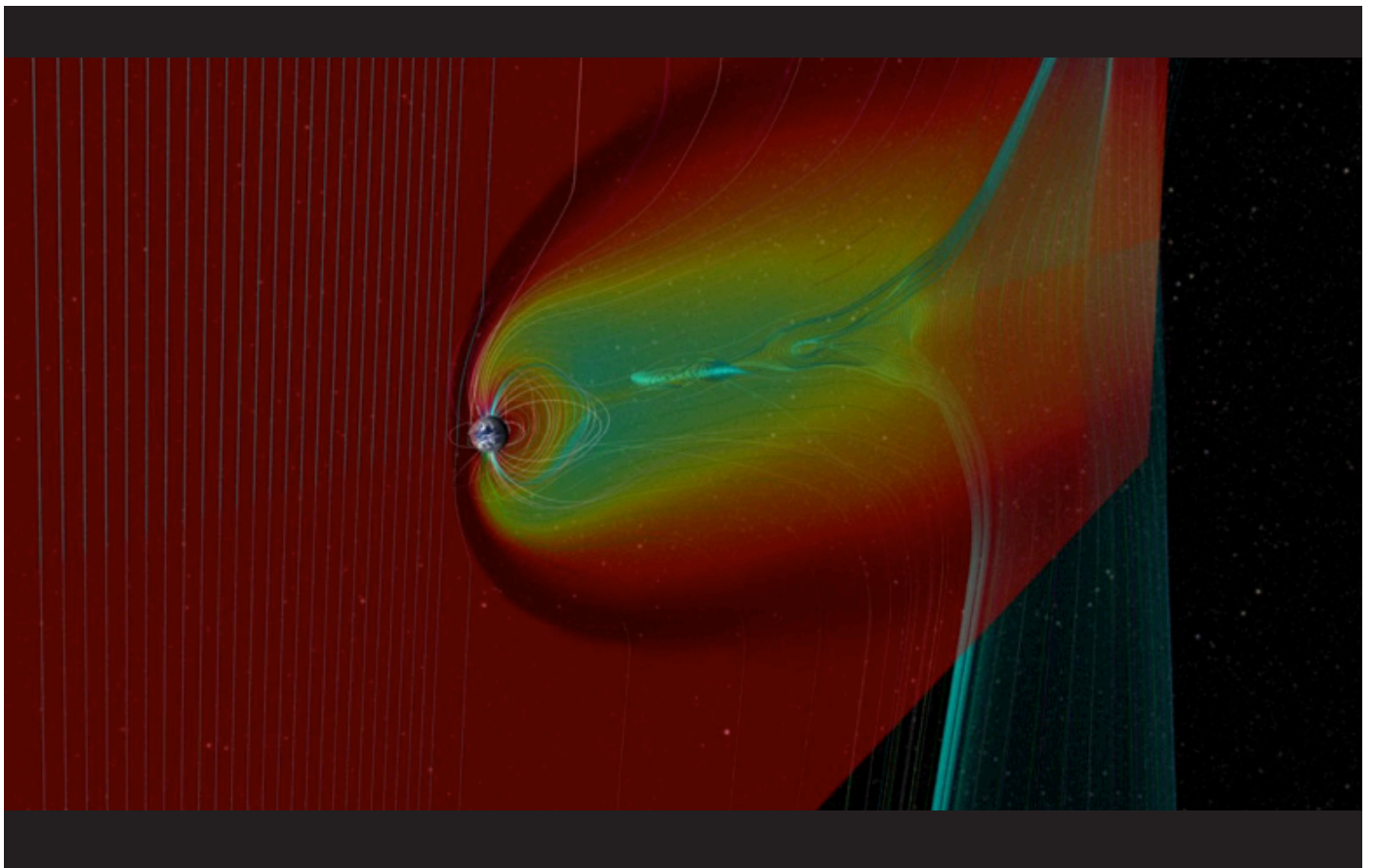


FURTHERING THE RESEARCH OF GEOMAGNETIC DISTURBANCES IMPACT ON THE BULK POWER SYSTEM



April 2018

Table of Contents

Background and Project Objectives	2
Basic Overview of GMDs	2
New Research to Enhance the Science of the 100-Year GMD Event Scenario	3
Ground Conductivity Analyses	4
Overview of Potential GIC Impacts on Transformers	5
Transformer Assessments	6
Overview	6
Analyzing the 75-Amp-Per-Phase Qualifying Threshold for Transformer Thermal Impact Assessment	6
GIC Field Orientation for Transformer Thermal Impact Assessments	6
Assessing the Impacts of Vibrations on Power Transformers	6
Improved Transformer Modeling	7
Harmonic Impact Analysis	9
Industry Communication	10
References	11
For More Information	12

In collaboration with the North American Electric Reliability Corporation (NERC), the utility industry, and other stakeholders, EPRI is building on decades of research in geomagnetic disturbances (GMDs) to better understand, predict, and mitigate the impacts of GMDs on electric power systems.

Leveraging on past GMD work, a two-year, comprehensive, multi-deliverable project that EPRI has recently launched helps the electric utility industry extend its collective understanding of GMDs, better prepare for them, and mitigate them when they occur. This project's objectives are the following:

- Advance the science of defining extreme events on bulk power systems to perform GMD vulnerability assessments
- Improve the accuracy of ground conductivity models used for geomagnetically induced current (GIC) studies
- Further study the impacts of GIC currents on power system assets
- Develop system tools needed to analyze these system impacts

This white paper serves as a guide to EPRI's GMD research work plan.

