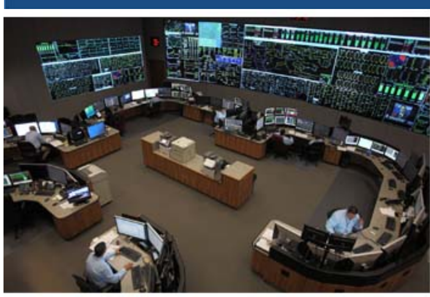
NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Order No. 830
GMD Research Work Plan

Addressing Geomagnetic Disturbance Events and Impacts on Reliability

April 2018

RELIABILITY | ACCOUNTABILITY

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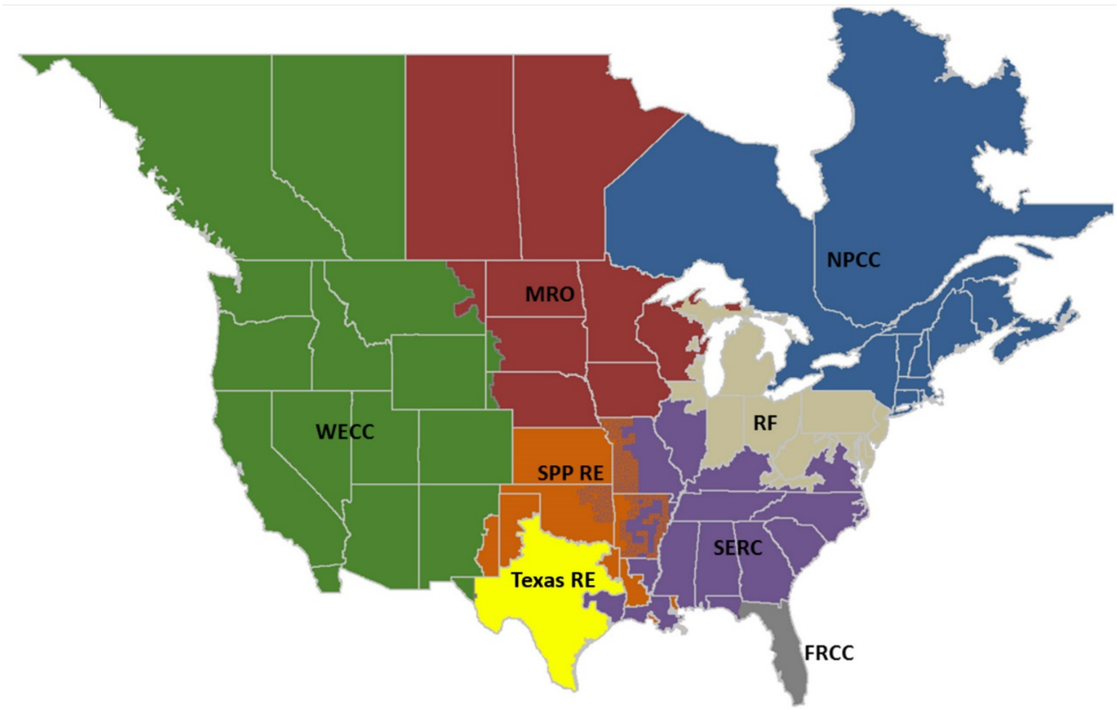
Preface

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

The North American BPS is divided into eight 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 events (GMDs) 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 data publicly available.[6]

In January 2018, NERC filed proposed TPL-007-2 and the Supplemental GMD Event to address FERC's directives for modifications to the TPL-007 Reliability Standard.[7]

NERC filed a preliminary work plan for GMD research in May 2017, addressing the second and third directives listed above. The preliminary research work plan set 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. In October 2017, FERC issued an Order accepting NERC's plan and directing NERC to file for Commission review a final, or otherwise updated, work plan by April 2018.[8]

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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) ("Order No. 830").

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

[5] *See generally id*. at P 77.

[6] *Id*. at P 89.

[7] *Petition of the North American Electric Reliability Corporation for Approval of Proposed Reliability Standard TPL-007-2*, Docket No. RM18-8-000 (Jan. 22, 2018) ("TPL-007-2 Petition").

[8] *Order on GMD Research Work Plan*, 161 FERC ¶ 61,048 (2017) at P 9. In addition to accepting NERC's preliminary work plan and directing the filing of a final or updated plan within six months, FERC provided guidance on what research tasks should receive priority as requested by NERC, reiterated certain directives for evaluation in the work plan, and addressed other issues raised in public comments.

Revised GMD Work Plan Overview

NERC's GMD Research Work Plan (Work Plan), described herein, contains current research details and project management information that NERC will use as a guide in accomplishing its research objectives. This 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 Amps per Phase Criterion Used for Transformer Thermal Impact Assessments
6. Support for Section 1600 Data Request
7. Geoelectric Field Tool Evaluation and Calculation of Beta Factors
8. Improve Harmonics Analysis Capability
9. Harmonic Impact Studies

Specific research activities and estimated completion timeframes for each of these tasks are identified in the subsequent sections of this Work Plan. NERC developed the research activities in coordination with Electric Power Research Institute (EPRI), NERC's research collaborators, and stakeholders, to advance industry understanding of GMD risk to the BPS and achieve research objectives specified in Order No. 830. The research direction described in the Work Plan is based on current capabilities, resources, and understanding. During the course of Work Plan execution, NERC, in conjunction with research partners and stakeholders, may identify modifications or alternatives to specified research activities that support accomplishing Work Plan tasks. NERC will maintain an up to date Work Plan on NERC's GMD Task Force (GMDTF) project page, including any modifications to the initial Work Plan along with justification, and share it with stakeholders.

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.

Research Project Management

Overview

NERC and EPRI initiated the Work Plan in November 2017 with funding commitment of $3.5M from participating EPRI members and NERC. The Work Plan extends into the first quarter of 2020. The anticipated schedule for individual tasks described in the following sections. NERC and EPRI will make technical reports and other deliverables available to the public free of charge. NERC will make a series of informational filings to FERC that contain hyperlinks to the final technical reports for all tasks. NERC anticipates these filings would occur within six months of EPRI completing the associated deliverable.

Opportunities to Comment on Research

NERC will afford interested entities with an opportunity to comment on research results prior to filing with FERC. EPRI will update the GMDTF regularly on progress of the Work Plan and will provide technical reports to the GMDTF for comment.[9]

Research Priorities

In filing its preliminary GMD Research Work Plan, NERC described its research focus and invited FERC to provide guidance on research priorities. Accordingly, the following outlines priorities that NERC would use as a guide in the event that resource constraints or timeline conflicts necessitate research prioritization (listed highest priority to lower priority):

- **Task 3** (Improve Earth Conductivity Models for GIC Studies)
- **Task 8** (Improve Harmonics Analysis Capability) and **Task 9** (Harmonic Impact Studies)
- **Task 4** (Study GIC Field Orientation for Transformer Thermal Impact Assessments)
- **Task 1** (Further Analyze Spatial Averaging Used in the Benchmark GMD Event) and **Task 2** (Further Analyze Latitude Scaling)
- **Task 5** (Further Analyze the 75 A per Phase Criterion Used for Transformer Thermal Impact Assessments) and **Task 7** (Geoelectric Field Tool Evaluation and Beta Scaling Factors Calculations)

FERC did not address the prioritization of **Task 6 (Section 1600 Data Request),** as it is not specifically a research task.

