# Consideration of Comments

## Project 2013-03 Geomagnetic Disturbance Mitigation

The Geomagnetic Disturbance (GMD) Mitigation Standard Drafting Team (SDT) thanks all commenters who submitted comments on the standard. Project 2013-03 is developing requirements for registered entities to employ strategies that mitigate risks of instability, uncontrolled separation and Cascading in the Bulk-Power System caused by GMD in two stages as directed in FERC Order No. 779:

- EOP-010-1 – Geomagnetic Disturbance Operations was approved by FERC in June 2014. This first stage standard in the project will require applicable registered entities to develop and implement Operating Procedures.

- TPL-007-1 – Transmission System Planned Performance for Geomagnetic Disturbance events is being developed to meet the Stage 2 directives. The proposed standard will require applicable registered entities to conduct initial and on-going assessments of the potential impact of benchmark GMD events on their respective system as directed in Order 779. If the assessments identify potential impacts, the standard(s) will require the registered entity to develop corrective actions to mitigate the risk of instability, uncontrolled separation, or Cascading as a result of benchmark GMD events.

TPL-007-1 was posted for a 25-day public comment period from October 28, 2014 through November 21, 2014. Stakeholders were asked to provide feedback on the standard and associated documents through a special electronic comment form. There were 50 sets of comments, including comments from approximately 100 individuals from approximately 70 companies representing all 10 Industry Segments as shown in the table on the following pages.

**Summary Consideration:**

The SDT appreciates the review and constructive comments provided by stakeholders. This active participation is critical to meeting the project scope outlined in the Standard Authorization Request (SAR) and all FERC directives prior to the January 21, 2015 filing deadline.

In response to stakeholder comments, the SDT made only clarifying and non-substantive changes to the proposed standard and supporting material as follows:

TPL-007-1:

- Requirement R1: corrected VRF terminology from "Low" to "Lower."
- Requirement R6: revised Part 6.4 to clarify that the thermal assessments must be performed within 24 calendar months of receipt of GIC flow information specified in Requirement R5, Part 5.1.

- Corresponding change was made to the VSL for Requirement R6.
- Rationale boxes and the application guidelines section were revised for clarity.
- Punctuation and grammatical changes were made throughout the standard.

Screening Criterion for Transformer Thermal Impact Assessment White Paper:

- added clarification on page 3 to indicate that the stated temperature refers to full load bulk oil temperature.
- Corrected table numbering and the example on page 8.

All comments submitted may be reviewed in their original format on the standard's project page.
If you feel that your comment has been overlooked, please let us know immediately. Our goal is to give every comment serious consideration in this process. If you feel there has been an error or omission, you can contact the Director of Standards, Valerie Agnew, at 404-446-2566 or at valerie.agnew@nerc.net . In addition, there is a NERC Reliability Standards Appeals Process.[1]

[1] The appeals process is in the Standard Processes Manual: http://www.nerc.com/comm/SC/Documents/Appendix_3A_StandardsProcessesManual.pdf

**The Industry Segments are:**

1 — Transmission Owners

2 — RTOs, ISOs

3 — Load-serving Entities

4 — Transmission-dependent Utilities

5 — Electric Generators

6 — Electricity Brokers, Aggregators, and Marketers

7 — Large Electricity End Users

8 — Small Electricity End Users

9 — Federal, State, Provincial Regulatory or other Government Entities

10 — Regional Reliability Organizations, Regional Entities

| | Group/Individual | Commenter | Organization | Registered Ballot Body Segment | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1. | Group | John Allen | Iberdrola USA | | | X | | | | | | | |
| 2. | Group | Guy Zito | Northeast Power Coordinating Council | | | | | | | | | | X |

Group 1 additional members:

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Joseph Turano | Central Maine Power | NPCC | 1 |
| 2. | Julie King | New York State Electric & Gas | NPCC | 6 |

Group 2 additional members:

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Alan Adamson | New York State Reliability Council, LLC | NPCC | 10 |
| 2. | David Burke | Orange and Rockland Utilities Inc. | NPCC | 3 |

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|---|---|---|---|---|
| 3. | Greg Campoli | New York Independent System Operator | NPCC | 2 |
| 4. | Sylvain Clermont | Hydro-Quebec TransEnergie | NPCC | 1 |
| 5. | Kelly Dash | Consolidated Edison Co. of New York, Inc. | NPCC | 1 |
| 6. | Gerry Dunbar | Noertheast Power Coordinating Council | NPCC | 10 |
| 7. | Mike Garton | Dominion Resources Services, Inc. | NPCC | 5 |
| 8. | Kathleen Goodman | ISO - New England | NPCC | 2 |
| 9. | Wayne Sipperly | New York Power Authority | NPCC | 5 |
| 10. | Mark Kenny | Northeast Utilities | NPCC | 1 |
| 11. | Helen Lainis | Independent Electricity System Operator | NPCC | 2 |
| 12. | Alan MacNaughton | New Brunswick Power Corporation | NPCC | 9 |
| 13. | Bruce Metruck | New York Power Authority | NPCC | 6 |
| 14. | Peter Yost | Consolidated Edison Co. of New York, Inc. | NPCC | 3 |
| 15. | Lee Pedowicz | Northeast Power Coordinating Council | NA - Not Applicable | 10 |
| 16. | Robert Pellegrini | The United Illuminating Company | NPCC | 1 |
| 17. | Si Truc Phan | Hydro-Quebec TransEnergie | NPCC | 1 |
| 18. | David Ramkalawan | Ontario Power Generation, Inc. | NPCC | 5 |
| 19. | Brian Robinson | Utility Services | NPCC | 8 |
| 20. | Ayesha Sabouba | Hydro One Networks Inc. | NPCC | 1 |
| 21. | Ben Wu | Orange and Rockland Utilities Inc. | NPCC | 1 |

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| 3. | Group | Kelly Dash | Con Edison, Inc. | X | | X | | X | X | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Edward Bedder | Orange & Rockland Utilities | NPCC | NA |

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| 4. | Group | Joe DePoorter | MRO NERC Standards Review Forum | X | X | X | X | | X | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Amy Casucelli | Xcel Energy | MRO | 1, 3, 5, 6 |
| 2. | Chuck Wicklund | Otter Tail Power | MRO | 1, 3, 5 |
| 3. | Dan Inman | Minnkota Power Cooperative | MRO | 1, 3, 5, 6 |
| 4. | Dave Rudolph | Basin Electric Power Coop | MRO | 1, 3, 5, 6 |
| 5. | Kayleigh Wilkerson | Lincoln Electric System | MRO | 1, 3, 5, 6 |

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|---|---|---|---|---|
| 6. | Jodi Jensen | WAPA | MRO | 1, 6 |
| 7. | Ken Goldsmith | Alliant Energy | MRO | 4 |
| 8. | Mahmood Safi | Omaha Public Power District | MRO | 1, 3, 5, 6 |
| 9. | Marie Knox | MISO | MRO | 2 |
| 10. | Mike Brytowski | Great River Energy | MRO | 1, 3, 5, 6 |
| 11. | Randi Nyholm | Minnesota Power | MRO | 1, 5 |
| 12. | Scott Nickels | Rochester Public Utilities | MRO | 4 |
| 13. | Terry Harbour | MidAmerican | MRO | 1, 3, 5, 6 |
| 14. | Tom Breene | Wisconsin Public Service | MRO | 3, 4, 5, 6 |
| 15. | Tony Eddleman | Nebraska Public Power District | MRO | 1, 3, 5 |