Background and Project Objectives

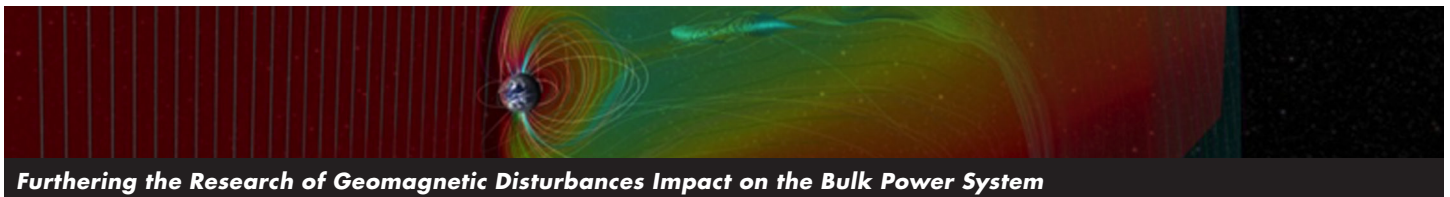
The interconnected bulk power system (BPS) has a long record of reliable, secure delivery of electric power. However, GMDs have demonstrated their ability to disrupt normal BPS operation. For example, in March of 1989, a GMD led to the collapse of the Hydro-Québec system. The 1989 event and other GMDs have resulted in numerous BPS impacts (e.g., capacitor bank tripping, line tripping, and transformer damage) across the continental United States and elsewhere.

To mitigate the potential risk that severe GMDs pose to the reliability and resiliency of the BPS, NERC developed Reliability Standard TPL-007-1 (Transmission System Planned Performance for Geomagnetic Disturbance Events). This standard requires owners and operators of BPS assets to conduct initial and ongoing assessments of the potential impact of a defined benchmark (1-in-100-year) GMD event on their individual BPS assets and on the entire bulk power system.

The Federal Energy Regulatory Commission (FERC) approved Reliability Standard TPL-007-1 in Order No. 830, issued on September 22, 2016 [1]. However, FERC directed NERC to develop modifications to the standard and undertake additional actions to improve understanding of GMD events and their potential impacts on reliability. The objective of this white paper is to enhance collaborative research in each of the areas identified in FERC Order 830. The outcome will lead to a better understanding of the threat that severe GMDs pose on the BPS, and as a result, will provide society with more reliable, secure, and economical delivery of electric power.

Basic Overview of GMDs

The source of GMDs is the sun. Coronal mass ejections (CMEs) are the primary type of solar activity that creates magnetic disturbances on the earth. CMEs involve ejection of large masses of charged solar particles that escape the solar atmosphere (corona). Propagation of individual CMEs from the solar corona to the orbit of the earth takes 1–4 days, depending on the speed of the ejected material. The charged particles associated with CMEs interact with the earth's magnetosphere-ionosphere and cause variation in near-space electric current systems. These electric currents can have amplitudes of millions of amperes, and they perturb the earth's geomagnetic field, induce an electric field at the earth's surface, and cause geomagnetically induced currents (GICs). These quasi-dc GICs flow in the



Furthering the Research of Geomagnetic Disturbances Impact on the Bulk Power System

earth and along manmade conducting paths that act as antennae, such as transmission lines, metallic pipes, telecommunications cables, and railways. The currents can enter and exit a power system at transformer neutral grounds. This entering and exiting of GIC through power system transformers is the main cause of nearly all GMD-related issues [2], which include the disruption of the normal power system operation, and damage to equipment.

New Research to Enhance the Science of the 100-Year GMD Event Scenario

The first step in any GMD assessment is to answer the following question: What is a meaningful profile of an extreme GMD? Over the years, researchers have measured GMD severity in various ways, but the industry needs consensus for use as a baseline. For example, a 1-in-100-year event definition could specify the characteristics of a geoelectric field in space and time. Engineers can then use these characteristics as input in their GMD analyses to do the following:

- Identify locations and assets on their power system that are most vulnerable to GMDs
- Harden critical, vulnerable portions of their power system in advance of GMDs to enhance resiliency
- Develop advance preparations to mitigate GMDs when they occur

Definition of a benchmark GMD scenario requires accurate characterization of the geoelectric field. A 2017 National Aeronautics and Space Administration (NASA) paper summarizes recent research and readiness for GIC events. Regarding GMD characterization and a benchmark scenario definition, the paper points out that “the spatial-temporal characteristics of the horizontal geoelectric field provide the ideal description of a GMD event” [3]. In addition to the temporal (time-based) characteristics, the fluctuations in the magnetic field, rather than the field’s instantaneous value, dictate the GIC. These fluctuations can be localized and complex. The paper concludes that “...while wide areas can be exposed to the storm footprint, the very highest levels of GIC can be regional or local in nature” [3].

Regarding spatial structure, to support the industry’s GMD vulnerability assessments, the definition needs to describe the geoelectric field (uniform or non-uniform) at spatial scales relevant to the bulk power system (hundreds of kilometers) [3]. FERC has directed

NERC to consider revising TPL-007-1 to address the localized extreme geoelectric fields, which FERC indicated could include effects such as “increases in GIC levels, volt-ampere reactive power consumption, harmonics on the Bulk-Power System (and associated misoperations) and transformer heating” [4].

In order to better define localized extreme geoelectric fields, EPRI and its partners will conduct new research to study both ground-based and space-based data¹ around the times of major GMD events to quantify the localized extreme geoelectric fields. Research will also use advanced magnetohydrodynamic (MHD) simulations to quantify the extreme CME interaction with the earth’s magnetosphere-ionosphere system and influence on near-space electric current systems. These MHD simulations will provide new insights into space physical processes that drive extreme geoelectric fields (see Figure 1). Furthermore, observational data analyses will quantify how the severity of GMD events may change as a function of the magnetic time of day (MTOD). Statistical analyses will provide new information about how 1-in-100-year GMD benchmarks could vary in local time.