Research activities supporting all tasks were initiated in 2017, and NERC anticipates concluding all research during the course of the Work Plan.

[9] The NERC GMD Task Force includes participants from the U.S. and Canadian governments, space weather researchers, representatives from the manufacturer and vendor community, and subject matter experts from both within and outside the electric power industry. GMDTF activities are open to the public.

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.

Background

Task 1 in NERC's 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, the Commission approved the benchmark GMD event but noted its concern that a spatially averaged benchmark may not adequately account for localized peak geoelectric fields that could potentially affect reliable operations. Accordingly, the Commission directed NERC, as part of the Work Plan, to "further analyze the area over which spatial averaging should be calculated for stability studies, including performing sensitivity analyses on squares less than 500 km per side (e.g., 100 km, 200 km)."[10]

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

Task 1 research will also provide insights for application in subsequent versions of the TPL-007 standard. For example, proposed Reliability Standard TPL-007-2 was developed to address FERC directives including concerns that the benchmark GMD event may not adequately account for localized peak geoelectric fields.[11] The proposed standard requires entities to perform supplemental GMD Vulnerability Assessments in addition to the benchmark GMD Vulnerability Assessments. Supplemental GMD Vulnerability Assessments are based on the supplemental GMD event, a second defined event that accounts for localized peak effects of GMDs and which is based on individual station measurements (i.e. not spatially averaged data). As noted, one aim of **Task 1** research is to improve understanding of characteristics and spatial scales of localized geoelectric field enhancements, which could inform the supplemental GMD event description.

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[12] 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.

[10] Order No. 830 at P 26.

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

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

- 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 leading NASA and LANL experts 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 documented and included in the technical report.

- Review technical basis of the NERC Benchmark GMD Event Description white paper (May 2016) 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.[13] 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 seconds 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. The initial GMD database will draw from three primary sources: SuperMAG, INTERMAGNET, and IMAGE. SuperMAG (http://supermag.jhuapl.edu) is a standardized collection of ground magnetometer measurements from a global network of stations, but its data is only available at a one-minute sample rate. INTERMAGNET (http://intermagnet.org) provides data from a smaller number of ground magnetometers than SuperMAG, but it provides data at potentially higher sample rates, up to one second in some cases. The IMAGE network (http://space.fmi.fi/image/) provides ten-second data for magnetometers in Northern Europe and Fennoscandia. These additional data sources will be incorporated in the compilation whenever possible, conditioning and processing the data as necessary. As other useful data sets are identified, they will be added to the database.
      - The newly developed database and derived products, including processed and corrected time series and APIs 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

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

magnetotelluric methods (based on 1D conductivity profiles, comparing results to those from empirical surface impedance tensors when available).

– For example, Looking at the distribution of peak GMD observations versus magnetic time of day (MTOD) in ***Figure 1.1***, it becomes clear that large GMDs can cluster in particular MTOD zones:

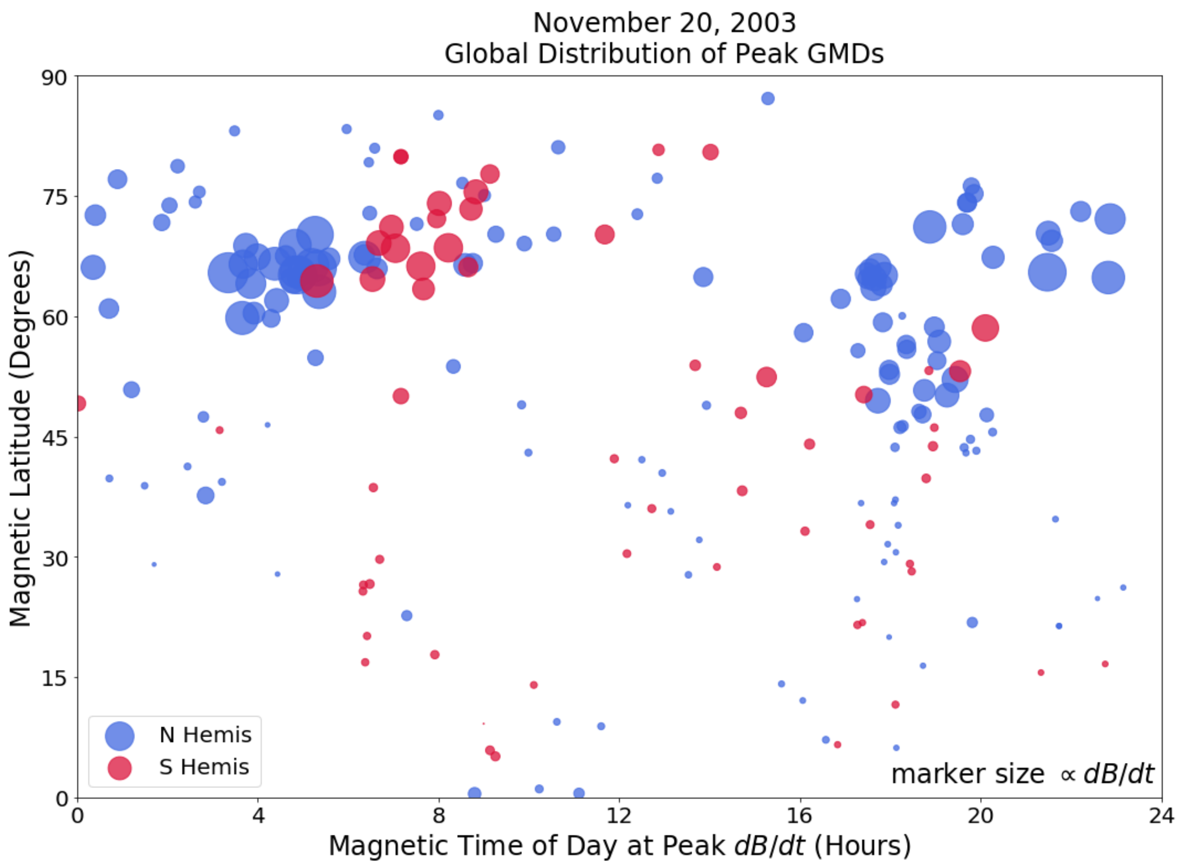

Figure 1.1: MTOD-MLAT distribution of peak GMDs during the November 20, 2003 geomagnetic storm. Larger GMDs are not distributed uniformly in MTOD, but rather tend to be clustered in the pre-dawn/dawn and evening/night sectors.

