UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

North American Electric Reliability Corporation	**)** **)**	**Docket No. RM15-11-003**

INFORMATIONAL FILING OF THE NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION REGARDING GEOMAGNETIC DISTURBANCE RESEARCH WORK PLAN FINAL REPORT

Lauren A. Perotti
Senior Counsel
North American Electric Reliability Corporation
1325 G Street, N.W., Suite 600
Washington, D.C. 20005
(202) 400-3000
lauren.perotti@nerc.net

Counsel for the North American Electric Reliability Corporation

April 30, 2021

TABLE OF CONTENTS

UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

North American Electric Reliability Corporation	**)** **)**	**Docket No. RM15-11-003**

INFORMATIONAL FILING OF THE NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION REGARDING GEOMAGNETIC DISTURBANCE RESEARCH WORK PLAN FINAL REPORT

Pursuant to paragraph 77 of Order No. 830,[1] the North American Electric Reliability Corporation ("NERC")[2] hereby submits an informational filing regarding the results of research performed under the NERC Geomagnetic Disturbance Research Work Plan ("GMD Research Work Plan"). The purpose of the GMD Research Work Plan was to conduct research on topics related to geomagnetic disturbances ("GMDs") and their impacts on the reliability of the Bulk Power System ("BPS"). NERC submitted the plan in its final form to the Commission on April 19, 2018,[3] and it was accepted by the Commission in Order No. 851.[4]

The completion of the GMD Research Work Plan marks an important milestone in NERC and industry's comprehensive approach to reducing the risks that severe GMD events can pose to the reliability and resilience of the North American grid. NERC has prepared a final report, titled *Order No. 830 GMD Research Work Plan: Results and Recommendations for the ERO* (Feb. 2021)

---

[1] Order No. 830, *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, 156 FERC ¶ 61,215 at P 77 (2016), *reh'g denied*, Order No. 830-A, 158 FERC ¶ 61,041 (2017) [hereinafter Order No. 830].

[2] The Commission certified NERC as the electric reliability organization ("ERO") in accordance with Section 215 of the FPA on July 20, 2006. *N. Am. Elec. Reliability Corp.*, 116 FERC ¶ 61,062 (2006).

[3] *See Revised Geomagnetic Disturbance Research Work Plan of the North American Electric Reliability Corporation*, Docket No. RM15-11-003 (April 19, 2018) at attach. 1.

[4] Order No. 851, *Geomagnetic Disturbance Reliability Standard; Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, 165 FERC ¶ 61,124 at P 65 (2018) (hereinafter Order No. 851).

("Final Report"), to summarize the results of the research and identify recommendations for further action. This report is included as **Attachment 1** to this filing.

As summarized below, and discussed in more detail in **Attachment 1**, the results from this research provide further technical justification and support for the currently effective GMD planning standard, TPL-007-4 (Transmission System Planned Performance for Geomagnetic Disturbance Events). The outcomes from this research project affirm the efficacy of the TPL-007 Reliability Standard and provide tools and insights for the ERO, industry, and research partners to use in accurately performing GMD Vulnerability Assessments. While the report has identified several opportunities for further monitoring and outreach, NERC has not identified any potential reliability gaps in the standard that must be addressed through the standard revision process. As part of the required periodic review of the TPL-007 Reliability Standard, NERC will consider these research findings, as well as any new developments in space weather research and other insights that are gained during the implementation of the standard, to determine whether further improvements and refinements to the standard are necessary.[5]

I. BACKGROUND

In Order No. 830, the Commission approved the first version of the GMD planning Reliability Standard, Reliability Standard TPL-007-1 – Transmission System Planned Performance for Geomagnetic Disturbance Events.[6] In this order, the Commission also directed NERC to submit a work plan describing how NERC would conduct research on the GMD-related topics specified by the Commission and any additional topics selected in NERC's discretion and

[5] NERC conducts periodic reviews of Reliability Standards in accordance with Section 317 of its Rules of Procedure and Section 13.0 of its Standard Processes Manual, Appendix 3A to the NERC Rules of Procedure. The NERC Rules of Procedure are available at https://www.nerc.com/AboutNERC/Pages/Rules-of-Procedure.aspx.

[6] Order No. 830 at P 22. In the United States, Reliability Standard TPL-007-4 is the currently effective version of the standard.

subsequently, one or more informational filings addressing the results of this research.[7] The Commission stated, "We expect that work completed through the GMD research work plan, as well as other analyses facilitated by the increased collection and availability of [geomagnetically induced current] GIC monitoring and magnetometer data…will lead to further modifications to Reliability Standard TPL-007-1 as our collective understanding of the threats posed by GMD events improves."[8]

NERC submitted a preliminary GMD Research Work Plan on May 30, 2017.[9] On October 19, 2017, the Commission accepted NERC's preliminary work plan and directed NERC to file a final, or otherwise updated, plan within six months.[10] As noted above, the Commission accepted NERC's revised GMD Research Work Plan in Order No. 851.

The GMD Research Work Plan contemplated the engagement of the Electric Power Research Institute ("EPRI"), electricity sector participants, U.S. national laboratories, equipment manufacturers, and other North American research collaborators in examining areas of GMD study. EPRI initiated a $3.6 million, multi-year project for GMD research, the costs of which were shared among NERC and electricity sector participants. The GMD Research Work Plan consisted of the nine research and work components, referred to as "tasks," intended to improve the capabilities and accuracy of GMD Vulnerability Assessments[11] performed by NERC entities and

---

7 *Id.* at P 77.

8 *Id.* at P 26.

9 *Geomagnetic Disturbance Research Work Plan of the North American Electric Reliability Corporation*, Docket No. RM15-11-002 (May 30, 2017).

10 *Order on GMD Research Work Plan*, 161 FERC ¶ 61,048 at PP 1 and 12 (2017).

11 GMD Vulnerability Assessment is defined in the *Glossary of Terms Used in NERC Reliability Standards* as "Documented evaluation of potential susceptibility to voltage collapse, Cascading, or localized damage of equipment due to geomagnetic disturbances." The Glossary is available at https://www.nerc.com/pa/Stand/Glossary%20of%20Terms/Glossary_of_Terms.pdf.

help ensure the effectiveness of GMD Reliability Standards in reducing risks to the BPS from severe GMD events.

On July 26, 2019, NERC provided an informational filing to the Commission summarizing the results of work completed up to that time.[12] Work continued under the GMD Research Work Plan throughout the remainder of 2019 and into 2020. For the research-related tasks, EPRI released technical reports summarizing the results and made those reports publicly available, free of charge.[13] NERC provided opportunities for technical and scientific review of EPRI's research results through the NERC GMD Task Force.[14]

II. Final Report: *Order No. 830 GMD Research Work Plan: Results and Recommendations for the ERO*

NERC is pleased to provide the GMD Research Work Plan Final Report to the Commission. The Final Report reflects the culmination of several years of collaborative research between NERC, its industry partners, and other research collaborators. This work has confirmed the technical underpinnings of the TPL-007 Reliability Standard and has provided industry with additional insights and tools to help protect the grid from the risks posed by severe GMD events. This section provides a summary of the key findings and recommendations from the GMD Research Work Plan final report, organized by research task. For additional details and analysis, please refer to final report included as **Attachment 1.**

---

12 *First Informational Filing of NERC Regarding Work Performed under the Geomagnetic Disturbance Research Work Plan*, Docket No. RM15-11-003 (Jul. 26, 2019) (summarizing work completed up until that time).

13 The cost to execute the research components of the plan was shared among NERC and electricity sector participants through a research program executed by EPRI.

14 The NERC GMD Task Force was open to the public and included participants from U.S. and Canadian government space weather researchers, representatives from the manufacturer and vendor community, and subject matter experts from both within and outside the electric power industry. The issuance of the attached final report marked the conclusion of the GMD Task Force's work, and NERC disbanded the GMD Task Force in early 2021. As noted below, further GMD work will occur through the NERC Reliability and Security Technical Committee.

Additional information on the GMD Task Force is available on NERC's website at https://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx.

Consistent with the recommendations in the final report, NERC will continue to monitor developments in scientific research and facilitate the sharing of new information and best practices to enhance the effectiveness of GMD Vulnerability Assessments through the NERC Reliability and Security Technical Committee.

A. Task 1: Further Analyze Spatial Averaging Used in the Benchmark GMD Event

The key findings from the work performed under Task 1: Further Analyze Spatial Averaging used in the Benchmark GMD Event are summarized as follows. Analysis of an extensive space weather data set supports the industry's use of the Benchmark GMD Event to represent a severe 100-year GMD event in GMD Vulnerability Assessments. In response to a separate Commission directive in Order No. 830,[15] NERC revised the TPL-007 standard to require entities to assess vulnerabilities to geoelectric field enhancements through the defined Supplemental GMD Event. Research into the characteristics and spatial scales of extreme GMD events (i.e., geographic size, locations affected, durations, intensity and direction) provided additional insight about geoelectric field enhancements that can occur during severe GMD events. These details can assist industry planners with how they apply the Supplemental GMD Event to assess the impact that geoelectric field enhancements can have on the system. Notably, studies have shown that the presence of a localized enhancement does increase GIC flow and reactive power losses and reduces system voltages in the vicinity of the field enhancements; the effects are not limited to within the localized enhancement itself.

Based on the research findings, there is no recommendation for any new, specific scales for localized enhancements for 1-in-100 year GMD event planning scenarios beyond that reflected in the current version of the standard, Reliability Standard TPL-007-4. The final report

---

[15] *See* Order No. 830 at P 44 (directing NERC "to develop revisions to the benchmark GMD event definition so that the reference peak geoelectric field amplitude component is not based solely on spatially-averaged data").

recommends that NERC: (1) monitor further research performed by the space weather community to further understand the characteristics of extreme GMD events, including localized geoelectric field enhancements; and (2) promote awareness of research findings and use of best practices among TPL-007 applicable entities, through the NERC Reliability and Security Technical Committee and industry forums.

B. Task 2: Further Analyze Latitude Scaling

The key findings from the work performed under Task 2: Further Analyze Latitude Scaling are as follows. Scaling the peak geoelectric field of the Benchmark GMD Event according to the geomagnetic latitude of the system area is consistent with analysis of space weather data and advanced simulation modeling. Researchers confirmed that the geoelectric field intensity during a severe 100-year GMD event is expected to decrease by an order of magnitude across the 60-degree to 40-degree geomagnetic latitude band.

The final report recommends that NERC monitor further research performed by the space weather community to characterize the latitude thresholds of extreme GMD events.

C. Task 3: Improve Earth Conductivity Models for GIC Studies

The results of the work performed under Task 3: Improve Earth Conductivity Models for GIC Studies are summarized as follows. Newly-available earth conductivity data for the U.S. was used to better define regional boundaries in conductivity maps used by industry to calculate geoelectric fields. Through the GMD Research Work Plan, conductivity maps, earth models, and earth conductivity scaling factors are available for industry and software designers to use in performing GMD Vulnerability Assessments. These models cover the North American BPS, with uncertainty only in regions where magnetotelluric (MT) measurements or other modeling information is unavailable to perform comparisons. In addition, EPRI published technical guidance for validating models with GIC and magnetometer data collected during actual GMD events.