The severity of the storm and its associated risk is a strong function of geomagnetic latitude and ground conductivity structure [3]. With regard to geomagnetic latitude, in its September 2016 final rule, FERC directed NERC “to reexamine the geomagnetic latitude scaling factors in Reliability Standard TPL-007-1 as part of the GMD research work plan, including using existing models and developing new models to extrapolate from historical data on small to moderate GMD events the impacts of a large, 1-in-100 year GMD event on lower geomagnetic latitudes” [4].

With new MHD-based global space weather modeling, EPRI and its partners will reevaluate the propagation of the auroral boundaries toward southern locations during extreme solar storms. Researchers will conduct modeling systematically using increasingly extreme solar wind conditions as the driver to investigate the response of the auroral boundaries. This work will lead to improved understanding of the theoretical maximum limits for the auroral oval expansion toward more southern locations. The study will use the conducted simulation results along with observations at a large number of stations to determine if the currently applied latitude scaling factors are sufficient or if the results call for more refined scaling factors.

¹ Publicly available data from repositories such as INTERMAGNETIC, World Data Center for Geomagnetism, SuperMAG, and NASA Space Physics Data Facility

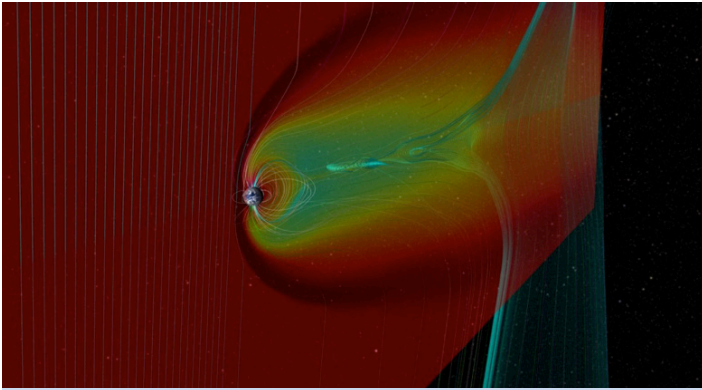


Figure 1 – Example of MHD-based global space weather modeling output. Courtesy NASA (Reference: <https://svs.gsfc.nasa.gov/4189/>)

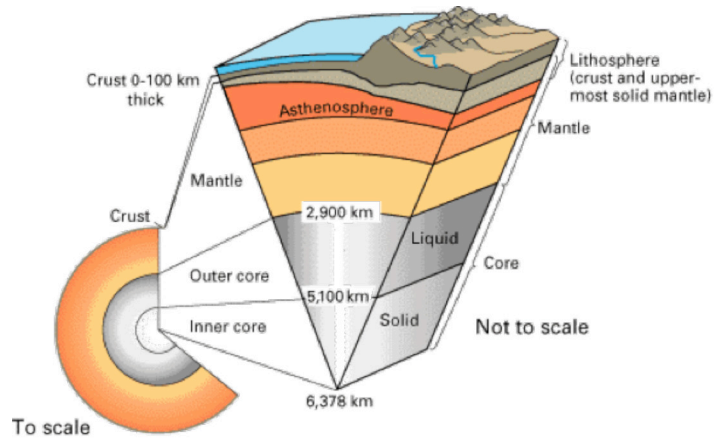


Figure 2 – One-dimensional earth conductivity structure

The work described in the first section of this paper involves research carried out in collaboration between EPRI, NASA, and the Los Alamos National Laboratory. The second section of this paper summarizes new research on ground conductivity structure and recommendations for next steps.

Ground Conductivity Analyses

As mentioned above, the ground conductivity is one of the key parameters in defining the geoelectric field associated with a GMD. Geoelectric field magnitudes and thus power system GIC flows can vary by orders of magnitude from one location to another due to spatial variation in ground conductivity. In general, for given external geomagnetic magnetic field variations, lower ground conductivity generates higher geoelectric fields at the earth's surface, which induces larger voltages in the transmission lines and hence larger GICs.

Although the earth's internal structure can have a complex three-dimensional (3D) distribution of electrical conductivity, one-dimensional (1D) models have provided a widely used tool for modeling the first-order response to a GMD across a specific region. A 1D model represents the ground as layers of differing conductivity that vary only as a function of depth from the surface down to the upper mantle and below (see Figure 2).

Peter Fernberg, an independent researcher from Ottawa, completed development of multiple 1D models that specify the ground conductivity in different physiographic regions of the continental United States and Alaska. This study was part of a joint project between NERC, EPRI, the United States Geological Survey (USGS) Geomagnetism Program, National Resources Canada, and

the USGS Crustal Geophysics Science Center. Natural Resources Canada and Professor Ian Ferguson at the University of Manitoba had already produced similar 1D models for Canada [5]. The 1D models were created using information obtained from government reports and scientific journals. The information includes determinations of crustal and mantle thickness from seismic surveys, and measurements of electrical conductivity using various geophysical survey methods such as magnetotellurics.

EPRI, in collaboration with NASA and industry partners, is further examining the 1D ground conductivity modeling approach to determine its overall impact on GIC calculations and to evaluate the efficacy of these first-order approximations. This new effort is leveraging the newly available direct empirical information about the ground response (and conductivity) across the contiguous United States. The EarthScope project funded by the National Science Foundation provided empirical information that shows a significant variation in the ground conductivity in some regions. However, it is not clear how much of this fine-scale variation affects GIC estimates in large, interconnected power grids. Examples of this research include how 1D earth conductivity models provide an average response across a region (see Figure 3), and how 3D earth conductivity models show a considerable variation in response across a region (see Figure 4). As a part of its research, EPRI will determine to what degree the spatial variation in ground conductivity affects GIC estimates. In general, this new research will evaluate how forecasters can use the latest empirical information about the ground response to improve the accuracy of the GMD hazard assessments.

