June 5, 2017

VIA ELECTRONIC FILING

Veronique Dubois
Régie de l'énergie
Tour de la Bourse
800, Place Victoria
Bureau 255
Montréal, Québec H4Z 1A2

Re: *North American Electric Reliability Corporation*

Dear Mr. Dubois:

The North American Electric Reliability Corporation hereby submits Geomagnetic Disturbance Research Work Plan of the North American Electric Reliability Corporation. NERC requests, to the extent necessary, a waiver of any applicable filing requirements with respect to this filing.

Please contact the undersigned if you have any questions concerning this filing.

Respectfully submitted,

/s/ Shamai Elstein

Shamai Elstein
Senior Counsel for the North American Electric Reliability Corporation

Enclosure

BEFORE THE
RÉGIE DE L'ÉNERGIE
THE PROVINCE OF QUÉBEC

NORTH AMERICAN ELECTRIC)
RELIABILITY CORPORATION)

GEOMAGNETIC DISTURBANCE RESEARCH WORK PLAN OF THE NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Gerald W. Cauley
President and Chief Executive Officer
Mark Lauby
Senior Vice President and Chief Reliability Officer
John Moura
Director of Reliability Assessment and System Analysis
North American Electric Reliability Corporation
3353 Peachtree Road, N.E.
Suite 600, North Tower
Atlanta, GA 30326
(404) 446-2560
(404) 446-2595 – facsimile

Charles A. Berardesco
Senior Vice President and General Counsel
Shamai Elstein
Senior Counsel
Lauren A. Perotti
Counsel
North American Electric Reliability Corporation
1325 G Street, N.W., Suite 600
Washington, D.C. 20005
(202) 400-3000
(202) 644-8099– facsimile
charles.berardesco@nerc.net
shamai.elstein@nerc.net
lauren.perotti@nerc.net

Counsel for the North American Electric Reliability Corporation

June 5, 2017

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BEFORE THE
RÉGIE DE L'ÉNERGIE
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NORTH AMERICAN ELECTRIC	**)**
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GEOMAGNETIC DISTURBANCE RESEARCH WORK PLAN OF THE NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Pursuant to paragraph 77 of the Federal Energy Regulatory Commission's ("FERC") Order No. 830,[1] the North American Electric Reliability Corporation ("NERC") hereby submits a preliminary work plan to conduct research on topics related to geomagnetic disturbances ("GMD") and their impacts on the reliability of the Bulk-Power System ("BPS"). In Order No. 830, FERC approved Reliability Standard TPL-007-1 - Transmission System Planned Performance for Geomagnetic Disturbance Events and directed NERC to, among other things, submit a work plan within six months of the effective date of the Final Rule describing how NERC would conduct research on the GMD-related topics specified by FERC and any additional topics selected in NERC's discretion. To address FERC's directive, NERC submits a preliminary Order No. 830 GMD Research Work Plan ("GMD Research Work Plan"), attached hereto as **Attachment 1.**

NERC collaborated with the Electric Power Research Institute ("EPRI") and the industry experts on the NERC GMD Task Force in developing the preliminary GMD Research Work Plan. EPRI's experience and expertise in electric industry research and development projects proved invaluable in identifying appropriate GMD research activities that build upon existing

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

work to address the key GMD-related research areas specified by FERC in Order No. 830. The specific research activities identified in the plan fall within nine broad research categories, called "Tasks," and are capable of producing work product that would advance understanding of GMD events and the risks these high-impact, low-frequency events pose to the reliability of the BPS. The preliminary GMD Research Work Plan also includes the estimated costs and timeframe for completing each of the Tasks.

NERC expects that executing a research plan of the type contemplated by Order No. 830 would require an extensive, multi-year effort requiring scientific and technical expertise from a variety of disciplines. NERC does not currently maintain the necessary scientific expertise in fields such as space weather and geology to complete these research tasks in-house. Early estimates suggest that outsourcing the research tasks identified in the preliminary GMD Research Work Plan to those with the necessary expertise would cost a minimum of $2.7 million. NERC expects that funding the costs of executing such a plan would have a substantial impact on NERC's budget and therefore its annual assessments, which ultimately flow back to the consumer. Further, managing a large scale research project such as this is not one of NERC's "core competencies". NERC recognizes that other organizations, like EPRI, already possess the type of specialized expertise and experience necessary to effectively manage complex, multidisciplinary research projects and would therefore be better structured for this sort of undertaking.

Therefore, NERC plans to continue work over the next several months to identify an appropriate project administration structure to drive completion of the activities identified in the preliminary GMD Research Work Plan in a cost-effective and efficient manner. NERC's plans for future work, which are described more fully in Section IV Next Steps, include continued outreach with representatives from governmental agencies in the U.S., Europe, and Canada. NERC's plans also include continued outreach to academia, vendors, and industry. The purpose of this outreach is to identify opportunities to leverage existing GMD-related work and research synergies, develop an appropriate research management structure, and identify alternative sources of funding. Further, NERC plans to conduct outreach to stakeholders regarding optimal approaches to structure the funding requirements, to include identifying opportunities for sharing costs, research management alternatives, and leveraging research responsibilities. These efforts, along with any comments and FERC guidance received through this proceeding, would inform the scope and structure of NERC's final GMD Research Work Plan and would aid in the development of a timetable for submitting informational filings to the applicable governmental authorities reporting on the results of research.

NERC expects to develop additional project details within the next six months and commits to keep FERC staff informed of the status of these efforts. As NERC continues its work to develop the final plan and address the resource and logistical challenges that lie ahead, NERC would welcome governmental authority guidance on the prioritization of specific Tasks, as discussed in Section IV below.

I. NOTICES AND COMMUNICATIONS

Notices and communications with respect to this filing may be addressed to the following:

Shamai Elstein
Senior Counsel
Lauren A. Perott
Counsel
North American Electric Reliability Corporation
1325 G Street, N.W., Suite 600
Washington, D.C. 20005
(202) 400-3000
(202) 644-8099– facsimile
shamai.elstein@nerc.net
lauren.perotti@nerc.net

Mark Lauby
Senior Vice President and Chief Reliability Officer
John Moura
Director of Reliability Assessment and System Analysis
North American Electric Reliability Corporation
3353 Peachtree Road, N.E.
Suite 600, North Tower
Atlanta, GA 30326
(404) 446-9731
(404) 446-2595 – facsimile
mark.lauby@nerc.net
john.moura@nerc.net

II. BACKGROUND

A. Order No. 830 Approving Reliability Standard TPL-007-1

On September 22, 2016, FERC issued Order No. 830 approving Reliability Standard TPL-007-1 - Transmission System Planned Performance for Geomagnetic Disturbance Events. This standard was the second of two GMD Reliability Standards developed in response to FERC's Order No. 779[2] to address the risks posed by GMD events on the reliable operation of the BPS. Reliability Standard TPL-007-1 requires owners and operators of the BPS to conduct initial and ongoing assessments of the potential impact of a benchmark GMD event on BPS equipment and the BPS as a whole, and to develop and implement plans to protect against adverse BPS impacts resulting from the benchmark GMD event.

[2] Order No. 779, *Reliability Standards for Geomagnetic Disturbances*, 143 FERC ¶ 61,147 (2013). The first GMD standard, Reliability Standard EOP-010-1 – Geomagnetic Disturbance Operations, was approved by FERC in Order No. 797 in 2014 and requires Reliability Coordinators and applicable Transmission Operators to implement plans, processes, and procedures to mitigate the effects of GMD events on reliable operations. Order No. 797, *Reliability Standard for Geomagnetic Disturbance Operations*, 147 FERC ¶ 61,209, *reh'g denied*, Order No. 797-A, 149 FERC ¶ 61,027 (2014).

In Order No. 830, FERC found that Reliability Standard TPL-007-1 addressed its directives for the second stage GMD Reliability Standard from Order No. 779 and stated that the standard "constitutes an important step in addressing the risks posed by GMD events to the Bulk Power System."[3] While approving the standard, FERC directed NERC to develop certain modifications and undertake additional actions to further understanding of GMDs and their impacts on reliability, as summarized below.

B. FERC Directs NERC to Modify TPL-007 and Conduct Further GMD Research

In Order No. 830, FERC directed NERC to:

- develop certain modifications to TPL-007-1;[4] specifically:
    - develop revisions to the benchmark GMD event definition so that the reference peak geoelectric field amplitude is not based solely on spatially averaged data (P 44);
    - develop revisions to Requirement R6 to require registered entities to apply spatially averaged and non-spatially averaged peak geoelectric field values, or some equally efficient and effective alternative, when conducting thermal impact assessments (P 65);
    - develop revisions to the standard to require responsible entities to collect geomagnetically induced current ("GIC") monitoring and magnetometer data as necessary to enable model validation and situational awareness (P 88); and
    - develop revisions to the standard to include deadlines for the development and completion of any required Corrective Action Plans (PP 101-102);
- research specific GMD-related topics identified by FERC and other topics in NERC's discretion, in accordance with a GMD research work plan filed with FERC (the research should be informed by the ongoing GMD research efforts of government agencies, academic, and other publicly available contributors);[5] and

[3] Order No. 830 at PP 1, 23.

[4] FERC directed NERC to submit these modifications to FERC within 18 months of the effective date of the Final Rule, or by May 2018. Order No. 830 at P 2. The standards modification directives are currently being considered by the Project 2013-03 Geomagnetic Disturbance Mitigation standard drafting team. This team expects to post the first draft of the revised TPL-007 standard in early summer 2017.

[5] *See generally* Order No. 830 at P 77.

