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Background

The highly complex, interconnected North American power grid has provided a long record of reliable, secure delivery of electric power. However, solar storm or geomagnetic disturbance (GMD) events have demonstrated that they can disrupt the normal operations of the power grid. The most recent example in North America occurred in March 1989, when a GMD triggered to the collapse of the Hydro-Québec system, leaving more than six million people without power for nine hours. Understanding the effects of GMD on bulk power systems and the ability of the industry to mitigate their effects are important to managing system reliability.

Interim Report Conclusions

The NERC interim report on GMD concluded\(^1\) that the most likely impact to the bulk power system resulting from a low-probability strong GMD event and the corresponding geomagnetic induced current (GIC) flows is voltage instability\(^2\), caused by a significant loss of reactive power support and a simultaneous substantial increase in transformer reactive power demand.\(^3\) The lack of sufficient reactive power support was a primary contributor of the 1989 Hydro-Québec GMD-induced blackout.

Though the most likely result is voltage collapse, it is accepted that particularly large GIC flows can result in transformer damage, and may ultimately result in the failure of some transformers. The industry is well-equipped to face a small number of transformer failures; however, due to the concerns about an extreme GMD event causing a larger than expected number of failures, it is important to carefully quantify the nature of the reliability risk.

For these two results, NERC proposes to coordinate its research with DOE, NOAA, SpaceWeather Canada, USGS, NRCan, NASA, Canadian Space Agency (CSA), EPRI, IEEE, the Transmission Forum, and other industry and scientific organizations in two key areas: (1) assessing the vulnerability of the North American transformer fleet, incorporating power system modeling with space weather simulation and transformer thermal characteristics, and (2) surveying the industry for best practices in operations to respond to GMD and updating the NERC Industry Alert. In tandem with these efforts, and in support of other high-impact, low-probability events, NERC is re-commissioning the Spare Equipment Database to support the sharing of equipment amongst entities in the face of a catastrophic event.

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2. Almost all bulk electric power in the United States is generated, transported and consumed in an alternating current (AC) network. Elements of AC systems produce/deliver and consume/absorb two kinds of power: real power (measured in watts) and reactive power (measured in volt-amperes reactive or var). Real power accomplishes useful work (e.g., running motors and lighting lamps). Reactive power supports the voltages that must be controlled for system reliability. Voltage collapse can occur when there is insufficient power capacity or reactive support in a wide area, leading to depressed voltages and eventually to blackout. The 2003 blackout experience shows that voltage collapse could result in blackout of hours or days in duration, but with minimal equipment damage.
3. Loss of reactive power support can be caused by the inadvertent protection operation of reactive compensation devices (e.g., shunt capacitor banks, SVCs) due to harmonics generated by transformer half-cycle saturation. Reactive power demand is increased by transformer saturation.
Scope

The primary goal of the GMDTF in phase 2 will be to review, and verify where applicable, the work products of NERC and other industry and scientific organizations in support of the key areas above, to provide industry subject-matter expertise, volunteer industry participation as appropriate, and augment and finalize the Special Assessment report. This work will require close coordination with the ongoing collaborative efforts of the Electric Power Research Institute (EPRI) along with governmental and private sector efforts. Specifically, the GMDTF will address the 4 recommendations identified in the interim report:

- Recommendation 1: Improvement of tools for industry planners to develop GMD mitigation strategies
- Recommendation 2: Improvement of tools for system operators to manage GMD impacts
- Recommendation 3: Education and information exchanges between researchers and industry
- Recommendation 4: Review the need to enhance NERC Reliability Standards

In addressing the recommendations above, phase 2 will also directly support the Electricity Sub-sector Coordinating Council (ESCC) Critical Infrastructure Strategic Roadmap⁴.

Assumptions and Limitations
The scope of work will be limited to the items described above and the actions described in the Action Plan below. The merits and content of the Special Assessment Interim Report will not be considered as an item for debate.

Task Force Membership
The task force is comprised of members and observers:

Members
The task force chair and vice chair are appointed from the task force membership by the chairs of the NERC Planning Committee (PC) and Operating Committee (OC). The vice chair should be available to act on the chair’s behalf should the chair be unavailable.

Members are users, owners, and operators of bulk power system assets and represent stakeholders with an associated NCR number, or subject matter experts from Regional Entity staff. Task Force members represent the owners and operators who are ultimately accountable for the reliable planning and operation of the bulk powers system, and they are responsible for approving the deliverables of the GMDTF.