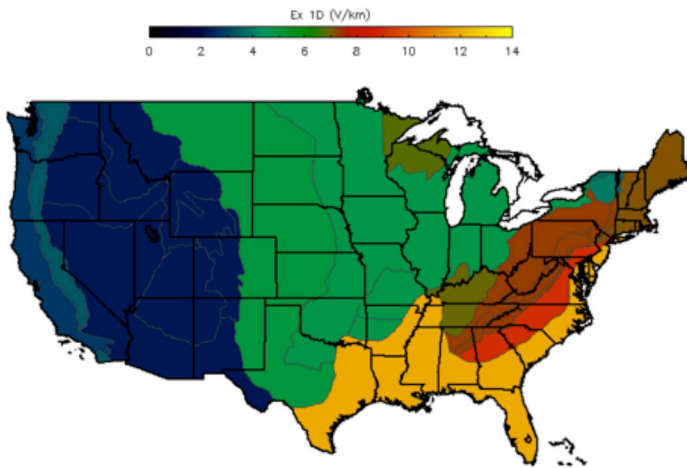


Figure 3 – One-dimensional earth conductivity models provide average response across a region.

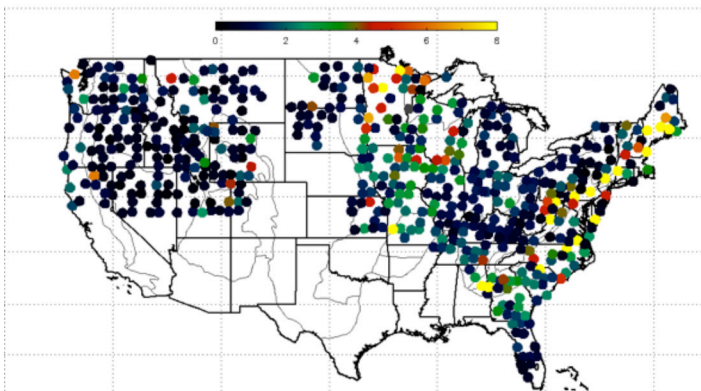


Figure 4 – Three-dimensional earth conductivity models show considerable variation in response across defined regions. (Note: regions in white did not have 3D conductivity data at the time of this analysis and therefore were not included.)

Overview of Potential GIC Impacts on Transformers

A parallel step in the GMD research plan is to assess the potential impacts of GICs on bulk power transformers. This involves various steps described in the next section. However, to explain the process flow for this portion of the GMD research, a brief summary of the potential impacts of GICs on transformers is useful.

When GICs flow through transformer windings, they cause a magnetic flux offset in the core. With sufficient offset, the crests of the flux waveform can exceed the saturation level of the ferromagnetic core material. Hence, GICs can saturate transformer cores and cause internal heating that may lead to loss of transformer life or failure during a solar storm. When this asymmetrical saturation occurs in a transformer, there are four main negative impacts. Two of these are electrical impacts (harmonics and reactive power consumption), one impact is thermal (heating), and one is mechanical (vibration).

- **Harmonics:** Asymmetrical saturation produces both even and odd harmonic distortion of both voltage and current. These harmonics can cause misoperation of protective relays, overloading of capacitor banks, and heating in power system equipment (e.g., generators).
- **Reactive power consumption:** The exciting current of a power transformer experiencing asymmetrical saturation has a large fundamental frequency (60-Hz) component that varies with GIC. The increase in the fundamental component of the exciting current results in an increase in reactive power losses. This increase in reactive power loading on the electric power grid can lead to voltage depression, transmission line disconnection, and even system voltage collapse.
- **Heating:** During core saturation, magnetic flux extends out beyond the core into parts of the transformer where it would normally be negligible. The fringing flux fields can produce eddy currents in conductive objects the flux field encounters, causing localized heating and increased losses. This can potentially cause hot spots in a transformer that are damaging to insulation, windings, leads, bracing, and tank walls. The heating may also cause gassing of the transformer oil where it comes into contact with hot metal. Over the long term, the localized heating may cause accelerated aging of the insulation in the transformer. In the short term, if the heating is intense enough, it may cause failure of the transformer.
- **Vibration:** Transformers may experience significant changes in sound levels and tank vibrations when subjected to even low levels of GIC flowing into the neutral of these transformers. The risks that transformer vibrations from a GMD event pose to transformer health require more research.

Transformer Assessments

Overview

A key aspect of a GMD vulnerability assessment is to determine the potential impact of GIC flows in bulk power transformers. Ongoing EPRI GMD research to address the potential impacts of GICs on transformers includes the following:

- Analyzing the 75-amp-per-phase qualifying threshold for transformer thermal impact assessment specified in TPL-007-1
- Studying GIC field orientation for transformer thermal impact assessments
- Assessing the impacts of vibrations on power transformers and determining whether these vibrations compromise transformer mechanical integrity

Analyzing the 75-Amp-Per-Phase Qualifying Threshold for Transformer Thermal Impact Assessment

Reliability Standard TPL-007-1 was designed to identify transformers that are potentially at risk from GIC flows experienced during a severe GMD event. Presently, TPL-007-1 has a 75-A-per-phase GIC threshold on transformers. When this value is exceeded compared to the 1-in-100-year GMD benchmark event, an additional detailed thermal impact assessment is required. NERC chose this screening threshold based on previous studies [6] of transformers with an effective GIC of less than 75 A per phase that technical organizations considered unlikely to exceed known temperature limits.

As part of the FERC directive, industry research must conduct further studies on the 75-A-per-phase thermal impact assessment qualifying threshold. Specifically, FERC has asked the industry to address the “effects of harmonics, including tertiary winding harmonic heating and any other effects on transformers” in NERC’s GMD research work plan [4].

Therefore, EPRI’s ongoing GMD research is re-examining the screening criteria and will develop an alternative criterion if needed. This analysis will consist of examining detailed validated models of various transformer types along with advanced harmonic analysis.