- Although it is the case that every station will have a peak value during a storm, many of these will be in the wrong MTOD sector to observe strong disturbances. Consequently, when peak GMDs from all MTODs are considered, this leads to a systematic decrease in the average peak GMD at a given latitude and it implies a greater variation of magnitudes (possibly skewing towards lower values) than is actually representative.
  - 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. A statistical analysis that accounts for MTOD clustering of peak GMDs would provide a better estimate of the true worst-case scenario. This research would be incorporated into TPL-007 as a possible new scaling factor.

- **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.** Study Markov Chain models for generating spatiotemporal behavior of defined GMD events.
  - The purpose of this work is to study credible models of extreme GMD events based on historical data. Data from the database developed in Step 1 will be used to study 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.

    For example, the current reference time series is taken from the 1989 Quebec Hydro event. It is unknown if this is a representative time series for a 1-in-100 year or Carrington-type event (it does not represent the largest disturbances measured during this event). This is very important because, although past storms may be similar to future ones, it is almost certainly the case that they will not be identical to them. Predicting the characteristics of future events requires the research to quantify and understand the range of potential values that model variables could take on, even though it may not be observed. Severe GMDs are the result of multiple physical processes occurring on different spatial and temporal scales and many of these processes are, for all practical purposes, random. A Markov Chain approach acknowledges the inherently random nature of these processes and evolves the state of the system (e.g., a ground magnetometer time series) in a probabilistic manner rather than assuming a given historical behavior.

    Using this probabilistic Markov Chain approach, it is possible to generate an arbitrary number of statistically similar but functionally different time series. An ensemble of many such time series can be used to provide uncertainty bounds on the characteristics of extreme GMDs, and the properties of the current reference time series can be contextualized by its relationship to these bounds. If the reference time series is well-bounded by the MC ensemble, then it can continue to be used, with its application justified by rigorous statistical analysis; if the reference time series falls outside of the Markov Chain ensemble bounds, then the research can identify the factors that lead to its being unrepresentative and can propose a new, more appropriate model.

  - A product of this research will be a detailed report describing the findings, which will include quantification of uncertainty (QU) in the statistical models.

- 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.[14,15] Ngwira et al showed that modern MHD models are now mature enough for extreme studies and indicated possible fundamental changes in the system response under extreme solar driving conditions. This research will include the latest advancements in geospace models implemented at NASA and move from initial exploration by Ngwira et al into systematic analysis of modeled extremes. 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 documented 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 North American BPS 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 BPS.

[14] 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).

[15] 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 and documented accordingly.[16,17]
- 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. Results will be documented in the technical report.

Expected Deliverables and Estimated Completion

Table 1.1: Task 1 Deliverables	
Deliverable	**Estimated Completion**
Database of localized extreme events, including ground-based and space-based data (**Task 1A**). The database will be made available to the public.	Q1 2019
Final technical report to provide additional technical support for the existing supplementary (localized) benchmark; or, propose update to the benchmark, as appropriate	Q4 2019

[16] *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.

[17] *Transformer Thermal Impact Assessment* white paper, NERC Project 2013-03 Geomagnetic Disturbance Mitigation (May 2016, and October 2017), available at 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 1-in-100 year GMD event on lower geomagnetic latitudes.

Background

Task 2 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," the Commission directed NERC to reexamine the geomagnetic latitude scaling factors provided in TPL-007-1.[18] Consistent with the Commission's directive, NERC would use existing models and develop new models to extrapolate from historical data the impacts of a large, 1-in-100 year GMD event on lower geomagnetic latitudes under this task.

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

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 new published work (e.g., by United States Geological Survey (USGS) and Los Alamos National Laboratory (LANL)), on the geomagnetic latitude scaling. The review will include discussions with the researchers that published the works to determine whether modifications are needed to the scaling factors in Reliability Standard TPL-007-1.
  - This review will include recommendations for further actions, which 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 USGS, 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.

[18] Order No. 830 at P 57.

- For example, during the extreme storms of solar cycle 23, there were approximately 200 active ground magnetometer stations distributed across a broad range of latitudes and longitudes during each event. Even so, as demonstrated in ***Figure 2.1***, the global distribution of stations is still rather sparse.

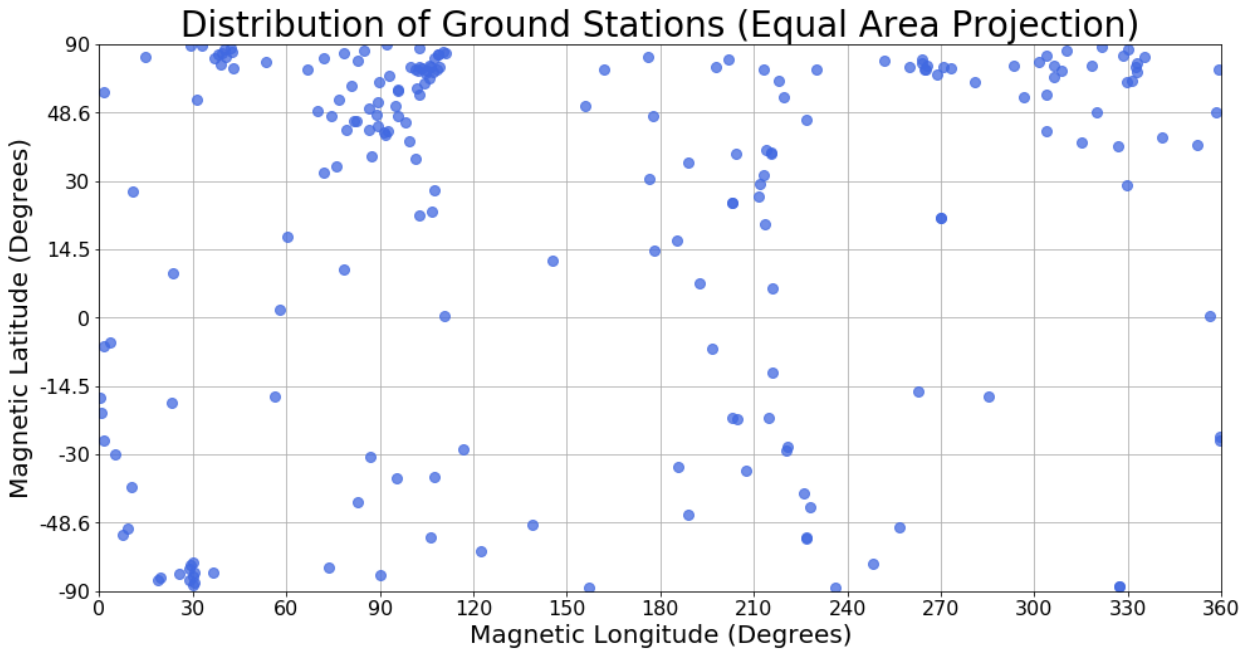

Figure 2.1: Spatial distribution of ground magnetometer stations.

- However, if the research only looks at the magnetic latitude of stations, their distribution is actually quite good. This is particularly true at mid-to-high latitude where the spatial density of the stations is higher. This is also the region, which typically features the most intense GMDs, as can be seen by looking at the latitudinal profile of peak GMDs in ***Figure 2.2***.
- By discretizing the latitude range and considering groups of stations rather than individual stations, as suggested by ***Figure 2.2***, the research can characterize the GMDs based on statistics of the group of stations. This research could be incorporated into TPL-007 as a possible revision to the latitudinal scaling coefficient, α.