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Observers
Observers provide essential subject matter expertise to the GMDTF, particularly in areas not directly related to bulk power system planning and operation. Observers may represent Federal, State and Provincial Government agencies, vendors, academics, the scientific community, or other interested parties. Guest participation of subject matter experts may be requested by the GMDTF Chair.

Order of Business
The GMDTF will develop its conclusions using sound engineering judgment on the basis of sound peer-reviewed data and analysis. In general, the desired, normal tone of GMDTF business is to strive for consensus. If consensus cannot be achieved, the GMDTF will defer to a vote by GMDTF members, or if necessary by the Planning Committee, to make decisions.

Resources
The GMDTF is expected to require face-to-face meetings once per quarter and two conference calls per month (2 hours each).

Deliverables
The GMDTF phase 2 deliverables will include the review of items specified in the Action Plan, the detailed Action Plan schedule, and the finalization of the Special Assessment report on GMD.

Reporting
The task force is responsible to the OC and PC for the completion of work associated with the scope items outlined above, and final work products of the task force will be approved as necessary by the Planning Committee and the Board of Trustees. Quarterly updates will be provided to the Technical Committees and the Electricity Subsector Coordinating Council (ESCC). The ESCC will support the GMDTF by providing direction and support regarding policy-level issues that may arise.

The GMDTF will coordinate closely with the OC and PC concerning the reported analysis and recommendations, as well as providing regular feedback to the ESCC. OC and PC input should be solicited frequently to align analysis and recommendations with ongoing and emerging issues.
## Action Plan

### Recommendations from the Interim Report

The Special Assessment interim report on GMD identified recommendations in Chapter 13 Table 5. This table is repeated below; the first three columns are verbatim reproductions from the report, and the additional column has been added to identify the specific tasks that are needed to address the recommendations. The task specifics and deliverables are described in the Detailed Action Plan later in this section.

<table>
<thead>
<tr>
<th>Recommendation Identification</th>
<th>Recommendation</th>
<th>Estimated Completion</th>
<th>Required Tasks</th>
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</thead>
</table>
| **NERC-1.1**                  | Develop a vulnerability assessment tool that categorizes transformer vulnerability and expected GIC levels. This tool will assess the transient and thermal effects, along with dynamic and transient impacts from increased reactive consumption and harmonic currents. | 12-24 months         | Task 1.1: Transformer construction survey  
Task 1.2: Provide and maintain data confidentiality  
Task 1.3: Transformer thermal model development  
Task 1.4: Transformer testing  
Task 1.5: GIC model development |
| **NERC-1.2**                  | Continue to refine and improve a set of defined reference storms (most severe occurrence in a 100-year time horizon) and support ongoing research to identify the maximum theoretical GMD. | 18-36 months         | Task 1.6: Extreme “Carrington” GMD scenario development |
| **NERC-1.3**                  | Support the development of open-source simulation tools and models to calculate GIC flows. | 18-36 months         | Task 1.3: Transformer thermal model development  
Task 1.5: GIC model development  
Task 1.6: Extreme “Carrington” GMD scenario development  
Task 1.7: Finalize 1-D ground conductivity models |
<table>
<thead>
<tr>
<th>Recommendation Identification</th>
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<th>Estimated Completion</th>
<th>Required Tasks</th>
</tr>
</thead>
</table>
| NERC-1.4                      | Work with NERC Regional Interconnection Modeling Groups to enhance system models in support of the study of GMD impacts. | 12-24 months        | Task 1.1: Transformer construction survey  
Task 1.2: Provide and maintain data confidentiality  
Task 1.3: Transformer thermal model development  
Task 1.4: Transformer testing  
Task 1.5: GIC model development  
Task 1.8: Facilitate system-wide vulnerability analysis |
| NERC-1.5                      | Support the development of improved Earth conductivity and ground impedance models for the North American geology. | 18-36 months        | Task 1.7: Finalize 1-D ground conductivity models |
| NERC-1.6                      | Identify GIC monitoring capability on transformers, and determine optimum locations based on studies and operational experience. | 18-36 months        | Task 1.1: Transformer construction survey  
Task 1.8: Facilitate system-wide vulnerability analysis  
Task 2.1: GMD operating practices survey |
| NERC-1.7                      | Review industry transformer procurement specifications and identify suitable GIC-withstand criteria. In coordination with equipment standards organizations, develop minimum benchmark criteria for incorporation into procurement processes. | 12-24 months        | Task 1.2: Provide and maintain data confidentiality  
Task 1.9: Review industry transformer specifications |