GIC Field Orientation for Transformer Thermal Impact Assessments

As stated above, when 75 A per phase is exceeded, TPL-007-1 requires an additional thermal impact assessment. This additional thermal impact assessment includes studying the transformer’s response to a benchmark geoelectric field time-series waveform. This is because both the magnitude and the time duration determine the thermal response of the transformer. As part of the GMD research work plan, FERC directed NERC to study how “the geoelectric field time series can be applied to a particular transformer so that the orientation of the time series, over time, will maximize GIC flow in the transformer . . .” [4]. This task will subsequently consist of work to determine how the benchmark geoelectric field wave shape or other supplemental wave shapes can apply to a particular transformer to determine worst-case hot-spot heating.

Therefore, this task will research an approach for applying the benchmark geoelectric field time series to individual transformers in thermal impact assessments, and also the potential for developing alternative methods of applying the benchmark to individual transformers to represent worst-case hot-spot heating conditions in transformer thermal impact assessments. This analysis will consist of examining validated models of various transformer types along with advanced harmonic analysis.

Assessing the Impacts of Vibrations on Power Transformers

In addition to the thermal impacts experienced during a GMD event, the transformer also experiences induced vibrations. As part of Order No. 830, FERC directed NERC to undertake additional actions to improve understanding of GMD events and their potential impacts on reliability of the power system and its components. A potential impact is the possible effects of vibrations on transformers during a GMD event. EPRI experts have worked directly on noise pollution issues from transformers exposed to GIC currents during a GMD event. Subsequently, as part of this research, EPRI will research whether GIC-related increases in the magnitudes and harmonics of vibrations in power transformer tanks can cause mechanical damage.

This research will consist of examining models of various transformer types typically used to estimate compliance with audible noise requirements. In addition, EPRI will conduct long-term transformer vibration monitoring to quantify typical magnitudes and frequency spectrums of vibrations of transformers in the absence of GIC and when exposed to GIC.

Improved Transformer Modeling

Better understanding of these phenomena requires analyses of validated electrical and thermal models of transformers, and may also require correlation of these models with vibrational impact. One challenge is that of the approximately 2000 power and generator step-up (GSU) transformers on the North American transmission system, few are alike. In fact, North American utilities may currently use as many as 1500 different designs. One way to address this challenge is to analyze electrical and thermal models for a reasonable number of primary design types of transformers (see Figure 5). These designs can account for the primary variability in design parameters (e.g., GSU transformer designs versus power transformer designs, single-phase versus three-phase designs, shell-form or core-form construction, number of core legs). These models are manifested as electrical and thermal relationships that show how the transformer is predicted to respond when exposed to a defined input GIC. Conservatively designing these relationships helps to ensure that the simplification of multiple secondary design variations into a single relationship will yield reasonably accurate results. Therefore, EPRI will obtain as much of this modeling data as possible and use it to develop these enhanced electrical and thermal relationships.

As made apparent with the transformer research tasks, the industry vitally needs transformer modeling data from manufacturers and validation of existing transformer tools to ensure their ability to accurately predict transformer electrical and thermal response to GICs. A recent NASA paper raises the need for more extensive validation of models: "...thermal models are needed for individual transformers, and at this time the validation level of the models is not high" [3]. Hence the paper points out that "Comparisons between thermal models and actual observed transformer thermal responses are thus needed" [3].

Part of this GMD research is validating existing transformer tools with actual observed data to ensure the tools can accurately predict the transformers' electrical and thermal response to GICs. This will aid in providing confidence in the transformer tool results. The industry can then use the results of these validated tools to better perform transformer and system vulnerability research.

This actual observed data will be obtained from a combination of both GIC transformer testing and field monitoring of transformers.

The field monitoring data collection will consist of installing advanced field sensors on field service transformers to measure GIC, reactive power, harmonics, and vibrations. The selection of transformers for field monitoring is critical to ensure useful data collection. EPRI is presently working with utilities and ABB in this selection process. A list of criteria for a good transformer candidate consists of the following:

- Exposure to high GICs during GMD events
- Equipped with fiber temperature monitoring, including tertiary and structure temperature monitoring
- Different transformers to obtain a cross-section of types (e.g., 3-phase, 3-limb; shell form; 1-phase core form)

To perform these measurements EPRI will leverage the advanced GIC and vibration sensors that the industry has developed (see Figures 6 and 7). For example, Figures 6 and 7 show the EPRI GIC sensor that allows the measurement of GIC in lines and transformers. When connected to the energized phase conductors, sensors can directly provide the effective GIC current information as opposed to the traditional method of installing the sensor on the grounded neutral and estimating the effective GIC values. In addition, this sensor provides ac current measurements and harmonic measurements needed to meet the objectives of GMD research.

The EPRI transformer vibration sensor provides a measurement of both the harmonics and displacements occurring in real time (see Figure 8). This sensor is easy to install and can provide constant vibration monitoring needed for this research.