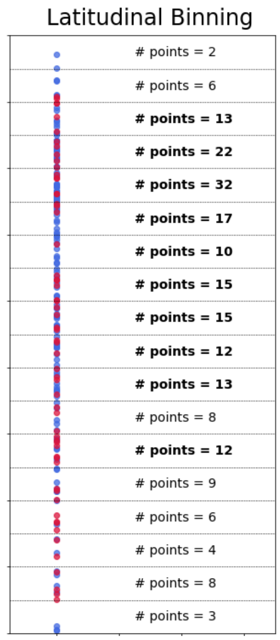

Figure 2.2: Latitudinal distribution of GMDs and binning of stations for statistical analysis.

- 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.
  - This includes determining whether new analyses and observations support modifying the use of single station readings to modify the latitude scaling based on the above analysis. A detailed investigation of data from stations at all latitudes and local times will be conducted in order to determine how GMD scaling is affected by variations in magnetic time of day, geomagnetic storm intensity, and conditions in the solar wind.
  - Understanding that, in the absence of new observations of geomagnetic field variations 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 included in the final technical report.

Expected Deliverable and Estimated Completion

Table 2.1: Task 2 Deliverables	
Deliverable	**Estimated Completion**
Review of peer-reviewed research regarding the effects of geomagnetic latitude on geoelectric fields	Q2 2019
Technical report to provide either additional technical support for existing latitude scaling factors; or, propose updated values for latitude scaling factors, as appropriate.	Q4 2019

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).

Background

In Order No. 830, the Commission expressed concerns regarding the ground conductivity models that form the basis for the earth conductivity scaling factors used in TPL-007-1 and directed NERC to study this issue as part of its Work Plan.[19] Accordingly, research activities in **Task 3** address the Commission'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 "coastal effects."

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

Activities

Task 3A: 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 empirical 3D Electromagnetic Transfer Functions (EMTFs)[20]. 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 magnitude and 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. This analysis will be displayed in a map illustrating the differences of the 1D and 3D response.
        - **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).

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

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

– Modified 1D models for all physiographic regions where changes are deemed necessary. These will be given as surface impedances or descriptions of conductivity versus depth. This will be displayed in a table and a figure for each physiographic region.

– A NERC operating area map identifying regions of 1D and 3D validity, based on potential for geoelectric field rotation.

– Guidance for the use of 1D models in continental U.S. regions that are ambiguous or not covered by the Fernberg report.[21]

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 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 sample rate, 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. Published works (e.g., Gannon et al., 2017; Butala et al., 2017; USGS and NASA publications) will be used to support this task, and collaboration with National Science Foundation (NSF) and other research efforts (e.g. Texas A&M University Hazard Science Engineering and Education for Sustainability (SEES) project, NASA research) will be utilized, as possible.
  - 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 Electromagnetic Transfer Functions (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

[21] See EPRI report 1026430, *One-Dimensional Earth Resistivity Models for Selected Areas of Continental United States & Alaska*, 2012

bathymetry data must be used to estimate the potential coastal effect. The following steps will be performed to produce a frequency dependent model:

- **Step 1**. Calculate the geoelectric field using best available conductivity models 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 coastal 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 complex conductivity effects.
  - **Step 2**. Calculate the electric field using 1D and 3D models.
  - **Step 3**. Estimate GIC using these electric field inputs and compare to GIC measurements, where possible.
  - **Step 4**. Modify spatial extent of complex conductivity region 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 coastal 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 Deliverables and Estimated Completion

Table 3.1: Task 3 Deliverables	
Deliverable	**Estimated Completion**
Task 3A technical report	Q4 2018
Task 3B technical report	Q3 2019
Task 3C technical report	Q4 2019

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

Background

Task 4 research 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 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.[22]

In Order No. 830, the Commission directed NERC to perform additional research related to the transformer thermal impact assessments required by the TPL-007 standard. Specifically, the Commission directed NERC to study, as part of its Work Plan, how "the geoelectric field time series can be applied to a particular transformer so that the orientation of the time series, over time, will maximize GIC flow in the transformer . . . ."[23] **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.

Task 4 research will also provide insights for application in subsequent versions of the TPL-007 standard. For example, proposed Reliability Standard TPL-007-2 was developed to address FERC directives including revision to transformer thermal impact assessment requirements to account for potential impacts of geoelectric field enhancements.[24] The proposed standard requires entities to perform supplemental thermal impact assessments of applicable power transformers based on GIC information for the supplemental GMD event described in **Task 1**. The screening criterion for performing supplemental thermal impact assessments is 85 A per phase or greater based on analysis described in the Screening Criterion for Transformer Thermal Impact Assessment White Paper that was developed by the TPL-007-2 Standard Drafting Team (SDT).[25]

Activities

- Determine how the benchmark geoelectric field wave shape can be applied to individual transformers to determine worst-case hotspot heating.

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

[23] Order No. 830 at P 66.

[24] See TPL-007-2 Petition at Section IV.B.2.

[25] *See id.* at Exhibit H.

- **Step 1**. Calculate GIC (t) using the Benchmark geoelectric field time series and steady state GIC results for an equivalent circuit orientation (using a GIC_E and GIC_N, worst case for an 8 V/km peak geoelectric field) 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 equivalent circuit orientations, e.g. 0°, 10°, 20°, 180°, and compare the resulting hotspot temperatures, θ (t), for each orientation and a maximum GIC value established in Step 1.
- **Step 3.** The results from Step 2 provide a range of equivalent circuit orientations that produce different hot spot temperatures for the same maximum steady state GIC. Determine temperature variability as a function of orientation for the benchmark waveform.
- **Step 4.** Evaluate the effects of phase shifting the benchmark geoelectric field time series on θ (t). Examine if there is a dominant geoelectric field orientation during the time period material to peak hot spot temperatures.
- **Step 5.** Compare the benchmark waveform with other major GMD events, (e.g. TPL-007-2 supplemental GMD event, Halloween storm) and determine if there are physically justified phase angle variations during the time period that leads to highest hot spot temperatures. If this is not the case, identify the equivalent circuit orientations where that is the case.
- **Step 6.** Examine and quantify in a technical report the effects of phase shifting and equivalent circuit orientation with respect to maximum hot spot temperatures.
  - Identify and quantify potential error bars in transformer thermal assessments.
  - Apply methods to transformer thermal assessments such that geoelectric field orientation maximizes GIC flow and/or hot spot temperatures.