The final report contains four recommendations for additional work in this area. First, the final report recommends that NERC Staff and EPRI continue to work with software vendors to adopt new region boundaries and modeling information in available GIC software. Second, the final report recommends that NERC and EPRI engage technical experts, researchers, and software vendors to develop advanced modeling techniques that address unique challenges of areas with significant non-uniformity that impact GIC estimates. Third, the final report recommends that NERC, working collaboratively with Regional Entities Northeast Power Coordinating Council and Western Electricity Coordinating Council, support application of this and future research into the described coastal effect through regional technical committees and working groups. Fourth, the final report recommends that NERC, working through the Reliability and Security Technical Committee, Real-time Operations Subcommittee, and technical partners: (i) promote model validation best practices; (ii) encourage planning entities to validate GMD models with data collected during GMD events of interest; and (iii) support technical groups in continuing to advance GMD modeling disciplines.

D. Task 4: Study Transformer Thermal Impact Assessment Approach and Task 5: Further Analyze the 75 A per Phase Criterion Used for Transformer Thermal Impact Assessments

The results and key findings from the work performed under Task 4: Study Transformer Thermal Impact Assessment Approach and Task 5: Further Analyze the 75 A per Phase Criterion Used for Transformer Thermal Impact Assessments are summarized as follows.

The GMD Research Work Plan improved industry capabilities for assessing transformer thermal impacts from GMD events and provided further technical justification for the 75 A/phase screening criterion used in TPL-007 to mitigate risk to the BPS. Transformer thermal impact screening and assessment, along with an evaluation of system susceptibility to voltage collapse and Cascading, is part of the GMD Vulnerability Assessment process required by Reliability Standard TPL-007. The research produced thermal models for over 80 different transformer types and designs which can be used in an industry-available thermal modeling tool. Simulations using the expanded set of models indicate that the TPL-007 thermal impact screening criterion is generally effective, however specific designs were identified that could possibly exceed transformer thermal criteria. The findings enable industry to expand screenings for these designs and perform additional risk analysis.

The final report recommends that NERC monitor further technical development supporting transformer thermal modeling and GMD risk assessment. As additional transformer models are developed through industry and research partner efforts, techniques such as those demonstrated as part of this work should be used to evaluate the continued efficacy of the benchmark GMD event for GMD Vulnerability Assessments. The final report also recommends that NERC continue to prioritize efforts to enable industry to assess and mitigate GMD risk to transformers by: (1) expanding the availability of transformer thermal models to represent more manufacturers, and using field measurement data collected by EPRI and industry to validate theoretical models; (2) updating the ERO-endorsed Implementation Guidance *TPL-007 Transformer Thermal Impact Assessment* with results of EPRI's research in this task;[16] and (3) engaging TPL-007 applicable

[16] Specifically, Table 1 provides upper-bound hot spot heating. This table should be revised to reflect the results of EPRI's analysis, including transformer models T24 and T25. The Implementation Guidance is available on NERC's web site at https://www.nerc.com/pa/comp/guidance/Pages/default.aspx.

entities through the Reliability and Security Technical Committee and industry forums to promote awareness of transformer thermal model availability and assessment best practices.

E. Task 6: Section 1600 Data Request

The activities in Task 6: Section 1600 Data Request consisted of developing the necessary guidance, technical guidelines, and solutions to support a request for data or information under Section 1600 of the NERC Rules of Procedure for the collection of existing and new GIC data and magnetometer data. The purpose of this data collection is to respond to the Commission's Order No. 830 directive to collect GMD monitoring data and to make that data available.[17]

The GMD Data Collection portal became operational in October 2020. The first annual reporting deadline is June 2021 and will include recorded information going back to May 2013.[18] NERC will monitor implementation and conduct outreach to identify whether and to what extent additional guidance or support is necessary. The objective is to maintain a high-quality collection of GIC and magnetometer data for industry and research use. Although the NERC GMD Data Collection Program is not a real-time application, industry GIC monitors and magnetometers can provide data to system operators in real-time for enhancing their GMD operating procedures.

F. Task 7: Geoelectric Field Tool Evaluation and Calculation of Beta Factors

Work under Task 7: Geoelectric Field Tool Evaluation and Calculation of Beta Factors built upon the other components of NERC's GMD Research Work Plan to improve scientific understanding and advance the models and tools available for modeling GIC. This task involved evaluating available tools for calculating geoelectric field from magnetic field data for a given earth conductivity structure and developing guidance as necessary to meet the needs of the

---

[17] *See* Order No. 830 at P 93.

[18] GMD data reporting information is available on the NERC website: https://www.nerc.com/pa/RAPA/GMD/Pages/GMDHome.aspx.

industry. The final report provides updated beta scaling factors for calculating geoelectric fields used in GMD Vulnerability Assessments based on newly available MT information.

As it is presently written, the TPL-007 standard provides flexibility to accommodate the updated beta scaling factors in GMD planning studies. The final report recommends updating Attachment 1 during the next periodic review of the standard. The final report also recommends that NERC collaborate with EPRI and GIC modeling software vendors to incorporate beta scaling factors or modeling techniques into the software that is available for industry planners.

G. Task 8: Improve Harmonics Analysis Capability

Under Task 8: Improve Harmonics Analysis Capability, EPRI developed an open-source tool that industry can use to perform GMD-related harmonic studies of the power system and made it available at no cost. GMD-related harmonics are caused by the part-cycle saturation of transformers. These harmonic currents and voltages resulting from transformer saturation can impact system operations during severe GMD events. The tool, GICHarm, provides planners with capability to perform wide-area harmonic analysis that existing commercial tools did not address.

The final report recommends that NERC engage TPL-007 applicable entities through the NERC Reliability and Security Technical Committee and industry forums to promote awareness of available tools, support development, and promote use of best practices for GMD-related harmonic analysis.

H. Task 9: Harmonic Impact Studies

The results and key findings from the work performed under Task 9: Harmonic Impact Studies are summarized as follows. Research on transformer mechanical vibrations caused by GIC concluded that severe GMD events are not likely to adversely impact transformer mechanical integrity. EPRI, participating utilities, and transformer manufacturers collaborated to examine factory and field test data on power transformers of various construction types and sizes. Among other findings, the factory data revealed that vibrations reach their maximum at low levels of GIC and do not increase significantly as GIC levels rise.

Task 9 also included research into vibration and other effects that severe GMD events can have on turbine generators. Harmonic currents from severe GMD events have the potential to cause rotor heating and stimulate mechanical vibrations at frequencies turbine generator designers did not anticipate. A Harmonic Assessment Guide was released that includes generator harmonic screening criteria, a generator case study, and generator protection guidance. Generator impact analysis was also included in the GIC harmonic tool.

The final report recommended that industry continue to support ongoing research and tool development to assess generator risk from severe GMD events. The final report also recommended that NERC request EPRI provide updates to the Reliability and Security Technical Committee periodically on the status of its efforts.

III. CONCLUSION

The completion of the GMD Research Work Plan marks an important milestone in NERC and industry's comprehensive approach to reducing the risks that severe GMD events can pose to the reliability and resilience of the North American grid. Importantly, the findings of this GMD research support the use of the TPL-007 Reliability Standard and provide tools and insights for the ERO, industry, and research partners to use in accurately performing the GMD Vulnerability Assessments required by the standard. As part of the required periodic review of the TPL-007 Reliability Standard, NERC will consider these research findings, as well as any new developments in space weather research and other insights that are gained during the implementation of the standard, to determine whether further improvements and refinements to the standard are necessary.

NERC respectfully requests that the Commission accept this final informational filing and the attached Final Report, *Order No. 830 GMD Research Work Plan: Results and Recommendations for the ERO* (Feb. 2021).

Respectfully submitted,

/s/ Lauren A. Perotti

Lauren A. Perotti
Senior Counsel
North American Electric Reliability Corporation
1325 G Street, N.W., Suite 600
Washington, D.C. 20005
(202) 400-3000
lauren.perotti@nerc.net

Counsel for the North American Electric Reliability Corporation

April 30, 2021

<u>CERTIFICATE OF SERVICE</u>

I hereby certify that I have served a copy of the foregoing document upon all parties listed on the official service list compiled by the Secretary in the above-referenced proceeding.

Dated at Washington, D.C. this 30th day of April, 2021.

<u>/s/ Lauren A. Perotti</u>

Lauren A. Perotti
Counsel for North American Electric Reliability Corporation

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Attachment 1

GMD Research Work Plan
Results and Recommendations for the ERO

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Order No. 830 GMD Research Work Plan

Results and Recommendations for the ERO

February 2021

RELIABILITY | RESILIENCE | SECURITY




3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

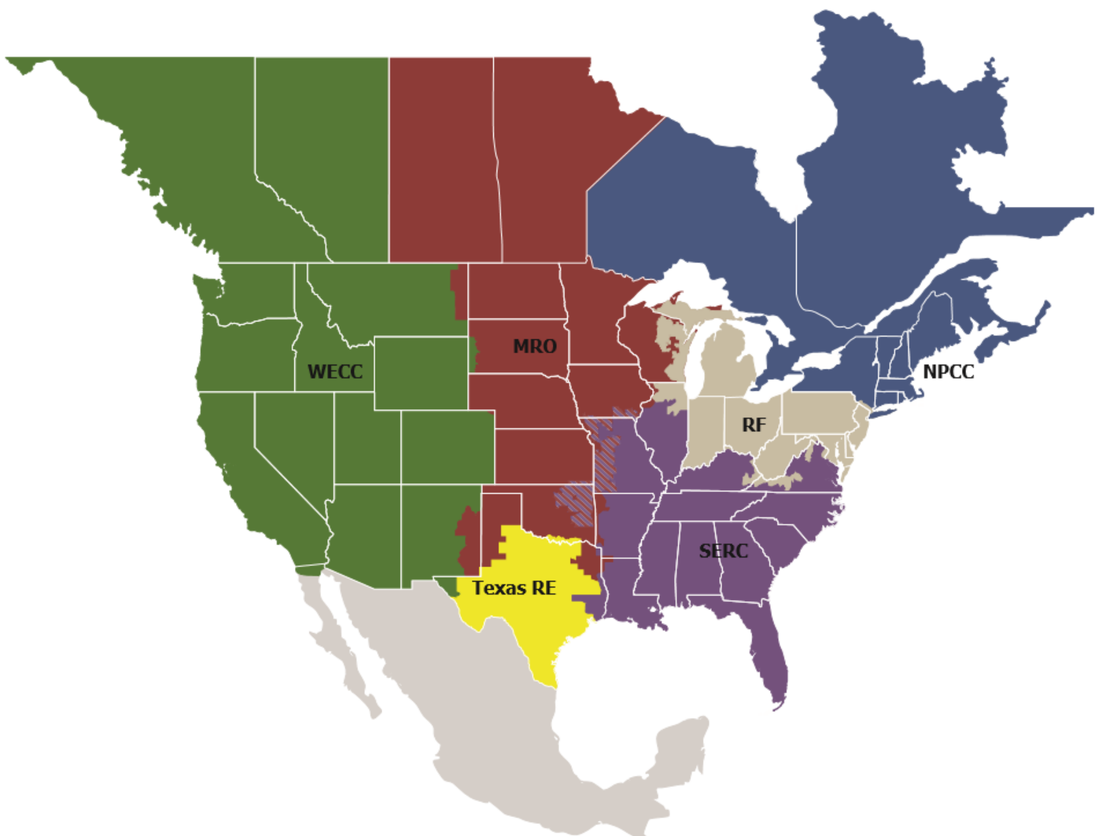
Table of Contents

Preface

Electricity is a key component of the fabric of modern society and the Electric Reliability Organization (ERO) Enterprise serves to strengthen that fabric. The vision for the ERO Enterprise, which is comprised of the North American Electric Reliability Corporation (NERC) and the six Regional Entities (REs), is a highly reliable and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

Reliability | Resilience | Security
Because nearly 400 million citizens in North America are counting on us

The North American BPS is made up of six RE boundaries as shown in the map and corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one RE while associated Transmission Owners (TOs)/Operators (TOPs) participate in another.



MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
Texas RE	Texas Reliability Entity
WECC	WECC

Executive Summary

Beginning in 2018, NERC and its technical committees partnered with the Electric Power Research Institute (EPRI) and North American utilities in a wide-ranging research project to further the understanding of severe geomagnetic disturbance (GMD) risk to the North American BPS. Launched following the regulatory approval of new GMD Reliability Standards, the project scope included examining the technical underpinnings of the Reliability Standards and advancing the state-of-the-art tools, techniques, and processes used by owners and operators to assess and mitigate severe GMD event risks. Over the course of the three-year project, EPRI has released 17 publications supporting NERC and the industry's efforts to implement effective GMD Reliability Standards.

NERC's GMD Reliability Standards are important tools for reducing the risk of severe, rare GMD events from disrupting the electric grid upon which our North American society depends. NERC and the electric industry, in consultation with research partners at NOAA, NASA, and Space Weather Canada, began development of Reliability Standards in 2013. These standards establish requirements for owners and operators to study and design their systems to be resilient during a severe 100-year GMD, as well as to implement operating procedures during strong GMD events that can reduce system impacts.

In approving GMD Reliability Standards, the Federal Energy Regulatory Commission (FERC) recognized that "the understanding of threats posted by GMD is evolving as additional research and analysis is conducted."[1] FERC directed NERC to submit a research work plan addressing research areas related to the TPL-007 Reliability Standard and provide informational filings. Collectively, the tasks in GMD Research Work Plan were directed at the following areas:

- Evaluate the severe GMD event benchmarks that are the basis for the industry's GMD Vulnerability Assessments with the latest space weather data sets and new space weather simulation models
- Improve the accuracy of ground conductivity models used by BPS planners for GMD Vulnerability Assessments
- Further study the impacts of GIC from severe GMD events on BPS transformers and other BPS equipment
- Develop tools for BPS planners to use in performing GMD Vulnerability Assessments.

Outcomes from this research project affirm the efficacy of the TPL-007 Reliability Standard and provide tools and insights for the ERO, industry, and research partners to use in accurately performing GMD Vulnerability Assessments. Below is a summary of key findings and outcomes that are described in later sections and available in the published reports (see list in the appendix.) EPRI has made all reports in the GMD Research Work Plan available to the public at no cost.

- Analysis of an extensive space weather data set supports the industry's use of the Benchmark GMD Event to represent a severe 100-year GMD event in GMD Vulnerability Assessments. Research into the characteristics and spatial scales of extreme GMD events (i.e., geographic size, locations affected, durations, intensity and direction) provided additional insight about geoelectric field enhancements that can occur during severe GMD events. These details can assist industry planners with how they apply the Supplemental GMD Event to assess the impact that geoelectric field enhancements can have on the system.
- Scaling the peak geoelectric field of the Benchmark GMD Event according to the geomagnetic latitude of the system area is consistent with analysis of space weather data and advanced simulation modeling. Researchers confirmed that the geoelectric field intensity during a severe 100-year GMD event is expected to decrease by an order of magnitude across the 60-degree to 40-degree geomagnetic latitude band.
- Newly-available earth conductivity data for the U.S. was used to better define regional boundaries in conductivity maps used by industry to calculate geoelectric fields. Through the GMD Research Work Plan,

[1] FERC Order No. 830, P. 76

conductivity maps, earth models, and earth conductivity scaling factors are available for industry and software designers to use in performing GMD Vulnerability Assessments. These models cover the North American BPS, with uncertainty only in regions where magnetotelluric (MT) measurements or other modeling information is unavailable to perform comparisons. In addition, EPRI published technical guidance for validating models with GIC and magnetometer data collected during actual GMD events.

- The GMD Research Work Plan improved industry capabilities for assessing transformer thermal impacts from GMD events and provided further technical justification for the 75 A/phase screening criterion used in TPL-007 to mitigate risk to the BPS. The research produced thermal models for over 80 different transformer types and designs which can be used in an industry-available thermal modeling tool. Simulations using the expanded set of models indicate that the TPL-007 thermal impact screening criterion is generally effective, however specific designs were identified that could possibly exceed transformer thermal criteria. The findings enable industry to expand screenings for these designs and perform additional risk analysis.
- EPRI developed an open-source tool that industry can use to perform GMD-related harmonic studies of the power system and made it available at no cost. GMD-related harmonics are caused by the part-cycle saturation of transformers. These harmonic currents and voltages resulting from transformer saturation can impact system operations during severe GMD events. The tool, *GICHarm*, provides planners with capability to perform wide-area harmonic analysis that existing commercial tools did not address.
- Research on transformer mechanical vibrations caused by GIC concluded that severe GMD events are not likely to adversely impact transformer mechanical integrity. EPRI, participating utilities, and transformer manufacturers collaborated to examine factory and field test data on power transformers of various construction types and sizes. Among other findings, the factory data revealed that vibrations reach their maximum at low levels of GIC and do not increase significantly as GIC levels rise.

The completion of the GMD Research Work Plan is an important milestone in the ERO and industry's comprehensive approach to reducing the risks that severe GMD events can pose to the reliability and resilience of the North American grid. Results do not reveal reliability gaps in the approved TPL-007 Reliability Standard and provide technical details that justify its use and support its application in assessing and reducing risk to the electricity grid. The ERO will consider these research results and potential modifications to the standard, however, as part of normal periodic review of standards as prescribed in NERC's Rules of Procedure. Additionally, in 2020, the ERO added another component to the GMD risk reduction effort by implementing its NERC Rules of Procedure Section 1600 Data Request for the collection of GIC and magnetometer data during strong GMD events.[2] GMD data from this program can support industry and researchers as they develop and improve their GIC models and advance the state-of-the-art in GMD vulnerability assessment capabilities.

[2] See the NERC GMD Data Collection page: https://www.nerc.com/pa/RAPA/GMD/Pages/GMDHome.aspx

Introduction

Background

In Order No. 830, FERC approved Reliability Standard TPL-007-1 - Transmission System Planned Performance for Geomagnetic Disturbance Events. In this order, FERC also directed NERC to submit a work plan to conduct research on certain GMD-related topics.[3] NERC's GMD Research Work Plan (Work Plan) was accepted by FERC in Order No. 851.

GMD Work Plan Overview

The Work Plan consisted of the following nine research "Tasks":

1. Further Analyze Spatial Averaging Used in the Benchmark GMD Event[4]
2. Further Analyze Latitude Scaling
3. Improve Earth Conductivity Models for GIC Studies
4. Study Transformer Thermal Impact Assessment Approach
5. Further Analyze the 75 Amps per Phase Criterion Used for Transformer Thermal Impact Assessments
6. Support for Section 1600 Data Request
7. Geoelectric Field Tool Evaluation and Calculation of Beta Factors
8. Improve Harmonics Analysis Capability
9. Harmonic Impact Studies

NERC developed the research activities in coordination with EPRI, NERC's research collaborators, and stakeholders, to advance industry understanding of GMD risk to the BPS and achieve research objectives specified in Order No. 830. The research direction was based on current capabilities, resources, and understanding.

EPRI is a nonprofit corporation organized under the laws of the District of Columbia Nonprofit Corporation Act and recognized as a tax-exempt organization under Section 501(c) (3) of the U.S. Internal Revenue Code of 1986, as amended. EPRI was established in 1972 and has principal offices and laboratories located in Palo Alto, California; Charlotte, North Carolina; Knoxville, Tennessee; and Lenox, Massachusetts. EPRI 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, health, safety, and the environment.

Work Plan Implementation

NERC and EPRI initiated the Work Plan in November 2017 with funding commitment of $3.5M from participating EPRI members and NERC. The Work Plan was concluded in the first quarter of 2020. NERC and EPRI made technical reports and other deliverables available to the public free of charge. In July 2020, NERC made an informational filings to FERC that contain hyperlinks to the technical reports completed up to that date.[5] This summary report of results and recommendations, and links to all final technical reports, will be filed with FERC.

[3] Order No. 830 at P 22 and P 77.

[4] Benchmark GMD Event white paper:
https://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Benchmark_Clean_May12_complete.pdf

[5] Informational Filing of NERC Regarding Work Performed Under the Geomagnetic Disturbance Research Work Plan:
https://www.nerc.com/FilingsOrders/us/NERC%20Filings%20to%20FERC%20DL/First%20%20Info%20Filing%20re%20%20GMD%20Work%20Plan%20(7-26-2019).pdf

Task 1: Further Analyze Spatial Averaging Used in the Benchmark GMD Event

Summary

The activities in this task consisted of performing further research and analysis on geoelectric field enhancements and the use of spatial averaging in defining benchmark GMD events that entities use when conducting the GMD Vulnerability Assessments required by the TPL-007 standard.

Background

Reliability Standard TPL-007-1 requires entities to conduct initial and ongoing assessments of the potential impact of a defined GMD event on BPS equipment and the BPS as a whole. This defined GMD event, referred to as the benchmark GMD event in TPL-007-1, and relies upon the use of an innovative spatial averaging technique to estimate the wide area impacts of a GMD event on the BPS. In Order No. 830, the Commission approved the benchmark GMD event but noted its concern that a spatially averaged benchmark may not adequately account for localized peak geoelectric fields that could potentially affect reliable operations. Accordingly, the Commission directed NERC, as part of the Work Plan, to "further analyze the area over which spatial averaging should be calculated for stability studies, including performing sensitivity analyses on squares less than 500 km per side (e.g., 100 km, 200 km)."[6]

Broadly speaking, the research falling under **Task 1** would consist of two main components: (i) research to improve understanding of the characteristics and spatial scales of localized geoelectric field enhancements caused by severe GMD events; and (ii) research to determine the impacts of spatial averaging assumptions on BPS reliability.

Task 1 also provides insights for application in subsequent versions of the TPL-007 standard. For example, proposed Reliability Standard TPL-007-2 was developed to address FERC directives including concerns that the benchmark GMD event may not adequately account for localized peak geoelectric fields.[7] The proposed standard requires entities to perform supplemental GMD Vulnerability Assessments in addition to the benchmark GMD Vulnerability Assessments. Supplemental GMD Vulnerability Assessments are based on the supplemental GMD event, a second defined event that accounts for localized peak effects of GMDs and which is based on individual station measurements (i.e. not spatially averaged data). As noted, **Task 1** research also supports understanding characteristics and spatial scales of localized geoelectric field enhancements to inform the supplemental GMD event description.