- collect GMD monitoring data pursuant to Section 1600 of the NERC Rules of Procedure and make that information available.[6]

This filing addresses the second of FERC's directives to submit a work plan describing how NERC plans to conduct research on specific GMD-related topics. FERC's directives and guidance for work plan topics, as well as how NERC plans to address those areas as part of its preliminary GMD Research Work Plan, are described in Section III below. NERC's preliminary GMD Research Work Plan also includes activities to facilitate the efficient and effective collection of GMD monitoring data in response to FERC's third directive, as discussed below.

III. GMD RESEARCH WORK PLAN

In accordance with Order No. 830, NERC hereby submits a preliminary GMD Research Work Plan, attached hereto as **Attachment 1.** In this plan, NERC identifies specific research activities that are intended to derive insights into GMD-related impacts on reliability. NERC worked collaboratively with EPRI in developing this plan and received input on specific project activities from the GMD Task Force and NERC technical committees.

The research activities described in the preliminary GMD Research Work Plan are grouped into nine research Tasks. Each Task has an expected deliverable, such as a technical report or a publicly-available model or tool to aid in assessing GMD risk. As some tasks and activities are at the forefront of evolving science and engineering capabilities, the anticipated, expected, or desired deliverable may not be attained on a predicted timeline, or at all. In any event, these research activities should be pursued to the extent they reasonably can, taking into account expected costs, benefits, and available resources. This research would be helpful to advance understanding of GMD events and the potential impact on the reliable operation of the

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6 *Id*. at PP 89, 93.

BPS. NERC contemplates that the final deliverable for each Task would be subject to technical and scientific review through the NERC GMD Task Force,[7] engaging outside researchers as necessary. In accordance with FERC's directive, NERC would submit periodic informational filings to the applicable governmental authorities reporting on the results of its research.

In this section, NERC summarizes the nine research Tasks and how the activities under each Task are intended to address FERC's research directives in Order No. 830 and promote increased understanding of and effective planning against GMD-related risks. NERC also provides an estimated timeframe for the completion of each Task based on estimates supplied by EPRI. **Attachment 1** includes a list of specific research activities for each Task, more detailed estimates of the time necessary to complete each of the activities falling under each Task, and a preliminary estimate of the costs to complete each Task.

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

Task 1 in NERC's preliminary GMD Research Work Plan is to perform further research and analysis on the use of spatial averaging in defining the GMD events that entities use when conducting the GMD Vulnerability Assessments required by the TPL-007 standard. 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, FERC approved the benchmark GMD event but noted its concern that a

[7] The NERC GMD Task Force includes 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.

spatially-averaged benchmark may not adequately account for localized peak geoelectric fields that could potentially affect reliable operations. Accordingly, FERC directed NERC to revise the benchmark so that the definition does not rely upon spatially averaged data.[8] In addition, FERC directed NERC, as part of the GMD research 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)."[9]

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. NERC estimates that this Task would require approximately 24-36 months to complete from start of work.

B. Task 2: Further Analyze Latitude Scaling

Task 2 in NERC's preliminary GMD Research Work Plan is to perform further analysis of the geomagnetic latitude scaling factors used in the TPL-007 standard. 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," FERC directed NERC to reexamine the geomagnetic latitude scaling factors provided in TPL-007-1.[10] Consistent with FERC's directive, NERC would use existing models and develop new models to

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8 Order No. 830 at PP 44, 47.

9 *Id.* at P 26.

10 *Id.* at P 57.

extrapolate from historical data the impacts of a large, 1-in-100 year GMD event on lower geomagnetic latitudes under this Task. NERC estimates that this Task would require approximately 24 months to complete from start of work.

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

Task 3 of NERC's preliminary GMD Research Work Plan is to perform further research to improve the accuracy and efficacy of the earth conductivity models used for GIC studies. In Order No. 830, FERC 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 GMD research work plan.[11] Accordingly, NERC's preliminary plan identifies research activities to address FERC's specific concerns, including comparing the accuracy of 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 the so-called "coastal effects." NERC estimates that this Task would require approximately 24-36 months to complete from start of work.

D. Task 4: Study GIC Field Orientation for Transformer Thermal Impact Assessments

Task 4 of NERC's preliminary GMD Research Work Plan is 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

[11] *See id*. at PP 78-80.

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 transformers with an effective GIC of less than 75 A per phase during the benchmark GMD event are unlikely to exceed known temperature limits established by technical organizations.[12]

In Order No. 830, FERC directed NERC to perform additional research related to the transformer thermal impact assessments required by the TPL-007 standard. Specifically, FERC directed NERC to study, as part of its GMD research work plan, how "the geoelectric field time series can be applied to a particular transformer so that the orientation of the time series, over time, will maximize GIC flow in the transformer . . . ."[13] Task 4 would therefore consist of work to determine how the benchmark geoelectric field wave shape can be applied to a particular transformer to determine worst-case hotspot heating. NERC estimates that this Task would require approximately 10-12 months to complete from start of work.

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

Task 5 of NERC's preliminary GMD Research Work Plan is to conduct additional research and analysis to assess the transformer thermal impact of the benchmark GMD event or other realistic GMD events. This Task is intended to address FERC'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

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[12] The *Screening Criterion for Transformer Thermal Impact Assessment* white paper was filed on March 3, 2015 with NERC's filing of TPL-007-1. NERC filed a corrected version of this white paper on June 29, 2016.

[13] Order No. 830 at P 66.

transformers" in NERC's GMD research work plan.[14] NERC estimates that this Task would require 24 months to complete from start of work.

F. Task 6: Section 1600 Data Request

As noted in the Background section of this filing, FERC issued two sets of directives in Order No. 830 in addition to the directives to conduct GMD research. First, FERC directed NERC to revise Reliability Standard TPL-007-1 to, among other things, require the collection of GIC monitoring and magnetometer data "as necessary to enable model validation and situational awareness, including from any devices that must be added to meet this need."[15] Second, FERC 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.[16]

Efforts are currently underway through Project 2013-03 Geomagnetic Disturbance Mitigation to address FERC's directive to revise the TPL-007 standard to require the collection of GIC and magnetometer data. Task 6 of NERC's preliminary GMD Research Work Plan would build upon the work of the Project 2013-03 standard drafting team to develop the necessary guidance and technical guidelines to support a request for data or information under Section 1600 of the NERC Rules of Procedure.[17] In addition, this Task contains activities to identify and develop the information technology system(s) to support data collection, hosting, and access. NERC estimates that the activities of this Task, which focus on laying the

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14 *Id*. at PP 67-68.

15 *Id*. at P 88.

16 *Id*. at P 89.

17 NERC's rules require that each proposed request for data or information include certain information, such as the data to be collected and how it will be used, how the data will be validated, who is obligated to respond, the due date, a description of restrictions on dissemination, and an estimate of the relative burden to respond to the request. *See* NERC Rules of Procedure § 1602, http://www.nerc.com/AboutNERC/Pages/Rules-of-Procedure.aspx.

groundwork for the Section 1600 request for data or information, would require approximately 12 months to complete from start of work.

Following the completion of this Task, NERC would then proceed with the posting and approval process set forth in Section 1600 of the NERC Rules of Procedure.[18] NERC plans to conduct outreach through the NERC GMD Task Force to determine the degree to which industry is following NERC's guidance and to identify whether and to what extent additional guidance or support is necessary. The eventual goal is to maintain a high-quality collection of GIC and magnetometer data for industry and research use.

G. Task 7: Geoelectric Field Evaluation and Calculation Tool

Task 7 of NERC's preliminary GMD Research Work Plan builds upon the other items in NERC's plan and is intended to improve scientific understanding and advance the models and tools available for modeling GIC. Task 7 would involve evaluating available tools for calculating geoelectric field from magnetic field data for a given earth conductivity structure and developing additional tools as necessary to meet the needs of the industry. This task would include 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 FERC's guidance.[19] NERC estimates this Task would require approximately 24-36 months to complete from start of work.

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[18] NERC's rules require that the draft request be submitted to the Office of Electric Reliability for informational purposes and be posted for a 45-day public comment period prior to being submitted to the NERC Board of Trustees for approval. *See* id.

[19] *See* Order No. 830 at P 79, in which FERC 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

H. Task 8: Improve Harmonics Analysis Capability

Task 8 of NERC's preliminary GMD Research Work Plan would focus on developing guidelines for harmonics analysis and developing tools for entities to use in performing system-wide assessment of GMD-related harmonics. The work under this Task would build upon the work in Task 5 and is intended to address FERC's directive to address the effects of harmonics in NERC's GMD research work plan.[20] The effects of GMD-related harmonics on reliable operations are only beginning to be understood. Harmonics could cause protection system misoperations, result in damage to capacitor banks and other electrical equipment, or affect the operating temperature of transformers. The development of tools and accurate models would aid in understanding these potential effects and how they may best be mitigated. NERC estimates this Task would require approximately 24-36 months to complete from start of work.

I. Task 9: Harmonic Impact Studies

Task 9 of NERC's preliminary GMD Research Work Plan is intended to further understanding of the other effects of harmonics, including vibrational effects, on power system equipment such as transformers and generators. This Task contemplates testing of two transformers, one with no vibration issues and one with vibration issues. This work should identify what, if any, future actions and research activities are needed to effectively mitigate identified risks. NERC estimates this Task would require approximately 24 months to complete from start of work.

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assessments in order to capture the time series that produces the most vulnerability for an area.

20 *See id*. at P 68 and *supra* Section III.E.

