

Agenda

Project 2013-03 Geomagnetic Disturbance Mitigation Standard Drafting Team Meeting

March 28, 2017 | Noon - 1:15 p.m. Eastern

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NERC Antitrust Compliance Guidelines and Public Announcement

Agenda Items

1. Chair's Remarks
2. Review working draft Supplemental GMD Event Description white paper*
3. Review working draft TPL-007-2*
4. Discuss meeting objectives and details for April in-person meeting
5. Future Meetings
 - a. April 18-20 | NERC Headquarters, Atlanta
 - i. Meeting starts at 1 p.m. eastern on April 18 and concludes by noon on April 20

A. Introduction

1. **Title:** Transmission System Planned Performance for Geomagnetic Disturbance Events
2. **Number:** TPL-007-~~1~~2
3. **Purpose:** Establish requirements for Transmission system planned performance during geomagnetic disturbance (GMD) events.
4. **Applicability:**
 - 4.1. **Functional Entities:**
 - 4.1.1 Planning Coordinator with a planning area that includes a Facility or Facilities specified in 4.2;
 - 4.1.2 Transmission Planner with a planning area that includes a Facility or Facilities specified in 4.2;
 - 4.1.3 Transmission Owner who owns a Facility or Facilities specified in 4.2;
 - 4.1.4 Generator Owner who owns a Facility or Facilities specified in 4.2.
 - 4.2. **Facilities:**
 - 4.2.1 Facilities that include power transformer(s) with a high side, wye-grounded winding with terminal voltage greater than 200 kV.
5. **Background:**

During a GMD event, geomagnetically-induced currents (GIC) may cause transformer hot-spot heating or damage, loss of Reactive Power sources, increased Reactive Power demand, and Misoperation(s), the combination of which may result in voltage collapse and blackout.
6. **Effective Date:**

See Implementation Plan for TPL-007-1

B. Requirements and Measures

- R1.** Each Planning Coordinator, in conjunction with its Transmission Planner(s), shall identify the individual and joint responsibilities of the Planning Coordinator and Transmission Planner(s) in the Planning Coordinator's planning area for maintaining models and performing the study or studies needed to complete GMD Vulnerability Assessment(s).
[Violation Risk Factor: Lower] [Time Horizon: Long-term Planning]
- M1.** Each Planning Coordinator, in conjunction with its Transmission Planners, shall provide documentation on roles and responsibilities, such as meeting minutes, agreements, copies of procedures or protocols in effect between entities or between departments of a vertically integrated system, or email correspondence that identifies an agreement has been reached on individual and joint responsibilities for maintaining models and

performing the study or studies needed to complete GMD Vulnerability Assessment(s), in accordance with Requirement R1.

- R2.** Each responsible entity, as determined in Requirement R1, shall maintain System models and GIC System models of the responsible entity’s planning area for performing the study or studies needed to complete GMD Vulnerability Assessment(s). *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*
- M2.** Each responsible entity, as determined in Requirement R1, shall have evidence in either electronic or hard copy format that it is maintaining System models and GIC System models of the responsible entity’s planning area for performing the study or studies needed to complete GMD Vulnerability Assessment(s).
- R3.** Each responsible entity, as determined in Requirement R1, shall have criteria for acceptable System steady state voltage performance for its System during the benchmark GMD event described in Attachment 1. *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*
- M3.** Each responsible entity, as determined in Requirement R1, shall have evidence, such as electronic or hard copies of the criteria for acceptable System steady state voltage performance for its System in accordance with Requirement R3.

Benchmark GMD Vulnerability Assessment(s)

- R4.** Each responsible entity, as determined in Requirement R1, shall complete a **benchmark** GMD Vulnerability Assessment of the Near-Term Transmission Planning Horizon once every 60 calendar months. This **benchmark** GMD Vulnerability Assessment shall use a study or studies based on models identified in Requirement R2, document assumptions, and document summarized results of the steady state analysis. *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*
 - 4.1.** The study or studies shall include the following conditions:
 - 4.1.1.** System On-Peak Load for at least one year within the Near-Term Transmission Planning Horizon; and
 - 4.1.2.** System Off-Peak Load for at least one year within the Near-Term Transmission Planning Horizon.
 - 4.2.** The study or studies shall be conducted based on the **benchmark** [PAL1]GMD event described in Attachment 1 to determine whether the System meets the performance requirements for the steady-state planning benchmark GMD event contained in Table 1.
 - 4.3.** The **benchmark** GMD Vulnerability Assessment shall be provided within 90 calendar days of completion to the responsible entity’s Reliability Coordinator, adjacent Planning Coordinators, adjacent Transmission Planners, and to any functional entity that submits a written request and has a reliability-related need.

- 4.3.1. If a recipient of the benchmark GMD Vulnerability Assessment provides documented comments on the results, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.
- M4.** Each responsible entity, as determined in Requirement R1, shall have dated evidence such as electronic or hard copies of its GMD Vulnerability Assessment meeting all of the requirements in Requirement R4. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has distributed its GMD Vulnerability Assessment within 90 calendar days of completion to its Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and to any functional entity who has submitted a written request and has a reliability-related need as specified in Requirement R4. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email notices or postal receipts showing recipient and date, that it has provided a documented response to comments received on its GMD Vulnerability Assessment within 90 calendar days of receipt of those comments in accordance with Requirement R4.
- R5.** Each [PAL2] responsible entity, as determined in Requirement R1, shall provide GIC flow information to be used for the transformer thermal impact assessment specified in Requirement R6 to each Transmission Owner and Generator Owner that owns an applicable Bulk Electric System (BES) power transformer in the planning area. The GIC flow information shall include: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*
- 5.1. The maximum effective GIC value for the worst case geoelectric field orientation for the benchmark GMD event described in Attachment 1. This value shall be provided to the Transmission Owner or Generator Owner that owns each applicable BES power transformer in the planning area.
- 5.2. The effective GIC time series, GIC(t), calculated using the benchmark GMD event described in Attachment 1 in response to a written request from the Transmission Owner or Generator Owner that owns an applicable BES power transformer in the planning area. GIC(t) shall be provided within 90 calendar days of receipt of the written request and after determination of the maximum effective GIC value in Part 5.1.
- M5.** Each responsible entity, as determined in Requirement R1, shall provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided the maximum effective GIC value to the Transmission Owner and Generator Owner that owns each applicable BES power transformer in the planning area as specified in Requirement R5, Part 5.1. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided GIC(t) in response to a written request

from the Transmission Owner or Generator Owner that owns an applicable BES power transformer in the planning area.

- R6.** Each Transmission Owner and Generator Owner shall conduct a benchmark thermal impact assessment for its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A per phase or greater. The benchmark thermal impact assessment shall: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*
- 6.1.** Be based on the effective GIC flow information provided in Requirement R5;
 - 6.2.** Document assumptions used in the analysis;
 - 6.3.** Describe suggested actions and supporting analysis to mitigate the impact of GICs, if any; and
 - 6.4.** Be performed and provided to the responsible entities, as determined in Requirement R1, within 24 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1.
- M6.** Each Transmission Owner and Generator Owner shall have evidence such as electronic or hard copies of its benchmark thermal impact assessment for all of its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A per phase or greater, and shall have evidence such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided its thermal impact assessment to the responsible entities as specified in Requirement R6.
- R7.** Each responsible entity, as determined in Requirement R1, that concludes, through the benchmark GMD Vulnerability Assessment conducted in Requirement R4, that their System does not meet the performance requirements of Table 1 shall develop a Corrective Action Plan addressing how the performance requirements will be met. The Corrective Action Plan shall: *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*
- 7.1.** List System deficiencies and the associated actions needed to achieve required System performance. Examples of such actions include:
 - Installation, modification, retirement, or removal of Transmission and generation Facilities and any associated equipment.
 - Installation, modification, or removal of Protection Systems or Special Protection Systems.
 - Use of Operating Procedures, specifying how long they will be needed as part of the Corrective Action Plan.
 - Use of Demand-Side Management, new technologies, or other initiatives.
 - 7.2.** Be developed within one year of completion of the GMD Vulnerability Assessment. [PAL3]

- 7.3.** Include a timetable for implementing the selected actions from Part 7.1. The timetable shall:
- 7.3.1.** Specify implementation of non-hardware mitigation, if any, within two years of development of the Corrective Action Plan;
 - 7.3.2.** Specify implementation of hardware mitigation, if any, within four years of development of the Corrective Action Plan;
 - ~~Be developed within one year of completion of the GMD Vulnerability Assessment. [PAL4]~~
 - ~~Be revised, when necessary, to document actions taken by the Responsible Entity to address circumstances outside the Responsible Entity's control that prevent the implementation of actions according to the timetable in Part 7.2. [MOSH] [PAL6]~~
- 7.4.** Be reviewed in subsequent GMD Vulnerability Assessments until it is determined that the System meets the performance requirements contained in Table 1.
- 7.5.** Be revised and reported to the Regional Entity if situations beyond the control of the responsible entity, as determined in Requirement R1, prevent implementation of the Corrective Action Plan within the timetable for implementation provided in Part 7.3, the responsible entity shall report the prohibiting circumstances, and provide an updated Corrective Action Plan and timetable for implementing the selected actions from Part 7.1 [PAL7] to the Regional Reliability Organization [CC:ERO?] [PAL8]. The report to the Regional Entity shall be updated at least once every 12 months until the actions of Part 7.3 are implemented provided documentation [PAL9] and shall include the following:
- 7.5.1.** Prohibiting circumstances causing the delay for fully or partially implementing the selected actions in Part 7.1; [reason/rationale] [PAL10]
 - 7.5.2.** Description of the original and any previous changes to the Corrective Action Plan with the associated timetable(s) for implementing the selected actions in Part 7.1; [present CAP] and
 - 7.5.3.** Description of changes to the previous Corrective Action Plan(s), including utilization of Operating Procedures, and the [PAL11] updated timetable for implementing the selected actions in Part 7.1. [new CAP]
- 7.3-7.6.** If updated Corrective Action Plan(s) including timetable(s) for implementation has been filed with the Regional Reliability Organization [cc: ERO?] [PAL12], the responsible entity, as determined in Requirement R1, shall update the filing(s) provided in Part 7.5 on an annual basis until it is determined that the System meets the performance requirements for the steady-state planning benchmark GMD event contained in Table 1. [periodic review requirement] [PAL13] [MO14]

~~7.4.7.7.~~ Be provided within 90 calendar days of ~~completion~~development or revision to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), functional entities referenced in the Corrective Action Plan, and any functional entity that submits a written request and has a reliability-related need.

~~7.4.1.7.7.1.~~ If a recipient of the Corrective Action Plan provides documented comments on the results, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.

M7. Each responsible entity, as determined in Requirement R1, that concludes, through the benchmark GMD Vulnerability Assessment conducted in Requirement R4, that the responsible entity's System does not meet the performance requirements for the steady-state planning benchmark GMD event of Table 1 shall have evidence such as electronic or hard copies of its Corrective Action Plan, as specified in Requirement R7. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has distributed its Corrective Action Plan or relevant information, if any, within 90 calendar days of its completion to its Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), a functional entity referenced in the Corrective Action Plan, and any functional entity that submits a written request and has a reliability-related need, as specified in Requirement R7. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email notices or postal receipts showing recipient and date, that it has provided a documented response to comments received on its Corrective Action Plan within 90 calendar days of receipt of those comments, in accordance with Requirement R7. [PAL15]

Supplemental GMD Vulnerability Assessment(s)

R8. Supplemental GMD Vulnerability Assessment. [PAL16] In addition to the bBenchmark GMD Vulnerability Assessment described in R4, each responsible entity, as determined in Requirement R1, shall complete a sSupplemental [PAL17] GMD Vulnerability Assessment of the Near-Term Transmission Planning Horizon once every 60 calendar months. This sSupplemental GMD Vulnerability Assessment shall use a study or studies based on models identified in Requirement R2, document assumptions, and document summarized results of the steady state analysis. [Violation Risk Factor: High] [Time Horizon: Long-term Planning]

8.1. The study or studies shall include the following conditions:

8.1.1. System On-Peak Load for at least one year within the Near-Term Transmission Planning Horizon; and

8.1.2. System Off-Peak Load for at least one year within the Near-Term Transmission Planning Horizon.

~~System On Peak Load for at least one year within the Near Term Transmission Planning Horizon; and~~

~~System Off Peak Load for at least one year within the Near Term Transmission Planning Horizon.~~ [PAL18]

8.2 Study or studies shall be conducted based on the Supplemental GMD event described in Attachment 1 to determine whether the System meets the performance requirements for the Supplemental GMD event in Table 1.

8.3 If the analysis concludes there is Cascading caused by the Supplemental GMD event described in Attachment 1, an evaluation of possible actions designed to reduce the likelihood or mitigate the consequences and adverse impacts of the event(s) shall be conducted.

8.4 The GMD Vulnerability Assessment shall be provided within 90 calendar days of completion to the responsible entity's Reliability Coordinator, adjacent Planning Coordinators, adjacent Transmission Planners, and to any functional entity that submits a written request and has a reliability-related need.

8.5 4.4.1. If a recipient of the GMD Vulnerability Assessment provides documented comments on the results, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.

M8. Each responsible entity, as determined in Requirement R1, shall have dated evidence such as electronic or hard copies of its GMD Vulnerability Assessment meeting all of the requirements in Requirement R4. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has distributed its GMD Vulnerability Assessment within 90 calendar days of completion to its Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), and to any functional entity who has submitted a written request and has a reliability-related need as specified in Requirement R4. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email notices or postal receipts showing recipient and date, that it has provided a documented response to comments received on its GMD Vulnerability Assessment within 90 calendar days of receipt of those comments in accordance with Requirement R4.

R9. Each [PAL19] responsible entity, as determined in Requirement R1, shall provide GIC flow information to be used for the supplemental transformer thermal impact assessment specified in Requirement R10 to each Transmission Owner and Generator Owner that owns an applicable Bulk Electric System (BES) power transformer in the planning area. The GIC flow information shall include: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

9.1. The maximum effective GIC value for the worst case geoelectric field orientation for the supplemental GMD event described in Attachment 1. This value shall be

provided to the Transmission Owner or Generator Owner that owns each applicable BES power transformer in the planning area.

9.2. The effective GIC time series, GIC(t), calculated using the supplemental GMD event described in Attachment 1 in response to a written request from the Transmission Owner or Generator Owner that owns an applicable BES power transformer in the planning area. GIC(t) shall be provided within 90 calendar days of receipt of the written request and after determination of the maximum effective GIC value in Part 5.1.

M9. Each responsible entity, as determined in Requirement R1, shall provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided the maximum effective benchmark GIC value to the Transmission Owner and Generator Owner that owns each applicable BES power transformer in the planning area as specified in Requirement R5, Part 5.1. Each responsible entity, as determined in Requirement R1, shall also provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided GIC(t) in response to a written request from the Transmission Owner or Generator Owner that owns an applicable BES power transformer in the planning area.

R10. Supplemental Transformer Thermal Impact Assessment. [PAL20] Each Transmission Owner and Generator Owner shall conduct a thermal impact assessment for its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is xxx A per phase or greater. The thermal impact assessment shall: [Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]

10.1. Be based on the effective GIC flow information provided in Requirement R8;

10.2. Document assumptions used in the analysis;

10.3. Describe suggested actions and supporting analysis to mitigate the impact of GICs, if any; and

10.4. Be performed and provided to the responsible entities, as determined in Requirement R1, within 24 calendar months of receiving GIC flow information specified in Requirement R9, Part 9.1 [PAL21]

~~R9 [PAL22]. Supplemental Transformer Thermal Impact Assessment. Each Transmission Owner and Generator Owner shall conduct a thermal impact assessment for its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is xxx A per phase or greater. The thermal impact assessment shall: [Violation Risk Factor: Medium] [Time Horizon: Long term Planning]~~

~~9.1. Be based on the effective GIC flow information provided in Requirement R8;~~

~~9.2. Document assumptions used in the analysis;~~

~~9.3. Describe suggested actions and supporting analysis to mitigate the impact of GICs, if any; and~~

~~9.4. Be performed and provided to the responsible entities, as determined in Requirement R1, within 24 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1. M10 [PAL23] Each Transmission Owner and Generator Owner [PAL24] shall have evidence such as electronic or hard copies of its supplemental thermal impact assessment for all of its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R9, Part 9.1, is XX A per phase or greater, and shall have evidence such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided its thermal impact assessment to the responsible entities as specified in Requirement R10.~~

GMD Data Processes

~~R11. GIC Monitor Data Collection. Each responsible entity, as determined in Requirement R1, shall implement a process to obtain GIC monitor data from at least one (1) GIC monitor located in the Planning Coordinator's planning area or other part of the system included in the Planning Coordinator's GIC System model.~~

~~M11. Each responsible entity, as determined in Requirement R1, shall provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has ... [PAL25]~~

~~R12. Magnetometer Data Collection. Each responsible entity, as determined in Requirement R1, shall implement a process to obtain geomagnetic field data from at least one (1) magnetometer located in the Planning Coordinator's planning area or other part of the system included in the Planning Coordinator's GIC System model~~

~~M12. Each responsible entity, as determined in Requirement R1, shall provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has ... [PAL26]~~

~~R10. GIC Monitor Data Collection. Each responsible entity, as determined in Requirement R1, shall implement a process to obtain GIC monitor data from at least one (1) GIC monitor located in the Planning Coordinator's planning area or other part of the system included in the Planning Coordinator's GIC System model.~~

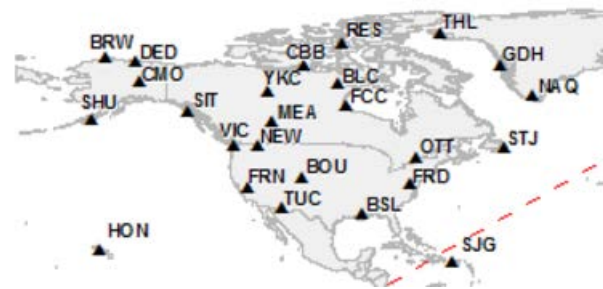
~~R11. Magnetometer Data Collection. Each responsible entity, as determined in Requirement R1, shall implement a process to obtain geomagnetic field data from at least one (1) magnetometer located in the Planning Coordinator's planning area or other part of the system included in the Planning Coordinator's GIC System model. [PAL27]~~

Rationale for Requirements R110 and R124: The proposed requirements addresses Order No. 830 directives for requiring responsible entities to collect GIC monitoring and magnetometer data as necessary to enable model validation and situational awareness (P. 88; P. 90-92). See the Guidelines and Technical Basis Section of this standard for technical information.