Activities

Research Task Overview: Perform Research to Improve Understanding of Characteristics and Spatial Scales of Localized Geoelectric Field Enhancements Caused by Severe GMD Events

Product: *Furthering the Understanding of the Characteristics and Scales of Geoelectric Field Enhancements. EPRI, Palo Alto, CA: 2020. 3002017900.*

Summary: EPRI investigators developed and analyzed an extensive data set to address questions regarding the occurrence, strength, and direction of GMD as well as examine the effects of spatial averaging to determine input waveforms. EPRI collaborated with researchers at the Los Alamos National Lab (LANL) to develop a comprehensive data set that will analyze severe GMD event characteristics. Researchers obtained and processed magnetic field data from a global consortium of magnetic observatories to create a single data set to analyze large GMD events across magnetometer stations of interest. [8] The data set was used in subsequent analysis.

---

[6] Order No. 830 at P 26.

[7] *See* TPL-007-2 Petition at Section IV.

[8] See *Improving Understanding of Characteristics of Geoelectric Field Enhancements Caused by Severe GMD Events: Examining Existing Ground-Based Data.* EPRI, Palo Alto, CA: 2019. 3002016832.

Outcomes: The research findings support the TPL-007 Reliability Standard and add to the body of knowledge for performing accurate GMD vulnerability assessments.

Characteristics of geoelectric field enhancements during strong GMD events:

- **Geographic Size, strength, and direction.** Spatial scales are on the order 200-300km. Enhancements are not expected to cover areas less than 200km. Assessments of the impact of localized enhancements should not use scale sizes smaller than 200 km to represent the localized enhancement; using a 200 x 200 km area for localized enhancement—with the supplemental peak electric field—for impact analysis should provide a conservative estimate of the system impact. The direction of the geoelectric field within the localized region can be treated as independent of the direction of the geoelectric field in the surrounding region.
- **Locations affected.** Peaks in GMD are largely confined to the auroral zone. As the auroral zone expands during strong geomagnetic activity, this exposes locations further equatorward to GMD hazards. Localized enhancements should be considered in impact assessments for regions that would reasonably expect to be in the auroral zone during a severe GMD event.
- **Durations.** Typical durations of around 2.5 minutes, with durations in excess of 8 minutes being rare.

Research Task Overview: Determine the Impacts of Spatial Averaging Assumptions on the BPS

Product: *Furthering the Understanding of the Characteristics and Scales of Geoelectric Field Enhancements. EPRI, Palo Alto, CA: 2020. 3002017900.*

Summary: EPRI investigators performed analysis to compare power system impacts of localized enhancements. The analysis included studying GIC and system voltages with and without a 200 km square geoelectric field enhancement applied to various synthetic planning areas.

Outcomes: The research findings support the TPL-007 Reliability Standard and add to the body of knowledge for performing accurate GMD vulnerability assessments. The presence of a localized enhancement will increase GIC flow, reactive power losses and reduce system voltages in the vicinity of the geoelectric field enhancement. These effects are not limited to within the localized enhancement itself (i.e., other parts of the planning area also exhibited increased GIC and voltage impacts).

ERO Recommendation

The ERO should:

- Monitor further research performed by the space weather community to characterize the characteristics of extreme GMD events including localized geoelectric field enhancements.
- Engage TPL-007 applicable entities through the RSTC and industry forums to promote awareness of these research findings and promote use of best practices

Task 2: Further Analyze Latitude Scaling

Summary

The activities in this task consisted of evaluating the latitude scaling factors in Reliability Standard TPL-007-1, including using existing models and developing new models to extrapolate, from historical data, the potential scaling of a 1-in-100 year GMD event on lower geomagnetic latitudes.

Background

The benchmark GMD event defined in TPL-007-1 includes scaling factors to enable entities to tailor the geoelectric field to their specific location for conducting GMD Vulnerability Assessments. These factors are intended to account for differences in the intensity of a GMD event due to geographical considerations, such as geomagnetic latitude and local earth conductivity. Finding that there are "questions regarding the effects of GMDs at lower geomagnetic latitudes," the Commission directed NERC to reexamine the geomagnetic latitude scaling factors provided in TPL-007-1.[9] Consistent with the Commission's directive, NERC would use existing models and develop new models to extrapolate from historical data the impacts of a large, 1-in-100 year GMD event on lower geomagnetic latitudes under this task.

Task 2 also provides insight for application in subsequent versions of the TPL-007 standard. For example, proposed Reliability Standard TPL-007-2 also uses latitude-scaling factors.

Activities

Research Task Overview: Analyze scaling the geoelectric field of severe GMD events for magnetic latitude

Product: *Magnetohydrodynamic (MHD) Modeling for the Further Understanding of Geoelectric Field Enhancements and Auroral Behavior During Geomagnetic Disturbance Events. EPRI, Palo Alto, CA: 2020. 3002017952.*

Summary: Researchers developed an algorithm to estimate the auroral boundary, which separates the quieter subauroral region from the more geomagntically disturbed auroral region. During the evolution of a large geomagnetic storm, this boundary has been observed using ground-based magnetometers to move toward the equator. Researchers have limited data to understand the phenomenon because the spatial density of magnetometers for these networks is often low. In addition, for high-impact, low-frequency events, there are a limited number of storm examples for digital magnetometer network databases.

MHD simulations of the near-Earth environment (such as the Space Weather Modeling Framework (SWMF)) are now available that can be used to simulate different configurations of large geomagnetic storm events and to specify the resolution of the outputs. Using these, resesarchers investigated the auroral boundary and geoelectric field enhancement characteristics using higher-density magnetic field outputs, as well as larger storm events. Threshold boundaries from simulations were consistent with those calculated from historical geomagnetic field data, indicating that the simulations can reproduce observed boundary behavior.

Outcomes: The research findings support the TPL-007 Reliability Standard and add to the body of knowledge for performing accurate GMD vulnerability assessments.

- Using estimates for a 1-in-100-year geomagnetic storm Dst, the auroral threshold in simulation is between 43° and 50° MLAT.

[9] Order No. 830 at P 57.

- NASA researchers concluded that, taking into account the uncertainties in determining the precise auroral region location, the boundary residing in the 43–50° band is consistent with the current benchmark latitude scaling that indicates an order-of-magnitude increase in the geoelectric field amplitudes across the band of 40–60° of geomagnetic latitude.

ERO Recommendation

The ERO should monitor further research performed by the space weather community to characterize the latitude thresholds of extreme GMD events.

Task 3: Improve Earth Conductivity Models for GIC Studies

Summary

The research activities under this task consist of activities to evaluate the accuracy of existing earth conductivity models for GIC studies, provide updates based on newly-available data, and give guidance where needed.

Background

In Order No. 830, the Commission expressed concerns regarding the ground conductivity models that form the basis for the earth conductivity scaling factors used in TPL-007-1 and directed NERC to study this issue as part of its Work Plan.[10] Accordingly, research activities in **Task 3** address the Commission's specific concerns, including comparing the accuracy of geomagnetically induced current (GIC) calculations derived from available 1D models with 3D models that have recently been developed for some areas of the U.S. and examining modeling to account for "coast effects."

Task 3 research will support accuracy of GIC calculations performed to meet requirements in TPL-007-1 and subsequent versions of the standard.

Activities

Task 3A Research Overview: Use Magnetotelluric Measurement Data to Validate/Improve Existing Earth Conductivity Models Available to Industry and Researchers

Product: *Use of Magnetotelluric Measurement Data to Validate/Improve Existing Earth Conductivity Models. EPRI, Palo Alto, CA: 2020. 3002019425.*

Summary: This report provides the results of EPRI's earth conductivity model evaluation project. Newly-available magnetotelluric data from NSF Earthscope have supported the development of ground response models, also known as three-dimensional or 3D models, that capture directional variability.[11, 12] These new models can also provide more localized information about the induced geolectric fields in comparison to the average response that results from the use of one-dimensional (1D) or scaling factor techniques that have been predominant in GIC estimation and hazard analysis. However, geoelectric field calculations using these 3D models are more complex, and their use in GIC estimation is at an earlier stage. The EPRI analysis compares estimates of electric field peak intensity derived from 3D and 1D conductivity profiles with the goal of identifying differences between these models and potential areas of improvement for their use in GIC estimation and hazard analysis.

EPRI estimated geoelectric fields using existing 1D models[13] and 3D models derived from electromagnetic transfer functions (EMTFs) based on the U.S. National Science Foundation (NSF) Earthscope project measurement data. At the time of EPRI's work the Earthscope project had completed MT mapping of much of the northern half of the contiguous United States (U.S.) (See Figure 1).

[10] Order No. 830 at PP 78-80.

[11] Schultz, A., G. D. Egbert, A. Kelbert, T. Peery, V. Clote, B. Fry, and S. Erofeeva, USArray TA magnetotelluric transfer functions, Technical Report, National Geoelectromagnetic Facility: 2006-2017.

[12] Kelbert, A., G. Egbert, and A. Schultz, IRIS DMC Data Services Products: EMTF, the magnetotelluric transfer functions, Tech. rep. National Geoelectromagnetic Facility, 2011-2017.

[13] *One-Dimensional Earth Resistivity Models for Selected Areas of Continental United States and Alaska.* EPRI, Palo Alto, CA: 2012. 1026430.

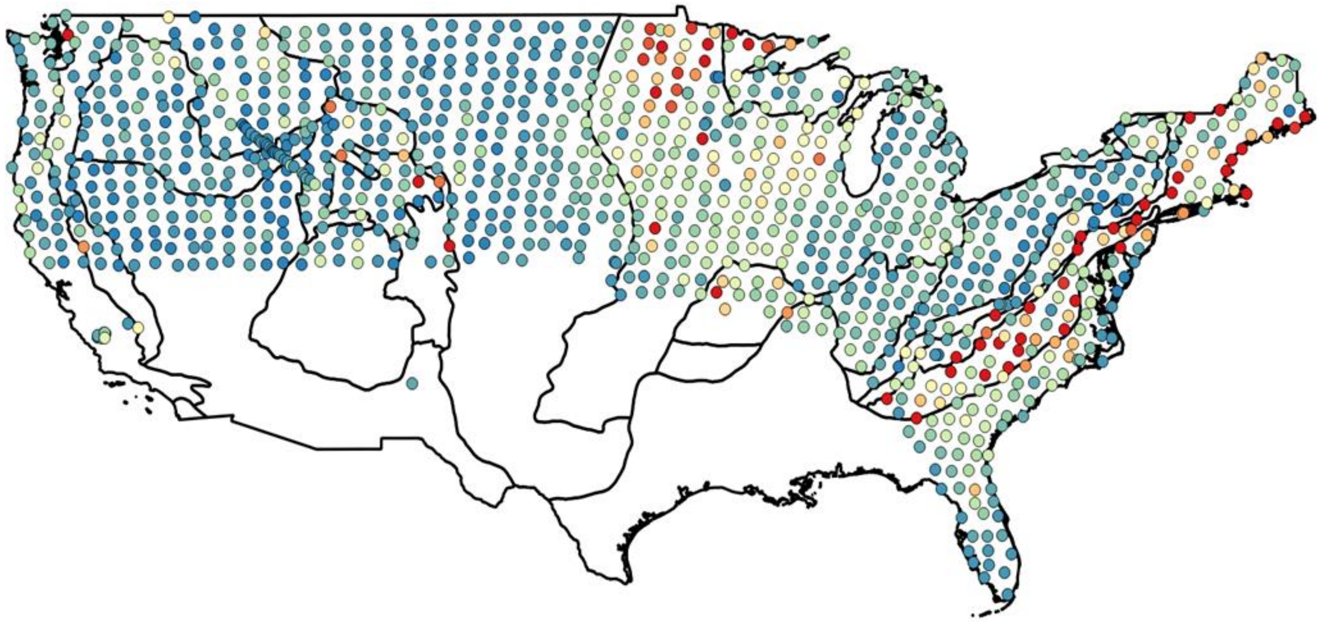


Figure 1: Map of local EMTFs overlaid on the TPL-007-1 physiographic regions

To model realistic extreme geomagnetic disturbance conditions, EPRI calculated electric field response for 1D and 3D models using a scaled extreme geomagnetic storm scenario. The average and median EMTF peak electric field response within each physiographic region is compared to the 1D model response. This comparison indicates how accurately the existing 1D models can reflect average peak geoelectric field response to a severe GMD event and takes into account newly-available MT measurement data, where available. Additionally, the range of electric field values within each region that resulted from the region's EMTFs were examined to understand the degree of non-uniformity.