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| 5. | Group | Thomas Popik | Interested Parties on NERC Standard TPL-007-1 | | | | | | | | X | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | William Harris | Foundation for Resilient Societies | NA - Not Applicable | 8 |
| 2. | George Baker | Foundation for Resilient Societies | NA - Not Applicable | 8 |
| 3. | William Graham | Foundation for Resilient Societies | NA - Not Applicable | 8 |
| 4. | Andrea Boland | Maine State Legislature | NA - Not Applicable | 9 |
| 5. | William Joyce | Advanced Fusion Systems | NA - Not Applicable | 8 |
| 6. | John Kappenman | Storm Analysis Consultants | NA - Not Applicable | 8 |

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| 6. | Group | Phil Hart | Associated Electric Cooperative, Inc. | X | | X | | X | X | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Central Electric Power Cooperative | | SERC | 1, 3 |
| 2. | KAMO Electric Cooperative | | SERC | 1, 3 |
| 3. | M & A Electric Power Cooperative | | SERC | 1, 3 |
| 4. | Northeast Missouri Electric Power Cooperative | | SERC | 1, 3 |
| 5. | N.W. Electric Power Cooperative, Inc. | | SERC | 1, 3 |
| 6. | Sho-Me Power Electric Cooperative | | SERC | 1, 3 |

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| 7. | Group | Don Hargrove | OG&E | X | | X | | X | X | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Terri Pyle | OG&E | SPP | 1 |

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| 2. | Leo Staples | OG&E | SPP | 3, 5 |
| 3. | Jerry Nottnagel | OG&E | SPP | 6 |

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| 8. | Group | Brent Ingebrigtson | PPL NERC Registered Affiliates | X | | X | | X | X | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Charlie Freibert | LG&E and KU Energy, LLC | SERC | 3 |
| 2. | Brenda Truhe | PPL Electric utilities Corporation | RFC | 1 |
| 3. | Annette Bannon | PPL Generation, LLC | RFC | 5 |
| 4. | | PPL Susquehanna, LLC | RFC | 5 |
| 5. | | PPL Montana LLC | WECC | 5 |
| 6. | Elizabeth Davis | PPL EnergyPlus, LLC | MRO | 6 |
| 7. | | | NPCC | 6 |
| 8. | | | RFC | 6 |
| 9. | | | SERC | 6 |
| 10. | | | SPP | 6 |
| 11. | | | WECC | 6 |

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| 9. | Group | Michael Lowman | Duke Energy | X | | X | | X | X | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Doug Hils | | RFC | 1 |
| 2. | Lee Schuster | | FRCC | 3 |
| 3. | Dale Goodwine | | SERC | 5 |
| 4. | Greg Cecil | | RFC | 6 |

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| 10. | Group | David Greene | SERC PSS | | | | | | | | | | X |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | John Sullivan | Ameren | SERC | 1, 3 |
| 2. | Jim Kelley | PowerSouth | SERC | 1, 5 |
| 3. | Phil Kleckley | SCE&G | SERC | 1, 3, 5, 6 |
| 4. | Shih-Min Hsu | Southern Company | SERC | 1, 5 |

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| 11. | Group | Brian Van Gheem | ACES Standards Collaborators | | | | | | X | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
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|---|---|---|---|---|
| 1. | Bob Solomon | Hoosier Energy Rural Electric Cooperative, Inc. | RFC | 1 |
| 2. | John Shaver | Arizona Electric Power Cooperative | WECC | 1, 4, 5 |
| 3. | John Shaver | Southwest Transmission Cooperative, Inc. | WECC | 1, 4, 5 |
| 4. | Ellen Watkins | Sunflower Electric Power Corporation | SPP | 1 |
| 5. | Ginger Mercier | Prairie Power, Inc. | SERC | 3 |
| 6. | Kevin Lyons | Central Iowa Power Cooperative | MRO | 1 |
| 7. | Scott Brame | North Carolina Electric Membership Corporation | SERC | 3, 4, 5 |
| 8. | Ryan Strom | Buckeye Power, Inc. | RFC | 3, 4, 5 |
| 9. | Michael Brytowski | Great River Energy | MRO | 1, 3, 5, 6 |
| 10. | Shari Heino | Brazos Electric Power Cooperative, Inc. | ERCOT | 1, 5 |