IV. NEXT STEPS

Since the issuance of Order No. 830, NERC has worked diligently to address FERC's GMD research directives by collaborating with EPRI, the NERC GMD Task Force, and the NERC technical committees to develop the preliminary GMD Research Work Plan described in this filing. The preliminary GMD Research Work Plan addresses each of the GMD-related research areas identified by FERC in Order No. 830 with a specific and targeted set of GMD research activities that are at the forefront of GMD research. The preliminary plan provides a solid framework for improving understanding of the threats posed by GMDs and how they may be addressed effectively.

With the scientific and technical components of the plan now in place, NERC plans to shift its focus toward developing the administrative components of the plan. This includes developing the appropriate project administration and funding structures to support the completion of GMD research. NERC expects that this work, which is described below, will take approximately six months to complete. NERC commits to keep FERC staff apprised of the status of its efforts.

As the ERO, NERC possesses extensive expertise and experience in matters affecting the reliability of the North American BPS. As noted earlier in this filing, however, NERC does not currently possess the necessary scientific expertise to conduct the described GMD research activities in-house, nor does it count among its "core competencies" the ability to manage such a large and complex GMD research undertaking. To satisfy FERC's directive, NERC would want to work with organizations that do possess the type of specialized scientific, technical, and research project management knowledge and experience necessary to successfully manage and execute such a project. Therefore, over the next several months, NERC plans to continue work to identify opportunities to incorporate the contributions and leadership of outside organizations into the overall project plan. NERC plans to continue discussions with EPRI, which has provided key contributions and leadership to the development of the plan to date. NERC also plans to continue outreach with: (i) representatives from governmental agencies in the U.S., Europe, and Canada, such as the U.S. Geological Survey, National Aeronautics and Space Administration, the U.S. Department of Energy, the National Oceanic and Atmospheric Administration, the National Science Foundation, and Natural Resources Canada; (ii) researchers in academia, such as Oregon State University; (iii) vendors; and (iv) industry. The purpose of this outreach is to identify opportunities to build on existing GMD research work, identify opportunities for research synergies, develop an appropriate research management structure, and identify alternative sources of funding. In addition, NERC plans to conduct outreach with stakeholders to explore approaches for structuring the funding requirements of the plan, including identifying opportunities for sharing costs, research management alternatives, and leveraging research responsibilities.

NERC expects that these efforts, as well as the comments and FERC guidance received through this proceeding, would inform the scope and structure of NERC's final GMD Research Work Plan and NERC's funding responsibilities. Given these uncertainties, NERC has not included costs related to GMD research activities in its draft 2018 Business Plan and Budget.[21] Depending on the timing of the start of work, final project structure, and the extent of NERC's funding responsibilities, NERC may need to prepare and seek approval for a supplemental GMD research budget that could include a request for a special assessment.

[21] Final project funding requirements would be subject to approval through NERC's budget process. NERC's budget process is set forth in Section 1100 of the NERC Rules of Procedure. The draft 2018 Business Plan and Budget is available at: http://www.nerc.com/gov/bot/FINANCE/Pages/2018-NERC-Business-Plan-and-Budget.aspx.

Looking ahead, NERC appreciates FERC's willingness to be flexible regarding changes to the specific project tasks and timelines set forth in this filing as it works to develop the final plan.[22] NERC recognizes the importance of ensuring that work remains performed in a timely manner, but asks that FERC recognize that this is a significant expansion of NERC's role and would require a substantial investment of time and costs. NERC may ultimately face resource constraints that limit its ability to ensure completion of the Tasks in the timeframe contemplated by the preliminary GMD Research Work Plan. For example, NERC may be unable to obtain adequate funding for GMD research in a given year due to other pressing reliability needs, or it may encounter issues locating research partners that both possess the necessary expertise and are available to assist in a given timeframe.

NERC would therefore welcome guidance regarding the prioritization of the specific research activities directed in Order No. 830. If faced with resource constraints, NERC would plan to prioritize the completion of Tasks to improve the alpha and beta factors used in the TPL-007 benchmark GMD event; specifically, Task 1 (Further Analyze Spatial Averaging Used in the Benchmark GMD Event) and Task 3 (Improve Earth Conductivity Models for GIC Studies). NERC would welcome feedback on this prioritization. In addition, NERC would welcome any guidance on which research activities should be assigned a lower priority or whose completion be made contingent on resource availability (e.g., availability of outside funding). This information would be particularly helpful to NERC as it continues its work to develop the final plan and address the challenges that lay ahead.

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22 *See* Order No. 830 at P 81.

Respectfully submitted,

/s/ Lauren A. Perotti

Charles A. Berardesco
Senior Vice President and General Counsel
Shamai Elstein
Senior Counsel
Lauren A. Perotti
Counsel
North American Electric Reliability Corporation
1325 G Street, N.W., Suite 600
Washington, D.C. 20005
(202) 400-3000
(202) 644-8099– facsimile
charles.berardesco@nerc.net
shamai.elstein@nerc.net
lauren.perotti@nerc.net

Counsel for the North American Electric Reliability Corporation

June 5, 2017

Attachment 1

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

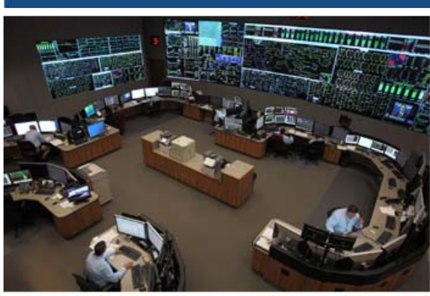
Order No. 830
GMD Research Work Plan

Addressing Geomagnetic Disturbance Events and Impacts on Reliability

PRELIMINARY PLAN

May 2017

RELIABILITY | ACCOUNTABILITY




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

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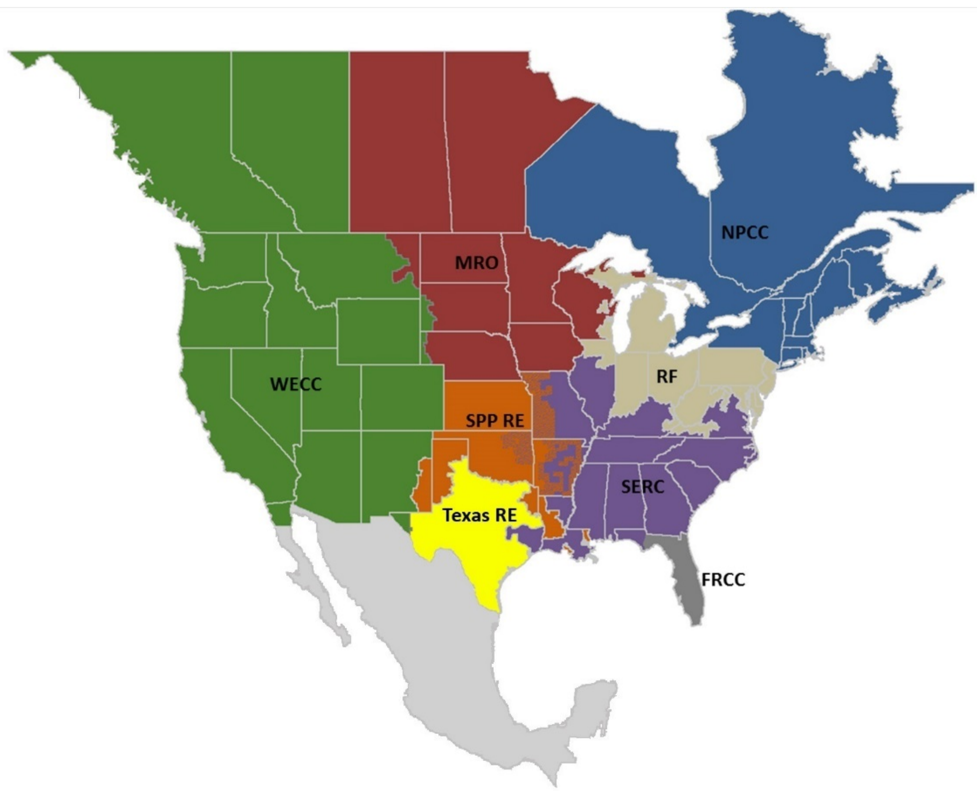
Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to assure the reliability and security of the bulk power system (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the Electric Reliability Organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.

The North American BPS is divided into eight Regional Entity (RE) boundaries as shown in the map and corresponding table below.



The North American BPS is divided into eight RE boundaries. The highlighted areas denote overlap as some load-serving entities participate in one Region while associated transmission owners/operators participate in another.

FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
SPP RE	Southwest Power Pool Regional Entity
Texas RE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Introduction

Background

In Order No. 779,[1] FERC directed the development of Reliability Standards in two stages to address the potential impacts of geomagnetic disturbance (GMD) events on the reliability of the BPS. The first stage Reliability Standard, EOP-010-1 (*Geomagnetic Disturbance Operations*), requires owners and operators of the BPS to develop and implement operational procedures to mitigate the effects of GMDs consistent with the reliable operation of the BPS. This standard was approved by FERC in 2014.[2]

The second stage Reliability Standard, TPL-007-1 (*Transmission System Planned Performance for Geomagnetic Disturbance Events*), requires owners and operators of the BPS to conduct initial and ongoing assessments of the potential impact of a defined benchmark GMD event on BPS equipment and the BPS as a whole. FERC approved Reliability Standard TPL-007-1 in Order No. 830, issued on September 22, 2016.[3] FERC, however, directed NERC to develop certain modifications to the standard and undertake additional actions to further understanding of GMDs and their potential impacts on reliability.