Based on the comparisons of 1D model and EMTF-based peak geoelectric field response, regional 1D models and boundaries are updated to improve regional geoelectric field distribution uniformity. The report provides regional 1D transfer functions based on EMTF response and gives guidance on their use.

Finally, EPRI evaluated the differences in GIC estimation to 1D- and EMTF-derived geoelectric response using a synthetic but realistic system model. The comparison of GIC estimates provides insights into modeling sensitivity to local 3D-type characteristics.

Outcomes: The results of this research objective validate existing 1D modeling approaches in most parts of the U.S., and identify areas where more complex modeling or approaches are needed to assess GMD Risk.

Existing 1D-model results range from greater than, within 15% of, and less than the 3D/EMTF median in 40%, 30%, and 30% of the physiographic regions, respectively. The Blue Ridge, Piedmont, New England, Ozark Plateaus, Adirondacks, and Superior Uplands regions are underestimated using existing 1D models. See Figure 2.

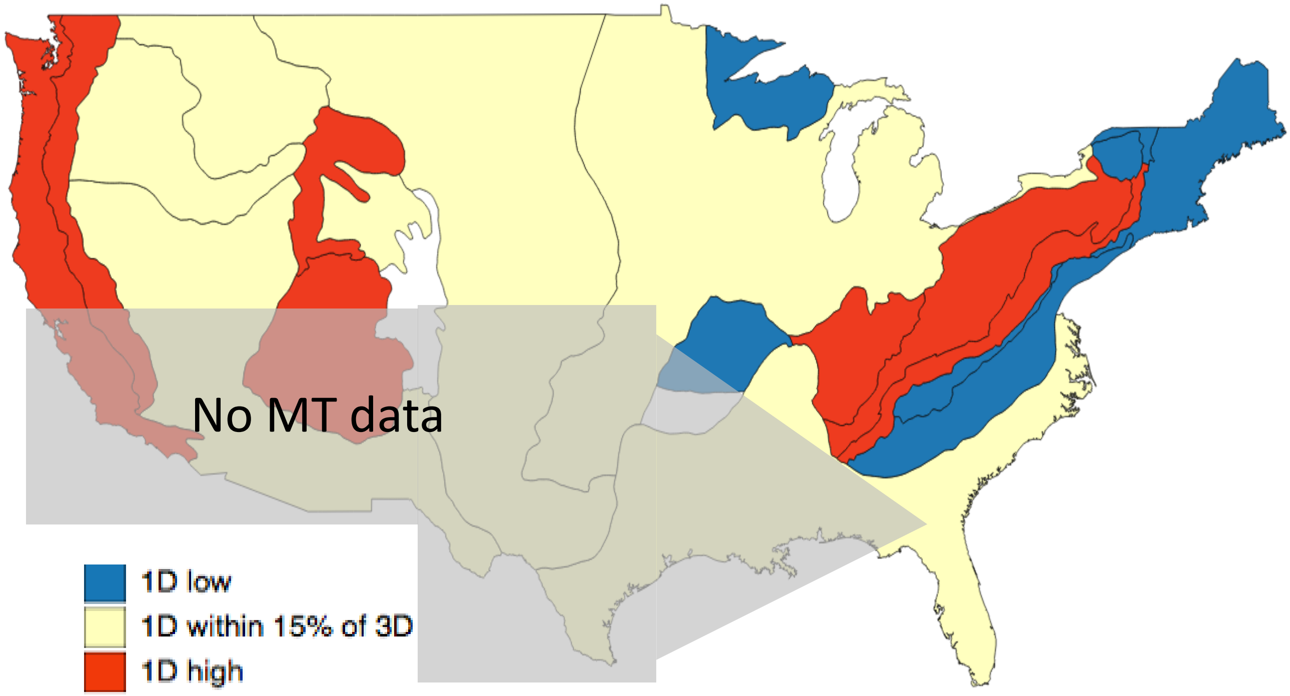


Figure 2: Physiographic regions of the contiguous United States, where geoelectric fields estimated using 1D models are low (blue), within 15% (yellow), and high (red), as compared to EMTF response distribution median. Shaded area indicates no MT data for the region

The analysis shows that MT measurements can be used to update 1D model response and regional boundaries. Some of the larger physiographic regions are not well-represented by a simple 1D model. These larger regions, such as the Interior Plateaus, may be divided into multiple sub-regions to improve estimates of regional peak geoelectric field response. EPRI identified new regional boundaries for 1D modeling shown in Figure 3, that provide better uniformity over the existing 1D physiographic regions for the U.S., as well as updated 1D models for each of these regions.

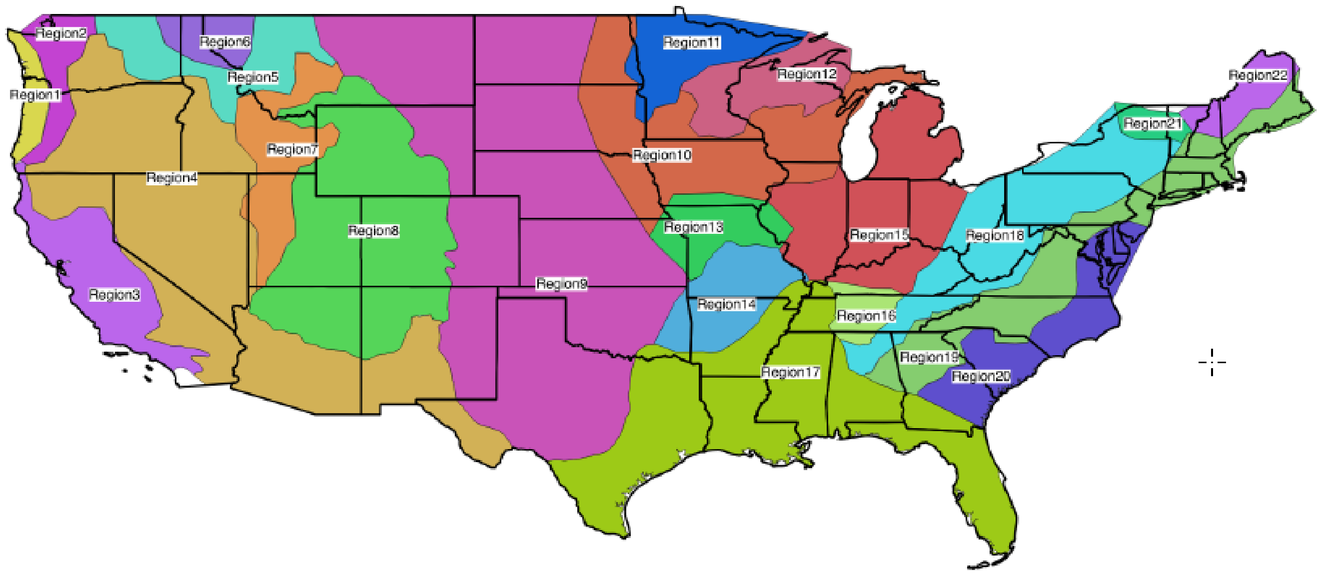


Figure 3: Updated 1D regional boundaries, with state outlines shown for reference. Colors are selected at random to differentiate regions.

Even with the new physiographic boundaries, EPRI identified some areas where 1D models may not be sufficient for GIC estimation due to non-uniform earth structure. The Blue Ridge, Piedmont, and New England physiographic regions (Regions 19 and 22 in Figure 3) exhibit this non-uniformity and have areas in which the ground response to GMD events could produce enhanced geoelectric fields affecting GICs. In regions of greater non-uniformity, more research is needed in these areas to support GIC estimation. System and earth conductivity model validation using GIC measurements, as discussed below, can aid planning entities in assessing the accuracy of the models used in GMD vulnerability assessments.

Task 3B Research Overview: Develop techniques and guidelines for using GIC and magnetometer data to perform model validation.

Product: *Improving Conductivity Models for GIC Estimation: Guidance for Validation of GIC Models. EPRI, Palo Alto, CA: 2020. 3002017897.*

Summary: This report provides a step-by-step approach for performing a model validation study. Such a study uses geomagnetic field time-series data as an input to ground response models and system models for calculating system GICs that are compared with measured GIC values. Reliability Standard TPL-007-4 requires designated planning entities to have processes for obtaining GIC data and geomagnetic field data, which can be used in model validation. The report includes an example study based on a 2015 GMD event using an actual power system model and GIC measurements.

The goal of model validation is to gain confidence in the estimates provided, or reduce the sources of modeling inaccuracies to an acceptable level. Figure 4 describes various error sources and their likely impact on GIC estimates based on analysis using the example study.[14] Other sources of error are also discussed including system parameter estimates and GIC measurements during weak GMD events.

[14] *Improving Conductivity Models for Geomagnetically Induced Current (GIC) Estimation: Guidance for Validation of GIC Models. EPRI, Palo Alto, CA: 2020. 3002017897.*

Parameter	Cause	Uncertainty impact
Substation grounding resistance	Using assumed values of substation grounds	High
Magnetic field	Too far from a magnetometer	High
Conductivity model	Incorrect models or the presence of nonuniform regional effects	Moderate
System configuration	Incorrect system configuration during time of the event	High

Figure 4: Potential Sources of Error in a Model Validation Assessment and Level of Impact

Techniques for reducing the impact of inaccuracies and estimated values to improve GIC study results are included in the report.

Outcomes: Industry planners can use the approach in this report to validate models used to calculate GICs. A model validation study will provide the planner improved confidence in GIC study results used in GMD Vulnerability Assessments. The report identifies best practices for model validation as well as sources of uncertainty and potential ways to improve GIC estimates.

Task 3C Research Overview: Assess the "coast effect" and develop models to capture non-uniform field effects

Product: *Nonuniform Field Modeling: Coast Effect Assessment. EPRI, Palo Alto, CA: 2020. 3002017898.*

Summary: The coast effect refers to an enhancement of the cross-shore (perpendicular to the shoreline) component of the horizontal electric field. It is a response to the along-shore (parallel to the shoreline) component of the magnetic field in the presence of a conductivity gradient between the shore and seawater.