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| 12. | Group | Tom McElhinney | JEA | X | | X | | X | | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Ted Hobson | | FRCC | 1 |
| 2. | Gary Baker | | FRCC | 3 |
| 3. | John Babik | | FRCC | 5 |

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| 13. | Group | Kathleen Black | DTE Electric | | | X | X | | | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Kent Kujala | NERC Compliance | RFC | 3 |
| 2. | Daniel Herring | NERC Training & Standards Development | RFC | 4 |
| 3. | Mark Stefaniak | Merchant Operations | RFC | 5 |
| 4. | David Szulczewski | Relay Engineering | RFC | |

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| 14. | Group | Aaron Gregory | SmartSenseCom, Inc. | | X | | | | | | | | |

N/A

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| 15. | Group | Sandra Shaffer | PacifiCorp | | | | | | X | | | | |

N/A

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| 16. | Group | Shannon V. Mickens | SPP Standards Review Group | | X | | | | | | | | |

N/A

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| 17. | Group | Andrea Jessup | Bonneville Power Administration | X | | X | | X | X | | | | |

| Additional Member | Additional Organization | Region | Segment Selection |
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| 1. | Berhanu Tesema | Transmission Planning | WECC | 1 |
| 2. | Richard Becker | Substation Engineering | WECC | 1 |
| 3. | Jim Burns | Technical Operations | WECC | 1 |
| 4. | Michelle Cowan | Customer Service Engineering | WECC | 1 |

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| 18. | Group | Paul Haase | Seattle City Light | X | | X | X | X | X | | | | |

| | Additional Member | Additional Organization | Region | Segment Selection |
|---|---|---|---|---|
| 1. | Pawel Krupa | Seattle City Light | WECC | 1 |
| 2. | Dana Wheelock | Seattle City Light | WECC | 3 |
| 3. | Hao Li | Seattle City Light | WECC | 4 |
| 4. | Mike Haynes | Seattle City Light | WECC | 5 |
| 5. | Dennis Sismaet | Seattle City Light | WECC | 6 |

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| 19. | Group | Kaleb Brimhall | Colorado Springs Utilities | X | | X | | X | X | | | | |
| N/A | | | | | | | | | | | | | |
| 20. | Individual | Sonya Green-Sumpter | South Carolina Electric & Gas | X | | X | | | X | | | | |
| 21. | Individual | Gul Khan | Oncor Electric Delivery LLC | X | | | | | | | | | |
| 22. | Individual | Sonya Green-Sumpter | South Carolina Electric & Gas | X | | X | | X | X | | | | |
| 23. | Individual | John Bee | Exelon and its Affiliates | X | | X | | X | | | | | |
| 24. | Individual | Andrew Z. Pusztai | American Transmission Company | X | | | | | | | | | |
| 25. | Individual | Maryclaire Yatsko | Seminole Electric Cooperative, Inc. | X | | X | X | X | X | | | | |
| 26. | Individual | David Thorne | Pepco Holdings Inc. | X | | X | | | | | | | |
| 27. | Individual | Martyn Turner | LCRA Transmission Services Corporation | X | | | | X | X | | | | |
| 28. | Individual | Michelle D'Antuono | Ingleside Cogeneration LP | | | | | X | | | | | |
| 29. | Individual | David Kiguel | David Kiguel | | | | | | | | X | | |
| 30. | Individual | Joe Seabrook | Puget Sound Energy, Inc. | X | | X | | X | | X | | | |
| 31. | Individual | Thomas Lyons | OMU | | | | | | | | | | |
| 32. | Individual | Nick Vtyurin | Manitoba Hydro | X | | X | | X | X | | | | |
| 33. | Individual | Thomas Foltz | American Electric Power | X | | X | | | X | | | | |
| 34. | Individual | John Seelke | Public Service Enterprise Group | X | | X | | X | X | | | | |