Expected Deliverable and Estimated Completion

Table 4.1: Task 4 Deliverables	
Deliverable	**Estimated Completion**
Technical report	Q4 2019

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. Research for this task will address these potential impacts on power transformers, which includes analyzing the 75A/phase TPL-007 criterion used for transformer thermal impact assessments. The work will:

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

Background

This task is intended to address the Commission's directive to "include further analysis of the thermal impact assessment qualifying threshold" of 75 A per phase and to "address the effects of harmonics, including tertiary winding harmonic heating and any other effects on transformers" in NERC's Work Plan.[26]

Task 5 research will also provide insights for application in subsequent versions of the TPL-007 standard. For example, proposed Reliability Standard TPL-007-2 was developed to address FERC directives including revision to transformer thermal impact assessment requirements to account for potential impacts of geoelectric field enhancements.[27] The proposed standard requires entities to perform supplemental thermal impact assessments of applicable power transformers based on GIC information for the supplemental GMD event described in **Task 1**.

Activities

- **Step 1.** Create and validate existing transformer tools to ensure accurate prediction of thermal responses to GICs. This step will consist of validating existing industry transformer tools with all data that is presently available [28] and with upcoming field/laboratory test results.
  - For example, the recently developed NERC thermal tool shown in **Figure 5.1** is one example of an industry transformer tool that can be used to study the additional hotspot heating which occurs when a transformer is driven into half-cycle saturation by the flow of GIC. This tool is an open source tool that provides the winding and structural hotspot heating of the modeled transformer. This tool can be used to study various GIC time-sequence waveforms that a transformer will be exposed to during a GMD storm. This tool will be used among others will be validated against all available data to ensure accurate prediction of thermal responses to GICs.

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

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

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

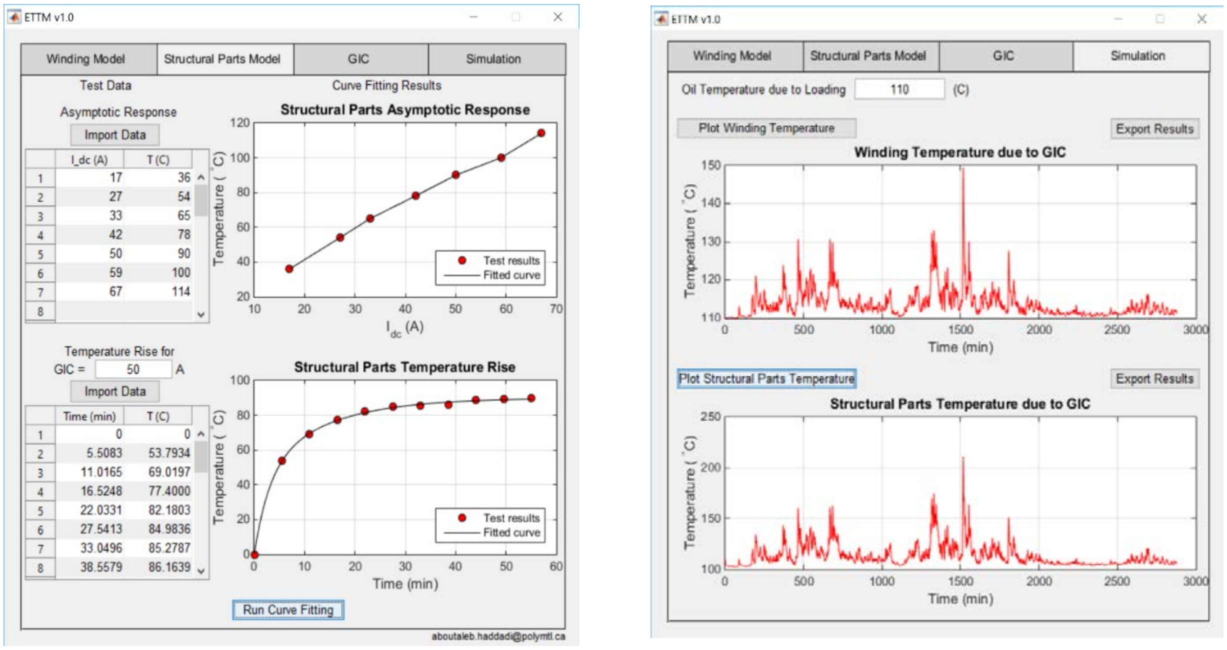


Figure 5.1: GIC Transformer Thermal Analysis Tool

- **Step 2**. 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 3**. Determine the effects of short-term harmonic currents resulting from part-cycle saturation on tertiary winding heating. This will be accomplished by using 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 (step 1). 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 4**. Additional transformer thermal analyses will be performed on transformer models (step 1) to assess the efficacy of the existing 75A/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 available transformer thermal models and the additional temperature limits developed in the above steps.
  - Additional transformer modeling will be included in a technical report.

Expected Deliverable and Estimated Completion

Table 5.1: Task 5 Deliverables

Deliverable	Estimated Completion
Technical report	Q4 2019

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 existing and new GIC data and magnetometer data. The purpose of this data collection is to respond to FERC's Order No. 830 directive to collect GMD monitoring data and to make that data publically available.

Background

The Commission directed NERC to collect GMD monitoring data pursuant to its authority under Section 1600 of the NERC Rules of Procedure for the period beginning May 2013, including data existing as of that date and new data going forward, and to make that information available.[29] The data is intended to promote greater understanding of GMD events and their potential impacts to the reliable operation of the BPS. For example, measured GIC and magnetometer data can help validate various models used in calculating GICs and assessing their impacts in power systems. FERC directed that NERC should make the collected GIC and magnetometer data available to support ongoing research and analysis of GMD risk.[30]

NERC and the GMDTF have drafted a proposed GMD Data Request for the collection of GIC monitoring and magnetometer data as required by Order No. 830. The GMD Data Request applies to U.S. registered Transmission Owners and Generator Owners. Although not required, Canadian registered Transmission Owners and Generator Owners are encouraged to participate. Many Transmission Owners and Generator Owners collect GMD data and may have GMD data for the period beginning in May 2013. The data request will apply to entities that have specified GMD data.

Activities in this task support development of data reporting instructions, data collection criteria, and development of processes for maintaining a GMD data collection program. NERC plans to conduct outreach through the GMDTF 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 objective is to maintain a high-quality collection of GIC and magnetometer data for industry and research use.

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

[29] Order No. 830 at P 89.

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

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.

- 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.
  - For example, the data request will specify methods for providing data to NERC database such as, email data files, upload to site using file transfer protocol (FTP).