The report provides a regional level assessment of the potential increase in GIC hazard resulting from the geoelectric coast effect and evaluates its presence or absence on the coast of the contiguous United States. EPRI used MT measurements from the USArray Earthscope project, published papers analyzing these data, and an assessment of coastal geometries and conductivity gradients from published sources that are realistic for coastal regions of the United States. The realistic geometries and conductivity gradients described in the report provide the physical reasoning for the relative lack of an observed coast effect in most parts of the contiguous United States and can improve local coast effect assessments and modeling efforts.

Outcomes: The width of the continental shelf—along with the specific coastal geometries, conductivity gradients, and presence of wet sediment shorelines—suggest that the coast effect will be small for much of the contiguous United States. A coast effect is expected for coastal Maine and parts of Massachusetts. Several local sites in California are identified for further study due to complex geological conditions.

ERO Recommendation

NERC Staff and EPRI should continue to work with software vendors to adopt new region boundaries and modeling information in available GIC software. NERC and EPRI should also engage technical experts, researchers, and software vendors to develop advanced modeling techniques that address unique challenges of areas with significant non-uniformity that impact GIC estimates.

The ERO, working collaboratively through NERC and the NPCC and WECC Regional Entities, should support application of this and future research into the described coastal effect through regional technical committees and working groups.

Working through the Reliability and Security Technical Committee (RSTC), Real-time Operations Subcommittee (RTOS), and technical partners, the ERO should (i) promote model validation best practices; (ii) encourage planning entities to validate GMD models with data collected during GMD events of interest; and (iii) support technical groups in continuing to advance GMD modeling disciplines.

Task 4: Study Transformer Thermal Impact Assessment Approach

Summary

The research activities under this task consisted of: 1) evaluating the existing approach used to perform transformer thermal assessments; and 2) examining alternative methods of applying the benchmark geoelectric field time series to individual transformers to represent worst-case hot-spot heating conditions in transformer thermal impact assessments.

Background

Task 4 research focused on performing analysis to evaluate the ability of GIC flow calculated as specified in TPL-007 to represent worst-case transformer hot-spot heating conditions. Reliability Standard TPL-007-1 was designed to identify transformers that are potentially at risk from GIC flows experienced during a severe GMD event. Requirement R6 of the standard requires owners of applicable transformers to perform transformer thermal impact assessments of transformers where the maximum effective GIC value for the benchmark GMD event, as provided in Requirement R5.1, is 75 A per phase or greater. The results of these assessments are then shared so they may be incorporated into the overall GMD Vulnerability Assessment and any necessary Corrective Action Plan. As described in NERC's Screening Criterion for Transformer Thermal Impact Assessment White Paper, this threshold was chosen because healthy transformers with an effective GIC of less than 75 A per phase during the benchmark GMD event are unlikely to exceed known temperature limits indicated in IEEE Std. C57.91-2011 (IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators).[15]

In Order No. 830, the Commission directed NERC to perform additional research related to the transformer thermal impact assessments required by the TPL-007 standard. Specifically, the Commission directed NERC to study, as part of its Work Plan, how "the geoelectric field time series can be applied to a particular transformer so that the orientation of the geoelectric field time series, over time, will maximize GIC flow in the transformer . . ."[16] **Task 4** therefore consisted of work to determine how the benchmark geoelectric field wave shape can be applied to a particular transformer to determine worst-case hotspot heating.

Activities

Research Task Overview: Examine methods of applying the benchmark geoelectric field time series to represent worst-case hot-spot heating conditions in transformer thermal impact assessments

Product: *Geomagnetically Induced Current (GIC) Transformer Thermal Impact Assessment: Impact of Field Orientation on Transformer Thermal Screenings. EPRI, Palo Alto, CA: 2020. 3002017948.*

Summary: EPRI investigators reviewed approaches for applying the approved Benchmark GMD Event geoelectric field to transformer thermal impact assessments. Simulations techniques enabled investigators to determine the upper bound maximum heating for selected transformers, representing worst-case metallic hot-spot heating for all field orientations of a given severe GMD event relative to the orientation of the equivalent power system seen at the transformer terminals. Using this technique, investigators examined worst-case metallic hot-spot heating for several severe GMD events, each with unique waveforms and field orientations, for comparison with the benchmark GMD event.

---

[15] The *Screening Criterion for Transformer Thermal Impact Assessment* white paper was filed in this proceeding on January 21, 2015 with NERC's petition for approval of TPL-007-1. NERC filed a corrected version of this white paper on June 28, 2016. See https://www.nerc.com/pa/Stand/pages/project-2013-03-geomagnetic-disturbance-mitigation.aspx

[16] Order No. 830 at P 66.

Outcomes: The simulation technique demonstrated by EPRI provides a method for determining the maximum hot-spot heating for all field orientations of the benchmark GMD event relative to the orientation of a notional power system. EPRI determined that the benchmark GMD event is the most conservative (i.e., produces largest metallic hot-spot heating) waveform compared to other severe GMD events for the transformers examined in this report.

ERO Recommendation

The ERO should monitor further technical development supporting transformer thermal modeling and GMD risk assessment. As additional transformer models are developed through industry and research partner efforts, techniques such as those demonstrated in this research task should be used to evaluate the continued efficacy of the benchmark GMD event for GMD Vulnerability Assessments.

Task 5: Further Analyze the 75 A per Phase Criterion Used for Transformer Thermal Impact Assessments

Summary

Research for this task will address the potential impact of the benchmark GMD event or other realistic GMD events on power transformers, which includes analyzing the 75A/phase TPL-007 criterion used for transformer thermal impact assessments. The work will:

- re-examine the screening criteria and if needed, an alternative criterion will be developed; and
- study tertiary winding harmonic heating and determine if this affects the thermal screening criteria.

Background

This task addresses the Commission's directive to "include further analysis of the thermal impact assessment qualifying threshold" of 75 A per phase and to "address the effects of harmonics, including tertiary winding harmonic heating and any other effects on transformers" in NERC's Work Plan.[17]

Task 5 research also provided insights for application in subsequent versions of the TPL-007 standard, which require entities to perform supplemental thermal impact assessments of applicable power transformers based on GIC information for the supplemental GMD event described in **Task 1**.

Activities

Research Task Overview: Create and Document a Transformer Thermal Modeling Tool

Product: *GMD Transformer Thermal Analysis Tool. EPRI, Palo Alto, CA: 2018. 3002014059*

Summary: an accurate thermal transformer model for the estimation of the hotspot heating in the transformer during GMDs has been developed. The tool is referred to as EPRI Transformer Thermal Model (ETTM). The thermal model is based on the transfer function approach which does not require the detailed information about the studied transformers. To obtain the model parameters, the model step response is fitted to the GIC test data. The simulation results of the transformers with available GIC test data are presented, revealing the accuracy of the developed model in duplication of the measurements.

Outcome: The task demonstrates that the EPRI tool is acceptable for use in the Research Work Plan. Additionally, EPRI makes this tool available through the public free of charge from the EPRI website.

Research Task Overview: Assess transformer thermal-limits to GIC, including effects on tertiary windings

Product: *Transformer Thermal Impact Assessments for DC Withstand Capability: Examining the Impacts of GIC on Transformer Thermal Performance. EPRI, Palo Alto, CA: 2019. 3002017708.*

Summary: In this task, EPRI identified transformer designs with the most thermal-limiting capacity to GIC in order to more fully assess the impact of the benchmark GMD event and other realistic GMD events on power transformers. More than 40 transformer design types were evaluated accounting for primary variability in design parameters (see Figure 5 for different core designs, winding geometry, voltage levels, and additional design considerations). Additionally, for each core design, two different tie-bar geometries were investigated that provide a range of achievable temperatures for over 80 total designs. Transformer modeling was performed using a major

[17] Order No. 830 at PP 67-68.

manufacturer's validated modeling approach to predict transformer thermal response to GICs. In the report, EPRI presents the results of that analysis along with the individual transformer design details. In addition, the effects of harmonic currents on tertiary winding (TW) heating resulting from asymmetrical saturation were explored. This was accomplished by examining seven electrical models of typical high-voltage autotransformers with TWs of varying design (i.e., different core designs, winding geometry, voltage levels, rated TW current densities, and additional design considerations).

Transformer No.	Core Type	HV rating	HV voltage	Type
-	-	MVA	kV	-
T1	1	92	526	GSU
T2	1	374	525	Auto
T3	2	500	525	Auto
T4	3	300	525	Auto
T5	3	560	525	Auto
T6	4	292	500	Auto
T7	4	672	500	Auto
T8	4	460	525	Auto
T9	5	840	500	Auto
T10	5	300	525	GSU
T11	2	100	735	GSU
T12	4	373.33	765	Auto
T13	4	750	746	Auto
T14	1	167	400	Auto
T15	1	360	420	Auto
T16	2	121,33	433	GSU
T17	2	94	410	GSU
T18	3	750	420	Auto
T19	3	160	400	GSU
T20	4	570	405	GSU
T21	5	450	405	TRA
T22	5	310	400	GSU
T23	5	910	420	GSU
T24	1	100	335	Auto
T25	1	133.33	345	Auto
T26	3	120	275	TRA

Transformer No.	Core Type	HV Rating	HV Voltage	Type
-	-	MVA	kV	-
T27	3	500	275	Auto
T28	3	200	330	Auto
T29	4	500	345	GSU
T30	5	500	345	Auto
T31	5	800	345	Auto
T32	5	315	345	GSU
T33	1	133.33	230	Auto
T34	1	66,6	231	Auto
T35	2	100	230	GSU
T36	3	160	230	Auto
T37	3	290	230	GSU
T38	3	420	230	Auto
T39	4	300	242	GSU
T40	4	466	240	GSU
T41	5	240	225	GSU
T42	5	560	230	Auto

Figure 5: Overview of Transformer Designs Studied

Core type description:

1. Single-phase, core-form: one wound limb, two-flux return limbs (1LEG)
2. Single-phase, core-form, two wound limbs (2LEG)
3. Three-phase, core-form: three-wound limbs (3LEG)
4. Single-phase, core-form, two-wound limbs, two-flux return limbs (4LEG)
5. Three-phase, core-form: three-wound limbs, two-flux return limbs (5LEG)

Outcome: The report provides the following:

- **<u>Tertiary winding study</u>**

  No critical steady-state temperatures were reached in the seven investigated tertiary winding designs, even with a constant 200 A DC per phase in the high-voltage windings. Nonetheless, some specific designs examined can experience more significant hot-spot heating under DC.

- **Tie bar study**

  The analysis showed that structural parts can be significantly heated with an additional DC current in the high-voltage winding of the transformer. The models provided in the study can be used in simulation of transformer thermal response to GIC signatures.

  The most thermal-limiting transformer was a single-phase, core-form with two-return legs autotransformer. The high number of turns in the 335/√3 kV high-voltage system is a main contributing factor to the very high temperature rise in the tie bars.

Research Task Overview: Assess the 75A/phase thermal impact screening criteria

Product: *GIC Transformer Thermal Impact Assessment: Impact of Field Orientation on Transformer Thermal Screenings. EPRI, Palo Alto, CA: 2020. 3002017948.*

Summary: EPRI used transformer thermal models described above for thermal simulation to determine whether their response to the Benchmark GMD Event could exceed thermal criteria. This report uses eight most thermal-limiting transformers of the 84 to carry thermal analysis to provide a representative range of responses. Table XX shows the relevant physical and electrical characteristics of these transformers.