**Recommendation 2: Improve tools for system operators to manage GMD impacts.**

<table>
<thead>
<tr>
<th>Recommendation Identification</th>
<th>Recommendation</th>
<th>Estimated Completion</th>
<th>Required Tasks</th>
</tr>
</thead>
</table>
| NERC-2.1                      | Develop guidelines for transmission operators and owners to enhance monitoring and mitigation of GIC. | 12-24 months        | Task 1.1: Transformer construction survey  
Task 2.1: GMD operating practices survey  
Task 2.2: Update and release NERC Alert |
<table>
<thead>
<tr>
<th>Recommendation Identification</th>
<th>Recommendation</th>
<th>Estimated Completion</th>
<th>Required Tasks</th>
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</thead>
<tbody>
<tr>
<td>NERC-2.2</td>
<td>When improved NOAA and NRCan alert and warning notification actions are available, enhance GMD notification procedures used in the Reliability Coordinator Information System (RCIS).</td>
<td>12-24 months</td>
<td>Task 2.2: Update and release NERC Alert</td>
</tr>
</tbody>
</table>

**Recommendation 3: Education and information exchanges between researchers and industry.**

| Recommendation Identification | Recommendation                                                                                                                                                                                                 | Estimated Completion | Required Tasks                                                                                   |
|-------------------------------|--------------------------------------------------------------------------------------------------------------------------------Adam                                                                                                                                         |                      |                                                                                                  |
| NERC-3.1                      | Develop training material and conduct ongoing periodic webinars (including during dormant period) to inform industry planners and system operators of system vulnerabilities from GMD and actions that can be taken to mitigate the impact. | 12-24 months         | Task 1.1: Transformer construction survey  
Task 2.1: GMD operating practices survey  
Task 3.1: Develop introductory GMD webinar  
Task 3.2: Update System Operator training with GMD best practices |
| NERC 3.2                      | Establish a GMD data clearinghouse for use by industry and researchers to share information and enhance reliability.5                                                                                      | 18-36 months         | Task 3.3: Establish GMD data clearinghouse                                                        |
| NERC-3.3                      | Raise awareness in industry, regulators, policymakers, and government agencies, of GMD impacts on the bulk power system.                                                                               | 12-24 months         | Task 3.1: Develop introductory GMD webinar  
Task 3.3: Establish GMD data clearinghouse                                                         |

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5 Any data clearinghouse established by NERC would follow appropriate standards and regulations relating to NERC Critical Infrastructure Protection Standards and FERC Regulations on Critical Energy Infrastructure Information. This clearinghouse would need to establish standardized data formats for GIC data for continued use by industry and researchers.
Recommendation 4: *Review the need to enhance NERC Reliability Standards.*

<table>
<thead>
<tr>
<th>Recommendation Identification</th>
<th>Recommendation</th>
<th>Estimated Completion</th>
<th>Required Tasks</th>
</tr>
</thead>
</table>
| NERC-4.1                     | Investigate enhancements to existing standards and need for additional standards development projects to ensure the continued reliability of the bulk power system in North America. | 18-36 months         | Task 1.1: Transformer construction survey  
Task 1.8: Facilitate system-wide vulnerability analysis  
Task 1.9: Review industry transformer specifications  
Task 2.1: GMD operating practices survey  
Task 4.1: Review Reliability Standards |

**Supporting Tasks Underway/ Completed**

- **Ground conductivity model development:** USGS has provided ground conductivity models and physiologic maps for some of the uniform conductivity regions in North America along with the 1-D conductivity models for each mapped region.

- **1-in-100 year storm scenario development:** NASA has developed 1-in-100-year GMD E-field models and the associated waveforms for different geomagnetic latitude conditions.

- **GIC model development:** EPRI has released a version of OpenDSS (open-source) that incorporates GIC calculation from reference GMD E-fields. PowerWorld (commercial off-the-shelf) has released a module for public consumption that incorporates the effects of a uniform E-field.

- **Spare Equipment Database (SED):** NERC is implementing the SED effort, and expects the new database of spare transformers to be operational in Q3 2012.

**Short Term Actions for NERC**

While the key efforts associated with phase 2 are technically and scientifically challenging, there are also a number of short-term solutions that NERC will work to implement within the next three months:

- Update the NERC GMD Industry Advisory to reflect the findings of the interim assessment and encourage system operators to develop procedures or ensure that existing procedures are up-to-date in order to manage the affects from GMD events.