Expected Deliverables and Estimated Completion

Table 6.1: Task 6 Deliverables

Deliverable	Estimated Completion
Criteria to Support a Request for Data or Information under Section 1600 of the NERC Rules of Procedure	Q2 2018
NERC Board-approval of Section 1600 Data Request	Q3 2018
Data Reporting Instruction with details of GIC monitor and magnetometer specifications, format for data request, and information technology requirements	Q1 2019
Implementation of GMD Data Collection	Q4 2019

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

Summary

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

Background

Task 7 builds upon the other work in NERC's Work Plan and is intended to improve scientific understanding and advance the models and tools available for modeling GIC. **Task 7** involves evaluating available tools for calculating geoelectric field from magnetic field data for a given earth conductivity structure and developing guidance as necessary to meet the needs of the industry. This task 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 the Commission's guidance.[31]

Activities

- Evaluate project tools
  - Although there are standard methods for estimating geo-electric field, differences in data processing methods and algorithm implementation may affect the estimation of peak geo-electric fields. Evaluation of the tools used in this project will be made based on comparison with publicly available geo-electric field calculation tools. This will provide benchmarking of electric field estimates against established algorithms, to ensure that calculated beta factor results are accurate and consistent with best practice techniques.
- Calculate and evaluate beta scaling factors
  - The benchmark GMD event associated with TPL-007-1 applies scaling factors that take into account the location of interest with respect to high-latitude electric currents systems (alpha scaling factor) and local geological conditions. The local geological conditions are captured in terms of "beta scaling" factors that are used to adjust the benchmark geoelectric field amplitude to account for the variations in the ground response. The default beta factors are based on approximate 1-dimensional physiographic ground conductivity models that were developed by Fernberg.[32]
  - Since the Fernberg (2012) work, significant new information has become available about the local ground conductivity structures and corresponding ground electromagnetic responses. In the U.S., the new information was provided by the NSF's EarthScope project that implemented very large magnetotelluric (MT) survey across the U.S. The surface impedance tensors obtained from the MT survey are now available and provide an opportunity to update the ground responses used in TPL-

[31] *See* Order No. 830 at P 79, in which the Commission stated:

> In addition, the large variances described by [United States Geological Survey] in actual 3-D ground conductivity data raise the question of whether one time series geomagnetic field is sufficient for vulnerability assessments. The characteristics, including frequencies, of the time series interact with the ground conductivity to produce the geoelectric field that drives the GIC. Therefore, the research should address whether additional realistic time series should be selected to perform assessments in order to capture the time series that produces the most vulnerability for an area.

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

007-1. More specifically, there is an opportunity to revise the beta scaling factors with the direct empirical MT information from EarthScope. The goal of this task is to improve the accuracy of beta scaling factors for updated US conductivity regions based on newly available 3D conductivity information. In addition, an assessment of how much beta factors can vary under different conditions will be performed.

- **Step 1**. New MT information from EarthScope will be used together with the benchmark waveform to compute new "local" beta factors. The beta factors are revised for all locations from which MT information is available. Full three-dimensional induction effects are taken into account by using the full surface impedance tensors derived from the MT surveys. Smoothing techniques will be considered to account for the sometimes extremely local response of the geoelectric field in the MT surveys. Comparisons will be made with the original Fernberg model-based beta factors and recommendations will be made about possible revisions. All new results will documented and included in the technical report.

- **Step 2**. Using the latest empirical information about the ground response in the NERC operating area, 1D ground model-based beta factors will be modified as required to accurately reflecting the average 3D response. Step 1 will provide calculated "local" beta factors calculated at locations where 3D empirical response information is available. These will be considered in generating new "regional" beta factors. The inclusion of 3D conductivity outliers and highly localized effects will be evaluated to determine the impact, if any, on regional average response.
- **Step 3**. Recommendations will also be made about the best practices in utilizing the new beta scaling information. The effectiveness of regional averages will be evaluated for each conductivity region and recommendations will be made on the appropriate usage of scaling factors in each region.
- **Step 4**. Evaluate the sensitivity of beta factor calculation to a varying magnetic field input. The directionality of the geomagnetic field used to calculate peak electric fields may greatly affect results when using 3D conductivity models. The evaluations will include tests of magnetic field direction on 3D estimates to determine the worst case orientation conditions, and evaluation of the impact of storm-time spectral content on beta factor calculation. Multiple magnetic field inputs of different spectral characteristics will be tested; including recorded past events and modeled waveforms.
- **Step 5**. Simple GIC estimates will be made using on beta factor ranges and comparisons with **Task 3** results will be made.

Expected Deliverables and Estimated Completion

Table 7.1: Task 7 Deliverables

Deliverable	Estimated Completion
Technical report of tool evaluation and electric field estimate benchmarking results.	Q4 2018
Technical report of calculated beta factors based on updated conductivity profiles for the NERC operating area, with evaluation of scaling factor ranges and sensitivities to differences in magnetic field input	Q4 2019

Task 8: Improve Harmonics Analysis Capability

Summary

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

Background

GMD-related harmonics are caused by the part-cycle saturation of transformers. These harmonic currents and voltages resulting from transformer saturation have had major impact on system operations and security during severe GMD events in the past.[33] Harmonics studies are an integral part of any TPL-007 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 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 benchmark GMD events can be accurately assessed. Such difficulties and gaps include (but are not limited to)[34]:

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

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

Activities

- **Step 1**. Perform research necessary to develop models and methods to improve capability of performing harmonic assessments of benchmark GMD events. Initial focus will be on developing an algorithm 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 GMD analysis tool will be developed. Included in this development, a benchmark GMD system model will be created to accurately assess and verify both time-domain models and the newly developed GMD harmonic tool. This will provide confidence in models that

[33] *See, e.g.,* NERC, *March 13, 1989 Geomagnetic Disturbance* white paper, available at http://www.nerc.com/files/1989-quebec-disturbance.pdf.

[34] EPRI, *Analysis of Geomagnetic Disturbance (GMD) Related Harmonics* (2014). 3002002985.

are developed as a part of this research activity. The developed software tool will be documented to provide a benchmark example.

- **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 (SVCs), etc.); and
  - Facilitate the implementation of GMD harmonic assessments in commercially available software tools.
- Additionally, a harmonics modeling demonstration will be conducted at the GMDTF meeting to facilitate knowledge transfer.
- The deliverables from this task would be open source harmonics assessment software/tools and technical report on the harmonic tool and guidelines in its use.

Expected Deliverables and Estimated Completion

Table 8.1: Task 8 Deliverables	
Deliverable	**Estimated Completion**
Beta version of the open source software tool	Q4 2018
Open source software tool	Q4 2019
Technical report	Q4 2019

Task 9: Harmonic Impact Studies

Summary

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

Background

GMD-related harmonics can cause the phenomenon of magnetostriction in the cores of large power transformers, resulting in noise and vibration during GMD events. In Order No. 830, FERC directed NERC to examine the effects of harmonics on BPS equipment as part of the Work Plan.[35]

Activities

Transformer Harmonic Assessment Overview:[36]

- In Phase 1 of the project, available data on the following will be presented and reviewed:
  - Typical magnitudes and frequency spectrum of tank vibrations of power transformers in absence of GIC
  - Detailed analysis of impact of GIC on Sound level and harmonic content of power transformer audible noise.
- In Phase 2 of the project, tank vibration measurements will be performed on two large power transformers when under typically low levels of GIC and mathematical relationships between these tank vibrations and low and high levels of GIC flowing in the neutral of these transformers will be developed. The overall objective of this research is to advance the research to provide guidance on the following:
  - Would a severe GMD storm / high levels of GIC mechanically damage transformers?
  - Could vibration measurements be used to develop a GIC level screening criterion?
  - How would long – term exposure to vibrations (caused by GIC) impact the integrity of transformers?