Technical considerations for GIC monitoring are contained in the NERC 2012 GMD Report (see Chapter 6). GIC monitoring is generally performed by Hall-effect transducers that are attached to the neutral of the transformer and measure dc current flowing through the neutral.

Magnetometers measure changes in the earth's magnetic field. Entities should obtain data from the nearest accessible magnetometer. Sources of magnetometer data include:

- Observatories such as those operated by U.S. Geological Survey and Natural Resources Canada, see below for locations (<http://www.intermagnet.org/>):



- Research institutions and academic universities;
- Entities with installed magnetometers.

Entities that choose to install magnetometers are requested to use the equipment specifications and data format protocols contained in the latest version of the Intermagnet Technical Reference Manual (http://www.intermagnet.org/publications/intermag_4-6.pdf)

Table 1 – Steady State Planning Benchmark GMD Events				
<p>Steady State:</p> <ul style="list-style-type: none"> a. Voltage collapse, Cascading and uncontrolled islanding shall not occur. b. Generation loss is acceptable as a consequence of the planning Benchmark GMD event. c. Planned System adjustments such as Transmission configuration changes and re-dispatch of generation are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings. 				
Category	Initial Condition	Event	Interruption of Firm Transmission Service Allowed	Load Loss Allowed
GMD GMD Event with Outages	1. System as may be postured in response to space weather information ¹ , and then 2. GMD event ²	Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event	Yes ³	Yes ³

Table 1 – Steady State Performance Footnotes
<ol style="list-style-type: none"> 1. The System condition for GMD planning may include adjustments to posture the System that are executable in response to space weather information. 2. The GMD conditions for the planning event are described in Attachment 1 (under Benchmark GMD eEvent). 3. Load loss as a result of manual or automatic Load shedding (e.g. UVLS) and/or curtailment of Firm Transmission Service may be used to meet BES performance requirements during studied GMD conditions. The likelihood and magnitude of Load loss or curtailment of Firm Transmission Service should be minimized.

<u>Table 2 –Supplemental GMD Event</u>				
<p>Steady State:</p> <p>a. <u>Voltage collapse, Cascading and uncontrolled islanding shall not occur.</u></p> <p>b. <u>Generation loss is acceptable as a consequence of the supplemental GMD event.</u></p> <p>c. <u>Planned System adjustments such as Transmission configuration changes and re-dispatch of generation are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings.</u></p>				
<u>Category</u>	<u>Initial Condition</u>	<u>Event</u>	<u>Interruption of Firm Transmission Service Allowed</u>	<u>Load Loss Allowed</u>
<u>GMD GMD Event with Outages</u>	<p>1. <u>System as may be postured in response to space weather information¹, and then</u></p> <p>2. <u>GMD event²</u></p>	<p><u>Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event</u></p>	<u>Yes</u>	<u>Yes</u>
<u>Table 1 – Steady State Performance Footnotes</u>				
<p>1. <u>The System condition for GMD planning may include adjustments to posture the System that are executable in response to space weather information.</u></p> <p>2. <u>The GMD conditions for the planning event are described in Attachment 1 (under supplemental Benchmark GMD eEvent).</u></p>				

Attachment 1

Calculating Geoelectric Fields for the Benchmark and Supplemental GMD Events

The benchmark bBenchmark GMD event¹ defines the geoelectric field values used to compute GIC flows that are needed to conduct a GMD Vulnerability Assessment. It is composed of the following elements: (1) a reference peak geoelectric field amplitude of 8 V/km derived from statistical analysis of historical magnetometer data; (2) scaling factors to account for local geomagnetic latitude; (3) scaling factors to account for local earth conductivity; and (4) a reference geomagnetic field time series or waveshape to facilitate time-domain analysis of GMD impact on equipment. The sSupplemental GMD event follows the same process, except (1) the reference peak geoelectric field amplitude is 17 V/km; and (2) a modified wave shape is used which includes a theoretical “local enhancement” in the wave shape.²

The regional geoelectric field peak amplitude used in GMD Vulnerability Assessment, E_{peak} , can be obtained from the reference geoelectric field value of 8 V/km for the bBenchmark GMD event (1) or 17 V/km for the sSupplemental GMD event (2) using the following relationship

$$E_{\text{peak}} = 8 \times \alpha \times \beta \text{ (V/km)} \quad (1)$$

$$\underline{E_{\text{peak}} = 17 \times \alpha \times \beta \text{ (V/km)}} \quad (2)$$

where α is the scaling factor to account for local geomagnetic latitude, and β is a scaling factor to account for the local earth conductivity structure.

Scaling the Geomagnetic Field

The benchmark GMD event is defined for geomagnetic latitude of 60° and it must be scaled to account for regional differences based on geomagnetic latitude. Table 2 provides a scaling factor correlating peak geoelectric field to geomagnetic latitude. Alternatively, the scaling factor α is computed with the empirical expression

$$\alpha = 0.001 \cdot e^{(0.115 \cdot L)} \quad (23)$$

where L is the geomagnetic latitude in degrees and $0.1 \leq \alpha \leq 1$

For large planning areas that cover more than one scaling factor from Table 2, the GMD Vulnerability Assessment should be based on a peak geoelectric field that is:

¹ The benchmark GMD event description is available on the Project 2013-03 Geomagnetic Disturbance Mitigation project page: <http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx>

² A “local enhancement” is a characteristic of a geomagnetic storm, usually associated with substorm activity, which results in a brief peak excursion of the geoelectric field to an elevated amplitude. The excursion generally occurs over a period of 2-5 minutes and only impacts a part of the transmission system, primarily parallel to the east-west electrojet. Observations to date have only occurred in the auroral regions, but the sSupplemental GMD event is assumed to occur in the lower latitudes until the observations indicate otherwise.

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- calculated by using the most conservative (largest) value for α ; or
- calculated assuming a non-uniform or piecewise uniform geomagnetic field.

Geomagnetic Latitude (Degrees)	Scaling Factor ¹ (α)
≤ 40	0.10
45	0.2
50	0.3
54	0.5
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

Scaling the Goelectric Field

The benchmark GMD event is defined for the reference Quebec earth model described in Table 4. The peak goelectric field, E_{peak} , used in a GMD Vulnerability Assessment may be obtained by either

- Calculating the goelectric field for the ground conductivity in the planning area and the reference geomagnetic field time series scaled according to geomagnetic latitude, using a procedure such as the plane wave method described in the NERC GMD Task Force GIC Application Guide;³ or
- Using the earth conductivity scaling factor β from Table 3 that correlates to the ground conductivity map in Figure 1 or Figure 2. Along with the scaling factor α from equation (23) or Table 2, β is applied to the reference goelectric field using equation (1 or 2, as applicable) to obtain the regional goelectric field peak amplitude E_{peak} to be used in GMD Vulnerability Assessments. When a ground conductivity model is not available, the planning entity should use the largest β factor of adjacent physiographic regions or a technically justified value.

The earth models used to calculate Table 3 for the United States were obtained from publicly available information published on the U. S. Geological Survey website.⁴ The models used to calculate Table 3 for Canada were obtained from Natural Resources Canada (NRCan) and reflect the average structure for large regions. A planner can also use specific earth model(s) with documented justification and the reference geomagnetic field time series to calculate the β factor(s) as follows:

$$\beta = E/8 \text{ for the benchmark GMD event} \quad (34)$$

$$\beta = E/17 \text{ for the supplemental GMD event} \quad (5)$$

³ Available at the NERC GMD Task Force project page: [http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-\(GMDTF\)-2013.aspx](http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx)

⁴ Available at <http://geomag.usgs.gov/conductivity/>

where E is the absolute value of peak geoelectric in V/km obtained from the technically justified earth model and the reference geomagnetic field time series.

For large planning areas that span more than one β scaling factor, the most conservative (largest) value for β may be used in determining the peak geoelectric field to obtain conservative results. Alternatively, a planner could perform analysis using a non-uniform or piecewise uniform geoelectric field.

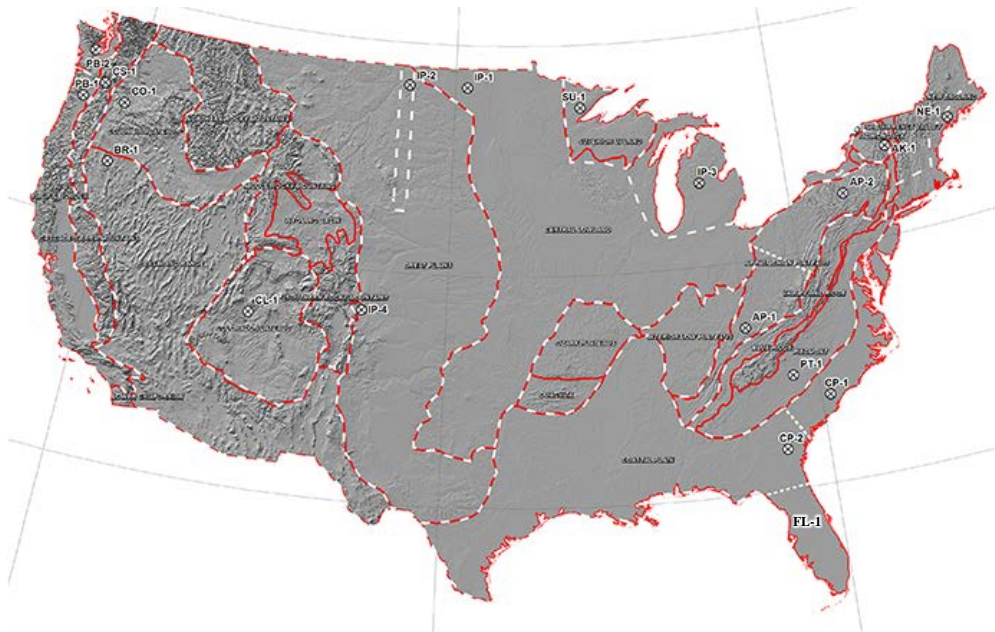


Figure 1: Physiographic Regions of the Continental United States⁵



Figure 2: Physiographic Regions of Canada

⁵ Additional map detail is available at the U.S. Geological Survey (<http://geomag.usgs.gov/>)

Table 3 – Geoelectric Field Scaling Factors	
USGS Earth model	Scaling Factor (β)
AK1A	0.56
AK1B	0.56
AP1	0.33
AP2	0.82
BR1	0.22
CL1	0.76
CO1	0.27
CP1	0.81
CP2	0.95
FL1	0.74
CS1	0.41
IP1	0.94
IP2	0.28
IP3	0.93
IP4	0.41
NE1	0.81
PB1	0.62
PB2	0.46
PT1	1.17
SL1	0.53
SU1	0.93
BOU	0.28
FBK	0.56
PRU	0.21
BC	0.67
PRAIRIES	0.96
SHIELD	1.0
ATLANTIC	0.79

Table 4 – Reference Earth Model (Quebec)	
Layer Thickness (km)	Resistivity (Ω -m)
15	20,000
10	200
125	1,000
200	100
∞	3

Reference Geomagnetic Field Time Series or Waveshape for the Benchmark GMD Event⁶

The geomagnetic field measurement record of the March 13-14 1989 GMD event, measured at NRCan’s Ottawa geomagnetic observatory is the basis for the reference geomagnetic field waveshape to be used to calculate the GIC time series, $GIC(t)$, required for transformer thermal impact assessment.

The geomagnetic latitude of the Ottawa geomagnetic observatory is 55° ; therefore, the amplitude of the geomagnetic field measurement data were scaled up to the 60° reference geomagnetic latitude (see Figure 3) such that the resulting peak geoelectric field amplitude computed using the reference earth model was 8 V/km (see Figures 4 and 5). Sampling rate for the geomagnetic field waveshape is 10 seconds.⁷ To use this geoelectric field time series when a different earth model is applicable, it should be scaled with the appropriate conductivity scaling factor β .

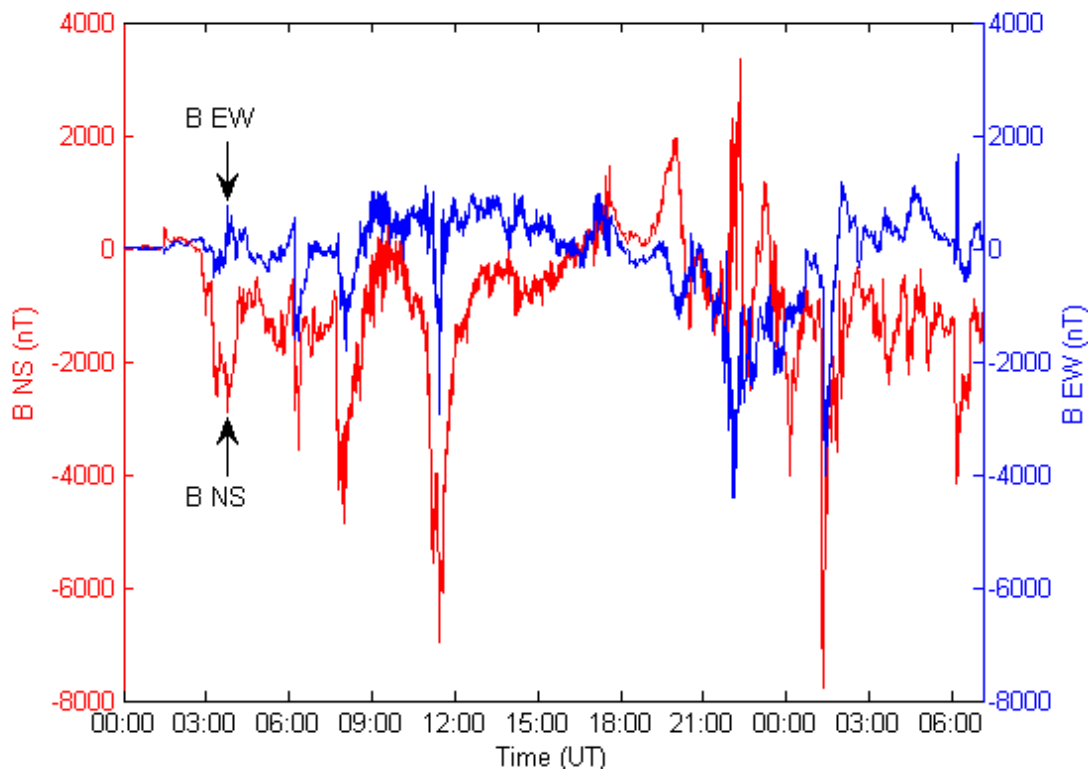


Figure 3: Benchmark Geomagnetic Field Waveshape. Red B_n (Northward), Blue B_e (Eastward)

⁶ Refer to the Benchmark GMD Event Description for details on the determination of the reference geomagnetic field waveshape: <http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx>

⁷ The data file of the benchmark geomagnetic field waveshape is available on the NERC GMD Task Force project page: [http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-\(GMDTF\)-2013.aspx](http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx)

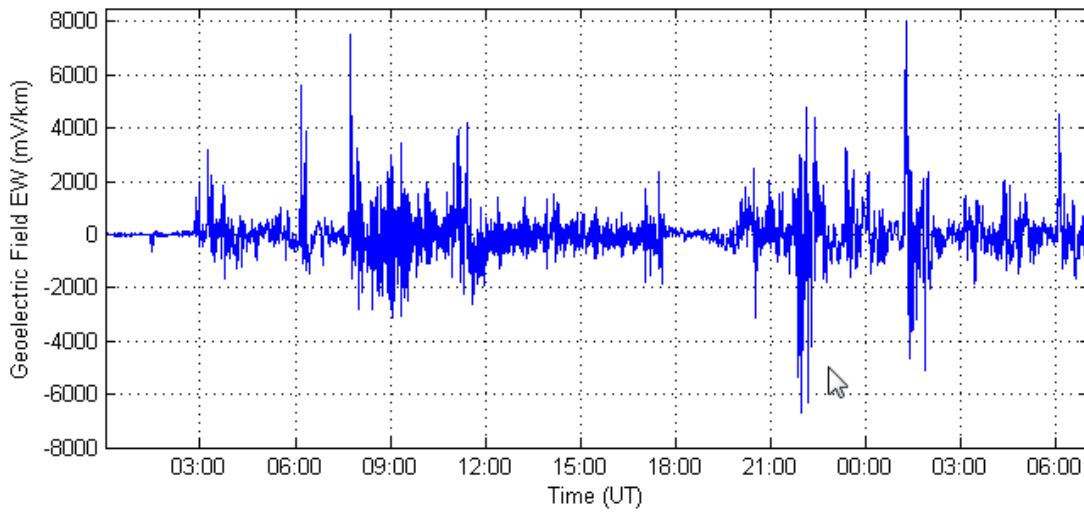


Figure 4: Benchmark Geoelectric Field Waveshape - E_E (Eastward)

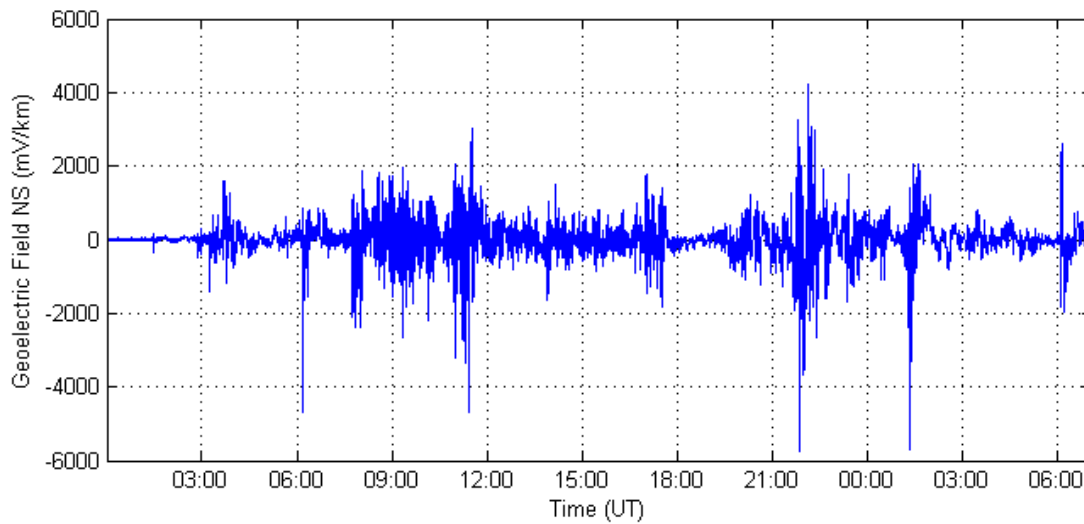


Figure 5: Benchmark Geoelectric Field Waveshape - E_N (Northward)

Reference Geomagnetic Field Time Series or Waveshape for the Supplemental GMD Event⁸

The geomagnetic field measurement record of the March 13-14 1989 GMD event, measured at NRCan's Ottawa geomagnetic observatory is the basis for the reference geomagnetic field waveshape to be used to calculate the GIC time series, GIC(t), required for transformer thermal impact assessment for the Supplemental GMD Event. However, due to the incorporation of a "local enhancement" into the wave shape for the Supplemental GMD event, the wave shape is different from the Benchmark GMD Event wave shape.