Specifically, FERC directed NERC to:

- develop certain modifications to TPL-007-1, including: (i) revising the benchmark GMD event to not rely solely on spatially-averaged data; (ii) revising the standard to require entities to collect geomagnetically induced current (GIC) monitoring and magnetometer data as necessary to enable model validation and situational awareness; and (iii) revising the standard to include deadlines for the development and completion of any required Corrective Action Plans;[4]
- research specific GMD-related topics identified by the Commission and other topics in NERC's discretion, in accordance with a GMD research work plan filed with the Commission;[5] and
- collect GMD monitoring data pursuant to Section 1600 of the NERC Rules of Procedure and make that information available.[6]

This document addresses the second and third directives listed above. It sets forth a plan for driving research into the specific areas of GMD-related concern identified by the Commission and developing the framework to support a request for information under Section 1600 of the NERC Rules of Procedure. This preliminary work plan consists of the following nine research "Tasks":

1. Further Analyze Spatial Averaging Used in the Benchmark GMD Event
2. Further Analyze Latitude Scaling
3. Improve Earth Conductivity Models for GIC Studies
4. Study GIC Field Orientation for Transformer Thermal Impact Assessments
5. Further Analyze the 75 A per Phase Criterion Used for Transformer Thermal Impact Assessments
6. Section 1600 Data Request

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1 Order No. 779, *Reliability Standards for Geomagnetic Disturbances*, 143 FERC ¶ 61,147 (2013).

2 Order No. 797, *Reliability Standard for Geomagnetic Disturbance Operations*, 147 FERC ¶ 61,209, *reh'g denied*, Order No. 797-A, 149 FERC ¶ 61,027 (2014).

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

4 *See* Order No. 830 at PP 44, 65, 88, and 101-102.

5 *See generally* id. at P 77.

6 Id. at PP 89, 93.

7. Geoelectric Field Evaluation and Calculation Tool
8. Improve Harmonics Analysis Capability
9. Harmonic Impact Studies

Specific research activities and estimated completion timeframes for each of these Tasks are identified in the subsequent sections of this work plan.

NERC collaborated with the Electric Power Research Institute (EPRI) to develop the specific research activities in this preliminary plan. 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.

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

Summary

The research activities under this Task consist of performing further research and analysis on 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.

Activities

Task 1A: Perform Research to Improve Understanding of Characteristics and Spatial Scales of Localized Geoelectric Field Enhancements Caused by Severe GMD Events

- The analysis includes detection of a large number (10-20) of localized extreme events and collection of both ground-based and space-based data around the times of the events.
  - The ground-based and space-based data will be combined to build a comprehensive view of the solar wind-magnetosphere-ionosphere dynamic conditions at the times of the events.
  - The combined data will provide specification of the geospatial processes associated with the enhancements. Special attention will be paid to understand the possible association between localized enhancements and magnetospheric substorms.
  - The research team will collaborate with international leading experts (residing at NASA Goddard Space Flight Center) on substorms to improve understanding of which substorm-processes can lead to extreme localization of geomagnetic field observations on the ground.
  - These assessments will allow better characterization of both spatial and temporal characteristics as well as local time and geomagnetic latitude distribution of the localized geomagnetic field enhancements. The new results will be reported and reviewed via a peer-reviewed publication and included in the technical report.
- Review technical basis of the NERC Benchmark GMD Event Description white paper (May 2016)[7] including supporting peer-reviewed papers.
  - The NERC Benchmark GMD Event Description white paper will be reviewed in the light of the latest scientific research on the extreme GMD events. The review will include assessment of both geological work in terms of ground conductivity analyses and geospatial analyses characterizing the external drivers of extreme GMD events. Based on the review, recommendations will be made for possible modification of the benchmark GMD event. The review will be documented and included in the technical report.
- Perform analysis of magnetometer data to characterize the spatial structure of GMD events.
  - Step 1 - Develop dataset for large GMD events across all available magnetometer stations and resolve differences in temporal resolution and data gaps.
    - The purpose of this effort is to assemble a comprehensive data set to support GMD analyses. Ideally, such a data set would feature high-time resolution data (10 s or better) with rigorous error correction and background removal.
      - This task is necessary because existing community-wide efforts that serve geomagnetic data need to be improved upon to meet all of the above criteria. Specifically, one geomagnetic

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[7] *Benchmark Geomagnetic Disturbance Event Description,* NERC Project 2013-03 GMD Mitigation Standard Drafting Team (May 12, 2016), http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx.

data set provides error correction and background removal, but it provides data at too low of time resolution (60 s, with high-resolution data down sampled); and another geomagnetic data set provides data at its original time resolution, but it performs minimal error correction and no background removal. Moreover, existing collections are not comprehensive, and historical data from now defunct magnetometers is frequently absent. These additional data sources will be incorporated in the compilation whenever possible, conditioning and processing the data as necessary.

– The newly developed database and derived products, including processed and corrected time series and application programming interface (API) for appropriate software packages (e.g., MATLAB) and computer languages (e.g., Python), will be made available and documented in the technical report.

- Step 2 - Explore scaling of maximum E-field versus magnetic time of day.
  - The purpose of this effort is to characterize and quantify how the severity of GMD events depends on the magnetic time of day (MTOD). The data used in this study will be derived from the database compiled in the previous step. Magnetic fields will be converted to geoelectric fields using magnetotelluric methods (based on 1D conductivity profiles, comparing results to those from 2D impedance matrices when available).
  - Geoelectric field values will be processed in two different ways: 1) data from individual magnetometer sites will be analyzed using extreme value theory and the results of those studies will be binned by MTOD; and 2) data from all magnetometer sites will be binned by MTOD and extreme value analysis will be applied to the aggregate data set. The predictions of these complementary analyses will provide both a consistency check and an uncertainty estimate.
  - The results of the extreme value analysis will be used to develop a new statistical model of how geoelectric field magnitudes vary with MTOD. Because longitudinal data coverage is frequently very sparse, this model will allow for better application of latitudinal scaling when nearby reference measurements are unavailable.
  - Results from this work will be presented in a technical report describing a new MTOD scaling, analogous to the existing latitudinal scaling, along with a technical description of analysis methods.
- Step 3 - Compute the spatiotemporal autocorrelation in dB/dt and determine the characteristic time and length scales for variations in dB/dt.
  - The purpose of this work is to improve understanding of the extent to which localization (in space and time) affects the ability to predict geomagnetic fields at sites where measurements are unavailable. Data for this research effort will be obtained from the database compiled in a previous step. Using this data, the relationship between dB/dt and its individual frequency components at different spatial locations will be characterized. Correlations between time, frequency, magnetic latitude, and MTOD using both pairwise correlations and multivariate approaches such as multiple regression analysis will be investigated. Ultimately, this research will determine the appropriate spatial and temporal correlation parameters to inform Markov chain models of geomagnetic fields, which form the basis for developing a more sophisticated representation of the spatiotemporal behavior of geo-electric fields to better inform power systems GIC analysis.
  - The deliverable of this research will be a report (included in the technical report) describing the spatial and temporal scales (i.e., distances and durations) affected by GMDs as a function of geomagnetic latitude, MTOD, and frequency.

- Step 4 - Develop Markov chain models for generating spatiotemporal behavior of defined GMD events.
  - The purpose of this work is to develop a tool for building credible models of extreme GMD events based on historical data. Data from the database developed in Step 1 will be used to develop a Markov chain model that ingests data from historical events and produces new scenarios, which are consistent with the statistics of the original events. Ensembles of these synthetic events can be used to assess the potential vulnerability of systems to different spatial and temporal distributions of statistically identical GMDs, providing a means to credibly quantify the range of potential system effects due to disturbances of a given severity.
  - A product of this proposed research will be a software-based tool for scenario generation with APIs for appropriate software packages (e.g., MATLAB) and programming languages (e.g., Python), along with a detailed report describing the modeling techniques and software interfaces. This report will be included in the technical report.

- Perform magnetohydrodynamic (MHD) simulations and other analysis to improve understanding of localized geoelectric field enhancements.
  - The research will build on the simulations carried out by Ngwira, et al. (2013; 2014)[8,9]. New simulations will be carried out to study geospatial dynamics specifically associated with the localized geomagnetic field enhancements. Targeting of the localized enhancements will necessitate high spatiotemporal resolution simulations with careful attention to magnetotail dynamics, which are currently thought to be the geospatial origin of the localization seen on the ground. High-resolution simulations and associated processes in the magnetotail will be mapped into the ionosphere to look for signature that ultimately cause the localized magnetic field perturbations on the ground. The new results will be reported and reviewed via a peer-reviewed publication (and included in the technical report).

Task 1B: Determine the Impacts of Spatial Averaging Assumptions on the Bulk-Power System (BPS)

- Perform GIC, transformer thermal assessment and power flow analysis of North American regions to determine the effects of spatial scales of localized geoelectric field enhancements (e.g., 100 km x 100 km, 200 km x 200 km).
  - This task is to further analyze the area over which spatial averaging should be used in stability studies and transformer thermal assessments by performing GIC analysis on squares less than 500 km per side (e.g., 100 km, 200 km) and using the results to perform power flow and transformer thermal assessments.
  - This task will include the results from Task 1A to determine the enhanced electric field strength levels to be included in the localized geoelectric field enhancements.
  - A sliding window of varying areas (squares less than 500 km per side e.g., 100 km, 200 km per FERC Order No. 830) will be used over a model of the bulk power system to model the localized geoelectric field enhancements. This analysis will be conducted in a commercially available software package that is commonly used in the industry to study GIC flows in the bulk power system.

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[8] C. Ngwira et al., *Simulation of the 23 July 2012 Extreme Space Weather Event: What if This Extremely Rare CME was Earth Directed?*, 11 Space Weather 671 (2013).

[9] C.M. Ngwira et al., *Modeling Extreme 'Carrington-type' Space Weather Events using Three-dimensional Global MHD Simulations*, 119 J. of Geophysical Res.: Space Physics 4472 (2014).