Transformer Harmonic Assessment Research Activities

- Phase 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).

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

[36] *Note*: the impacts of transformer heating are covered in detail in Task 4 and 5 of this plan. This section will focus mainly on the impacts of vibrations on power transformers caused by the part-cycle saturation of the transformer due to GMD events.

- 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.

- Phase 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 Research Activities

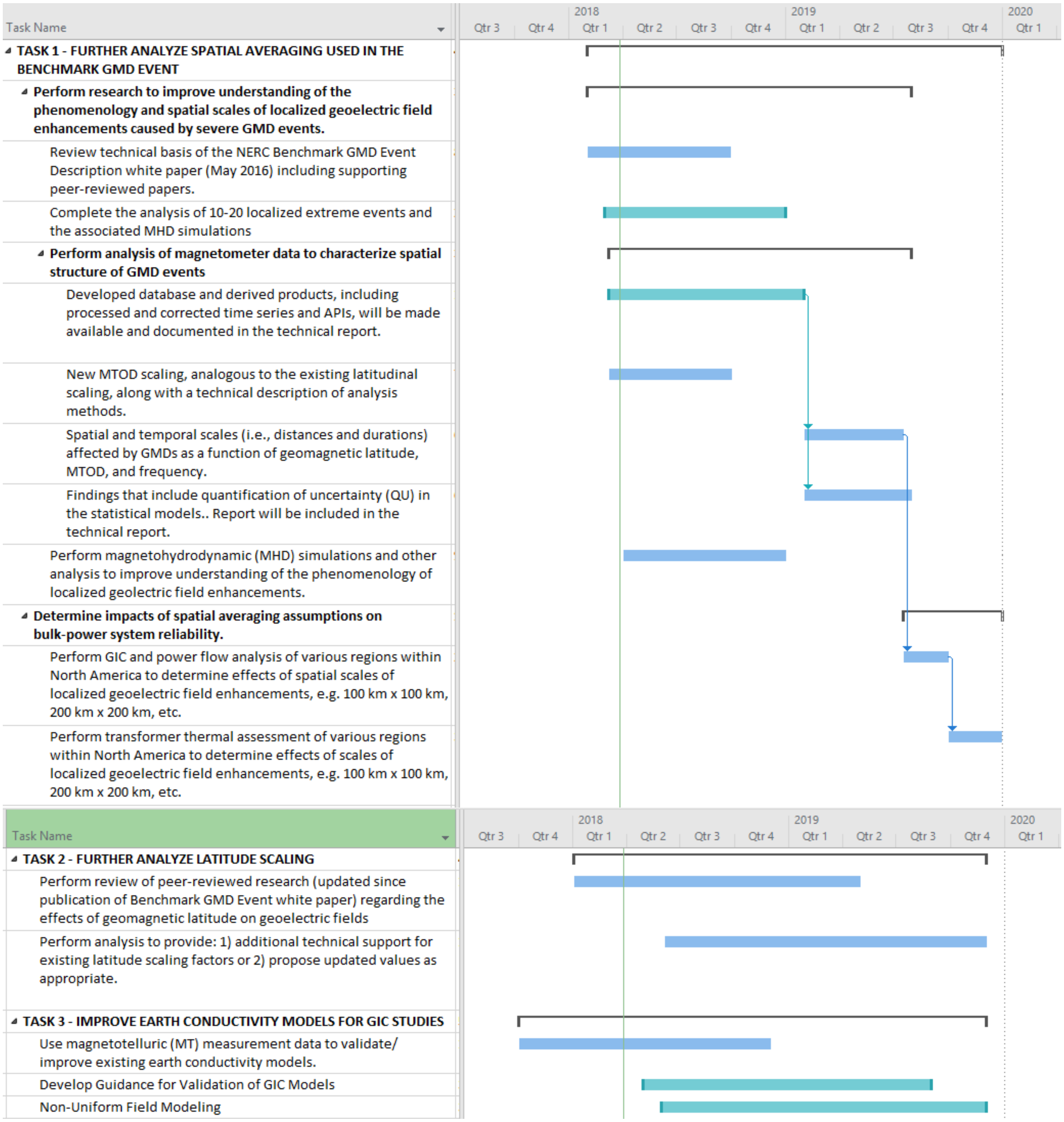
- **Step 1**. Perform assessment of harmonic effects on generators to improve understanding of gaps in existing Reliability Standards with harmonic levels that are unique to GMD events. This assessment will include all available published and existing EPRI research.
- **Step 2.** Provide example/guidance for the level of expected GMD related harmonics that could potentially be sourced from a generator.
- **Step 3.** Compare the results from step 2 to published standards (step 1) 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;
  - Identify potential issues that are already addressed in the standards; and
  - Identify future scoping and testing needs.

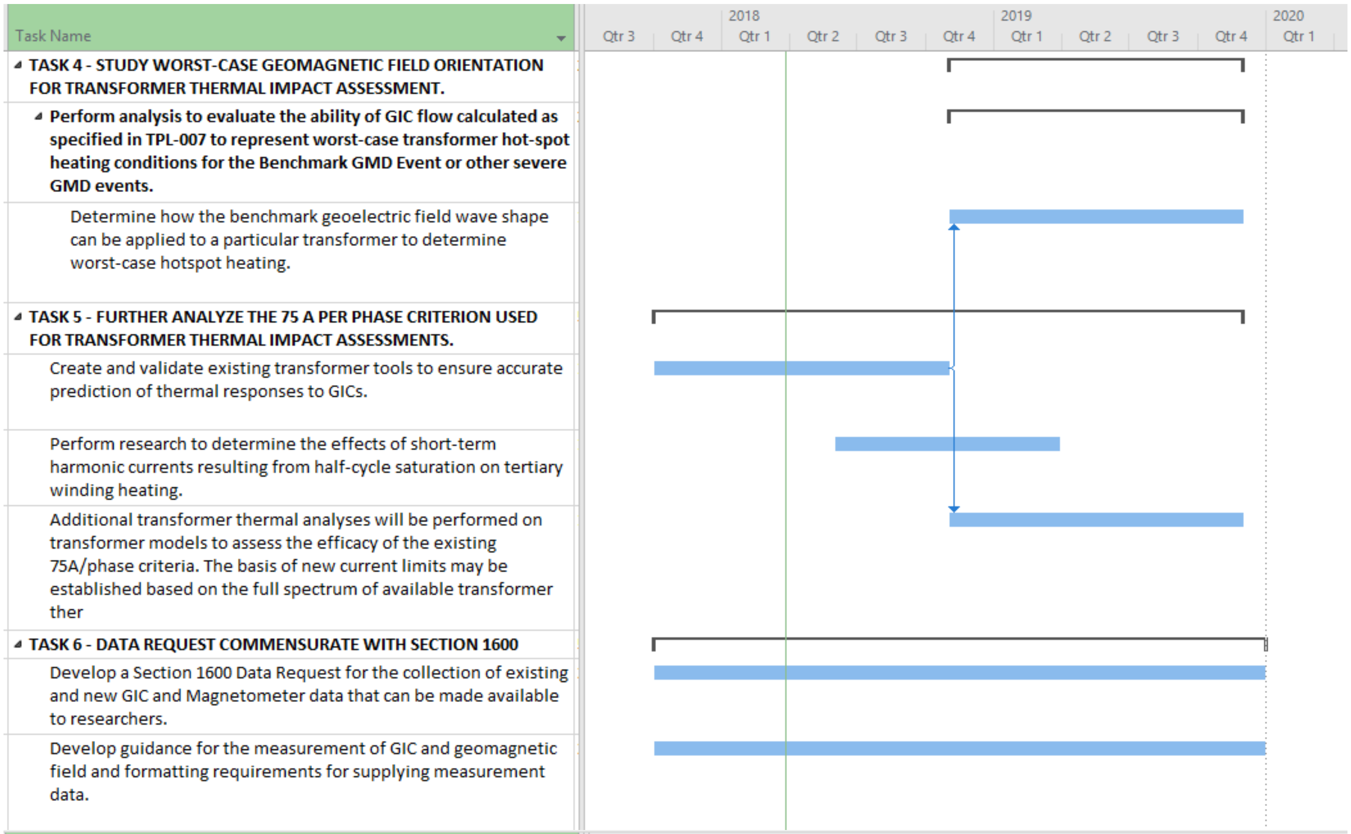
Expected Deliverable and Estimated Completion