To account for the fact that the Supplemental GMD Event is intended to represent a local impact, the waveshape is to be applied to a local area to be justified by the responsible entity. Given that the size of the area expected to be impacted by a "local enhancement" is still somewhat unknown, the responsible entity has flexibility to apply the Supplemental GMD Event waveshape in a limited area of the system and to a limited number of transformers at the discretion of the responsible entity. Assumptions in this regard will need to be documented.

The geomagnetic latitude of the Ottawa geomagnetic observatory is 55°; therefore, the amplitude of the geomagnetic field measurement data were scaled up to the 60° reference geomagnetic latitude (see Figure 2) such that the resulting peak geoelectric field amplitude computed using the reference earth model was 17 V/km (see Figures 8 and 9). Sampling rate for the geomagnetic field waveshape is 10 seconds.⁹ To use this geoelectric field time series when a different earth model is applicable, it should be scaled with the appropriate conductivity scaling factor β .

New Wave shapes inserted here

⁹ The data file of the benchmark geomagnetic field waveshape is available on the NERC GMD Task Force project page: [http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-\(GMDTF\)-2013.aspx](http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx)

C. Compliance

1. Compliance Monitoring Process

1.1. Compliance Enforcement Authority

As defined in the NERC Rules of Procedure, “Compliance Enforcement Authority” means NERC or the Regional Entity in their respective roles of monitoring and enforcing compliance with the NERC Reliability Standards

1.2. Evidence Retention

The following evidence retention periods identify the period of time an entity is required to retain specific evidence to demonstrate compliance. For instances where the evidence retention period specified below is shorter than the time since the last audit, the CEA may ask an entity to provide other evidence to show that it was compliant for the full time period since the last audit.

The Planning Coordinator, Transmission Planner, Transmission Owner, and Generator Owner shall keep data or evidence to show compliance as identified below unless directed by its Compliance Enforcement Authority to retain specific evidence for a longer period of time as part of an investigation:

For Requirements R1, R2, R3, R5, and R6, each responsible entity shall retain documentation as evidence for five years.

For Requirement R4, each responsible entity shall retain documentation of the current GMD Vulnerability Assessment and the preceding GMD Vulnerability Assessment.

For Requirement R7, each responsible entity shall retain documentation as evidence for five years or until all actions in the Corrective Action Plan are completed, whichever is later.

If a Planning Coordinator, Transmission Planner, Transmission Owner, or Generator Owner is found non-compliant it shall keep information related to the non-compliance until mitigation is complete and approved or for the time specified above, whichever is longer.

The Compliance Enforcement Authority shall keep the last audit records and all requested and submitted subsequent audit records.

1.3. Compliance Monitoring and Assessment Processes:

Compliance Audits

Self-Certifications

Spot Checking

Compliance Investigations

Self-Reporting

Complaints

1.4. Additional Compliance Information

None

Table of Compliance Elements

R #	Time Horizon	VRF	Violation Severity Levels			
			Lower VSL	Moderate VSL	High VSL	Severe VSL
R1	Long-term Planning	Lower	N/A	N/A	N/A	The Planning Coordinator, in conjunction with its Transmission Planner(s), failed to determine and identify individual or joint responsibilities of the Planning Coordinator and Transmission Planner(s) in the Planning Coordinator’s planning area for maintaining models and performing the study or studies needed to complete GMD Vulnerability Assessment(s).
R2	Long-term Planning	High	N/A	N/A	The responsible entity did not maintain either System models or GIC System models of the responsible	The responsible entity did not maintain both System models and GIC System models of the responsible

TPL-007-1.2 — Transmission System Planned Performance for Geomagnetic Disturbance Events

					entity’s planning area for performing the study or studies needed to complete GMD Vulnerability Assessment(s).	entity’s planning area for performing the study or studies needed to complete GMD Vulnerability Assessment(s).
R3	Long-term Planning	Medium	N/A	N/A	N/A	The responsible entity did not have criteria for acceptable System steady state voltage performance for its System during the benchmark GMD event described in Attachment 1 as required.
R4	Long-term Planning	High	The responsible entity completed a GMD Vulnerability Assessment, but it was more than 60 calendar months and less than or equal to 64 calendar months since the last GMD Vulnerability Assessment.	The responsible entity's completed GMD Vulnerability Assessment failed to satisfy one of elements listed in Requirement R4, Parts 4.1 through 4.3; OR The responsible entity completed a GMD Vulnerability Assessment, but it	The responsible entity's completed GMD Vulnerability Assessment failed to satisfy two of the elements listed in Requirement R4, Parts 4.1 through 4.3; OR The responsible entity completed a GMD Vulnerability Assessment, but it	The responsible entity's completed GMD Vulnerability Assessment failed to satisfy three of the elements listed in Requirement R4, Parts 4.1 through 4.3; OR The responsible entity completed a GMD Vulnerability Assessment, but it

				was more than 64 calendar months and less than or equal to 68 calendar months since the last GMD Vulnerability Assessment.	was more than 68 calendar months and less than or equal to 72 calendar months since the last GMD Vulnerability Assessment.	was more than 72 calendar months since the last GMD Vulnerability Assessment; OR The responsible entity does not have a completed GMD Vulnerability Assessment.
R5	Long-term Planning	Medium	The responsible entity provided the effective GIC time series, GIC(t), in response to written request, but did so more than 90 calendar days and less than or equal to 100 calendar days after receipt of a written request.	The responsible entity provided the effective GIC time series, GIC(t), in response to written request, but did so more than 100 calendar days and less than or equal to 110 calendar days after receipt of a written request.	The responsible entity provided the effective GIC time series, GIC(t), in response to written request, but did so more than 110 calendar days after receipt of a written request.	The responsible entity did not provide the maximum effective GIC value to the Transmission Owner and Generator Owner that owns each applicable BES power transformer in the planning area; OR The responsible entity did not provide the effective GIC time series, GIC(t), upon written request.

<p>R6</p>	<p>Long-term Planning</p>	<p>Medium</p>	<p>The responsible entity failed to conduct a thermal impact assessment for 5% or less or one of its solely owned and jointly owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase; OR The responsible entity conducted a thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase but did so more than 24 calendar months and less than</p>	<p>The responsible entity failed to conduct a thermal impact assessment for more than 5% up to (and including) 10% or two of its solely owned and jointly owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase; OR The responsible entity conducted a thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase but did so</p>	<p>The responsible entity failed to conduct a thermal impact assessment for more than 10% up to (and including) 15% or three of its solely owned and jointly owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase; OR The responsible entity conducted a thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase but did so</p>	<p>The responsible entity failed to conduct a thermal impact assessment for more than 15% or more than three of its solely owned and jointly owned applicable BES power transformers (whichever is greater) where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase; OR The responsible entity conducted a thermal impact assessment for its solely owned and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A or greater per phase but did so more than 30 calendar</p>
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			<p>or equal to 26 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1.</p>	<p>more than 26 calendar months and less than or equal to 28 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1; OR The responsible entity failed to include one of the required elements as listed in Requirement R6, Parts 6.1 through 6.3.</p>	<p>more than 28 calendar months and less than or equal to 30 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1; OR The responsible entity failed to include two of the required elements as listed in Requirement R6, Parts 6.1 through 6.3.</p>	<p>months of receiving GIC flow information specified in Requirement R5, Part 5.1; OR The responsible entity failed to include three of the required elements as listed in Requirement R6, Parts 6.1 through 6.3.</p>
R7	Long-term Planning	High	N/A	<p>The responsible entity's Corrective Action Plan failed to comply with one of the elements in Requirement R7, Parts 7.1 through 7.3.</p>	<p>The responsible entity's Corrective Action Plan failed to comply with two of the elements in Requirement R7, Parts 7.1 through 7.3.</p>	<p>The responsible entity's Corrective Action Plan failed to comply with all three of the elements in Requirement R7, Parts 7.1 through 7.3; OR The responsible entity did not have a Corrective Action Plan as required by Requirement R7.</p>

D. Regional Variances

None.

E. Interpretations

None.

F. Associated Documents

None.

Version History

Version	Date	Action	Change Tracking
1	December 17, 2014	Adopted by the NERC Board of Trustees	

Guidelines and Technical Basis

Benchmark GMD Event (Attachment 1)^[PAL28]

The benchmark GMD event defines the geoelectric field values used to compute GIC flows that are needed to conduct a benchmark GMD Vulnerability Assessment. A white paper that includes the event description, analysis, and example calculations is available on the Project 2013-03 Geomagnetic Disturbance Mitigation project page at:

<http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx>^[PAL29]

Supplemental GMD Event (Attachment 1)

The supplemental GMD event defines the geoelectric field values used to compute GIC flows that are needed to conduct a supplemental GMD Vulnerability Assessment. A white paper that includes the event description, analysis, and example calculations is available on the Project 2013-03 Geomagnetic Disturbance Mitigation project page:^[PAL30]

Requirement R2

A GMD Vulnerability Assessment requires a GIC System model, which is a dc representation of the System, to calculate GIC flow. In a GMD Vulnerability Assessment, GIC simulations are used to determine transformer Reactive Power absorption and transformer thermal response. Details for developing the GIC System model are provided in the NERC GMD Task Force guide: *Application Guide for Computing Geomagnetically-Induced Current in the Bulk Power System*. The guide is available at:

http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GIC%20Application%20Guide%202013_approved.pdf

Underground pipe-type cables present a special modeling situation in that the steel pipe that encloses the power conductors significantly reduces the geoelectric field induced into the conductors themselves, while they remain a path for GIC. Solid dielectric cables that are not enclosed by a steel pipe will not experience a reduction in the induced geoelectric field. A planning entity should account for special modeling situations in the GIC system model, if applicable.

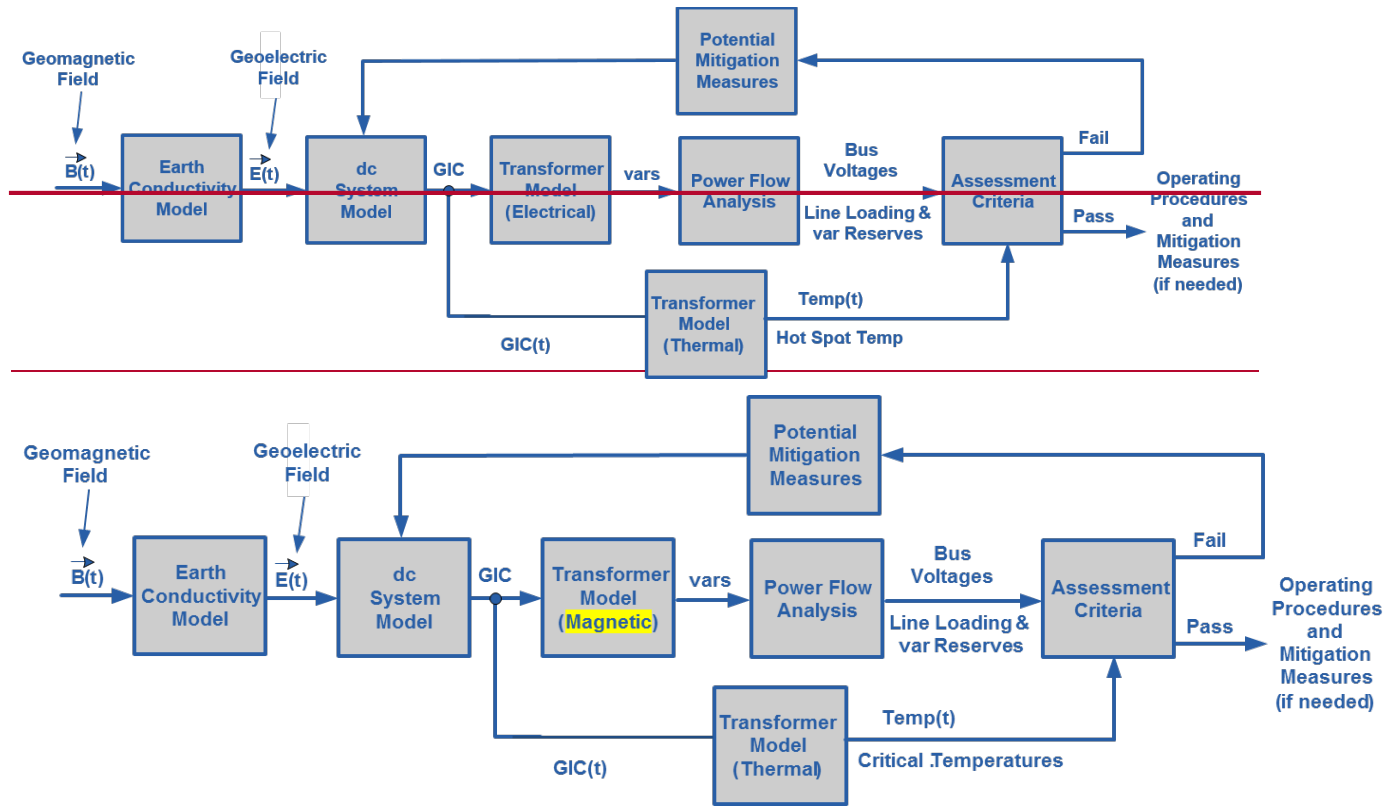
Requirement R4

The *GMD Planning Guide* developed by the NERC GMD Task Force provides technical information on GMD-specific considerations for planning studies. It is available at:

http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GMD%20Planning%20Guide_approved.pdf

The diagram below provides an overall view of the GMD Vulnerability Assessment process:

Application Guidelines



Requirement R5

The transformer thermal impact assessment specified in Requirement R6 is based on GIC information for the Benchmark GMD Event. This GIC information is determined by the planning entity through simulation of the GIC System model and must be provided to the entity responsible for conducting the thermal impact assessment. GIC information should be provided in accordance with Requirement R5 each time the GMD Vulnerability Assessment is performed since, by definition, the GMD Vulnerability Assessment includes a documented evaluation of susceptibility to localized equipment damage due to GMD.

The maximum effective GIC value provided in Part 5.1 is used for transformer thermal impact assessment. Only those transformers that experience an effective GIC value of 75 A or greater per phase require evaluation in Requirement R6.

GIC(t) provided in Part 5.2 is used to convert the steady-state GIC flows to time-series GIC data for transformer thermal impact assessment. This information may be needed by one or more of the methods for performing a thermal impact assessment. Additional information is in the following section and the thermal impact assessment white paper.

The peak GIC value of 75 Amps per phase has been shown through thermal modeling to be a conservative threshold below which the risk of exceeding known temperature limits established by technical organizations is low.

Requirement R6

Application Guidelines

The thermal impact assessment of a power transformer may be based on manufacturer-provided GIC capability curves, thermal response simulation, thermal impact screening, or other technically justified means. Approaches for conducting the assessment are presented in the *Transformer Thermal Impact Assessment* white paper posted on the project page.

<http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx>

Transformers are exempt from the thermal impact assessment requirement if the effective GIC value for the transformer is less than 75 A per phase, as determined by a GIC analysis of the System. Justification for this criterion is provided in the *Screening Criterion for Transformer Thermal Impact Assessment* white paper posted on the project page. A documented design specification exceeding this value is also a justifiable threshold criterion that exempts a transformer from Requirement R6.