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| 35. | Individual | David Jendras | Ameren | X | | X | | X | X | | | | |
| 36. | Individual | Mahmood Safi | Omaha Public Power District | X | | X | | X | X | | | | |
| 37. | Individual | Terry Volkmann | Volkmann Consulting, Inc | | | | | | | | X | | |
| 38. | Individual | Mr. Tracy Rolstad | Avista Utilities | X | | X | | | | | | | |
| 39. | Individual | Chris Mattson | Tacoma Power | X | | X | X | X | X | | | | |
| 40. | Individual | Trevor Schultz | Idaho Power Company | X | | | | | | | | | |
| 41. | Individual | Michiko Sell | Public Utility District No. 2 of Grant County, WA | X | | X | X | X | X | | | X | |
| 42. | Individual | Anthony Jablonski | ReliabilityFirst | | | | | | | | | | X |
| 43. | Individual | Mark Wilson | Independent Electricity System Operator | | X | | | | | | | | |
| 44. | Individual | Richard Vine | California ISO | | X | | | | | | | | |
| 45. | Individual | Texas Reliability Entity, Inc | Texas Reliability Entity, Inc | | | | | | | | | | X |
| 46. | Individual | Erika Doot | Bureau of Reclamation | X | | | | X | | | | | |
| 47. | Individual | Bill Temple | Northeast Utilities | X | | | | | | | | | |
| 48. | Individual | Thomas Popik | Foundation for Resilient Societies | | | | | | | | X | | |
| 49. | Individual | Cheryl Moseley | Electric Reliability Council of Texas, Inc. | | X | | | | | | | | |
| 50. | Individual | Charles Yeung | Southwest Power Pool Inc | | X | | | | | | | | |

**If you support the comments submitted by another entity and would like to indicate you agree with their comments, please select "agree" below and enter the entity's name in the comment section (please provide the name of the organization, trade association, group, or committee, rather than the name of the individual submitter).**

| Organization | Agree | Supporting Comments of "Entity Name" |
|---|---|---|
| Omaha Public Power District | Agree | The Omaha Public Power District (OPPD) supports comments submitted by the Midwest Reliability Organization's (MRO) NERC Standards Review Forum (NSRF). Additionally, OPPD doesn't believe this standard should be approved prior to the industry seeing the "NERC Transformer Modeling Guide. |
| Independent Electricity System Operator | Agree | NPCC Reliability Standards Committee |
| Southwest Power Pool Inc | Agree | ERCOT |
| Seattle City Light | Agree | Puget Sound Energy |
| Colorado Springs Utilities | Agree | Snohomish County Public Utility District |

1. **Transformer thermal impact assessment. The SDT has revised the Transformer Thermal Impact Assessmment white paper and Screening Criterion white paper with additional technical details. The screening criterion for transformer thermal assessments was increased from 15 A per phase to 75 A per phase. Additionally, look up tables provide a transformer thermal assessment approach based on available models. Do you agree with these changes? If not, please provide a specific recommendation and technical justification**

**Summary Consideration:** The SDT thanks all commenters. The following changes have been made:

- Rationale Box for Requirement R5 was revised to clearly indicate that a thermal assessment could be performed by using maximum effective GIC information from part 5.1 or GIC(t) from part 5.2.
- Clarifications and editorial changes to the Screening Criterion for Transformer Thermal Impact Assessment white paper. A parenthetical clarification was made on page 3 to indicate that the stated temperature refers to full load bulk oil temperature. Table numbering on page 8 was corrected. A mathematical error was corrected in the example on page 8.