- Update NERC Certified System Operators training requirements to include a subject matter focus on GMD.
- Encourage industry participants who have interest in GMD research and development to participate in the NERC/EPRI Research Collaborative on GMD.
- Periodically host public webinars to outline the results of this assessment and highlight next steps from NERC and the industry.
- Release and promote open-source code and ground impedance models for use in study of GIC flows as results become available.

**Detailed Action Plan**

The following Action Plan (Table 1) outlines the tasks required to address the recommendations, with responsibilities assigned to NERC, EPRI, GMDTF, and industry and scientific partners. These tasks are related to the specific recommendations in the interim report Chapter 13 Table 5. This Action Plan addresses the items outlined in the interim report Chapter 13 Table 6, but with focus on prioritizing each task and specifying the associated deliverables; the GMDTF will examine Table 6 to ensure all recommendations that are the responsibility of the GMDTF and NERC are addressed in the Detailed Action Plan.

**Table 1: Detailed Action Plan**

<table>
<thead>
<tr>
<th>Effort</th>
<th>Task #</th>
<th>Task Description</th>
<th>Lead Organization(s)</th>
<th>Priority</th>
<th>Deliverables</th>
<th>Estimated Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. vulnerability assessment</td>
<td>1.1</td>
<td>Transformer construction survey</td>
<td>NERC</td>
<td>High</td>
<td>1. Detailed listing of transformers by construction (e.g., core type, winding connection), age, power system connection (e.g., transmission network, generating station), location (i.e., latitude/longitude), etc. 2. List of in-service transformers with existing GIC monitoring in-place and capability</td>
<td>12-24 months</td>
</tr>
<tr>
<td>of the North American</td>
<td></td>
<td>1.2 Provide and maintain data confidentiality</td>
<td>NERC</td>
<td>High</td>
<td>1. Secure data repository and exchange process</td>
<td>12-24 months</td>
</tr>
<tr>
<td>transformer fleet</td>
<td></td>
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<tr>
<td>Effort</td>
<td>Task #</td>
<td>Task</td>
<td>Description</td>
<td>Lead Organization(s)</td>
<td>Priority</td>
<td>Deliverables</td>
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<tr>
<td>1.3</td>
<td>Transformer thermal model development</td>
<td>Define transformer thermal models with the support of transformer manufacturers, international organizations (e.g., National Grid UK, Svenska Kraftnät), and other bodies (e.g., IEEE Transformers Committee).</td>
<td>NERC</td>
<td>High</td>
<td>1. Thermal model relating transformer voltage and current input (ac+dc) to critical hot spot temperature</td>
<td>12-24 months</td>
</tr>
<tr>
<td>1.4</td>
<td>Transformer testing</td>
<td>Evaluate transformer thermal models by testing full-scale transformers. This would include voluntary non-destructive testing on fully-instrumented transformers in service, and could include destructive testing on retired equipment if feasible.</td>
<td>NERC, DOE</td>
<td>High</td>
<td>1. Live transformer testing results for thermal model validation by industry experts</td>
<td>18-36 months</td>
</tr>
<tr>
<td>1.5</td>
<td>GIC model development</td>
<td>Create open-source GIC modeling tools and training material. The input and output of the GIC modeling tools will be clearly documented to support integration with other commonly-used applications.</td>
<td>EPRI</td>
<td>High</td>
<td>1. Modeling tool to calculate GIC from E-field taking into account B-field and ground conductivity models  2. Modeling tool to calculate system parameters (e.g., reactive power absorption, harmonics) from GIC and dc power system model  3. Validation by industry experts</td>
<td>12-24 months</td>
</tr>
<tr>
<td>1.6</td>
<td>Extreme “Carrington” GMD scenario development</td>
<td>Develop extreme E-field models and associated waveforms that simulate a “Carrington” type event.</td>
<td>NASA, CSA</td>
<td>Low</td>
<td>1. Extreme event E-field waveform(s)</td>
<td>18-36 months</td>
</tr>
<tr>
<td>1.7</td>
<td>Finalize 1-D ground conductivity models</td>
<td>Develop 1-D conductivity models for all remaining physiographic zones.</td>
<td>USGS, NRCan</td>
<td>Medium</td>
<td>1. 1-D conductivity models for all physiographic regions in North America</td>