The threshold criteria and transformer thermal impact must be evaluated on the basis of effective GIC. Refer to the white papers for additional information.

Requirement R7

Technical considerations for GMD mitigation planning, including operating and equipment strategies, are available in Chapter 5 of the *GMD Planning Guide*. Additional information is available in the *2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk-Power System*:

<http://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/2012GMD.pdf>

Requirement R10

Technical considerations for GIC monitoring are contained in the NERC 2012 GMD Report (see Chapter 6). GIC monitoring is generally performed by Hall-effect transducers that are attached to the neutral of the wye-grounded transformer. Data from GIC monitors is useful model validation and situational awareness.

Responsible entities consider the following in developing a process for obtaining GIC monitor data:

- **Monitor locations.** An entity's operating process may be constrained by location of existing GIC monitors. However, when planning for 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 in the vicinity of 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 the operating process. When planning new GIC monitor installations, consider monitor data range (for example, -500A through + 500A) and ambient temperature ratings consistent with temperatures in the region in which the monitor will be installed.

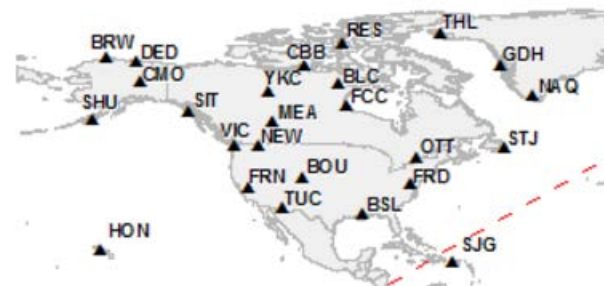
Application Guidelines

- **Sampling Interval.** An entity's operating process may be constrained by capabilities of existing GIC monitors. However, when possible specify data sampling during periods of interest at a rate of 10s or faster.
- **Collection Periods.** The process should specify when the entity expects GIC data to be collected. For example, collection could be required during periods where the Kp index is above a threshold, or when GIC values are above a threshold. Determining when to discontinue collecting GIC data should also be specified to maintain consistency in data collection.
- **Data format.** Specify time and value formats. For example, Greenwich Mean Time (GMT) (MM/DD/YYYY HH:MM:SS) and GIC Value (Amps). Positive (+) and negative (-) signs indicate direction of GIC flow (Positive reference is flow from ground into transformer neutral). Time fields should indicate the sampled time rather than system or SCADA time if GIC monitor system capability supports.
- **Data retention.** The entity's process should specify data retention periods, for example 1 year. Data retention periods should be adequately long to support availability for the entity's model validation process and external reporting requirements, if any.
- **Additional information.** The entity's process should specify collection of other information necessary for making the data useful, for example monitor location and type of neutral connection (e.g. three-phase or single-phase).

Requirement R11

Magnetometers measure changes in the earth's magnetic field. Entities should obtain data from the nearest accessible magnetometer. Sources of magnetometer data include:

- Observatories such as those operated by U.S. Geological Survey and Natural Resources Canada, see below for locations (<http://www.intermagnet.org/>):



- Research institutions and academic universities;

Application Guidelines

- Entities with installed magnetometers.

Entities that choose to install magnetometers should consider equipment specifications and data format protocols contained in the latest version of the Intermagnet Technical Reference Manual (http://www.intermagnet.org/publications/intermag_4-6.pdf)

Application Guidelines

Rationale:

During development of this standard, text boxes were embedded within the standard to explain the rationale for various parts of the standard. Upon BOT approval, the text from the rationale text boxes was moved to this section.

Rationale for Applicability:

Instrumentation transformers and station service transformers do not have significant impact on geomagnetically-induced current (GIC) flows; therefore, these transformers are not included in the applicability for this standard.

Terminal voltage describes line-to-line voltage.

Rationale for R1:

In some areas, planning entities may determine that the most effective approach to conduct a GMD Vulnerability Assessment is through a regional planning organization. No requirement in the standard is intended to prohibit a collaborative approach where roles and responsibilities are determined by a planning organization made up of one or more Planning Coordinator(s).

Rationale for R2:

A GMD Vulnerability Assessment requires a GIC System model to calculate GIC flow which is used to determine transformer Reactive Power absorption and transformer thermal response. Guidance for developing the GIC System model is provided in the GIC Application Guide developed by the NERC GMD Task Force and available at:

http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GIC%20Application%20Guide%202013_approved.pdf

The System model specified in Requirement R2 is used in conducting steady state power flow analysis that accounts for the Reactive Power absorption of power transformer(s) due to GIC in the System.

The GIC System model includes all power transformer(s) with a high side, wye-grounded winding with terminal voltage greater than 200 kV. The model is used to calculate GIC flow in the network.

The projected System condition for GMD planning may include adjustments to the System that are executable in response to space weather information. These adjustments could include, for example, recalling or postponing maintenance outages.

The Violation Risk Factor (VRF) for Requirement R2 is changed from Medium to High. This change is for consistency with the VRF for approved standard TPL-001-4 Requirement R1, which is proposed for revision in the NERC filing dated August 29, 2014 (RM12-1-000). NERC guidelines require consistency among Reliability Standards.

Rationale for R3:

Requirement R3 allows a responsible entity the flexibility to determine the System steady state voltage criteria for System steady state performance [for the steady-state planning benchmark](#)

Application Guidelines

GMD event contained in Table 1. Steady state voltage limits are an example of System steady state performance criteria.

Rationale for R4:

The GMD Vulnerability Assessment includes steady state power flow analysis and the supporting study or studies using the models specified in Requirement R2 that account for the effects of GIC. Performance criteria for the steady-state planning benchmark GMD event are specified in Table 1.

At least one System On-Peak Load and at least one System Off-Peak Load must be examined in the analysis.

Distribution of GMD Vulnerability Assessment results provides a means for sharing relevant information with other entities responsible for planning reliability. Results of GIC studies may affect neighboring systems and should be taken into account by planners.

The GMD Planning Guide developed by the NERC GMD Task Force provides technical information on GMD-specific considerations for planning studies. It is available at:

http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GMD%20Planning%20Guide_approved.pdf

The provision of information in Requirement R4, Part 4.3, shall be subject to the legal and regulatory obligations for the disclosure of confidential and/or sensitive information.

Rationale for R5:

This GIC information is necessary for determining the thermal impact of GIC on transformers in the planning area and must be provided to entities responsible for performing the thermal impact assessment so that they can accurately perform the assessment. GIC information should be provided in accordance with Requirement R5 as part of the GMD Vulnerability Assessment process since, by definition, the GMD Vulnerability Assessment includes documented evaluation of susceptibility to localized equipment damage due to GMD.

The maximum effective GIC value provided in Part 5.1 is used for transformer thermal impact assessment.

GIC(t) provided in Part 5.2 can alternatively be used to convert the steady-state GIC flows to time-series GIC data for transformer thermal impact assessment. This information may be needed by one or more of the methods for performing a thermal impact assessment. Additional guidance is available in the Transformer Thermal Impact Assessment white paper:

<http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx>

A Transmission Owner or Generator Owner that desires GIC(t) may request it from the planning entity. The planning entity shall provide GIC(t) upon request once GIC has been calculated, but no later than 90 calendar days after receipt of a request from the owner and after completion of Requirement R5, Part 5.1.

The provision of information in Requirement R5 shall be subject to the legal and regulatory obligations for the disclosure of confidential and/or sensitive information.

Application Guidelines

Rationale for R6:

The transformer thermal impact screening criterion has been revised from 15 A per phase to 75 A per phase. Only those transformers that experience an effective GIC value of 75 A per phase or greater require evaluation in Requirement R6. The justification is provided in the Thermal Screening Criterion white paper.

The thermal impact assessment may be based on manufacturer-provided GIC capability curves, thermal response simulation, thermal impact screening, or other technically justified means. The transformer thermal assessment will be repeated or reviewed using previous assessment results each time the planning entity performs a GMD Vulnerability Assessment and provides GIC information as specified in Requirement R5. Approaches for conducting the assessment are presented in the Transformer Thermal Impact Assessment white paper posted on the project page.

<http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx>

Thermal impact assessments are provided to the planning entity, as determined in Requirement R1, so that identified issues can be included in the GMD Vulnerability Assessment (R4), and the Corrective Action Plan (R7) as necessary.

Thermal impact assessments of non-BES transformers are not required because those transformers do not have a wide-area effect on the reliability of the interconnected Transmission system.

The provision of information in Requirement R6, Part 6.4, shall be subject to the legal and regulatory obligations for the disclosure of confidential and/or sensitive information.

Rationale for R7:

Corrective Action Plans are defined in the NERC Glossary of Terms:

A list of actions and an associated timetable for implementation to remedy a specific problem.

Corrective Action Plans must, subject to the vulnerabilities identified in the assessments, contain strategies for protecting against the potential impact of the Benchmark GMD event, based on factors such as the age, condition, technical specifications, system configuration, or location of specific equipment. Chapter 5 of the NERC GMD Task Force *GMD Planning Guide* provides a list of mitigating measures that may be appropriate to address an identified performance issue.

The provision of information in Requirement R7, Part 7.3, shall be subject to the legal and regulatory obligations for the disclosure of confidential and/or sensitive information.

Rationale for Table 3:

Table 3 has been revised to use the same ground model designation, FL1, as is being used by USGS. The calculated scaling factor for FL1 is 0.74.

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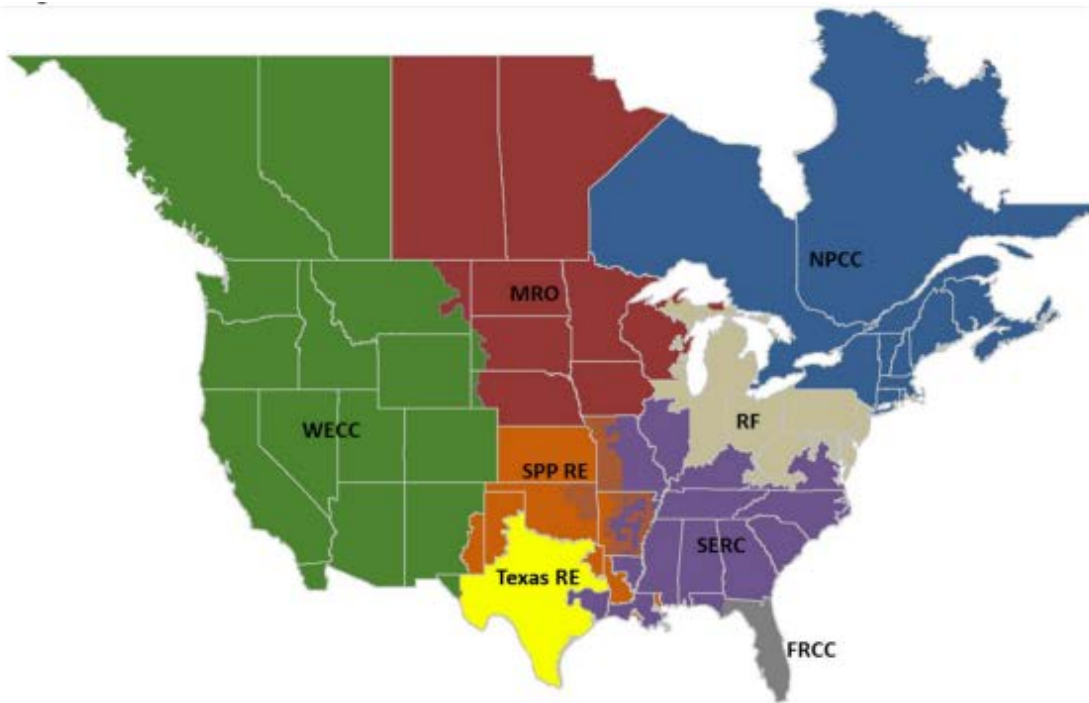
Example 2 23

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Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to ensure the reliability 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 several assessment areas within the eight Regional Entity (RE) boundaries, as shown in the map and corresponding table below.



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

Introduction

Background

The purpose of the ~~Supplemental-supplemental~~ Geomagnetic-geomagnetic Disturbance-disturbance (GMD) event description is to provide a defined event for assessing system performance for a ~~benchmark-GMD~~ event which includes a “local enhancement” of the geomagnetic field. This local enhancement is temporally and spatially limited and has been observed in a number of GMD events. ~~which is a high peak amplitude spike that can occur in the geoelectric field.~~ The ~~Supplemental-supplemental~~ GMD event defines the geomagnetic and geoelectric field values used to compute geomagnetically-induced current (GIC) flows for a supplemental GMD Vulnerability Assessment.

~~Proposed TPL-007-2 includes requirements for entities to perform two types of GMD Vulnerability Assessments to evaluate the potential impacts of GMD events on the Bulk Electric System (BES). The benchmark GMD Vulnerability Assessment is based on the benchmark GMD event associated with TPL-007-1 which was approved by the Federal Energy Regulatory Commission (FERC) in Order No. 830 in September 2016. The benchmark GMD event is derived from spatially-averaged geoelectric field values to address potential wide-area effects that could be caused by a severe 1-in-100 year GMD event.¹ Proposed TPL-007-2 also requires entities to perform a supplemental GMD Vulnerability Assessment to evaluate risks that localized enhancements of geomagnetic field during a severe GMD event “could potentially affect the reliable operation of the Bulk-Power System”.² (The Benchmark GMD event is explained in a separate whitepaper, Benchmark GMD Event Description.)~~

~~On September 22, 2016, FERC issued Order No. 830, directing NERC to develop modifications to the Benchmark GMD event, included in TPL-007-1, to enable the assessment of non-spatially-averaged data as part of the GMD Vulnerability Assessment.~~

General Characteristics

The ~~Supplemental-GMD~~supplemental GMD event described herein takes into consideration the characteristics of a “local enhancement”, recognizing that the science surrounding and understanding of these events is very preliminary and evolving. Based on observations, these characteristics of local enhancements are based on a limited set of observations and include:

- Geographic ~~Extent-area~~ – The extent of “local enhancements” is on the order of 100km in North-South (latitude) direction and 300-500km in East-West (longitude) direction.
- Amplitude – The amplitude of the resulting geoelectric field is on the order of twice the geoelectric field that is calculated in the spatially-averaged Benchmark GMD event.
- Pulse Width_[MO1] – The “local enhancement” occurs over the time period of 2-5 minutes.
- Latitude Extent – “Local enhancements” have only been observed thus far in the auroral regions, generally above 60 degrees geomagnetic latitude._[MO2]
- Geoelectric Field Waveshape – The geoelectric field waveshape has a strong influence on the hot spot heating of transformer windings and structural parts since thermal time constants of the transformer and time to peak of storm maxima are both on the order of minutes. The frequency content of the magnetic field (dB/dt) is a function of the waveshape, which in turn has a direct effect on the geoelectric field since the earth response to external dB/dt is frequency-dependent. As with the ~~Benchmark-benchmark~~ GMD event, the ~~Supplemental-GMD~~supplemental GMD event waveshape is from the NRCan OTT (NR-Canada Ottawa) geomagnetic observatory magnetometer station during the March 13-14 1989 event. The

¹ See Benchmark Geomagnetic Disturbance Event Description white paper, May 12, 2016. Filed by NERC in RM 15-11 on June 28, 2016.

² See Order No. 830 P. 47. On September 22, 2016, FERC directed NERC to develop modifications to the benchmark GMD event, included in TPL-007-1, such that assessments would not be based solely on spatially averaged data.

synthetic “local enhancement” has been inserted ~~at~~ⁱⁿ the time when data suggests the existence of a ~~the actual data appears to be experiencing a~~ “local enhancement” with the characteristics described above.

Supplemental GMD Event Description

Severe geomagnetic disturbance events are high-impact, low-frequency (HILF) events [2]; thus, any benchmark event should consider the probability that the event will occur, as well as the impact or consequences of such an event. The **Supplemental-supplemental Benchmark-benchmark** event is composed of the following elements: 1) a reference peak geoelectric field amplitude (V/km) derived from statistical analysis of historical magnetometer data; 2) scaling factors to account for local geomagnetic latitude; 3) scaling factors to account for local earth conductivity; and 4) a reference geomagnetic field time series or waveshape to facilitate time-domain analysis of GMD impact on equipment.

Supplemental GMD Event Geoelectric Field Amplitude

The **Supplemental-GMD-supplemental GMD** event field amplitude was determined through **statistical analysis** [MO3] using the plane wave method [3]-[10] of geomagnetic field measurements from geomagnetic observatories in northern Europe [11] and the reference (Quebec) earth model shown in **Table 1** [12], supplemented by data from Greenland and Alaska. For details of the statistical considerations, see Appendix I. The Quebec earth model is generally resistive and the geological structure is relatively well understood.

Thickness (km)	Resistivity (Ω -m)
15	20,000
10	200
125	1,000
200	100
∞	3

The statistical analysis (see Appendix I) resulted in conservative peak geoelectric field amplitude of approximately 17 V/km. For steady-state GIC and load flow analysis, the direction of the geoelectric field is assumed to be variable meaning that it can be in any direction (Eastward, Northward, or a vectorial combination thereof).

The regional geoelectric field peak amplitude, E_{peak} , to be used in calculating GIC in the GIC system model can be obtained from the reference value of 17 V/km using the following relationship

$$E_{\text{peak}} = 17 \times \alpha \times \beta \text{ (V/km)} \quad (1)$$

where α is the scaling factor to account for local geomagnetic latitude, and β is a scaling factor to account for the local earth conductivity structure (see Appendix II).