The use of this advanced monitoring equipment connected to ideal candidate transformers will be key in ensuring the data needed to answer research directives. In summary, EPRI's implementation of the transformer GIC field monitoring program and participation in GIC testing will accomplish the following:

- Validate electrical, thermal, and vibration models of the effects of GICs on transformers to meet the research needs of the industry
- Improve understanding of the GIC impacts on transformers
- Provide increased knowledge of GIC-related current distortion and unbalance to better predict transformer tertiary heating impacts

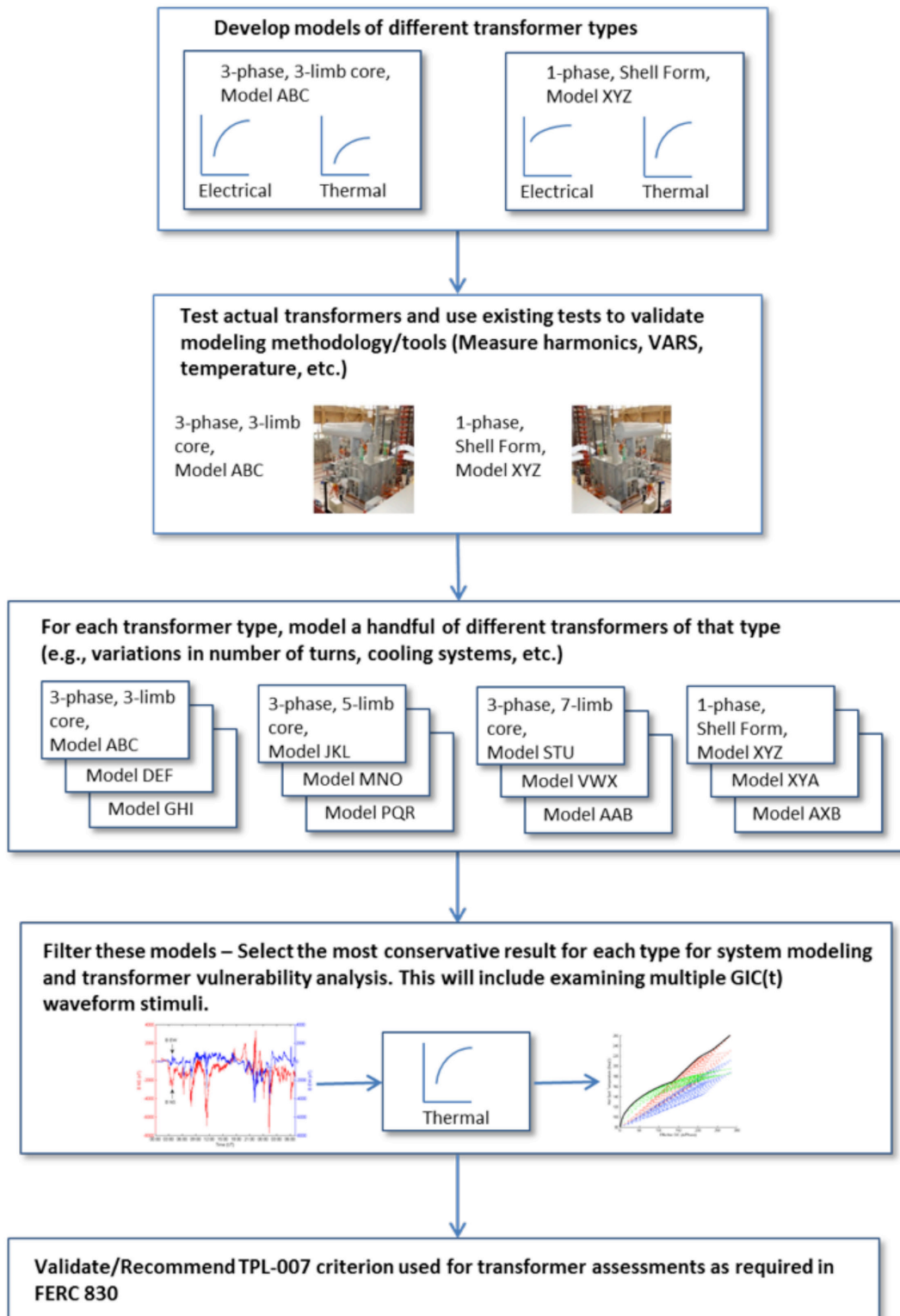


Figure 5 – Developing and validating transformer models

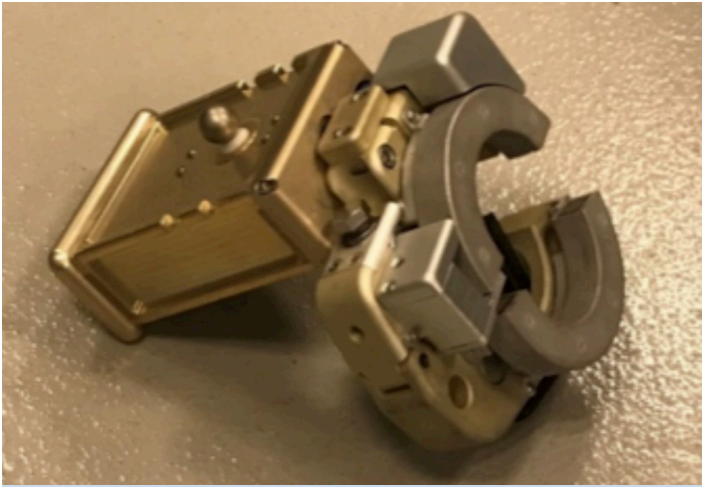


Figure 6 – EPRI’s GIC sensor for application on high voltage conductors



Figure 8 – EPRI’s vibration sensor installed



Figure 7 – EPRI’s GIC sensor installed at a transformer high-voltage bushing

In addition to the stated objectives of transformer monitoring, the field monitoring will also provide insight into questions concerning the long-term impacts of GICs on transformers (i.e., the low-impact, high-frequency phenomenon).