- Using the calculated GIC values, perform transformer thermal assessment of North American regions to determine the effects of scales of localized geoelectric field enhancements. The thermal impact assessment will be based on published information[10,11] and documented accordingly.
- Using the calculated GIC values, perform a power flow (voltage stability) assessment of North American regions to determine effects of scales of localized geoelectric field enhancements (e.g., 100 km x 100 km, 200 km x 200 km).
- The results of this study will provide guidance to entities on applying spatially averaged and non-spatially averaged peak geoelectric field values, or some equally efficient and effective alternative, when conducting thermal impact assessments and power flow analysis. This guidance will be documented in the technical report.

Expected Deliverable

Technical Report

Estimated Time for Completion

24-36 months from start of work

[10] *See, e.g.*, IEEE, *Guide for Establishing Power Transformer Capability While Under Geomagnetic Disturbances*, IEEE Standard C57.163-2015 and EPRI, *Magnetohydrodynamic Electromagnetic Pulse Assessment of the Continental U.S. Electric Grid: Geomagnetically Induced Current and Transformer Thermal Analysis* (2017). 3002009001.

[11] *Transformer Thermal Impact Assessment* white paper, NERC Project 2013-03 Geomagnetic Disturbance Mitigation (May 2016), http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx.

Task 2: Further Analyze Latitude Scaling

Summary

The research activities under this Task include 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 severe, 1-in-100 year event on lower geomagnetic latitudes.

Activities

- Perform review of peer-reviewed research (updated since the publication of the Benchmark GMD Event Description white paper) regarding the effects of geomagnetic latitude on geoelectric fields (based on a reference earth model).
    - This task will include an in-depth review of the newly-published work (e.g., by United States Geological Survey (USGS) and Los Alamos National Laboratory (LANL)), on geomagnetic latitude scaling. The review will include discussions with the researchers that published the works to find out if modifications are needed to the scaling factors in the Reliability Standard TPL-007-1.
    - This review will include recommendations for further actions and will be documented in the technical report.
- Determine which space weather indices are most effective in predicting latitude scaling of the maximum local geoelectric fields using current methods for conditioning magnetometer statistics. Extrapolate scaling to different benchmark event magnitudes.
    - The purpose of this work is to determine the best space weather index – or combination of indices – for predicting how maximum geoelectric fields scale with magnetic latitude. Ground-based magnetic field data for this investigation will be obtained from the database described in Step 1 of Task 1A: Further Analyze Spatial Averaging Used in the Benchmark GMD Event. Geomagnetic indices will be obtained from appropriate data providers, including the United States Geological Survey, the National Center for Environment Information, and the World Data Centers for Geomagnetism. This activity will use suitably-processed magnetometer data to estimate parameters of the latitudinal electric field profiles, and methods such as multiple regression analysis will be used to determine what index or combination(s) of indices most effectively predicts the latitudinal distribution of geoelectric fields.
    - A product of this research will be a report describing models, which are able to provide credible estimates of the geoelectric field profile along with a quantification of these models' uncertainties and an assessment of their potential ability to be used in an operational or predictive manner. This will be documented in the technical report.
- Perform analysis to provide additional technical support for existing latitude scaling factors or propose new values, as appropriate.
    - Understanding that no new observations of geomagnetic field variations are available for investigating the latitude scaling, state-of-the-art geospatial simulations can be used as a physics-based tool to investigate the processes that control the evolution of the auroral boundaries (i.e., the latitude scaling).
    - This task will include simulations with the latest updated models residing in the Community Coordinated Modeling Center (CCMC) to investigate the processes that control the propagation of the auroral boundaries toward more southern locations. The simulations will be conducted systematically using more extreme solar wind conditions as the driver and the response of the auroral boundaries will be recorded and investigated.

- A product of this research will be an establishment of the theoretical maximum limit for the auroral oval to expansion toward southern locations. Theoretical results will be analyzed in the observations-based latitude-scaling context to check if the two approaches (existing scaling factor and the new proposed scaling factor) converge toward the same scaling behavior.
    - The new results will be reported and evaluated via peer-reviewed publication and included in the final technical report.

Expected Deliverable

Technical Report

Estimated Time for Completion

24 months from start of work

Task 3: Improve Earth Conductivity Models for GIC Studies

Summary

The research activities under this Task consist of activities to improve the accuracy of existing earth conductivity models for GIC studies (TPL-007 beta scaling factor).

Activities

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

- Compare the accuracy of 1D-earth conductivity models to 3D-earth conductivity models.
  - The goal of this activity is to compare electric fields derived from 1D earth conductivity models to those obtained from 3D Electromagnetic Transfer Functions (EMTFs).[12] In this activity, the 3D response will be used as the "ground truth," representing the realistic earth response to a geomagnetic storm. Work includes evaluating the ability of the 1D model to represent the average response over a given physiographic region to determine where 3D models are necessary and to validate the 1D model's effectiveness for GIC estimation. The following steps will be performed:
    - Step 1 - Compare the electric field response over each physiographic region using both 1D and 3D models for the extreme event scenario, where 3D data exist. Using the peak electric field metric, the 1D electric field to the average 3D response over the same region will be compared. This will be repeated for large historical events if time allows.
    - Step 2 - Identify regions where the 1D assumptions break down by using the differences in field orientation between 1D and 3D results. Also, identify 3D regions that may be too small in spatial extent to impact the average response over a larger region. Consider differences between 1D and 3D for the entire spectral response, as well as peak intensity.
    - Step 3 - Using the results obtained in Step 1; modify the 1D models as required to make them more accurately reflect the average 3D response. In some areas, sub-regions may be identified, and new or "effective" 1D models produced. Because these changes are frequency-sensitive, validation with other historical events will be needed.
    - The following will be provided in the technical report as a result of this research task:
      - A NERC operating area map of the differences between the 3D EMTF and the 1D electric field response for the extreme event scenario (intensity and direction).
      - Modified 1D models for all physiographic regions where changes are deemed necessary.
      - A NERC operating area map identifying regions of 1D and 3D validity, based on potential for geoelectric field rotation.

Task 3B: Develop Guidance for Validation of GIC Models

- Develop techniques and guidelines for using GIC and magnetometer data to perform model validation.
  - When performing a GMD analysis, it is typical to calculate an estimated GIC and compare to a measured GIC. This connects the source (geomagnetic field) with the response (induced current). There is the potential for large sources of error in several steps of this process: magnetic field input, earth conductivity models, dc system models, and the GIC data itself. The goal for this activity is to

[12] For example, SPUD EMTF – IRIS, http://ds.iris.edu/spud/emtf.

provide guidance for identifying and reducing these sources of error. The following steps will be performed:

- Step 1 - Evaluate GIC data sets to determine best practices for time cadence, data quality and archiving techniques.
- Step 2 - Assess the impact of magnetometer distance by calculating the electric field at a source location and correlating with the GIC response at increasing distances. Improve this by estimating GIC response using a realistic system model, if available.
- Step 3 - Test the assumptions by "degrading" the magnetometer signal and using different values of conductivity from the error range.
- The following will be provided in the technical report as a result of this research task:
  - A report documenting recommendations on the impact to the GIC estimate of magnetometer distance and conductivity model selection.
  - Error estimates versus distance to magnetometer.

Task 3C: Non-uniform Field Modeling

- A realistic geoelectric field during a geomagnetic event is non-uniform due to spatial variations in both the earth conductivity and the geomagnetic field source. The goal of this activity is to evaluate the impact of non-uniformities on GIC estimates and develop methods and models to handle these effects.
  - Assess the "coastal effect" and develop models to capture its effects.
    - One of the most important 3D effects is the enhancement and rotation of the electric field along coastal boundaries. Where 3D EMTFs are available, the exact electric field enhancement for a given storm can be determined. In other cases, available 1D conductivity models, existing methods in geophysics literature and publicly available bathymetry data must be used to estimate the potential coast effect. The following steps will be performed to produce a frequency dependent coast model:
      - Step 1 - Calculate the geoelectric field using 3D EMTFs and the extreme storm scenario.
      - Step 2 - Plot the estimated geoelectric field response vs distance from the coast.
      - Step 3 - Use the published approximations to determine first order theoretical inland effective distances, by frequency.
      - Step 4 - Use available open source tools and bathymetry maps to produce a first order 1D model of coast effects. This will be a map of the enhancement factor by distance from the coast, for a set of characteristic frequencies.
  - Develop standardized methods or models for capturing non-uniform geoelectric fields. Develop models to assess GIC simulation tools against non-uniform fields and compare GIC calculations for 3D and 1D ground conductivity models.
      - Step 1 - Select several examples of areas where electric field results show local enhancements due to 3D conductivity effects.
      - Step 2 - Calculate the electric field using 1D and 3D models.
      - Step 3 - Estimate GIC using these electric field inputs and compare them to GIC measurements, where possible.

– Step 4 - Modify size of region and size of localized enhancement and rerun analysis to determine impact of changes.

- As a result of this research the following will be provided in the technical report:
    - First order coast effect model.
    - Guidance on the impact of non-uniform electric fields on GIC estimation.

- Establish a working group to promote the adoption including modeling of non-uniform geoelectric fields (including coastal effect) in commercially available software tools.

Expected Deliverable

Technical Report

Estimated Time for Completion

24-36 months from start of work

Task 4: Study GIC Field Orientation for Transformer Thermal Impact Assessments

Summary

This Task will develop an approach for applying the benchmark geoelectric field time series to individual transformers in thermal impact assessments. The research activities under this Task will consist of evaluating the existing approach used to perform transformer thermal assessments, and if deemed deficient, develop 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.