Reference Geomagnetic Field Waveshape

The reference geomagnetic field waveshape was selected after analyzing a number of recorded GMD events, including the reference storm of the NERC interim report of 2012 [14], measurements at the Nurmijarvi (NUR) and Memanbetsu (MMB) geomagnetic observatories for the “Halloween event” of October 29-31, 2003, and the March 1989 GMD event that caused the Hydro Quebec blackout. The geomagnetic field measurement record of the March 13-14 1989 GMD event, measured at NRCan’s Ottawa geomagnetic observatory, was selected as the reference geomagnetic field waveform because it provides generally conservative results when performing thermal analysis of power transformers (see Appendix I). The reference geomagnetic field waveshape is used to calculate the GIC time series, $GIC(t)$, required for transformer thermal impact assessment. The reference wave

shape includes a synthetic “local enhancement”, inserted at ~~UT 1:18 March 14xxxxx~~ in **Figure 1** below. The amplitude of the “local enhancement” is based on a statistical analysis of a number of GMD events, discussed in **Appendix II**.

The geomagnetic latitude of the Ottawa geomagnetic observatory is 55°; therefore, the amplitude of the geomagnetic field measurement data were scaled up to the 60° reference geomagnetic latitude (see **Figure 1**) such that the resulting peak geoelectric field amplitude computed using the reference earth model was 17 V/km (see **Figures 2**). Sampling rate for the geomagnetic field waveshape is 10 seconds.

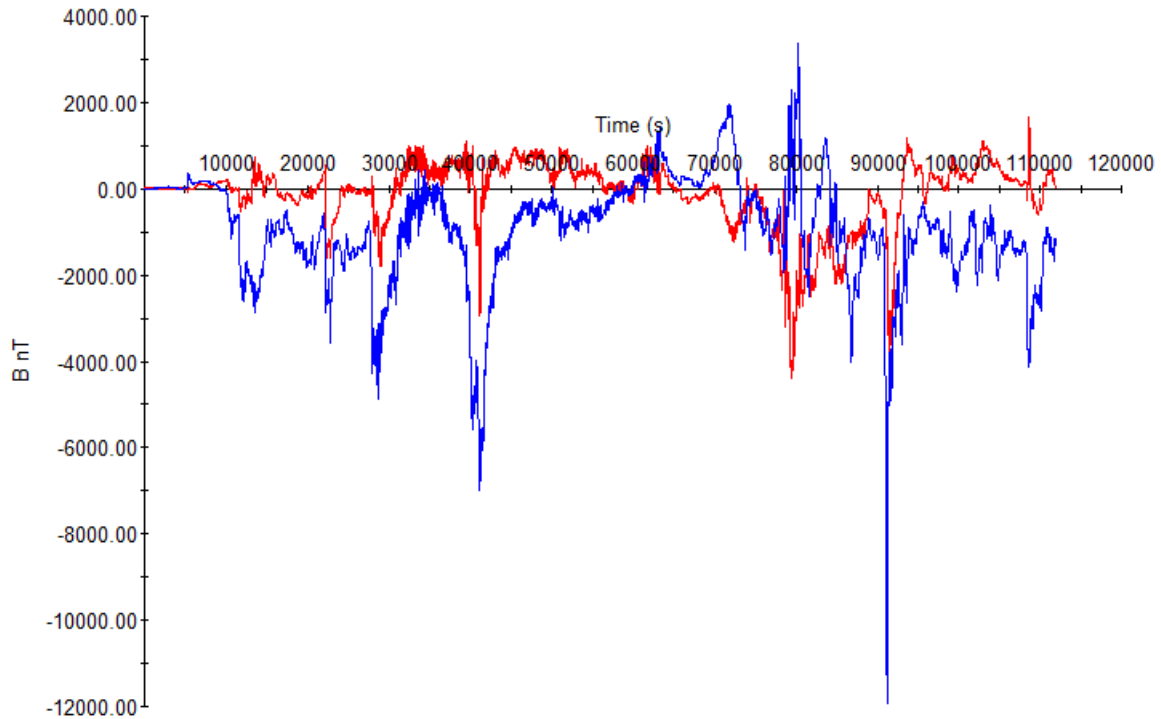


Figure 1: Supplemental Geomagnetic Field Waveshape
Red Bn (Northward), Blue Be (Eastward)
Referenced to pre-event quiet conditions

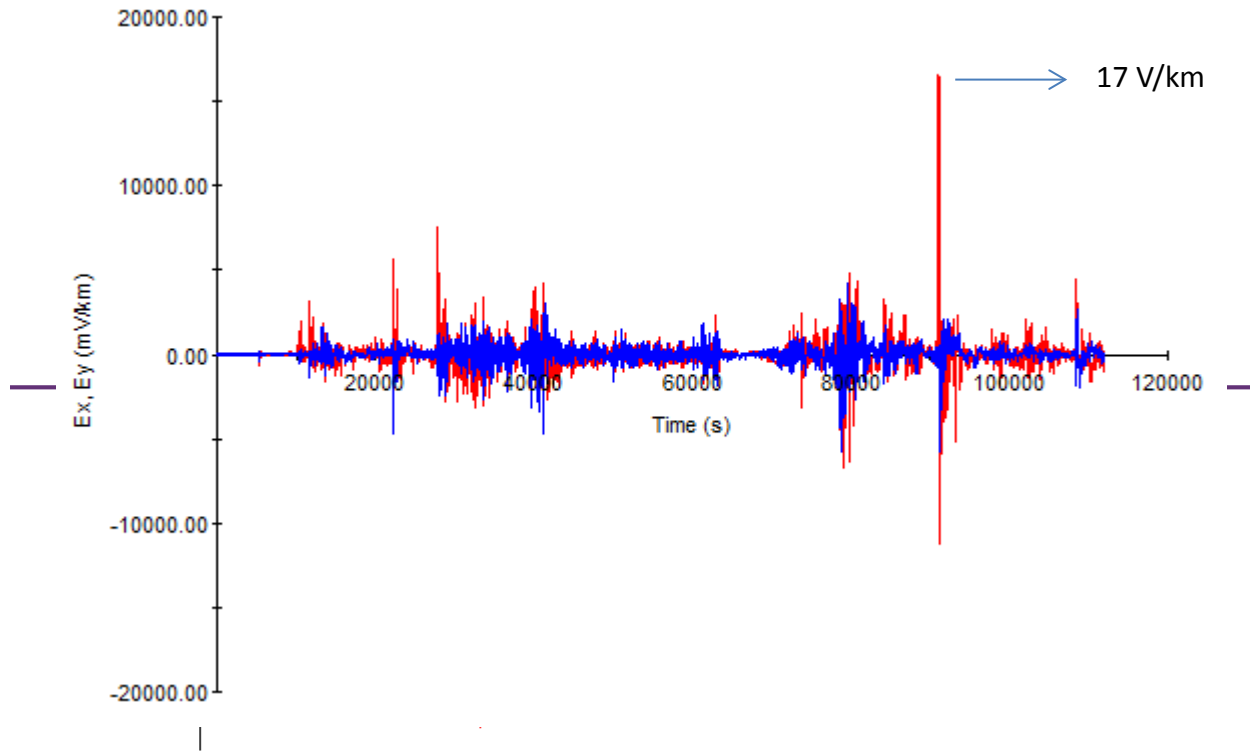


Figure 2: Supplemental Geoelectric Field Wavelshape (~~E_E Eastward~~)--Expanded Blue Ex (Northward), Red Ey (Eastward)

Appendix I – Technical Considerations

The following sections describe the technical justification of the assumptions that were made in the development of the ~~Supplemental GMD~~Supplemental GMD event.

Statistical Considerations

The spatial structure of high-latitude geoelectric fields can be very complex during strong geomagnetic storm events [17]-[18]. One reflection of this spatial complexity is localized geomagnetic field enhancements (local enhancements) that result in high amplitude geoelectric fields in regions of a few hundred kilometers or less. **Figure I-1**³ illustrates this spatial complexity of the storm-time geoelectric fields. In areas indicated by the bright red location, the geoelectric field can be a factor of 2-3 larger than at neighboring locations. Localized geomagnetic phenomena should not be confused with local earth structure/conductivity features that result in consistently high geoelectric fields (e.g., coastal effects). Localized field enhancements can occur at any region exposed to auroral ionospheric electric current fluctuations.

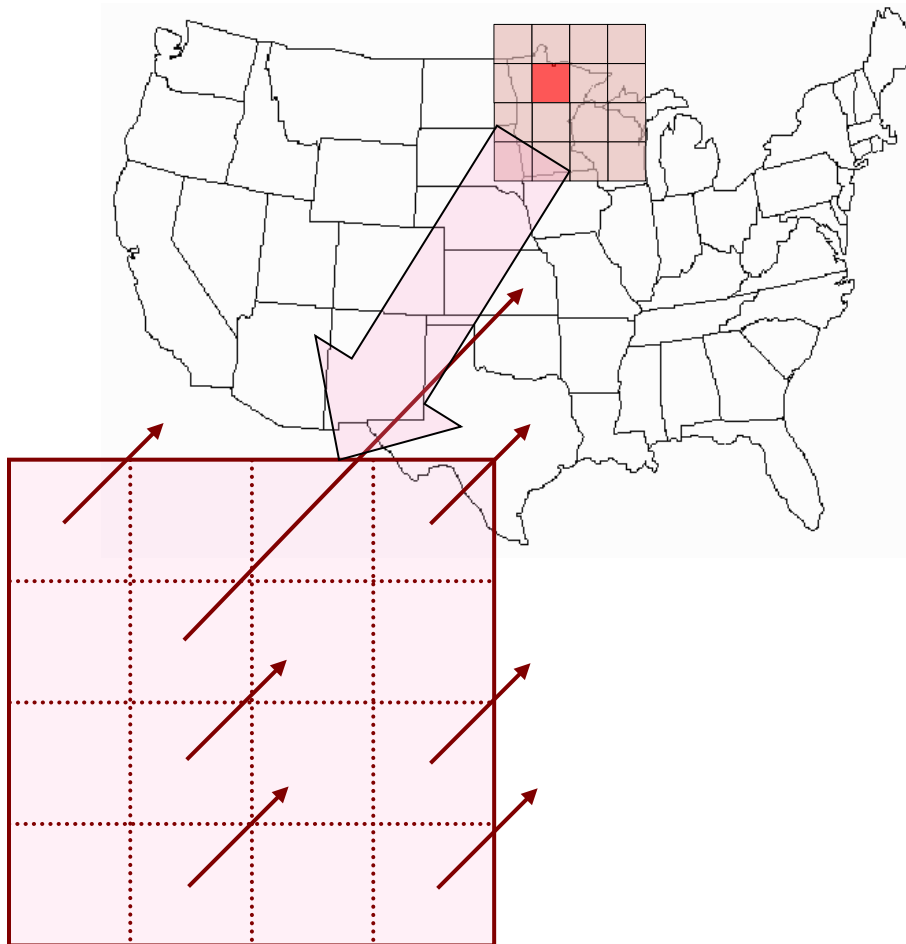


Figure I-1: Illustration of the Spatial Scale between Localized Enhancements and Larger Spatial Scale Amplitudes of Geoelectric Field Observed during a Strong Geomagnetic Storm.

In this illustration, the red square illustrates a spatially localized field enhancement.

³Figure I-1 is for illustration purposes only, and is not meant to suggest that a particular area is more likely to experience a localized enhanced geoelectric field.

The ~~Supplemental GMD~~ supplemental GMD event is designed to address local effects caused by a severe GMD event, such as increased var absorption and voltage depressions. It is important to note that most earlier geoelectric field amplitude statistics and extreme amplitude analyses have been built for individual stations thus reflecting only localized spatial scales [10], [19]-[22]. [MO4]

A number of GMD events were analyzed to identify the basic characteristics of existence of “local enhancements” and to determine the basic characteristics so that some form of analysis could proceed. The following tthree (3) events studied and described below are were studied:

- -March 13, 1989
- October 29-30, 2003
- March 17, 2015

Geomagnetic field recordings were collected for these storms and the geoelectric field was computed using the 1D plane wave method and the Quebec ground model. In each case, a “local enhancement” was correlated, generally oriented parallel to the westward ionospheric electrojet. (See **Figures 4-7** below)

Geoelectric field distribution 0089-03-13T21:44:00 UT. Max. IEI: 5.90 V/km.

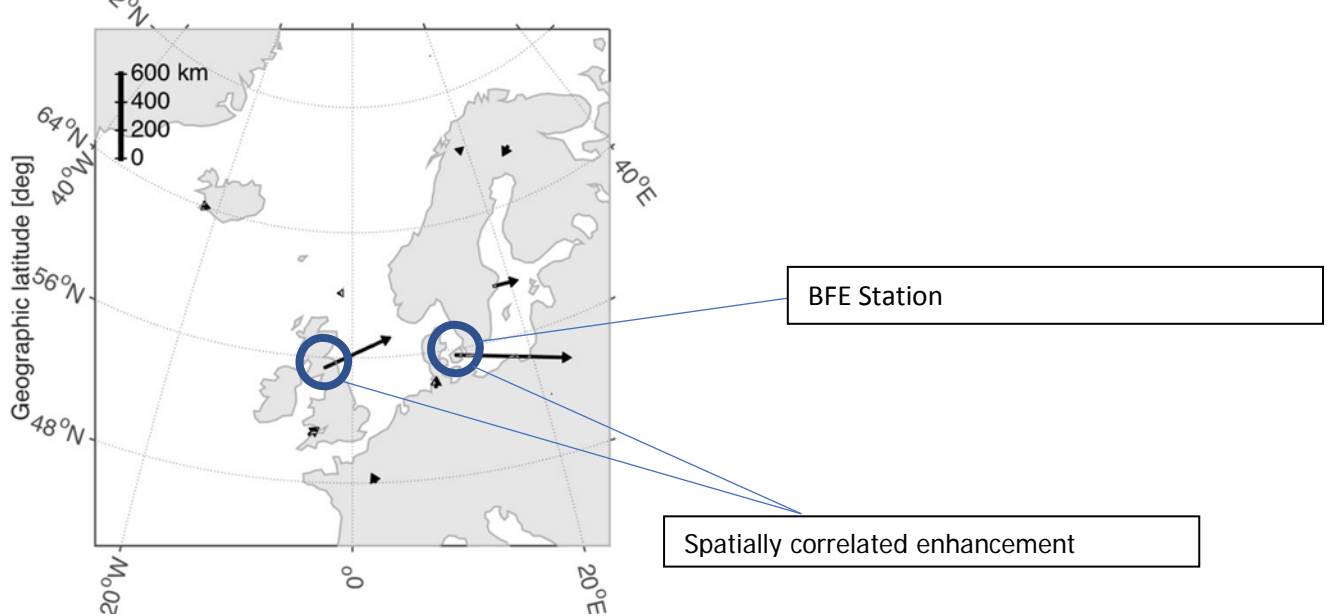


Figure 4 – March 13, 1989, at 21.44 UT , Brorfelde (BFE), Denmark

Goelectric field distribution 2003-10-29T06:47:20 UT. Max. IEI: 9.31 V/km.

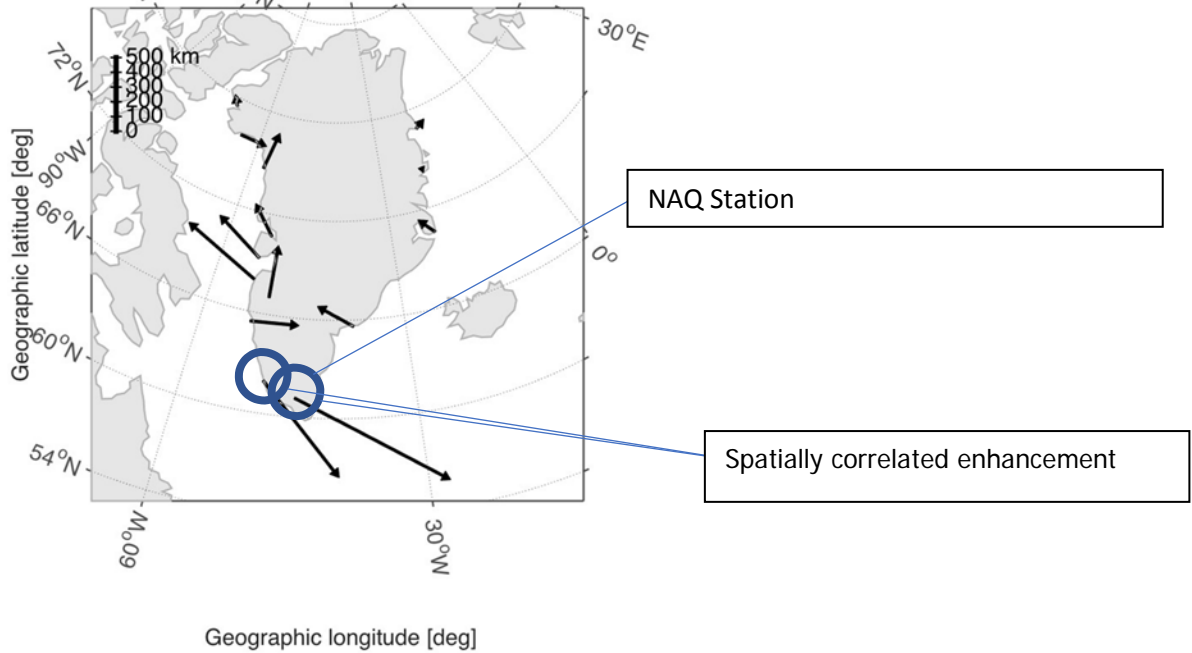


Figure 5 – October 29, 2003, at 06:47 UT, Narsarsuaq (NAQ), Greenland

Goelectric field distribution 2003-10-30T16:49:30 UT. Max. IEI: 5.68 V/km.