Transformer no.	Core type	HV rating MVA	HV voltage kV	Type
T4	Three-phase, core-form, three-limb	300	525	Auto
T5	Three-phase, core-form, three-limb	560	525	Auto
T24	Single-phase, core-form, three-limb	100	335	Auto
T25	Single-phase, core-form, three-limb	133.33	345	Auto
T28	Three-phase, core-form, three-limb	200	330	Auto
T33	Single-phase, core-form, three-limb	133.33	230	Auto
T34	Single-phase, core-form, three-limb	66,6	231	Auto
T36	Three-phase, core-form, three-limb	160	230	Auto

Figure 6: Description of Transformer Designs for 75A/phase Criterion Analysis

Outcome: The 75 A/phase criterion is effective for the majority of transformer designs analyzed, as shown in Figure 7. Six of the eight transformer models used in this report will remain below the temperature limit of 200° C for short-term emergency operation when peak GIC is 75 A/phase for the Benchmark GMD Event. Two unique transformer types could exceed the short-term temperature limits when peak GIC for the Benchmark GMD Event is below 75 A/phase (Transformers T24, T25).

Transformer	Benchmark hotspot heating temperature	
	200° C	180° C
T4 GIC(t) (A)	91	79
T5 GIC(t) (A)	85	75
T24 GIC(t) (A)	53	35
T25 GIC(t) (A)	62	45
T28 GIC(t) (A)	93	81
T33 GIC(t) (A)	92	74
T34 GIC(t) (A)	88	72
T36 GIC(t) (A)	78	65

Figure 7: Summary of Transformer Results

ERO Recommendation

The ERO should continue to prioritize efforts to enable industry to assess and mitigate GMD risk to transformers by:

- Expanding the availability of transformer thermal models to represent more manufacturers. Additionally, field measurement data collected by EPRI and industry should be used to validate theoretical models. EPRI has worked with transformer manufacturers to identify fielded units equipped with fiber-optic-thermal monitoring. New transformers are increasingly being manufactured with thermal hot-spot monitoring capability, which can support operator real-time decision making as well as provide field data for model validation. EPRI will continue to leverage this existing monitoring with plans to continue the expansion of GIC-related monitoring in order to gain further understanding of the thermal impacts on power transformers.
- Update the ERO-Endorsed Implementation Guidance *TPL-007 Transformer Thermal Impact Assessment* with results of EPRI's research in this task.[18]
- Engage TPL-007 applicable entities through the RSTC and industry forums to promote awareness of transformer thermal model availability and best assessment best practices

[18] Specifically, Table 1 provides upper-bound hot spot heating. This table should be revised results of EPRI's analysis, including transformer models T24 and T25.

Task 6: Section 1600 Data Request

Summary

The activities in this task consisted of developing the necessary guidance, technical guidelines, and solutions to support a request for data or information under Section 1600 of the NERC Rules of Procedure for the collection of existing and new GIC data and magnetometer data. The purpose of this data collection is to respond to FERC's Order No. 830 directive to collect GMD monitoring data and to make that data publically available.

Background

The Commission directed NERC to collect GMD monitoring data pursuant to its authority under Section 1600 of the NERC Rules of Procedure for the period beginning May 2013, including data existing as of that date and new data going forward, and to make that information available.[19] The data is intended to promote greater understanding of GMD events and their potential impacts to the reliable operation of the BPS. For example, measured GIC and magnetometer data can help validate various models used in calculating GICs and assessing their impacts in power systems. FERC directed that NERC should make the collected GIC and magnetometer data available to support ongoing research and analysis of GMD risk.[20]

Activities in this task supported development of data reporting instructions, data collection criteria, and development of processes for maintaining a GMD data collection program.

Activities

GMD Data Request

In August 2018, the NERC Board of Trustees approved the NERC Rules of Procedure Section 1600 Data Request for the Collection of GMD Data (GMD Data Request) developed by NERC and the GMDTF.[21] The GMD Data Request is for the collection of GIC monitoring and magnetometer data as required by Order No. 830 and applies to U.S. registered Transmission Owners and Generator Owners. Although not required, Canadian registered Transmission Owners and Generator Owners are encouraged to participate. Many Transmission Owners and Generator Owners collect GMD data and have GMD data for the period beginning in May 2013. The data request applies to entities that have specified GMD data.

NERC and the GMDTF held a public comment period in February - March 2018 that afforded stakeholders with opportunity to provide input on the GMD Data Request.

Under the approved GMD Data Request, reporting entities provide information related to their installed GIC monitor and magnetometer capabilities, and to provide data from these devices to NERC for strong GMD events (K-7 and greater as reported by U.S. Space Weather Prediction Center). The reporting threshold was selected to provide significant data for research and model validation purposes without imposing excess burden on reporting entities. Based on historical data, the reporting threshold is expected to be reached 200 times per 11-year solar cycle. Reporting entities are not expected to report data that is publicly available

---

[19] Order No. 830 at P 89.

[20] *Id.* at P 93. In the Order, FERC stated: "The record in this proceeding supports the conclusion that access to GIC monitoring and magnetometer data will help facilitate GMD research, for example, by helping to validate GMD models." If GIC monitoring and magnetometer data is already publicly available (e.g., form a government entity or university), FERC stated that NERC need not duplicate those efforts. *Id.* at n. 122.

[21] See the approved GMD Data Request:
https://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GMD_data_request_June_2018.pdf

GMD Data Reporting Instructions (GMD DRI)

The GMD DRI contains provisions for establishing and maintaining a GMD data collection program. NERC staff developed the GMD DRI with support from the GMDTF. The purpose of the GMD DRI is to assist NERC and reporting entities in fulfilling reporting requirements of the approved GMD Data Request.

As described in the GMD DRI, reporting entities provide the following types of data to NERC:

- GMD Monitoring Equipment (i.e., GIC monitor, magnetometer) information
- GIC measurement data for designated GMD events
- Geomagnetic field measurement data for designated GMD even

NERC will designate periods during which GMD events K_P = 7 or greater have occurred and request reporting entities provide data to NERC annually. Data are submitted by reporting entities using a GMD data collection portal.

Program Implementation

The GMD Data Collection portal became operational in October 2020. The first annual reporting deadline is June 2021.[22] After the first reporting deadline the ERO will begin making releasable data available.[23]

The ERO will monitor implementation and conduct outreach to identify whether and to what extent additional guidance or support is necessary. The objective is to maintain a high-quality collection of GIC and magnetometer data for industry and research use. Although the NERC GMD Data Collection Program is not a real-time application, industry GIC monitors and magnetometers can provide data to system operators in real-time for enhancing their GMD operating procedures.

[22] GMD data reporting information is available on the NERC website: https://www.nerc.com/pa/RAPA/GMD/Pages/GMDHome.aspx

[23] In Order No. 830, FERC stated, based on the record in the proceeding, that "GIC and magnetometer data typically should not be designated as Confidential Information under the NERC Rules of Procedure." 9 Accordingly, NERC does not anticipate that the requested information will contain Confidential Information as that term is defined by Section 1501 of the NERC Rules of Procedure. Reporting entities may request that NERC handle their data as Confidential Information using the process in the GMD DRI, Appendix E. Data that is designated as Confidential Information cannot be viewed or downloaded except by the submitting entity and the DRO data system administrators.

Task 7: Geoelectric Field Tool Evaluation and Calculation of Beta Factors

Summary

The activities under this task focused on calculating earth conductivity scaling factors (beta factors) as necessary to meet the needs of the industry. This includes the following: benchmark of electric field estimation results using available scientific and industry algorithms; production of beta factor averages over improved 1D regions; and determination of beta factor ranges from differences in magnetic field orientation, spectral content, and 3D contributions.

Background

Task 7 builds upon the other components of NERC's Work Plan to improve scientific understanding and advance the models and tools available for modeling GIC. **Task 7** involved evaluating available tools for calculating geoelectric field from magnetic field data for a given earth conductivity structure and developing guidance as necessary to meet the needs of the industry. This task included work to address "whether additional realistic time series should be selected to perform assessments in order to capture the time series that produces the most vulnerability for an area," consistent with the Commission's guidance.[24]

Activities

Research Task Overview: Evaluate project tools

Product: *Tool Evaluation and Electric Field Estimate Benchmarking Results. EPRI, Palo Alto, CA: 2019. 3002014853*

Summary: This report presents a validation of EPRI tools used for geoelectric field estimation in the GMD Research Work Plan, including conductivity evaluation in Tasks 3 and 7 and scaling factor evaluation in Task 2. This analysis shows that EPRI project tools produce nearly identical results to other frequency and time domain tools available to the industry. The tools were compared using both one-dimensional (1D) model and EMTF representations of ground response.

Outcome: This task indicates that the EPRI tools are acceptable for use in the Research Work Plan.

Research Task Overview: Calculate and evaluate beta scaling factors

Product: *Update of Earth Response Scaling Factors Using Magnetotelluric Measurements EPRI, Palo Alto, CA: 2020. 3002017899*

Summary: To assess system vulnerability to the benchmark GMD event associated with TPL-007-1, planning entities may apply scaling factors that take into account the location of interest with respect to high-latitude electric currents systems (alpha scaling factor) and local geological conditions as specified in TPL-007 Attachment 1. The local geological conditions can be captured in terms of "beta scaling" factors that are used to adjust the benchmark geoelectric field amplitude to account for the variations in the ground response. TPL-007 provides applicable entities with flexibility to use more updated or accurate earth model information and does not prescribe the use of beta

[24] *See* Order No. 830 at P 79, in which the Commission stated:
In addition, the large variances described by [United States Geological Survey] in actual 3-D ground conductivity data raise the question of whether one time series geomagnetic field is sufficient for vulnerability assessments. The characteristics, including frequencies, of the time series interact with the ground conductivity to produce the geoelectric field that drives the GIC. Therefore, the research should address whether additional realistic time series should be selected to perform assessments in order to capture the time series that produces the most vulnerability for an area.

scaling factors. The default beta factors are based on approximate 1-dimensional physiographic ground conductivity models that were developed by Fernberg.[25]

Since the Fernberg (2012) work, new information has been provided by the NSF's EarthScope project (Schultz reference), which implemented a magnetotelluric (MT) survey across the contiguous U.S.[26] These measurements have provided significant new insight into local ground conductivity structures and corresponding ground electromagnetic responses. Electromagnetic transfer functions (EMTFs) derived from the MT survey are now available[27] and provide an opportunity to update the ground response β scaling factors used in TPL-007-1. Based on the EMTFs, EPRI provided β scaling factors for the updated contiguous US conductivity regions developed in Task 3. In addition, an assessment of how much beta factors can vary under different conditions was performed.

Outcome: The report provides updated β scaling factors for calculating geoelectric fields used in GMD vulnerability assessments based on newly available MT information. Figure 8 provides these values for each of the 22 conductivity regions in the contiguous United States (discussed in Task 3).