Activities

- Determine how the benchmark geoelectric field wave shape can be applied to individual transformers to determine worst-case hotspot heating.
  - Step 1 - Calculate GIC (t) using the Benchmark geoelectric field time series and steady state GIC results for a specified field orientation (worst case) using the methodology provided in TPL-007-1 and supporting documentation. Using GIC (t), compute the time series hotspot temperature, θ (t), using the procedure described in TPL-007-1 and supporting documentation.
  - Step 2 - Repeat the previous procedure for various other field orientations (e.g., 0°, 10°, 20°, 180°), and compare the resulting hotspot temperatures, θ (t), for each orientation.
  - Step 3 - If the worst-case hotspot heating is not generated by the electric field orientation that results in the maximum steady-state GIC flow in the transformer, evaluate other methods including, but not limited to, phase shifting the benchmark geoelectric field time series, such that the resulting GIC(t) yields the worst-case hotspot heating conditions.
  - The following will be documented in the technical report and entities will be able to:
    - Evaluate the potential effects of non-uniform geoelectric fields on the thermal assessment approach presented in TPL-007-1 and supporting documentation; and
    - Identify and quantify potential sources of error that can occur.

Expected Deliverable

Technical Report

Estimated Time for Completion

10-12 months from start of work

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

Summary

Conduct additional research and analysis to assess transformer thermal impact of the benchmark GMD event or other realistic GMD events.

Activities

- The research activities under this Task consist of evaluating the existing 75A per phase criterion based on IEEE C57.163-2015[13] and if deemed deficient, develop alternative criteria. Recent research conducted as part of EPRI's electromagnetic pulse research will be leveraged in this task[14].
  - Step 1 - Evaluate the existing temperature limits used in TPL-007-1 and evaluate the potential for using other temperature limits based on various transformer conditions and other factors.
  - Step 2 - Determine the effects of short-term harmonic currents resulting from part-cycle saturation on tertiary winding heating. This will be accomplished by developing electrical models of typical high-voltage autotransformers with tertiary winding and generator step-up units that are suitable for estimating the flow of harmonic currents in the delta connected windings that are the result of part-cycle saturation. The models will be examined using various levels of GIC, and the additional hotspot temperature rise due to the flow of harmonic currents will be estimated. An analysis will be performed to determine the potential impact of this additional hotspot heating on the performance of the transformer.
  - Step 3 - Additional time-domain transformer thermal modeling parameters (asymptotic behavior and thermal time constants) will be developed for various transformer types and designs. Modeling parameters will be extracted from simulation results provided by transformer manufacturers and field/laboratory test results (if available). The results of the thermal models provided by the transformer manufacturer will be validated using field/laboratory test data where available.
  - Step 4 - Additional transformer thermal analyses will be performed to assess the efficacy of the existing 75 A/phase criteria. The basis of new current limits may be established based on the full spectrum of available transformer thermal models and the additional temperature limits developed as a part of this research task.
  - Based on the above analysis, the technical report will include:
    - The basis of new current limits if established based on the full spectrum of available transformer thermal models and the additional temperature limits developed in the above steps.
    - Additional transformer modeling parameters (e.g., asymptotic behavior and thermal time constants) will be included in a technical report.

Expected Deliverable

Technical Report

[13] IEEE, *Guide for Establishing Power Transformer Capability While Under Geomagnetic Disturbances,* IEEE Standard C57.163-2015.

[14] *Magnetohydrodynamic Electromagnetic Pulse Assessment of the Continental U.S. Electric Grid: Geomagnetically Induced Current and Transformer Thermal Analysis*. EPRI, Palo Alto, CA: 2017. 3002009001.

Estimated Time for Completion

24 months from start of work

Task 6: Section 1600 Data Request

Summary

The activities under this Task consist 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 GIC data and magnetometer data. In Order No. 830, FERC directed NERC, pursuant to Section 1600 of the NERC Rules of Procedure, to collect GIC monitoring and magnetometer data from registered entities for the period beginning May 2013, including both data existing as of the date of the Order and new data going forward.[15] Furthermore, FERC directed that NERC should make the collected GIC and magnetometer data available to support ongoing research and analysis of GMD risk.[16]

The data are intended to promote greater understanding of GMD events and their potential impacts to reliable operations. For example, measured GIC and magnetometer data can help validate various models used in calculating GICs and assessing their impacts in power systems.

Various entities, including some Transmission Owners, Generator Owners, Transmission Planners, and Planning Coordinators, collect GMD data and may have GMD data for the period beginning in May 2013. The data request would apply to entities that have the specified GMD data.

Activities

Develop guidance for the measurement of GIC and geomagnetic fields and formatting requirements for supplying measurement data and technical guidelines.

- A number of utilities have installed GIC monitoring equipment (e.g., participants in EPRI SUNBURST research project), which measure, acquire, and transmit GIC data to database which can be used for situational awareness and model validation. Additionally, some utilities have installed magnetometers. Guidance developed in this task will help entities plan for installing GIC monitoring and magnetometers. For example:
  - **Monitor locations.** When planning for new or additional GIC monitoring installations, consider that data from monitors located in areas found to have high GIC based on system studies may provide more useful information for validation and situational awareness purposes. Conversely, data from GIC monitors that are located near transportation systems using direct current (e.g. subways or light rail) may be unreliable.
  - **Monitor specifications.** Capabilities of Hall effect transducers, existing and planned, should be considered in entity operating processes. When planning new GIC monitor installations, consider monitor data range (e.g., -500 A through + 500 A) and ambient temperature ratings consistent with temperatures in the region in which the monitor will be installed.
  - **Magnetometers.** Entities that install magnetometers should consider equipment specifications and data format protocols contained in the latest version of the Intermagnet Technical Reference Manual.

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[15] Order No. 830 at P 89. FERC clarified that this directive would not apply to non-U.S. responsible entities, or Alaska and Hawaii. *See id*. at n. 118.

[16] Order No. 830 at P 93 ("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."). FERC clarified that "if GIC monitoring and magnetometer data is already publicly available (e.g., from a government entity or university), NERC need not duplicate those efforts." *See id*. at n. 122.

- Guidance to inform criteria for when entities should obtain data for future GMD events. For example:
  - Kp threshold (warning or attained).
  - Space weather alert indicating GMD commencement.
  - GIC threshold (dc measurement of current in the transformer neutral).
- Guidance to inform criteria that will promote data standardization and usability for model validation purposes. For example:
  - **Data format.** Greenwich Mean Time (GMT) (MM/DD/YYYY HH:MM:SS) time stamp and GIC Value (Ampere). Positive (+) and negative (-) signs indicate direction of GIC flow (Positive reference is flow from ground into transformer neutral). Time fields indicate the sampled time rather than system or SCADA time.
  - **Sampling Interval.** Data sampling during periods of interest at a continuous rate of 10 seconds or faster.
  - **Collect time-series data.**
- Guidance to inform development of information technology systems for data collection, hosting, and access.
  - The data request will specify methods for providing data to the NERC database (for example, email data files, upload to site using file transfer protocol (FTP)).

Expected Deliverables

Criteria to Support a Request for Data or Information under Section 1600 of the NERC Rules of Procedure
GIC/Magnetometer Specification, format for data request, and IT infrastructures to store the data

Estimated Time for Completion

12 months from start of work

Task 7: Geoelectric Field Evaluation and Calculation Tool

Summary

The activities under this Task consist of evaluating available tools for calculating geoelectric fields from magnetic field data for a given earth conductivity structure and developing additional tools as necessary to meet the needs of the industry.

Activities

- Evaluate publicly available software tools for calculating geoelectric field from magnetic field data for given earth conductivity structure.
  - The goal of this Task is to review all publicly-available tools for calculating geoelectric field data for a given earth conductivity structure and use this review to leverage the development of the following Task, which is to develop an open source tool capable of performing geoelectric field calculations using 1-D and 3-D layered earth model and time series geomagnetic data.
- Develop an open source tool capable of performing geoelectric field calculations using 1-D and 3-D layered earth model and time series geomagnetic data.
  - Step 1 - Develop a set of codes that can be used by utility analysts for GMD planning, including documentation and examples.
  - Step 2 - Include the option of using 1D layered earth conductivity models or a 3D EMTF.
- Perform time series simulations with improved 1D and 3D conductivity models to evaluate the earth conductivity (beta) scaling factors.
  - The goal is to improve the conductivity beta scaling factors and make some error estimates to guide their use. Improved conductivity models will be used to improve the scaling ratio calculation by looking at the entire spectral response instead of the ratio of one spectral component. This analysis will involve the following steps:
    - Step 1 - Choose several geomagnetic field time series as sources. Examples include the extreme storm scenario, some data from the recent historical record, and selected storms with different frequency content. An additional option is to use artificially constructed magnetic spectra with different characteristics to test the error bounds of the scaling factors.
    - Step 2 - Use the same "baseline" as the original beta factor calculations. Calculate the peak geoelectric field for each magnetic storm input using the 1D Canadian Shield (Quebec) earth conductivity model.
    - Step 3 - For each location/conductivity model, and for each input time series, calculate the peak electric field ratio: max (E_location)/max (E_CanadianShield).
    - Step 4 - For each set of results from Step 3, determine the beta factor, and the error bars for each location.
  - As a result of this research, the following will be delivered in the technical report:
    - Map of improved beta factors based on updated conductivity profiles, with error bars.

Expected Deliverables

Technical Report
Open Source Software Tool

Estimated Time for Completion

24-36 months from start of work

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. GMD-related harmonics are caused by the part-cycle saturation of transformers. The harmonic currents and voltages resulting from transformer saturation have had major impacts on system operations and security during severe GMD events in the past.[17] Harmonics studies are an integral part of any GMD Vulnerability Assessment, and as such, are a key component of related reliability and planning assessments and associated regulatory requirements.