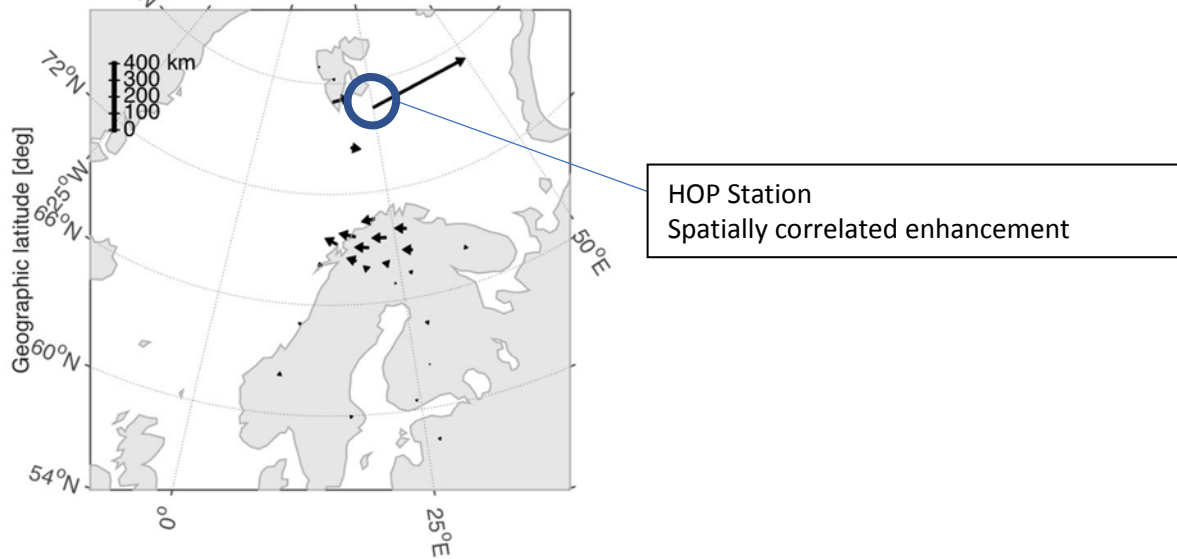


Figure 6 – October 30, 2003, at 16:49UT, Hopen Island (HOP), Svalbard, Norway

Goelectric field distribution 2015-03-17T13:33:00 UT. Max. IEI: 3.46 V/km.

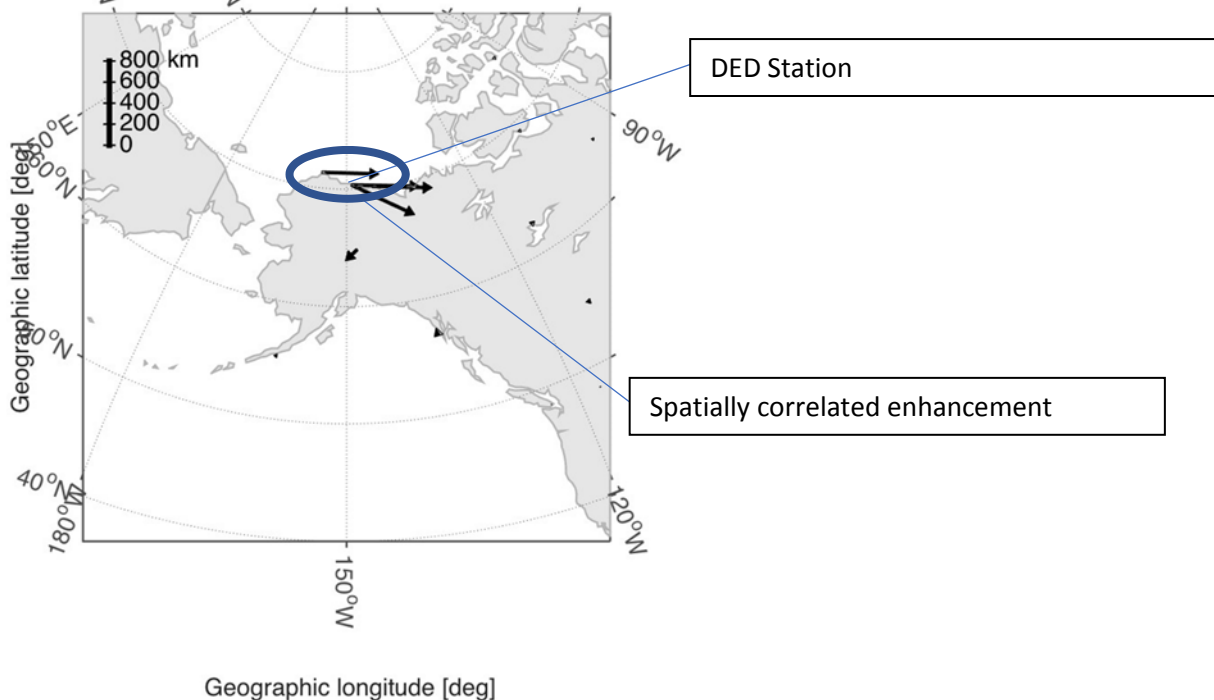


Figure 7 – March 17, 2015, at 13:33 UT, Deadhorse, Alaska

All of the above events were analyzed by reviewing the time series magnetic field data and transforming it to an electric field and focusing on the time period of the spatially correlated “local enhancement”. There were apparent similarities in the character of the “local enhancements”. The “local enhancements” occurred during peak periods of substorm activity and were distinguished by relatively brief excursions of rapid magnetic field variation. With respect to electric field amplitude, the “local enhancements” appeared to be on the order of 2 times the amplitude that was occurring during the substorm. With respect to time duration, the “local enhancements” generally occurred **on a time period of for** 2-5 minutes. (See Figures 8-11)

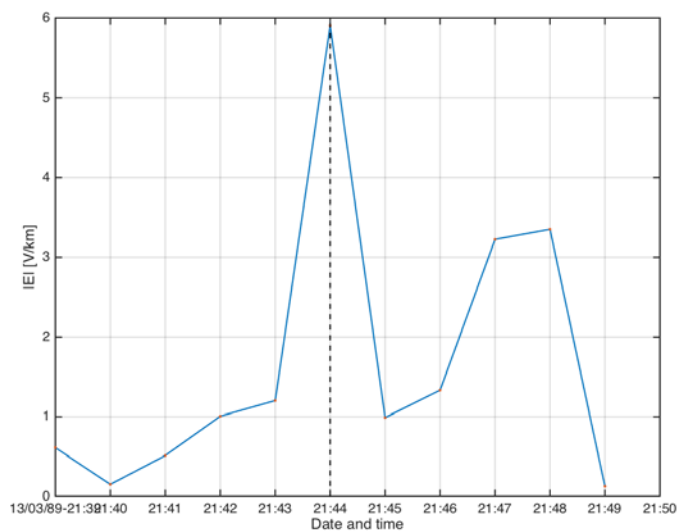


Figure 8 -- March 13, 1989, at 21.44 UT , Brorfelde (BFE), Denmark

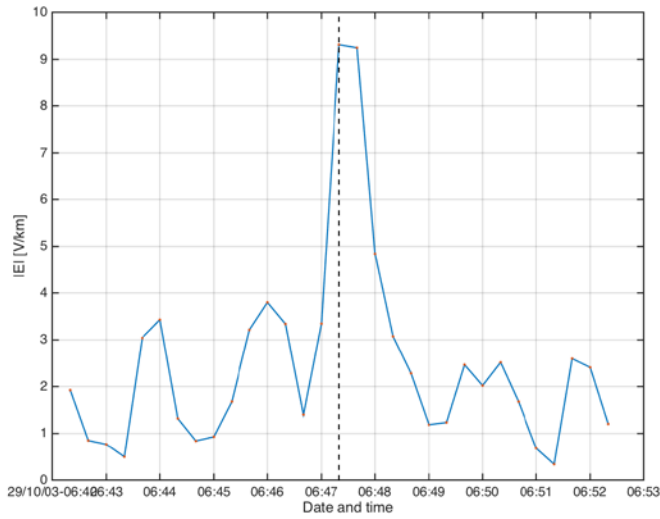


Figure 9 -- October 29, 2003, at 06:47 UT, Narsarsuaq (NAQ), Greenland

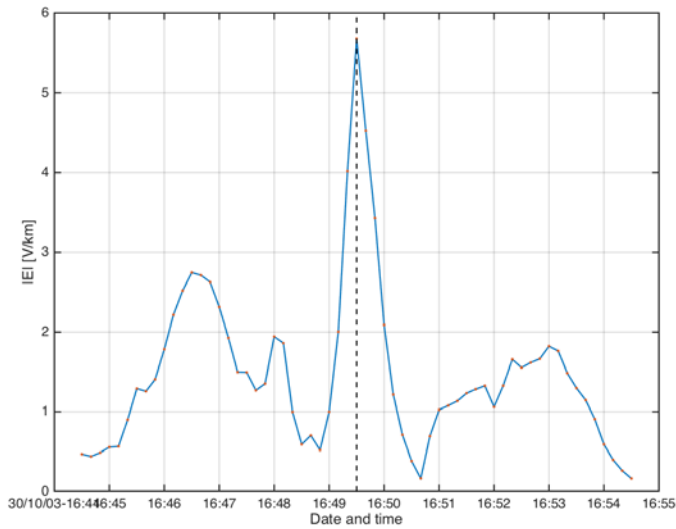


Figure 10 -- October 30, 2003, at 16:49UT, Hopen Island (HOP), Svalbard, Norway

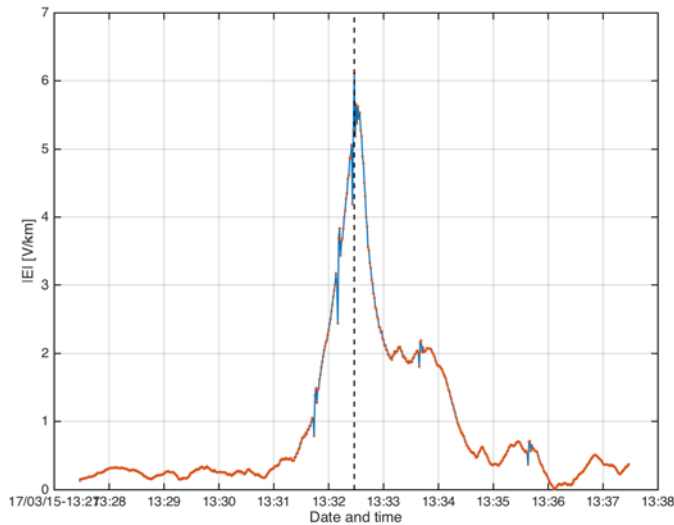


Figure 11 – March 17, 2015, at 13:33 UT, Deadhorse, Alaska

Based on the above analysis and the previous work associated with the ~~Benchmark benchmark~~ GMD event, it is reasonable to incorporate a second (or ~~supplementary~~~~supplemental~~) assessment into TPL-007 to account for the ~~potential impact of possibility~~ of a “local enhancement” in both the network analysis and the transformer hot-spot heating analysis. Given the factor of 2 amplitude enhancement and the 2-5 minute time duration from the recent analysis, the ~~Supplemental GMD~~~~supplemental GMD~~ event benchmark is set at 17 V/km with an ~~approximate pulse width duration~~ of 5 minutes to be conservative.

With respect to ~~spatial extent of “local enhancements” geographic area~~, the ~~historical geomagnetic field data is provides limited insight. only suggestive at best.~~ However, the westward ionospheric electrojet is a primary driver of the local enhancement phenomenon, indicating that the area of geomagnetic field enhancement will occur in a relatively narrow band of geomagnetic latitude and wider longitudinal width. ~~The degree to which the “local enhancement” parallels the westward ionospheric electrojet suggests a relatively narrow latitude extent as compared to the longitudinal extent. Given the uncertainty, the suggested “local enhancement” footprint is suggested to be.~~ This is represented in Figure 12 below, with geoelectric field enhancement in an area of at least 100km north-south ~~by~~~~and~~ 300 km east-west.

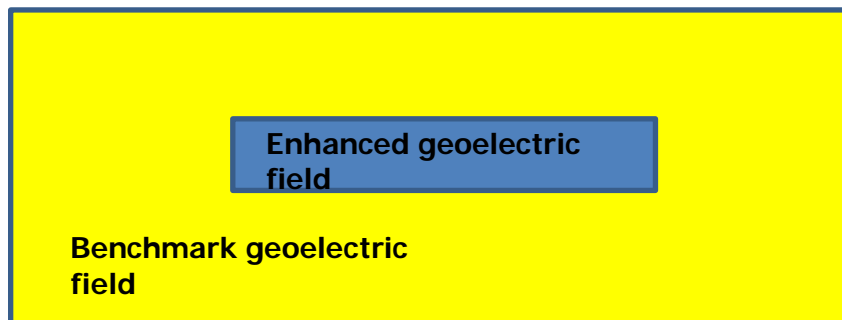


Figure 12

~~Proposed TPL-007-2 provides flexibility for planners to determine how to apply the supplemental GMD event to the planning area. How the geographic extent is applied in the Benchmark GMD event network analysis is left to the planner because there is a wide.~~ A continent-wide method is not practical and does not account for the variety in the size and topography of the various transmission systems in North America. ~~One example approach is for The the planner may choose to apply the Supplemental GMD enhanced geoelectric field event to the planner’s~~

entire system (over the entire geographic area). An alternative approach is for the planner to apply a 300 km by 500 km geoelectric field enhancement over a portion of the system and apply the benchmark GMD event over the rest of the system, or portions of it.

Also, the fact that “local enhancements” have only been observed thus far in the auroral regions (north of 60 degrees geomagnetic latitude) suggests that the network analysis be conducted with the application of the adjustment factors per the Benchmark GMD event to inform the planner of potential impacts. (See Appendix II) However, the development of a corrective action plan per TPL-007 is not required.

Synthetic Enhancement

The location of the synthetic enhancement was identified as a portion of the benchmark geomagnetic field that shared a number of the characteristics of observed local enhancements described above. This was also corresponds to part of the benchmark event with the highest geoelectric field. The synthetic enhancement was constructed by scaling linearly a 4.6 minute portion of the benchmark geomagnetic field so that the peak geoelectric field is 17 V/km at a geomagnetic latitude of 60° and the benchmark reference earth model. Figure I-x1 shows the benchmark geomagnetic field and Figure I-x2 shows the supplemental benchmark geomagnetic field. Figure I-x3 zooms into Bx, with and without the synthetic enhancement.

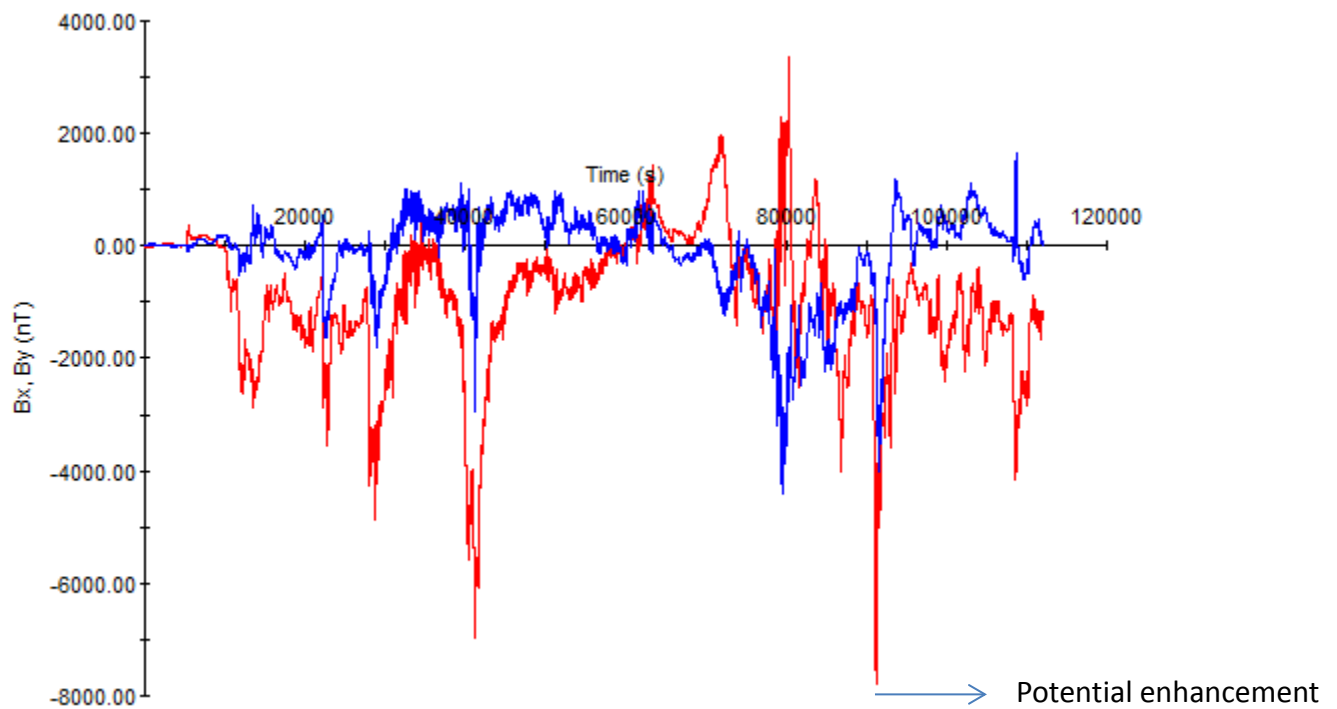


Figure I-x1: Benchmark geomagnetic field. Bx (red), By (blue)