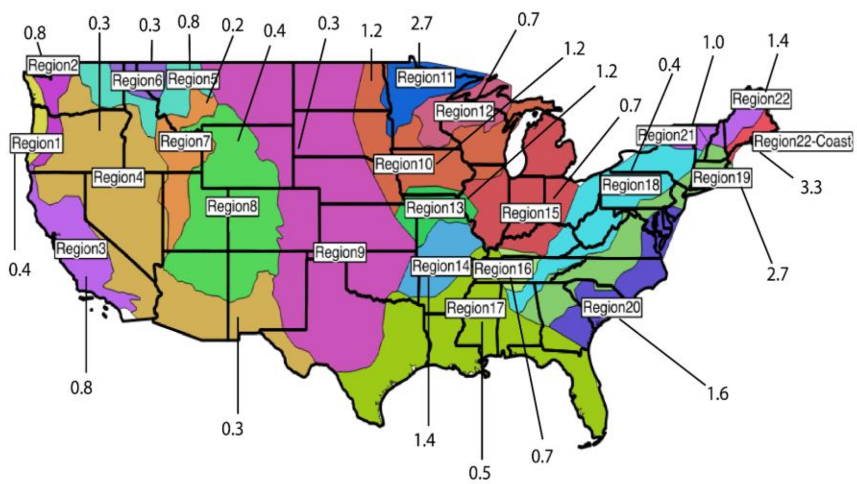


Figure 8: Updated β scaling factors for calculating geoelectric fields used in GMD vulnerability assessments based on newly available MT information

Several methods of describing "typical" ground response over a region as single value are explored using geomagnetic field time series data for a scaled extreme geomagnetic storm scenario based on the March 1989 GMD event as the input geomagnetic storm. The selected method is based on the median value of the calculated nonuniform geoelectric field distribution in each area.

Outcomes: The β-factors for each of the 22 conductivity regions in the contiguous US are updated based on newly-available MT information.

- Scaling factors can be used to produce geo-electric fields that are generally consistent with regionally-averaged models.

[25] EPRI, O*ne-Dimensional Earth Resistivity Models for Selected Areas of Continental United States and Alaska*, EPRI Technical Update 1026430 (2012).

[26] Schultz, A., G. D. Egbert, A. Kelbert, T. Peery, V. Clote, B. Fry, and S. Erofeeva, USArray TA magnetotelluric transfer functions, Technical Report, National Geoelectromagnetic Facility: 2006-2017

[27] Kelbert, A., G. Egbert, and A. Schultz, IRIS DMC Data Services Products: EMTF, the magnetotelluric transfer functions, Tech. rep. National Geoelectromagnetic Facility, 2011-2017.

- The peak geo-electric field derived from the use of scaling factors is usually higher (21 out of 22 cases) than when using regionally-averaged models.
- GICs estimated from geo-electric fields derived using scaling factors are similar to other methods, within the modeling uncertainties discussed in Task 3.

ERO Recommendation

The ERO should collaborate with EPRI and GIC modeling software vendors to incorporate beta scaling factors and/or modeling techniques into the software that is available for industry planners. The ERO should also consider this EPRI report during the Reliability Standards periodic review process for the TPL-007 standard so that steps can be taken to update Attachment 1 to the standard.

Task 8: Improve Harmonics Analysis Capability

Summary

The activities under this task consist of developing harmonics analysis guidelines and tools for entities to use in performing system-wide assessment of GMD-related harmonics.

Background

GMD-related harmonics are caused by the part-cycle saturation of transformers. These harmonic currents and voltages resulting from transformer saturation have had major impact on system operations and security during severe GMD events in the past.[28] Incorporating harmonic impacts is important for assessing system susceptibility to GMD.

Performing harmonic analysis is difficult, and commercial tools did not adequately address nuances of performing GMD-related harmonics studies. Important difficulties and modeling gaps needed to be addressed before the harmonic impacts of benchmark GMD events can be accurately assessed. Such difficulties and gaps include (but are not limited to)[29]:

- The effective GIC flow in all transformers in the network must be known beforehand, and mapping between GIC and the harmonics that are created is required.
- The magnitude and phase angle of the injected harmonic currents of each transformer is affected by local voltage distortion; thus, an iterative technique must be employed.
- The complex interaction of magnitude and phase angles of the injected harmonic currents of multiple transformers must be taken into account.
- Because part-cycle saturation creates zero sequence harmonics, standard positive sequence power flow data cannot be used alone as a basis for assembling the system model.
- Harmonic resonance created by shunt capacitor banks, and the damping effect of loads must be considered.

Task 8 research supported the identification and mitigation of GMD-related harmonic impacts as specified in TPL-007-1 and subsequent versions of the standard.

Activities

Research Task Overview: Develop Open-Source Software Tool for GMD-Related Harmonics Impact Assessment

Product: *Geomagnetically Induced Current Harmonic Tool (GICHarm): GIC Harmonic Analysis. EPRI, Palo Alto, CA: 2019. 3002017447*

Summary:

1. **Step 1**. EPRI performed research necessary to develop models, methods, and algorithms for performing harmonic assessments of benchmark GMD events.

[28] *See, e.g.,* NERC, *March 13, 1989 Geomagnetic Disturbance* white paper, available at http://www.nerc.com/files/1989-quebec-disturbance.pdf.
[29] EPRI, *Analysis of Geomagnetic Disturbance (GMD) Related Harmonics* (2014). 3002002985.

2. **Step 2.** Based on the research conducted in Step 1, EPRI developed an accurate GMD harmonic analysis approach using proper consideration of the closed-loop interactions between the harmonic current injections by the saturated transformers and the voltage distortion that these injections cause.
3. **Step 3.** Based on the results of Step 1 and 2, EPRI developed a GMD analysis tool and a benchmark GMD system model to accurately assess and verify both time-domain models and the newly developed GMD harmonic tool. Step 3 provided confidence in models that EPRI developed as a part of this research activity.
4. **Step 4.** EPRI implemented the models and techniques developed as a part of this research in an open-source software tool, GICHarm. This tool will be used to:
   a. Aid system planners in evaluating impacts of harmonics on reactive power resources (e.g. shunt capacitor banks, static var compensators (SVCs), etc.); and
   b. Facilitate the implementation of GMD harmonic assessments in commercially available software tools.

EPRI provided harmonics modeling demonstrations at GMDTF meetings to facilitate knowledge transfer.

Outcome: This task produced an open source harmonics assessment software tool, GICHarm, and a technical report with guidelines for using GICHarm.

ERO Recommendation

The ERO should engage TPL-007 applicable entities through the RSTC and industry forums to promote awareness of these tools, support development, and promote use of best practices for GMD-related harmonic analysis.

Task 9: Harmonic Impact Studies

Summary

The activities under this task support understanding the impacts of vibrations due to GMD-related harmonics on power system equipment. The impacts of transformer heating are covered in detail in **Task 4** and **Task 5** of the Work Plan. The activities under this task provide insight into the magnitudes of vibrations in power transformer tanks caused by GIC and assess the impact of these vibrations on the health of the transformer. This task is in response to FERC's request to NERC to address the effects of harmonics on transformers.

Background

GMD-related harmonics can cause the phenomenon of magnetostriction in the cores of large power transformers, resulting in noise and vibration during GMD events. In Order No. 830, FERC directed NERC to examine the effects of harmonics on BPS equipment as part of the Work Plan.[30]

Activities

Research Task Overview: Transformer GIC Vibration Analysis

Product: *Impact of Geomagnetically Induced Currents on Transformer Tank Vibrations: Transformer Vibration Analysis.* EPRI, Palo Alto, CA: 2019. 3002014855.

Summary: Working with utilities and transformer manufacturers, EPRI performed analysis to assess potential impacts of vibrations due to GMD-related harmonics on transformers. The analysis is based on factory and field test data of power transformers of various construction types and sizes, and on-site vibration measurement data from six transformers subject to 174 storms K6 and greater.

Outcomes: The research found that long-term exposure to vibrations caused by GIC does not result in increased tank vibration displacements, and therefore is not likely to adversely impact transformer mechanical integrity. Furthermore, the research suggests that a severe GMD event is not likely to lead transformer mechanical damage from vibrations. The basis for this is factory tests indicating that displacement magnitude of tank vibrations reaches its maximum at lower levels of GIC, and does not increase further with higher levels of GIC.

Research Task Overview: Generator Harmonic Impact Assessment

Product: *Assessment Guide: Geomagnetic Disturbance Harmonic Impacts and Asset Withstand Capabilities*. EPRI, Palo Alto, CA: 2019. 3002017707.

Summary: EPRI performed a thorough review of research to improve understanding of harmonic effects on turbine generators that are unique to GMD events. Harmonic currents from severe GMD events have the potential to cause excessive rotor heating and stimulate mechanical vibrations at frequencies turbine generator designers did not anticipate. Results were used to update the generator section of the *Assessment Guide* and enhance the modeling capability in the EPRI GMD harmonics analysis tool *GICHarm* (See Task 8).

Outcomes: The Assessment Guide includes recommended modeling and screening guidelines, a generator case study, and generator protection guidance for industry to use in evaluating and reducing thermal risk to turbine generators. In addition, the GICHarm tool developed in Task 8 provides improved generator harmonic analysis capabilities.

[30] *See* Order No. 830 at P 68, and Order No 830-A at P 18.

ERO Recommendation

Industry should continue to support ongoing research and tool development to assess generator risk from severe GMD events. The ERO should request EPRI provide updates periodically to the RSTC on the status of its efforts.

Appendix A: Listing of Research Publications

The following publications developed in this GMD Research Work Plan have been released by EPRI and are available free of charge. Publications may be obtained from the EPRI web site.

- EPRI, "Furthering the Research of Geomagnetic Disturbances Impact on the Bulk Power System," April 2018, 3002013736.
- EPRI, "Furthering the Understanding of the Characteristics and Scales of Geoelectric Field Enhancements," March 2020, 3002017900.
- EPRI, "Magnetohydrodynamic (MHD) Modeling for the Further Understanding of Geoelectric Field Enhancements and Auroral Behavior during Geomagnetic Disturbance Events," March 2020, 3002017952.
- EPRI, "Use of Magnetotelluric Measurement Data to Validate/Improve Existing Earth Conductivity Models Product," June 2020, 3002019425.
- EPRI, "Improving Conductivity Models for Geomagnetically Induced Current (GIC) Estimation: Guidance for Validation of GIC Models," March 2020, 3002017897.
- EPRI, "Non-Uniform Field Modeling: Coast Effect Assessment," March 2020, 3002017898.
- EPRI, "Geomagnetically Induced Current (GIC) Transformer Thermal Impact Assessment: Impact of Field Orientation on Transformer Thermal Screenings," March 2020, 3002017948.
- EPRI,"PRE-SW: EPRI Transformer Thermal Model (ETTM), version 1.0 – Beta," June 2018, 3002014059.
- EPRI, "Transformer Thermal Impact Assessments for DC Withstand Capability: Examining the Impacts of Geomagnetically Induced Current (GIC) on Transformer Thermal Performance," December 2019, 3002017708.
- EPRI, "Tool Evaluation and Electric Field Estimate Benchmarking Results," January 2019, 3002014853.
- EPRI, "Update of Earth Response Scaling Factors using Magnetotelluric (MT) Measurements," March 2020, 3002017899.
- EPRI, "Geomagnetically Induced Current Harmonic Analysis Tool (GICharm): Geomagnetically Induced Current (GIC) Harmonic Analysis," December 2019, 3002017447.
- EPRI, "Impact of Geomagnetically Induced Currents on Transformer Tank Vibrations," January 2019, 3002014855
- EPRI, "Assessment Guide: Geomagnetic Disturbance Harmonic Impacts and Asset Withstand Capabilities," December 2019, 3002017707.