Performing harmonic analysis is difficult, and to date, the commercially available frequency-domain tools do not adequately address nuances of performing GMD-related harmonics studies. For example, there are some important difficulties and modeling gaps that need to be addressed before the harmonic impacts of a GMD event can be accurately assessed. Such difficulties and gaps include (but are not limited to):[18]

- 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.

Activities

- Step 1: Perform research necessary to develop models and methods to improve capability of performing harmonic assessments of GMD events. Initial focus will be on developing frequency-domain transformer models that can be used in GIC-integrated harmonics studies.
- Step 2: based on the research conducted in Step 1, an accurate GMD harmonic analysis approach will be developed 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.
- Step 3: based on the results of Step 1 and 2, a frequency-domain based harmonic GMD analysis tool will be developed. Included in this development, a GMD system model will be created to accurately assess and verify both time-domain models and the newly developed frequency-domain models. This will provide confidence in the frequency-domain models that are developed as a part of this research Step.
- Step 4: All models and techniques developed as a part of this research will be implemented in an open source software tool. This tool will be used to:
  - Aid system planners in evaluating impacts of harmonics on reactive power resources (e.g. shunt capacitor banks, static var compensators, etc.); and

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17 NERC, *March 13, 1989 Geomagnetic Disturbance* white paper, http://www.nerc.com/files/1989-quebec-disturbance.pdf.

18 EPRI, *Analysis of Geomagnetic Disturbance (GMD) Related Harmonics* (2014). 3002002985.

    - Facilitate the implementation of GMD harmonic assessments in commercially available software tools.

- Additionally, a harmonics modeling workshop will be conducted to facilitate knowledge transfer.
- Harmonics assessment tools will be validated with available GIC data as part of software and model validation.
- The deliverables from this task would be open source harmonics assessment software/tools and a technical report on harmonics analysis guidelines.

Expected Deliverables

Report
Open Source Software Tool

Estimated Time for Completion

24-36 months from start of work

Task 9: Harmonic Impact Studies

Summary

The activities under this Task consist of activities to understand the impacts of harmonics on power system equipment. The Task will address the adverse impacts to transformers and generators caused by harmonics associated with GMD events. This Task responds to FERC's direction to address the effects of harmonics on transformers. The impacts of transformer heating are covered in detail in Tasks 4 and 5 of this plan. This section will focus mainly on the impacts of vibrations on power transformers.

Activities

- Transformer harmonic assessment:
  - Step 1 – Research and report on all available data (including published industry and EPRI documents and available transformer manufacture test data) on the following topics:
    - Typical tank vibration levels and frequency spectrum in absence of GIC. This information would be used to develop a baseline of tank vibration levels and frequency spectrum. The following would be included in this sample:
      - Transformers with no vibration issues (e.g., new construction).
      - Transformers with vibration issues (e.g., existing construction that may have existing loose hardware).
    - Impact of GIC on transformer noise. This information would be used to compare against a baseline of tank vibration levels and frequency spectrum.
      - Theoretical impact of GIC on core noise (analysis to be verified by testing) on transformer noise level and frequency spectrum.
    - Examples of measured impact of GIC on core noise.
      - Correlation between calculated and measured impact of GIC on core noise (i.e., correlation with neutral GIC and correlation with effective GIC).
    - Documented in the technical report will be recommendations on the feasibility of using tank vibration measurements to monitor impacts of GIC on transformers and impact of vibrations due to GIC on the integrity of transformers. This research will be needed to provide guidance in real-time monitoring to protect transformers against vibration damage caused by GIC.
    - Identify areas for future study.
  - Step 2 - Perform transformer tank vibration measurements on two (2) transformers when subjected to GIC. Testing to be conducted in a laboratory environment.
    - Compare measurements to the theoretical relationship between tank vibrations and level of GIC.
    - Develop expected relationship between tank vibrations and level of GIC for higher levels of GIC.
    - Documented in the technical report will be the following:
      - Impact of higher tank vibrations due to GIC on integrity of power transformers.
      - Future actions and/or research activities needed.

- Generator harmonic assessment:
  - Step 1 - Perform assessment of harmonic effects on generators to improve understanding of gaps in existing Reliability Standards with harmonic levels that are unique to GMD events. This assessment will include all available published and existing EPRI research.
  - Step 2 - The generator harmonic assessment will use the system level harmonic modeling research results. The system level harmonic modeling will provide guidance for the level of expected GMD related harmonics that would be sourced from a generator.
  - Step 3 - Results from the harmonic tool can then be compared to published standards to better understand the problems that will result from generator harmonics.
  - Documented in the technical report will be:
    - The gaps in published standards that are unique to GMD events;
    - Potential issues that are already addressed in the standards; and
    - Future scoping and testing needs.

Expected Deliverable

Technical Report

Estimated Time for Completion

24 months from start of work

Estimated Project Costs

It is estimated that this plan would require, over a minimum three-year period, approximately $3 million to $3.5 million to complete, including costs for research and time and costs associated with identifying and developing information technology (IT) systems for hosting collected GMD data.

The estimated cost for the completion of the research activities (i.e., excluding IT costs) is approximately $2.72 million, as detailed in Table 1 below.

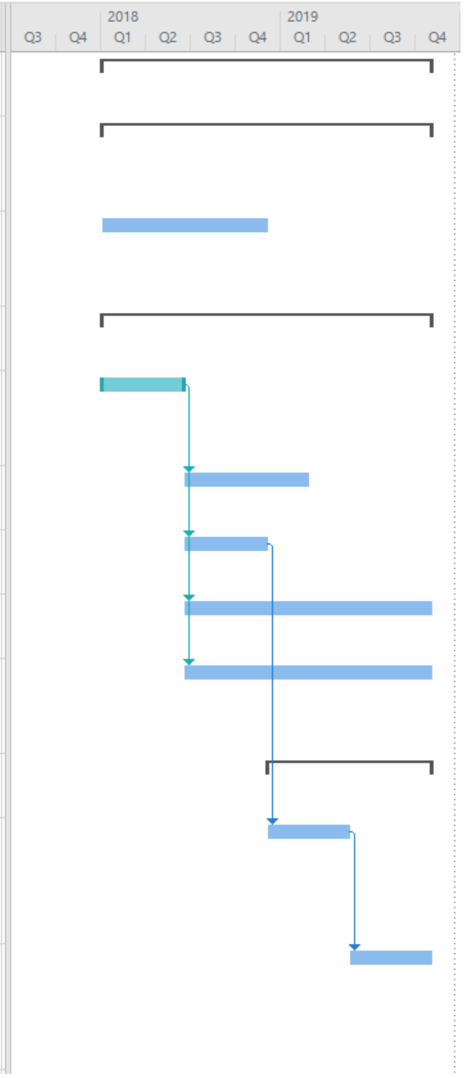
Table 1.1 Research and Development Costs, by Task (estimated)

Task	Topic	Time to Completion (from start of work)	Price
1	Spatial Averaging	24-36 months	$890,000
2	Latitude Scaling	24 months	$225,000
3	Earth Conductivity Models	24-36 months	$397,000
4	Geomagnetic Field Orientation	10-12 months	$50,000
5	Transformer Thermal Impact Assessment Criterion	24 months	$400,000 ($30k added per additional transformer model beyond 10)
6	Guidance and Guidelines to Support Section 1600 Data Request	12 months	$50,000
7	Geoelectric Field Evaluation and Calculation Tool	24-36 months	$305,000
8	Harmonics Analysis Capability	24-36 months	$200,000
9	Harmonic Impact Studies	24 months	$205,000
Total			**$2,722,000**

Project Schedule Example

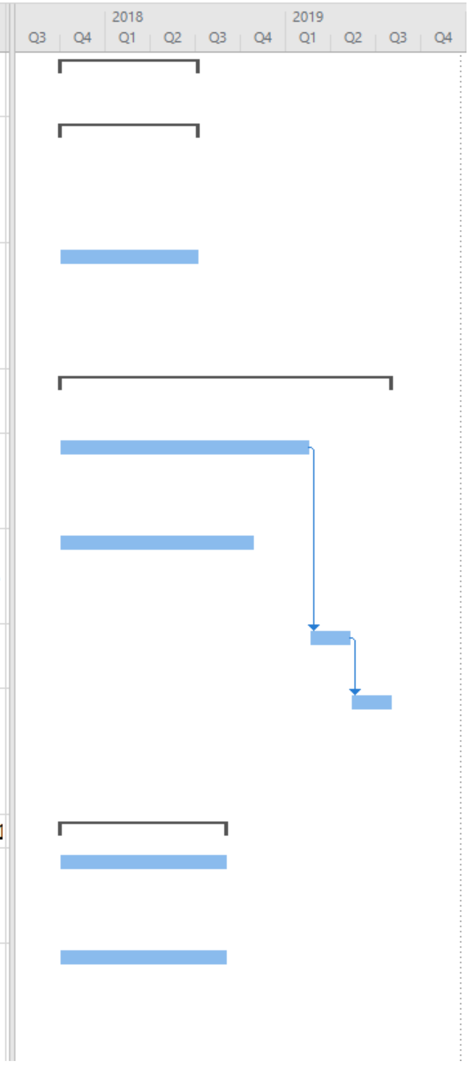
EPRI has provided the following as an example of a project schedule that shows the estimated timeframes for completing the research activities under each Task in the 2018-2019 timeframe.