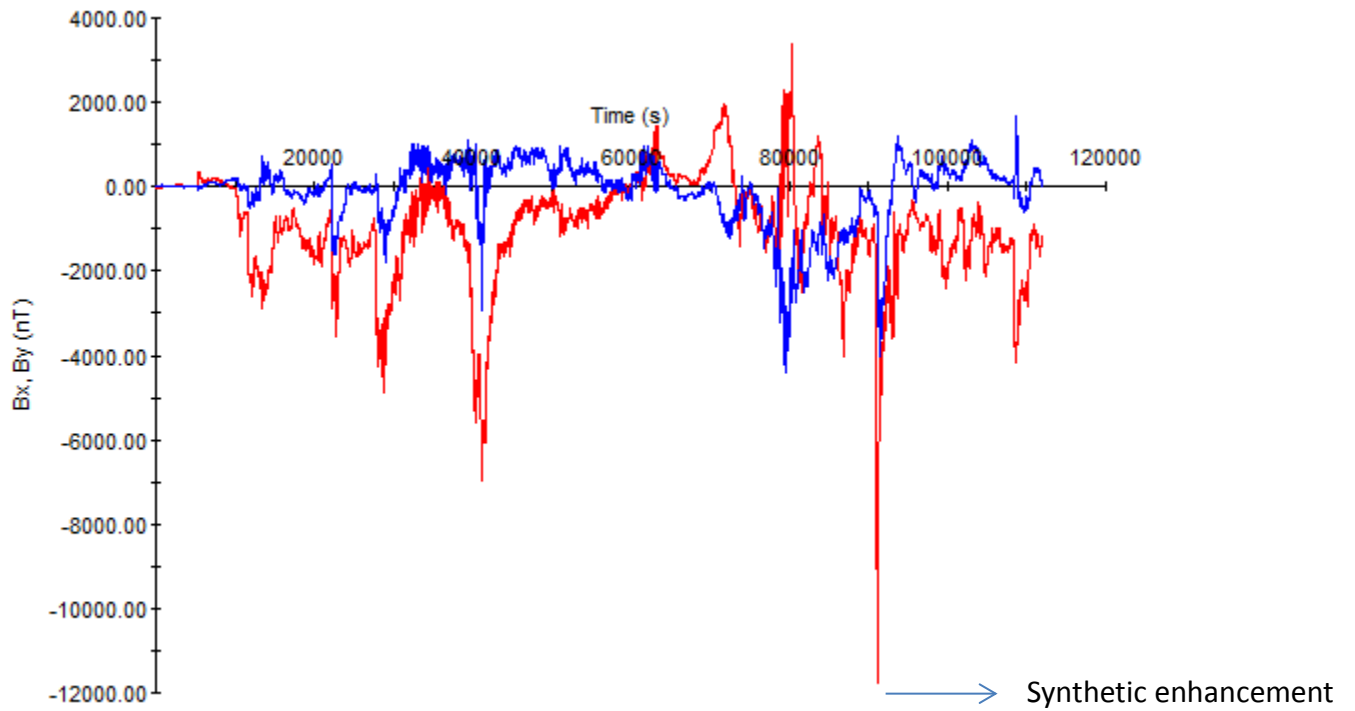


Figure I-x2: Supplemental Benchmark geomagnetic field. B_x (red), B_y (blue)

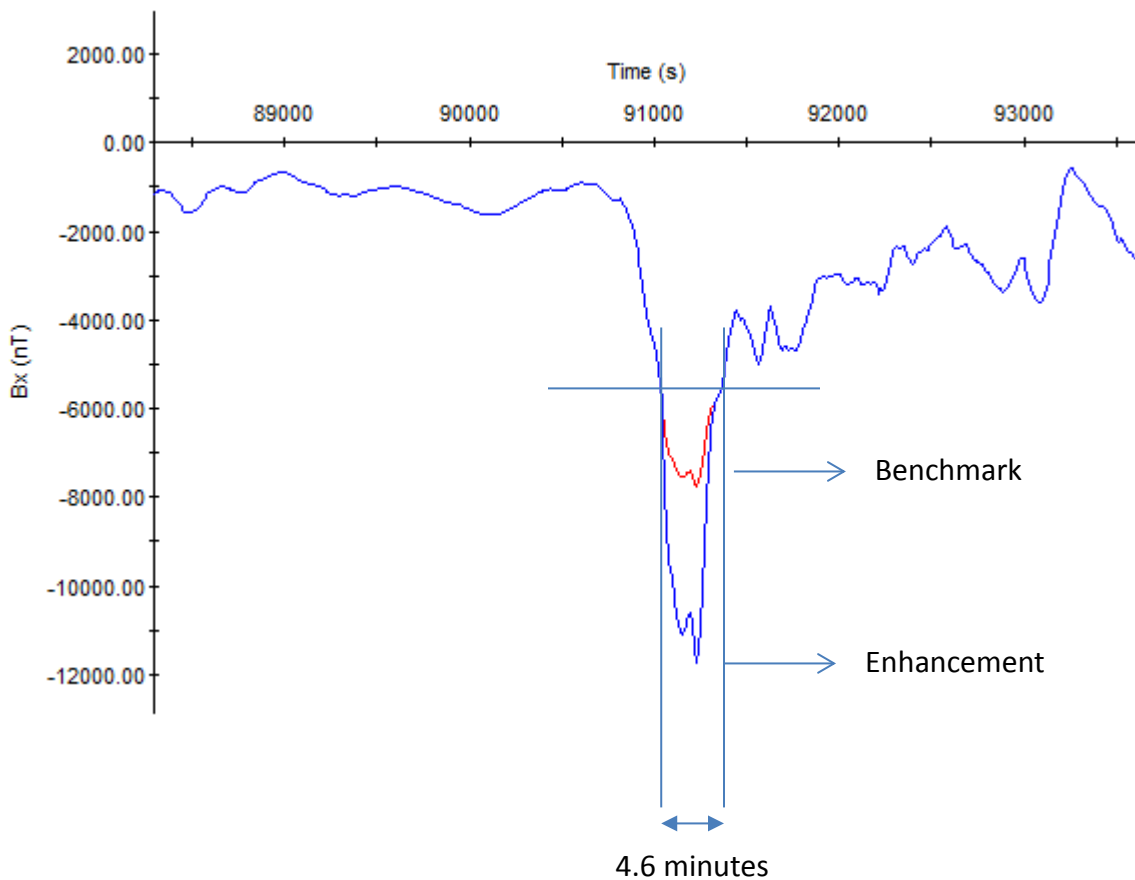


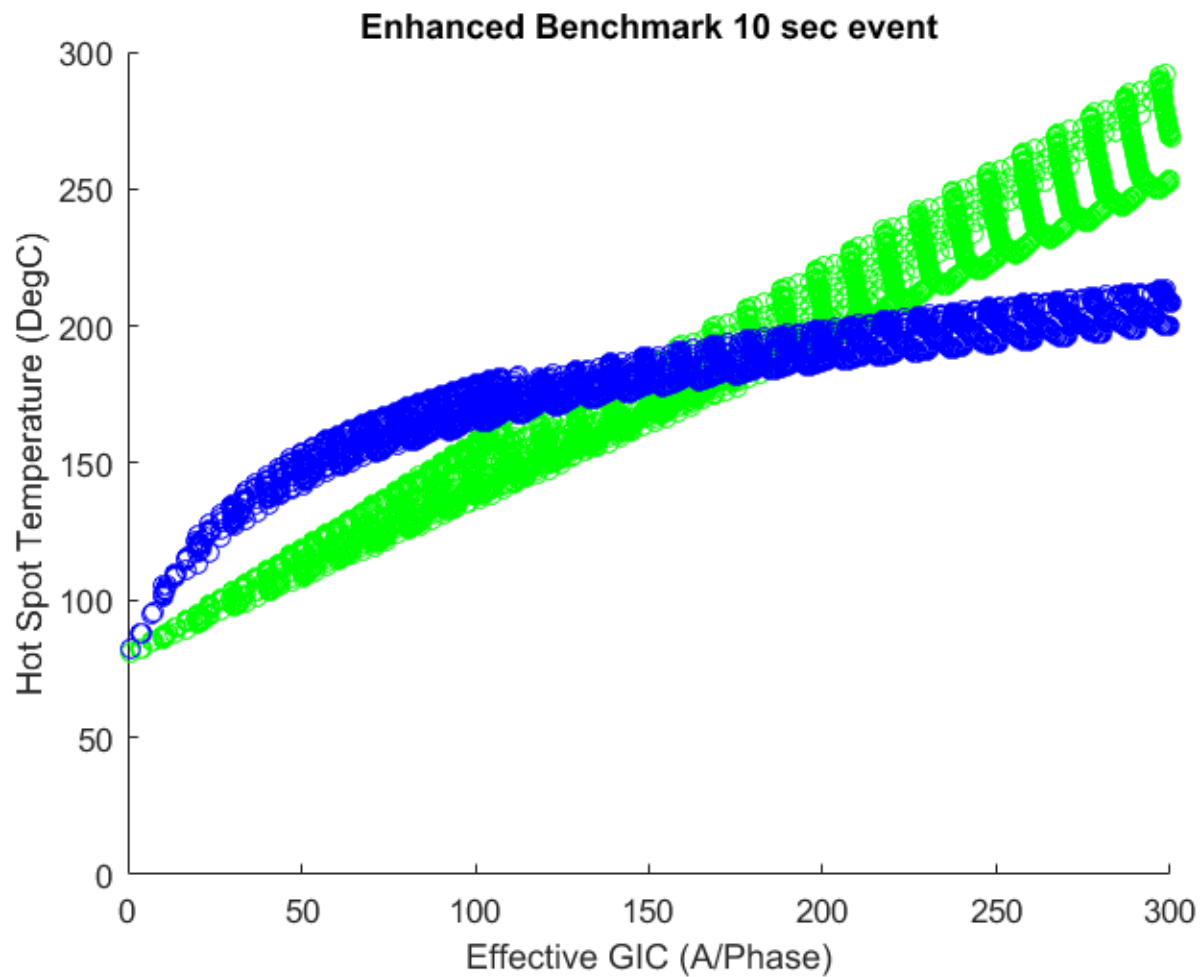
Figure I-x3: Benchmark Bx (red) and supplemental Bx field (blue) – expanded view

Impact of the supplemental Waveshape on Transformer Hot-spot Heating

Thermal effects (e.g. hot spot transformer heating) in power transformers are not instantaneous. Thermal time constants associated with hot spot heating in power transformers are in the 5-20 minute range; therefore, the waveshape of the geomagnetic and geoelectric field has a strong impact on transformer hot spot heating of windings and metallic parts since thermal time constants are of the same order of magnitude as the time-to-peak of storm maxima. ~~The waveshape of the March 13-14 1989 GMD event measured at the Ottawa geomagnetic observatory was found to be a conservative choice when compared with other events of the last 20 years, such as the measurements at the Nurmijarvi (NUR) and Memanbetsu (MMB) geomagnetic observatories for the “Halloween event” of October 29-31, 2003 described in the NERC GMD interim report of 2012 [14].~~

From a hot spot heating point of view, the local enhancement of the supplemental benchmark waveshape has a material impact on the temperature rise even though the duration of the local enhancement is approximately 5 minutes. Figure I-x4 shows ~~To incorporate the potential impact of a “local enhancement into the transformer thermal analysis, a synthetic “local enhancement” with an amplitude of 17 V/km and a pulse width of 5 minutes has been inserted into the March 13-14 1989 GMD time series that is used for the Benchmark GMD event.~~

~~To illustrate, the results of a thermal analysis performed on a relatively large test network with a diverse mix of circuit lengths and orientations is provided in **Figures I-7** and **I-8**. **Figure I-9** shows a more systematic way to compare the relative effects of storm waveshape on the thermal response of a transformer. It shows the results of thousands of 33,000 thermal assessments for all combinations of effective GIC due to circuit orientation. The horizontal axis represents peak effective GIC(t) current and the vertical axis represents peak metallic hot spot temperature. The combined envelope of these two curves is similar to the screening criterion of the benchmark event.~~



(similar to Figures I-7 and I-8 but systematically taking into account all possible circuit orientations). These results illustrate the relative effect of different waveshapes in a broad system setting and should not be interpreted as a vulnerability assessment of any particular network.

Figure I-x4: Calculated Peak Metallic for all possible circuit orientations and peak effective GIC(t). [ML5]

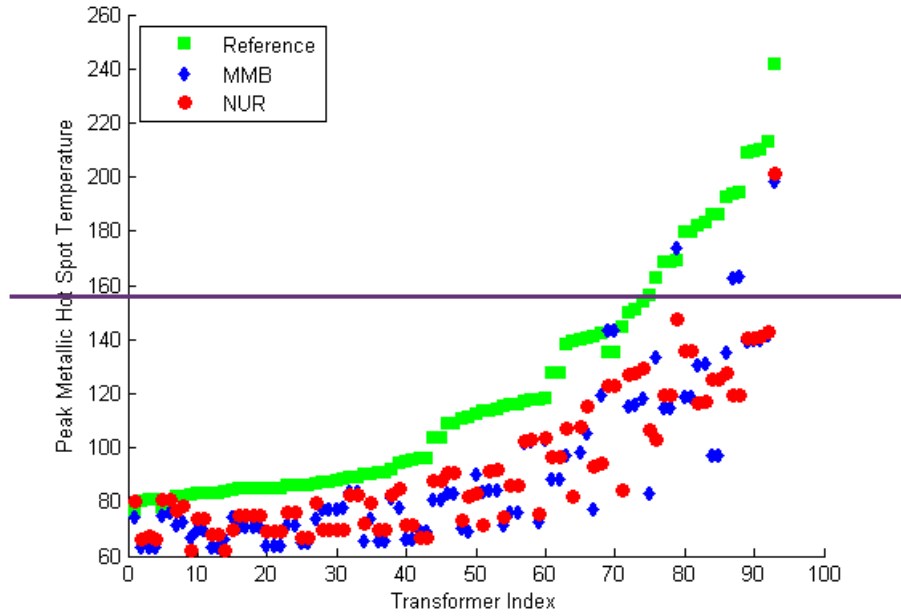


Figure I-7: Calculated Peak Metallic Hot Spot Temperature for All Transformers in a Test System with a Temperature Increase of More Than 20°C for Different GMD Events Scaled to the Same Peak Geoelectric Field

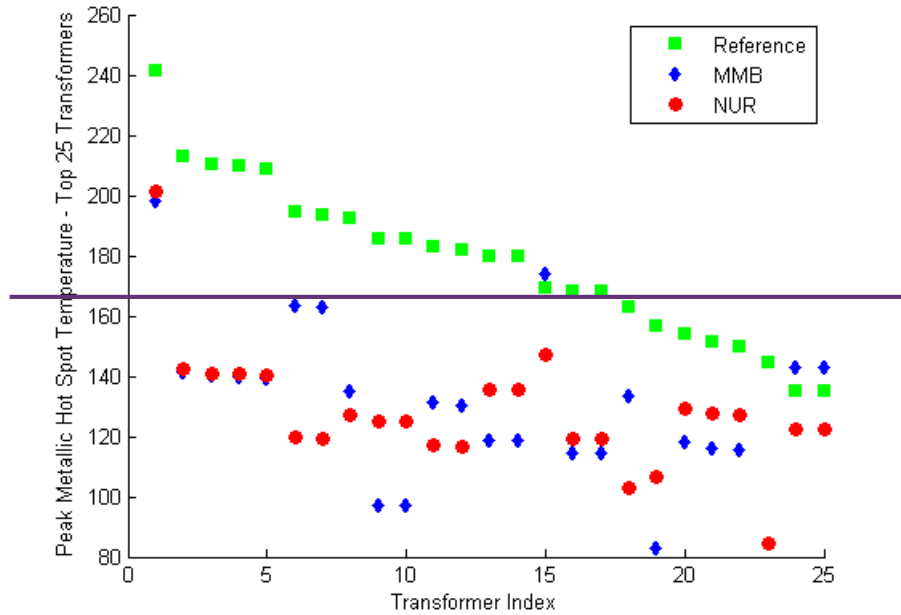


Figure I-8: Calculated Peak Metallic Hot Spot Temperature for the Top 25 Transformers in a Test System for Different GMD Events Scaled to the Same Peak Geoelectric Field

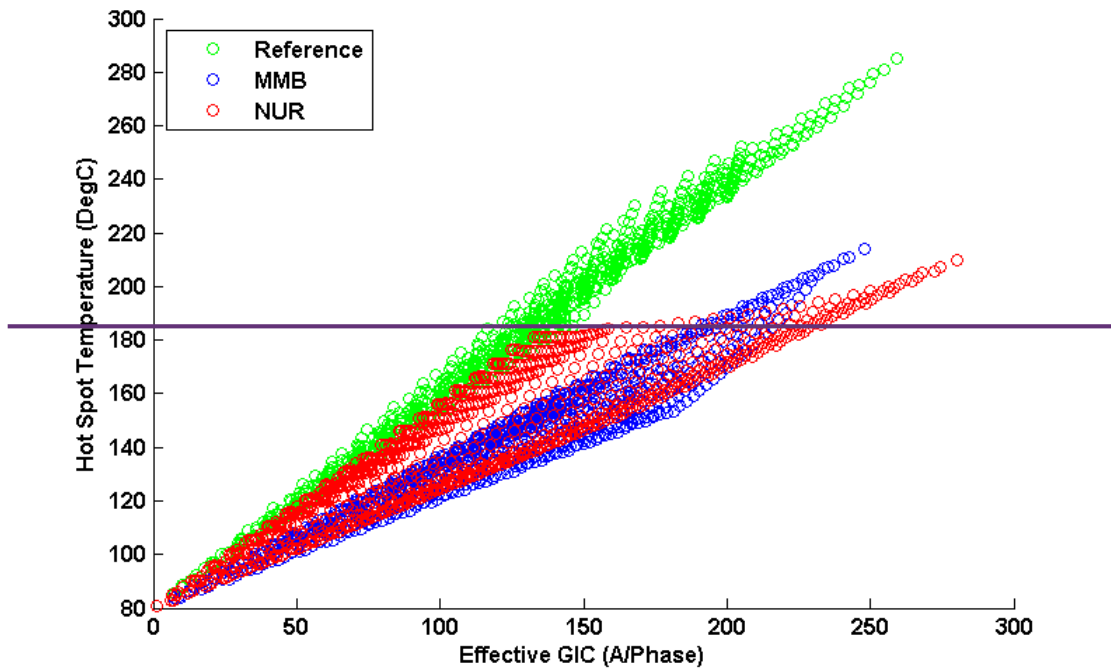


Figure I-9: Calculated Peak Metallic Hot Spot Temperature for all possible circuit orientations and effective GIC.