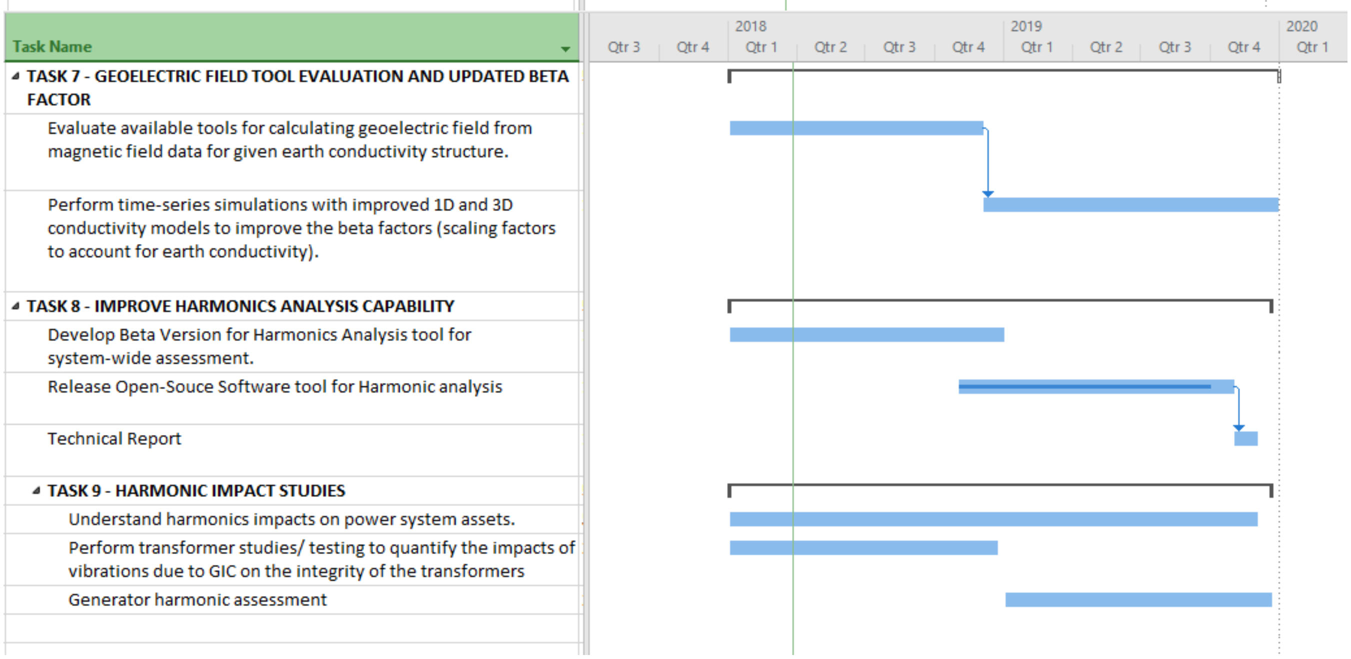
Table 9.1: Task 9 Deliverables	
Deliverable	**Estimated Completion**
Transformer technical report	Q4 2018
Generator technical report	Q4 2019

Schedule for Individual Tasks

EPRI has provided the following schedule of estimated completion times and activities for **Task 1 through Task 9**.




Task Name
2018
2019
2020
Qtr 3
Qtr 4
Qtr 1
Qtr 2
Qtr 3
Qtr 4
Qtr 1
Qtr 2
Qtr 3
Qtr 4
Qtr 1
TASK 4 - STUDY WORST-CASE GEOMAGNETIC FIELD ORIENTATION FOR TRANSFORMER THERMAL IMPACT ASSESSMENT.
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 severe GMD events.
Determine how the benchmark geoelectric field wave shape can be applied to a particular transformer to determine worst-case hotspot heating.
TASK 5 - FURTHER ANALYZE THE 75 A PER PHASE CRITERION USED FOR TRANSFORMER THERMAL IMPACT ASSESSMENTS.
Create and validate existing transformer tools to ensure accurate prediction of thermal responses to GICs.
Perform research to determine the effects of short-term harmonic currents resulting from half-cycle saturation on tertiary winding heating.
Additional transformer thermal analyses will be performed on transformer models to assess the efficacy of the existing 75A/phase criteria. The basis of new current limits may be established based on the full spectrum of available transformer ther
TASK 6 - DATA REQUEST COMMENSURATE WITH SECTION 1600
Develop a Section 1600 Data Request for the collection of existing and new GIC and Magnetometer data that can be made available to researchers.
Develop guidance for the measurement of GIC and geomagnetic field and formatting requirements for supplying measurement data.


Task Name
2018
2019
2020
Qtr 3
Qtr 4
Qtr 1
Qtr 2
Qtr 3
Qtr 4
Qtr 1
Qtr 2
Qtr 3
Qtr 4
Qtr 1
TASK 7 - GEOELECTRIC FIELD TOOL EVALUATION AND UPDATED BETA FACTOR
Evaluate available tools for calculating geoelectric field from magnetic field data for given earth conductivity structure.
Perform time-series simulations with improved 1D and 3D conductivity models to improve the beta factors (scaling factors to account for earth conductivity).
TASK 8 - IMPROVE HARMONICS ANALYSIS CAPABILITY
Develop Beta Version for Harmonics Analysis tool for system-wide assessment.
Release Open-Souce Software tool for Harmonic analysis
Technical Report
TASK 9 - HARMONIC IMPACT STUDIES
Understand harmonics impacts on power system assets.
Perform transformer studies/ testing to quantify the impacts of vibrations due to GIC on the integrity of the transformers
Generator harmonic assessment