<td>18-36 months</td>
</tr>
<tr>
<td>Effort</td>
<td>Task #</td>
<td>Task Description</td>
<td>Lead Organization(s)</td>
<td>Priority</td>
<td>Deliverables</td>
<td>Estimated Completion</td>
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<tr>
<td>1.8</td>
<td>Facilitate system-wide vulnerability analysis</td>
<td>Provide tools and training to the industry to support vulnerability analysis incorporating thermal, transient, geological, and GMD storm models. Training materials and tools will be released as related tasks are completed.</td>
<td>NERC, EPRI</td>
<td>High</td>
<td>1. Training material on the use of tools and the process to perform detailed vulnerability studies 2. Confidential validation of specific results with subject matter experts 3. Confidential validation specific results with asset owners 4. Validation of summary results with EPRI Project Funders 5. Validation of summary results with Technical Committees</td>
<td>12-24 months</td>
</tr>
<tr>
<td>1.9</td>
<td>Review industry transformer GIC-withstand specifications</td>
<td>Survey industry on transformer GIC-withstand specifications; work with IEEE Transformers Committee to identify appropriate specifications and design vulnerability</td>
<td>NERC, NATF</td>
<td>Medium</td>
<td>1. Report on industry survey and IEEE recommendations for transformer specifications to withstand GIC/dc-offset</td>
<td>12-24 months</td>
</tr>
<tr>
<td>1.10</td>
<td>Compile results for release to GMDTF (and industry)</td>
<td>Compile survey and assessment results into CEII-compliant public report (CEII-compliant if necessary).</td>
<td>NERC</td>
<td>High</td>
<td>1. Public assessment report</td>
<td>12-24 months</td>
</tr>
<tr>
<td>1.11</td>
<td>Update Special Assessment</td>
<td>Incorporate summary of surveys, tools and vulnerability assessments into Special Assessment.</td>
<td>GMDTF</td>
<td>Medium</td>
<td>1. Updated Special Assessment on GMD</td>
<td>12-24 months</td>
</tr>
<tr>
<td>2.1</td>
<td>GMD operating practices survey</td>
<td>Survey industry on current operating practices for response to GMD events.</td>
<td>NERC, NATF</td>
<td>High</td>
<td>1. Descriptions of operating practices/procedures for responding to GMD, with references to specific susceptible or monitored equipment, presented in full confidentiality. Review by industry subject matter experts</td>
<td>12-24 months</td>
</tr>
<tr>
<td>2.2</td>
<td>Update and release NERC Alert</td>
<td>Update Industry Advisory based on survey results and other input, and pass to appropriate bodies for review.</td>
<td>NERC</td>
<td>High</td>
<td>1. Updated draft NERC Alert 2. Second draft reviewed by NATF &amp; GMDTF 3. Third draft reviewed by OC/PC/CIPC &amp; FERC 4. Approved NERC Alert</td>
<td>First update: 3 months Detailed update: 12-24 months</td>
</tr>
<tr>
<td>Effort</td>
<td>Task #</td>
<td>Task Description</td>
<td>Lead Organization(s)</td>
<td>Priority</td>
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<td>Estimated Completion</td>
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<tr>
<td>3.1</td>
<td>Develop GMD webinar</td>
<td>Prepare webinar to introduce GMD concepts and highlight the need for studies and operating practices. Updates will include progress on tasks and training highlights.</td>
<td>NERC</td>
<td>Medium</td>
<td>1. Draft webinar to Legal and Communications for review 2. Final webinar</td>
<td>First webinar: 3 months Continuing updates: Quarterly</td>
</tr>
<tr>
<td>3.2</td>
<td>Update System Operator training with GMD best practices</td>
<td>Update System Operator training based on survey results and release to industry. Training will be reviewed and updated in an on-going basis.</td>
<td>NERC</td>
<td>Medium</td>
<td>1. Proposed changes to training 2. Review with operations experts 3. Updated training</td>
<td>12-24 months</td>
</tr>
<tr>
<td>3.3</td>
<td>Establish GMD data clearinghouse</td>
<td>Create open GMD reference library and collaboration site.</td>
<td>NERC</td>
<td>Medium</td>
<td>1. Website for GMD data</td>
<td>18-36 months</td>
</tr>
<tr>
<td>4.1</td>
<td>Review Reliability Standards</td>
<td>Identify changes to existing Standards or needed Standards to address GMD.</td>
<td>GMDTF</td>
<td>High</td>
<td>1. Recommendations for changes/additions to Reliability Standards</td>
<td>18-36 months</td>
</tr>
</tbody>
</table>