Appendix II – Scaling the Supplemental Benchmark GMD Event

The intensity of a GMD event depends on geographical considerations such as geomagnetic latitude⁴ and local earth conductivity⁵ [3]. Scaling factors for geomagnetic latitude take into consideration that the intensity of a GMD event varies according to latitude-based geographical location. Scaling factors for earth conductivity take into account that the induced geoelectric field depends on earth conductivity, and that different parts of the continent have different earth conductivity and deep earth structure.

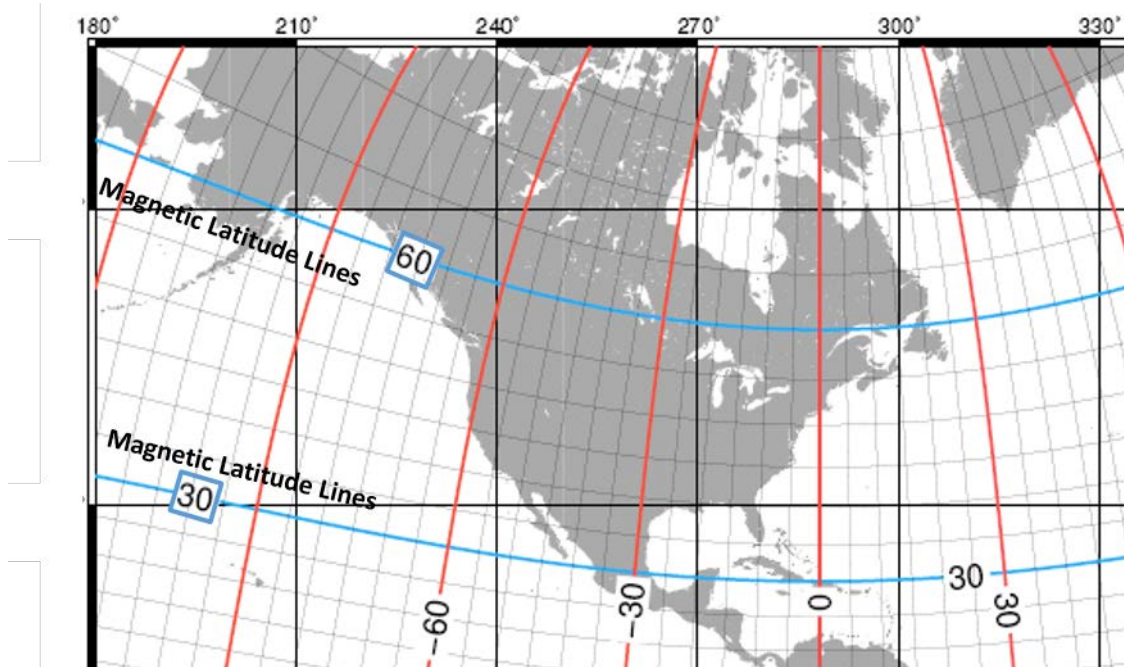
Scaling of the supplemental benchmark event is basically the same as the scaling of the benchmark event, except that E_{peak} is 17 V/km instead of 8 V/km. The application of the supplemental benchmark is different since it is assumed to be spatially limited.

Scaling the Geomagnetic Field

The supplemental benchmark GMD event is defined for geomagnetic latitude of 60° and it must be scaled to account for regional differences based on geomagnetic latitude. To allow usage of the reference geomagnetic field waveshape in other locations, **Table II-1** summarizes the scaling factor α correlating peak geoelectric field to geomagnetic latitude as described in **Figure II-1** [3]. This scaling factor α has been obtained from a large number of global geomagnetic field observations of all major geomagnetic storms since the late 1980s [15], [24]-[25], and can be approximated with the empirical expression in (II.1)

$$\alpha = 0.001 \cdot e^{(0.115 \cdot L)} \quad (\text{II.1})$$

where L is the geomagnetic latitude in degrees and $0.1 \leq \alpha \leq 1.0$.



⁴ Geomagnetic latitude is analogous to geographic latitude, except that bearing is in relation to the magnetic poles, as opposed to the geographic poles. Geomagnetic phenomena are often best organized as a function of geomagnetic coordinates.

⁵ Local earth conductivity refers to the electrical characteristics to depths of hundreds of km down to the earth's mantle. In general terms, lower ground conductivity results in higher geoelectric field amplitudes.

Figure II-1: Geomagnetic Latitude Lines in North America

Table II-1: Geomagnetic Field Scaling Factors	
Geomagnetic Latitude (Degrees)	Scaling Factor1 (α)
≤ 40	0.10
45	0.2
50	0.3
54	0.5
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

Scaling the Goelectric Field

The benchmark GMD event is defined for the reference Quebec earth model provided in **Table 1**. This earth model has been used in many peer-reviewed technical articles [12, 15]. The peak goelectric field depends on the geomagnetic field waveshape and the local earth conductivity. Ideally, the peak goelectric field, E_{peak} , is obtained by calculating the goelectric field from the scaled geomagnetic waveshape using the plane wave method and taking the maximum value of the resulting waveforms

$$\begin{aligned}
 E_N &= (z(t) / \mu_o) * B_E(t) \\
 E_E &= -(z(t) / \mu_o) * B_N(t) \\
 E_{peak} &= \max\{E_E(t), E_N(t)\}
 \end{aligned}
 \tag{II.2}$$

where,

* denotes convolution in the time domain,

$z(t)$ is the impulse response for the earth surface impedance calculated from the laterally uniform or 1D earth model,

$B_E(t)$, $B_N(t)$ are the scaled Eastward and Northward geomagnetic field waveshapes,

$E_E(t)$, $E_N(t)$ are the magnitudes of the calculated Eastward and Northward goelectric field $E_E(t)$ and $E_N(t)$.

As noted previously, the response of the earth to $B(t)$ (and dB/dt) is frequency dependent. **Figure II-2** shows the magnitude of $Z(\omega)$ for the reference earth model.

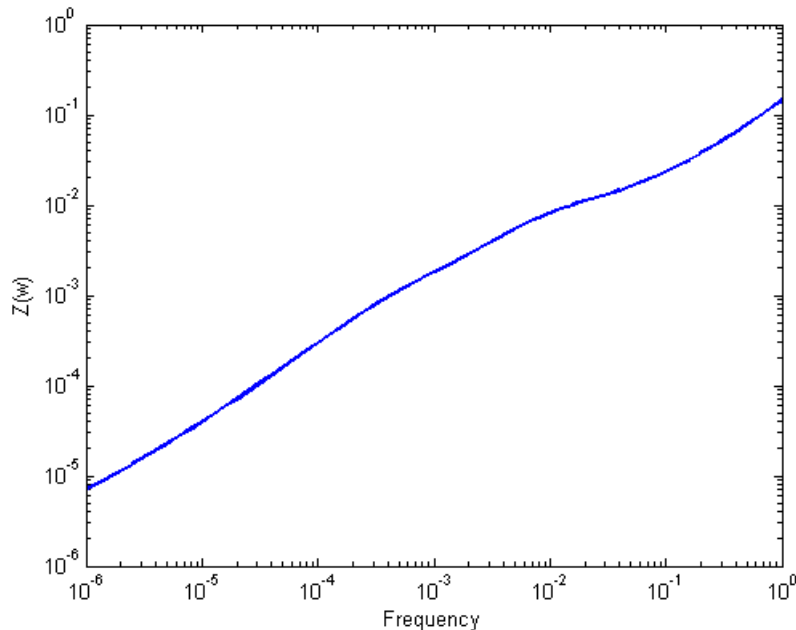


Figure II-2: Magnitude of the Earth Surface Impedance for the Reference Earth Model

If a utility does not have the capability of calculating the waveshape or time series for the geoelectric field, an earth conductivity scaling factor β can be obtained from **Table II-2**. Using α and β , the peak geoelectric field E_{peak} for a specific service territory shown in **Figure II-3** can be obtained using (II.3)

$$E_{\text{peak}} = 178 \times \alpha \times \beta \text{ (V/km)} \quad (\text{II.3})$$

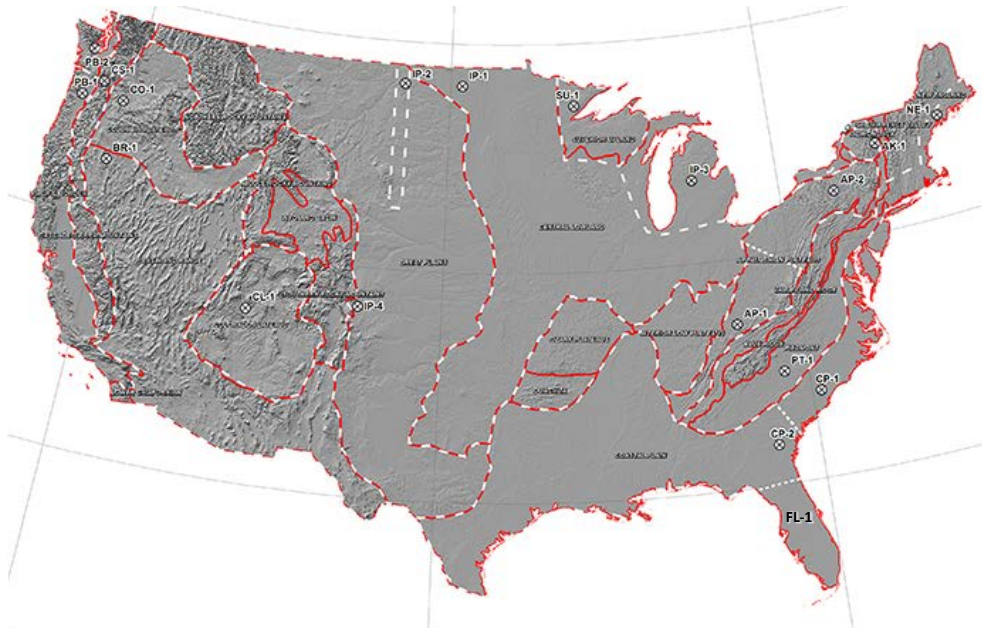
It should be noted that (II.3) is an approximation based on the following assumptions:

- The earth models used to calculate Table II-2 for the United States are from published information available on the USGS website.
- The models used to calculate Table II-2 for Canada were obtained from NRCan and reflect the average structure for large regions. When models are developed for sub-regions, there will be variance (to a greater or lesser degree) from the average model. For instance, detailed models for Ontario have been developed by NRCan and consist of seven major sub-regions.
- The conductivity scaling factor β is calculated as the quotient of the local geoelectric field peak amplitude in a physiographic region with respect to the reference peak amplitude value of 178 V/km. Both geoelectric field peaks amplitudes are calculated using the [reference supplemental \[ML6\]](#) geomagnetic field time series. If a different geomagnetic field time series were used, the calculated scaling factors β would be different than the values in Table II-2 because the frequency content of storm maxima is, in principle, different for every storm. ~~However, the reference time series produces generally more conservative values of β when compared to the time series of reference storm of the NERC interim report of 2012 [14], measurements at the Nurmijarvi (NUR) and Memanbetsu (MMB) geomagnetic observatories for the “Halloween event” of October 29–31, 2003, and other recordings of the March 1989 event at high latitudes (Meanook observatory, Canada). The average variation between minimum and maximum β is~~

approximately 12 percent. **Figure II-4** illustrates the values of β calculated using the 10-second recordings for these geomagnetic field time-series.

- If a utility has technically-sound earth models for its service territory and sub-regions thereof, then the use of such earth models is preferable to estimate E_{peak} .
- When a ground conductivity model is not available the planning entity should use the largest β factor of adjacent physiographic regions or a technically-justified value.

Physiographic Regions of the Continental United States



Physiographic Regions of Canada



Figure II-3: Physiographic Regions of North America^[ML7]^[MO8]

Table II-2 Geoelectric Field Scaling Factors	
USGS Earth model	Scaling Factor (β)
AK1A	0.4856
AK1B	0.4856
AP1	0.3328
AP2	0.07682
BR1	0.2222
CL1	0.7176
CO1	0.2527
CP1	0.8081
CP2	0.9195
FL1	0.74
CS1	0.3541
IP1	0.8994
IP2	0.2428
IP3	0.8893
IP4	0.3341
NE1	0.7481
PB1	0.5162
PB2	0.3646
PT1	1.1917
SL1	0.4653
SU1	0.8893
BOU	0.2228
FBK	0.5756
PRU	0.2221
BC	0.6067
PRAIRIES	0.8496
SHIELD	1.0
ATLANTIC	0.7479

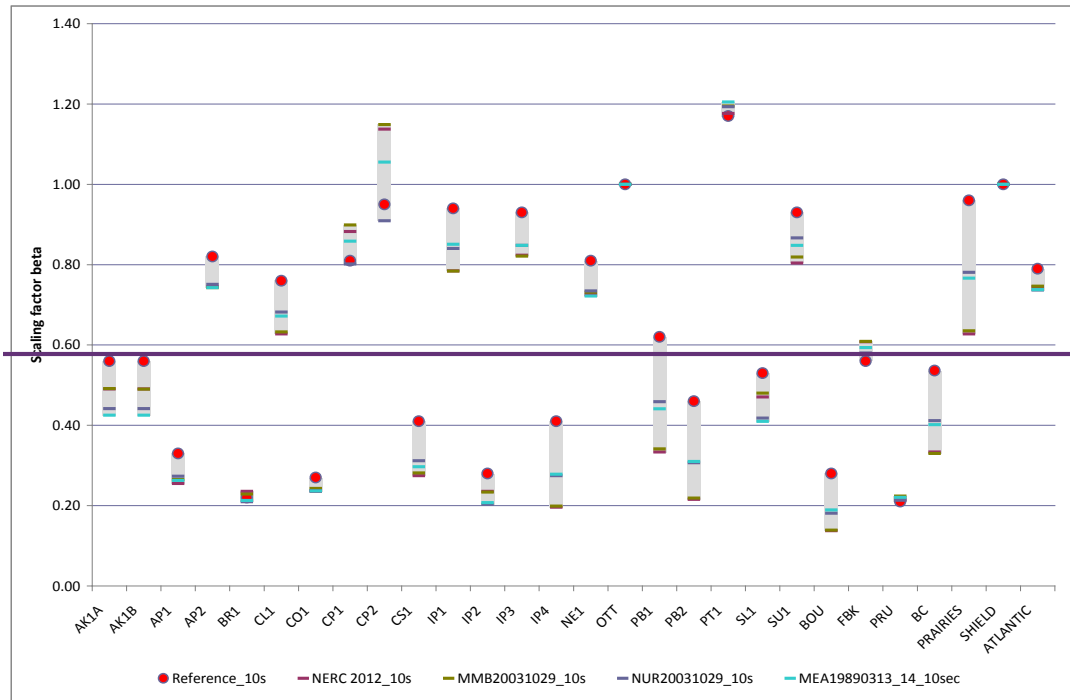


Figure II-4: Beta factors Calculated for Different GMD Events
Red circles correspond to the values in Table II-2

Example Calculations [ML9]

Example 1

Consider a transmission service territory that lies in a geographical latitude of 45.5° , which translates to a geomagnetic latitude of 55° . The scaling factor α calculated using II.1 is 0.56; therefore, the benchmark waveshape and the peak geoelectric field will be scaled accordingly. If the service territory has the same earth conductivity as the benchmark then $\beta=1$, and the peak geoelectric field will be

$$\alpha = 0.56$$

$$\beta = 1.0$$

$$E_{peak} = 17 \times 0.56 \times 1 = 9.5V / km$$

If the service territory spans more than one physiographic region (i.e. several locations within the service territory have a different earth model) then the largest α can be used across the entire service territory for conservative results. Alternatively, the network can be split into multiple subnetworks, and the corresponding geoelectric field amplitude can be applied to each subnetwork.

Example 2

Consider a service territory that lies in a geographical latitude of 45.5° which translates to a geomagnetic latitude of 55° . The scaling factor α calculated using II.1 is 0.56; therefore, the benchmark waveshape and the peak geoelectric field will be scaled accordingly.

The service territory has lower conductivity than the reference benchmark conductivity, therefore, according to the conductivity factor β from Table II-2., the calculation follows:

Conductivity factor $\beta=1.17$

$\alpha = 0.56$

$E_{peak} = 17 \times 0.56 \times 1.17 = 11.1 / km$

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