Task Name	Duration	Start	Finish
TASK 1 - FURTHER ANALYZE SPATIAL AVERAGING USED IN THE BENCHMARK GMD EVENT	**480 days**	**Tue 1/2/18**	**Mon 11/4/19**
Perform research to improve understanding of the phenomenology and spatial scales of localized geoelectric field enhancements caused by severe	**480 days**	**Tue 1/2/18**	**Mon 11/4/19**
Review technical basis of the NERC Benchmark GMD Event Description white paper (May 2016) including supporting peer-reviewed papers.	12 mons	Tue 1/2/18	Mon 12/3/18
Perform analysis of magnetometer data to characterize spatial structure of GMD events	**480 days**	**Tue 1/2/18**	**Mon 11/4/19**
Develop "full" dataset for large GMD events across all available magnetometer stations. Resolve issues/differences in temporal	6 mons	Tue 1/2/18	Mon 6/18/18
Explore scaling of maximum dB/dt versus magnetic time of day (TOD).	9 mons	Tue 6/19/18	Mon 2/25/19
Compute the spatiotemporal autocorrelation in dB/dt. Determine the characteristic time and	6 mons	Tue 6/19/18	Mon 12/3/18
Develop Markov Chain Models for generating spatiotemporal behavior of benchmark events	18 mons	Tue 6/19/18	Mon 11/4/19
Perform magnetohydrodynamic (MHD) simulations and other analysis to improve understanding of the phenomenology of localized	18 mons	Tue 6/19/18	Mon 11/4/19
Determine impacts of spatial averaging assumptions on bulk-power system reliability.	**240 days**	**Tue 12/4/18**	**Mon 11/4/19**
Perform GIC and power flow analysis of various regions within North America to determine effects of spatial scales of localized geoelectric field enhancements, e.g. 100 km x 100 km, 200 km x	6 mons	Tue 12/4/18	Mon 5/20/19
Perform transformer thermal assessment of various regions within North America to determine effects of scales of localized geoelectric field enhancements, e.g. 100 km x 100 km, 200 km x	6 mons	Tue 5/21/19	Mon 11/4/19

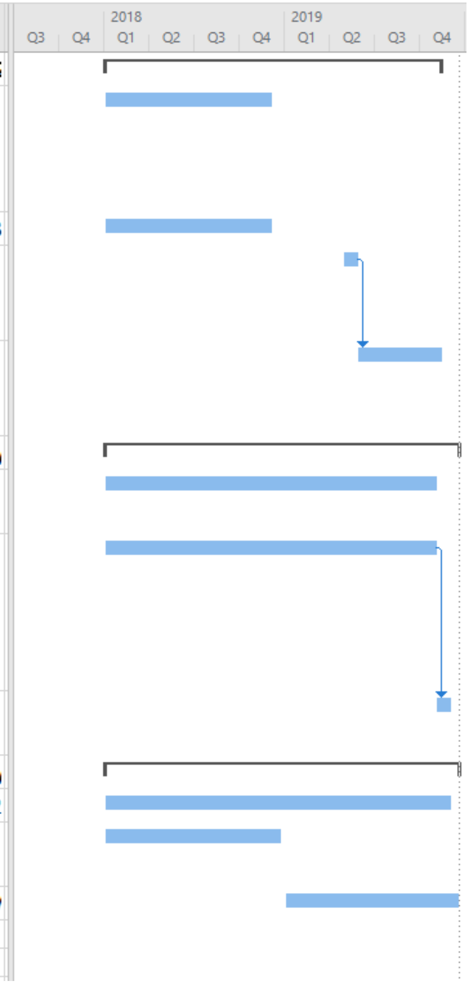


Task Name	Duration	Start	Finish
TASK 2 - FURTHER ANALYZE LATITUDE SCALING	**489 days**	**Tue 1/2/1**	**Fri 11/15/**
Perform review of peer-reviewed research (updated since publication of Benchmark GMD Event white paper) regarding the effects of geomagnetic latitude	12 mons	Tue 1/2/18	Mon 12/3/18
Using current methods for conditioning magnetometer statistics, determine which space weather indices (Dst, AE, etc....) are most effective in predicting the latitude scaling of the maximum local	12 mons	Tue 5/1/18	Mon 4/1/19
Perform analysis to provide: 1) additional technical support for existing latitude scaling factors or 2) propose updated values as appropriate.	19 mons	Mon 6/4/18	Fri 11/15/19
TASK 3 - IMPROVE EARTH CONDUCTIVITY MODELS FO	**480 days**	**Tue 1/2/1**	**Mon 11/4**
Use magnetotelluric (MT) measurement data to validate/ improve existing earth conductivity models.	12 mons	Tue 1/2/18	Mon 12/3/18
GMD Task force: guidelines for performing validation of GIC models	**480 days**	**Tue 1/2/18**	**Mon 11/4/19**
Develop techniques and guidelines for using GIC and magnetometer data to perform model	24 mons	Tue 1/2/18	Mon 11/4/19
Non-uniform Field Modeling	**480 days**	**Tue 1/2/1**	**Mon 11/4**
Assess coastal effect and develop models for accurately capturing its effects	24 mons	Tue 1/2/18	Mon 11/4/19
Develop standardized methods for modeling non-uniform geoelectric fields	24 mons	Tue 1/2/18	Mon 11/4/19
Develop benchmark models to assess GIC simulation tools against non-uniform fields	24 mons	Tue 1/2/18	Mon 11/4/19
Establish a working group to promote the adoption of modeling non-uniform geoelectric field (including coastal effect) into commercially available software tools	24 mons		

Task Name	Duration	Start	Finish
TASK 4 - STUDY WORST-CASE GEOMAGNETIC FIELD ORIENTATION FOR TRANSFORMER THERMAL	**200 days**	**Mon 10/2/17**	**Fri 7/6/18**
Perform analysis to evaluate the ability of GIC flow calculated as specified in TPL-007 to represent worst-case transformer hot-spot heating conditions for the Benchmark GMD Event or other	**200 days**	**Mon 10/2/17**	**Fri 7/6/18**
Determine how the benchmark geoelectric field wave shape can be applied to a particular transformer to determine worst-case hotspot heating.	10 mons	Mon 10/2/17	Fri 7/6/18
TASK 5 - FURTHER ANALYZE THE 75 A PER PHASE CRITERION USED FOR TRANSFORMER THERMAL	**480 days**	**Mon 10/2/17**	**Fri 8/2/19**
Conduct additional research and analysis to assess transformer thermal impact of the Benchmark GMD Event or other realistic GMD events.	18 mons	Mon 10/2/17	Fri 2/15/19
Perform research to determine the effects of short-term harmonic currents resulting from half-cycle saturation on tertiary winding heating.	14 mons	Mon 10/2/17	Fri 10/26/18
Evaluate the use of alternative performance criteria (e.g. the use of different temperature limits).	3 mons	Mon 2/18/19	Fri 5/10/19
Create additional thermal models (thermal response during heating and cooling, asymptotic behavior) and perform transformer thermal assessment using synthetic GIC.	3 mons	Mon 5/13/19	Fri 8/2/19
TASK 6 - DATA REQUEST COMMENSURATE WITH SECT	**240 days**	**Mon 10/2**	**Fri 8/31/1**
Develop a Section 1600 Data Request for the collection of existing and new GIC and Magnetometer data that can be made available to	12 mons	Mon 10/2/17	Fri 8/31/18
Develop guidance for the measurement of GIC and geomagnetic field and formatting requirements for supplying measurement data.	12 mons	Mon 10/2/17	Fri 8/31/18



Task Name	Duration	Start	Finish
TASK 7 - GEOELECTRIC FIELD CALCULATION TOOL	**486 days**	**Tue 1/2/1**	**Tue 11/1**
Evaluate available tools for calculating geoelectric field from magnetic field data for given earth conductivity structure, and develop additional tools as necessary to meet the needs of the industry.	12 mons	Tue 1/2/18	Mon 12/3/18
Perform assessment of commercially available tools.	12 mons	Tue 1/2/1	Mon 12/3
Develop open source tool capable of performing geoelectric field calculations using 1-D/3-D layered earth model and time series geomagnetic field data.	1 mon	Wed 5/1/19	Tue 5/28/19
Perform time-series simulations with improved 1D and 3D conductivity models to improve the beta factors (scaling factors to account for earth	6 mons	Wed 5/29/19	Tue 11/12/19
TASK 8 - IMPROVE HARMONICS ANALYSIS CAPABILIT	**514 days**	**Tue 1/2/1**	**Fri 12/20,**
Develop Harmonics Analysis guidelines; tools for system-wide assessment.	24 mons	Tue 1/2/18	Mon 11/4/19
Develop models and methods to improve capability of performing harmonic assessments of benchmark GMD events. Implement models and methods developed as a part of item 1 into an open source software environment (GIC integrated harmonics	24 mons	Tue 1/2/18	Mon 11/4/19
Hold a harmonics modeling workshop to facilitate knowledge transfer	1 mon	Tue 11/5/19	Mon 12/2/19
TASK 9 - HARMONIC IMPACT STUDIES	**514 days**	**Tue 1/2/1**	**Fri 12/20,**
Understand harmonics impacts on power system a	500 days	Tue 1/2/1	Mon 12/2
Perform transformer studies/ testing to quantify the impacts of vibrations due to GIC on the	254 days	Tue 1/2/18	Fri 12/21/18
Generator harmonic assessment	253 days	Wed 1/2/	Fri 12/20/



Next Steps

In the coming months, NERC will continue to explore ways to refine the plan based on feedback and will continue discussions with EPRI, industry, FERC, and other research partners to explore opportunities to leverage existing work, share project oversight and responsibilities, and establish a project schedule.

Final budget and funding mechanisms are subject to budget approval.