Some will argue that the thermal and electrical effects of GICs on transformers are fairly well understood but pertain only to high magnitudes of GIC flowing through high-voltage power transformers [3]. However, the NASA white paper summarizes research studies indicating that GIC levels much lower than 75 amps/phase may impact

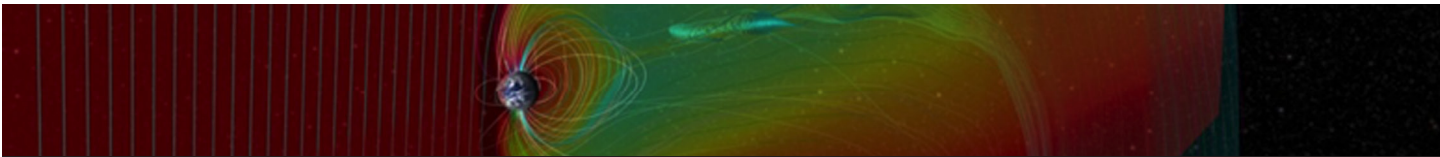
transformers and/or the power system. According to the NASA white paper, “these works are under ongoing debate, and the causal connections associated with the findings are not yet well defined” [3]. The paper goes on to explain the ramifications of GIC impacts at lower than 75 amps/phase: “If there is a true connection to low levels of GIC, this would constitute a transition from current thinking of GIC as only a high-impact, low-frequency phenomenon to considering the phenomenon as a background that continuously and gradually degrades components and the performance of the system” [3].

The NASA paper also raises the related question (which is addressed in more detail in a 2014 paper by Gaunt [6]) of whether GIC impacts can lead to premature transformer aging. This adds more complexity to assessments of transformer impacts, superimposing potential transformer failure long after the GIC itself (a low-impact, high-frequency phenomenon), rather than only assessing immediate transformer failure due to a high-impact, low-frequency phenomenon [3].

Therefore, an advanced field monitoring program is essential in understanding these longer-term impacts.

Harmonic Impact Analysis

Across a transmission system, a major GMD event can saturate many transformers, each injecting very high magnitude harmonic current. The consequences of high harmonic distortion levels during a severe GMD go far beyond the routine considerations of power quality, be-



Furthering the Research of Geomagnetic Disturbances Impact on the Bulk Power System

cause the distortion can have potentially significant impact on system security [8]. This is because protection systems may correctly operate to protect equipment from unusual stress caused by harmonic current or voltage, or the protection systems may incorrectly operate in response to the harmonic distortion and falsely trip equipment that need not be tripped. In either of these circumstances, the transmission system is deprived of a facility at a time of extraordinary stress caused by the excessive fundamental-frequency reactive power demand during the GMD. As a result, the severe and unusual harmonic distortion may substantially accelerate system collapse. A system that appears stable based on load flow analysis without outages may actually be unstable when harmonics trip reactive resources on the BPS. Therefore, harmonic evaluation is a critical part of bulk power system GMD vulnerability assessment [8].

This is recognized in NERC Standard TPL-007-1, as well as in the draft TPL-007-2 now pending approval. Both require consideration of harmonic impacts. FERC Order 830 directs NERC to “address the effects of harmonics... as part of the GMD research work plan” [4]. Assets deemed at significant risk of removal from service during a severe GMD event must be modeled accordingly during the steady-state evaluations, or appropriate mitigation must be implemented. Specifically, it is mandated that the BPS entity must perform steady-state fundamental-frequency voltage collapse (power flow) studies with “reactive power compensation devices and other transmission facilities” that are likely to trip “as a result of protection system operation or mis-operation due to harmonics during the GMD event”. Also highlighted in FERC Order 830 is the fact that research continues to examine more complex GMD vulnerability issues, such as harmonics, to enhance the modeling capabilities of the industry.

Determining the above requires knowledge not only of the equipment and protection system harmonic vulnerabilities, but also of the levels of harmonic current and voltage to which the equipment is exposed for the given geoelectric field strength and orientation. This requires performance of a system harmonic analysis [8].

However, the NASA white paper points out that “performing a system-wide harmonic load flow analysis with existing tools requires significant effort and certain level of expertise to tailor and manipulate multiple modeling tools. Given the critical role of harmonics in the overall geomagnetic storm risk assessment, there is a need to integrate wide-area GIC-driven harmonic load flow analysis into commercially-available software” [3].

EPRI has begun work on development of a tool that can meet the needs of the industry and provide the research needed to answer the research questions outlined in the FERC order. Requirements and details of the harmonic tool as derived from EPRI’s Geomagnetic Disturbance Vulnerability Assessment and Planning Guide [3] include the following:

- It must perform extensive system modeling and accept models with a large number of buses.
- It will provide full three-phase representation of the system including mutual couplings.
- It will accept data from other commercial software sources such as those from power-flow, stability, and short-circuit databases.
- It will convert fundamental-frequency data from these data sources to appropriate parameters for harmonic analysis.
- The tool must provide accurate representation of harmonic sources (saturated transformers) based on the results of GIC flow analysis. These sources are also dependent on fundamental-frequency voltage and angle, so it is desirable for the tool to accept power flow results with minimum user intervention.
- Representation of GIC-saturated three-phase transformers requires the capability within the tool to either perform nonlinear magnetic circuit analysis of transformers or accept multidimensional lookup tables of relationships between harmonic currents and GIC developed offline.
- The tool will need to represent closed-loop interaction to take into account voltage distortion.
- It should facilitate parametric analysis of a variety of system conditions and configurations.
- The tool must be able to accommodate a large number of simultaneous harmonic current injections.

EPRI is designing to the above requirements with the use of EPRI’s Open Source Distribution System Simulator (OpenDSS)² software. The OpenDSS software tool has capabilities that exceed those typically found in commercial power system analysis software. It is a script-based program that is ideal in a development stage such as this. GMD modeling is not something new to OpenDSS; EPRI

² The OpenDSS software is available as an open-source package. It may be found on www.Sourceforge.net by searching for the keyword: OpenDSS. The reader is referred to the open source sharing site for additional information on OpenDSS.

added GIC simulation model capabilities to OpenDSS in 2012 [9]. OpenDSS can take input from circuit models, which include the location (including latitude and longitude) of power system assets, along with the dc resistance, and then calculate the GIC flows. These existing GIC capabilities can be leveraged with OpenDSS's existing system harmonic analysis capabilities to provide a complete GMD vulnerability assessment. (See the state diagram in Figure 9.)

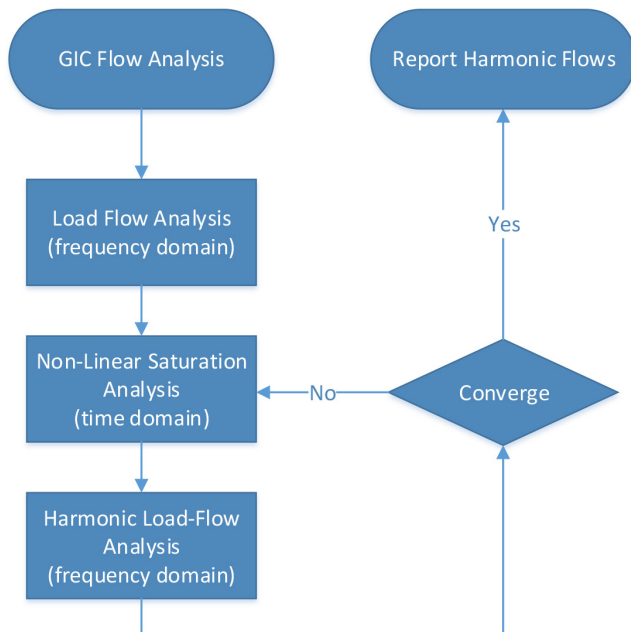


Figure 9 – The state diagram of the harmonic tool algorithm.

However, many challenges still remain in developing a complex system harmonic tool, including the following:

- Adding the non-linear transformer components
- Magnetic modeling of complex three-phase transformers
- Interactions between the harmonic voltage distortion and the saturated transformer that can alter its harmonic spectrum

Work on this software tool is ongoing, and EPRI plans to release the beta version at the end of 2018.

Industry Communication

Throughout these projects, EPRI is providing actionable information for industry leaders, regulators, scientists, and other stakeholders. This information is provided in the form of bi-yearly workshops, white papers, reports, webinars, and trade journal articles.

These deliverables cover the current state of GMD knowledge; methodologies, results, conclusions, and recommendations; operational approaches for lessening the impact of, and rapidly recovering from, solar storms; and the latest developments in these areas. EPRI also plans to periodically update these deliverables as needed with the latest information gathered, insights gained, and conclusions and recommendations decided in tasks of this project. These sets of documents serve as the primary repository of project information. They also arm utilities with information that will help them prepare for GMDs, avoid or minimize system disturbances due to GMDs, and avoid equipment damage or destruction due to GMDs.

References

1. Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events, Order No. 830, 156 FERC ¶ 61,215 (2016), reh'g denied, Order No. 830-A (2017) ("Order No. 830").
2. IEEE Transmission and Distribution Committee Work Group on Geomagnetic Disturbances and Power System Effects, "Geomagnetic Disturbance Effects on Power Systems," *IEEE Transactions on Power Delivery*, Vol. 8, No. 3, July 1993, pp. 1206–1216.
3. NASA, A. Pulkkinen, et al., "Geomagnetically Induced Currents: Science, Engineering, and Applications Readiness," *Space Weather*, 15, doi: 10.1002/2016SW001501.
4. FERC, "Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events," issued September 22, 2016, docket no. RM15-11-000, Order No. 830, <https://www.ferc.gov/whats-new/comm-meet/2016/092216/E-4.pdf>.
5. I. Ferguson and H. Odwar, "Appendix 3: Review of Conductivity Soundings in Canada," in *Geomagnetically Induced Currents: Geomagnetic Hazard Assessment Phase II*, Final Report, volume 3, (principal author) D.H. Boteler, Geological Survey of Canada and Canadian Electricity Association, 357 T 848A.
6. Screening Criterion for Transformer Thermal Impact Assessment White Paper TPL-007-2, Transmission System Planned Performance for Geomagnetic Disturbance Events, http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Screening_Criterion_Clean_2017_October_Clean.pdf.

7. C. Gaunt, "Reducing Uncertainty – Responses for Electricity Utilities to Severe Solar Storms," *Journal of Space Weather and Space Climate*, 4 (2014) A01, doi: 10.1051/swsc/2013058, <https://www.swsc-journal.org/articles/swsc/pdf/2014/01/swsc130019.pdf>.
8. EPRI, *Geomagnetic Disturbance Vulnerability Assessment and Planning Guide*, 3002010917, December 2017. <https://www.epri.com/#/pages/product/000000003002010917/>.
9. NERC and EPRI, "NERC, EPRI Release Open Source Code to Analyze Geomagnetically Induced Currents," NERC press release, April 25, 2012, http://www.nerc.com/fileUploads/File/News/NERC_DOE_EPRI25APR12.pdf.

For More Information

Robert Arritt, *Technical Executive*
865.218.5908, barritt@epri.com

Transmission Planning

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together . . . Shaping the Future of Electricity

Disclaimer of Warranties and Limitation of Liabilities

This document was prepared by the organization(s) named below as an account of work sponsored or cosponsored by the Electric Power Research Institute, Inc. (EPRI). Neither EPRI, any member of EPRI, any cosponsor, the organization(s) below, nor any person acting on behalf of any of them:

(a) Makes any warranty or representation whatsoever, express or implied, (i) with respect to the use of any information, apparatus, method, process, or similar item disclosed in this document, including merchant-ability and fitness for a particular purpose, or (ii) that such use does not infringe on or interfere with privately owned rights, including any party's intellectual property, or (iii) that this document is suitable to any particular user's circumstance; or

(b) Assumes responsibility for any damages or other liability whatsoever (including any consequential damages, even if EPRI or any EPRI representative has been advised of the possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process, or similar item disclosed in this document.

Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by EPRI.

The Electric Power Research Institute (EPRI) Prepared this Report.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

Note

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.