Responses to all comments are provided below.

| Organization | Yes or No | Question 1 Comment |
|---|---|---|
| PPL NERC Registered Affiliates | No | These comments are submitted on behalf of the following PPL NERC Registered Affiliates: LG&E and KU Energy, LLC; PPL Electric Utilities Corporation, PPL EnergyPlus, LLC; PPL Generation, LLC; PPL Susquehanna, LLC; and PPL Montana, LLC. The PPL NERC Registered Affiliates are registered in six regions (MRO, NPCC, RFC, SERC, SPP, and WECC) for one or more of the following NERC functions: BA, DP, GO, GOP, IA, LSE, PA, PSE, RP, TO, TOP, TP, and TSP.<br>Comments:<br>1. The R5 Rationale should be changed as shown below to make it clear that one can use a simplified approach (R5.1 inputs with Table 1 of the Transformer Thermal Impact Assessment Whitepaper) or R5.2 inputs and a detailed |

| Organization | Yes or No | Question 1 Comment |
|---|---|---|
| | | analysis."The maximum effective GIC value provided in Part 5.1 can be 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."<br><br>2. The simplified, R5.1-based approach has not yet been made practical. R5.1 inputs will consist of just an Amps-per-phase value corresponding to the red peak at hour 45.3 in Fig. 3 of the Transformer Thermal Impact Assessment White Paper, and the associated metallic hot spot temperature in Table 1 of the White Paper matches the hr-45.3 blue peak. This temperature is sustained for only an extremely brief period, and therefore means very little in determining the loss of transformer life. This point was discussed at length in the 11/5/14 teleconference of the SDT, Dr. Marti (the leading expert in the field) and the NAGF Standards Review Team. The conclusion was that Table 1 in the White Paper should be expanded to include maximum 1-hour and 4 or 5-hour temperatures, to supplement the present peak-temperature information. Only then would equipment owners have a tool suitable for deciding whether or not mitigation measures are needed. |

**Response:**

1. The SDT agrees and has revised the Rationale Box for Requirement R5 as follows:

Rationale for Requirement 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.

| Organization | Yes or No | Question 1 Comment |
|---|---|---|
| The maximum effective GIC value provided in Part 5.1 is used for transformer thermal impact assessment.<br><br>GIC(t) provided in Part 5.2 ~~is~~ 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-DisturbanceMitigation.aspx<br><br>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.<br><br>2. The SDT has carefully considered this comment and the discussion from the NAGF SRT. The analysis of the benchmark GMD event and available thermal models indicate that the more limiting factor is in fact the metallic hot spot temperature during short-term emergency loading criteria. Metallic hot spot temperatures are associated with the generation of gasses, not insulation loss of life. Consequently, Table 1 in the Transformer Thermal Impact Assessment white paper is the more conservative approach and is not improved with the addition of longer-duration metallic hot spot temperatures. | | |
| PacifiCorp | No | PacifiCorp has two areas of concern: (1) A continuing concern regarding assessment of impacts of harmonics; and (2) The change of the VRF for Requirement R2 from Medium to High.<br><br>1. Assessment of impacts of harmonics. PacifiCorp agrees with the comments of Bonneville Power Association, and shares their concern about assessing impacts of harmonics. BPA states: Table 1 of the standard under event column indicates that facilities removed as a result of protection system operation or misoperation due to harmonics during GMD event need to be modeled. There seems to be three options to perform the required assessment; 1. Performing harmonic studies to justify not taking the var devices outage analysis or 2. Replace all |

| Organization | Yes or No | Question 1 Comment |
|---|---|---|
| | | mechanical relays with microprocessor relays that have the capability to block harmonics or 3. Remove all SVCs or shunt caps and perform the assessment.<br><br>Option one is not practical for the transmission planner to perform harmonic analysis for the entire system due to lack of tools and expertise. Option two is an expensive solution for a one in a hundred year event. Utilities do not build for extreme contingencies such as one in ten probability event. Removing all reactive devices under option three defeats the purpose of installing these reactive devices in the first place. BPA suggests that this low probability extreme GMD event should be evaluated under normal system conditions not under system contingency events.<br><br>PacifiCorp appreciates the drafting team's acknowledgement that the tools and capability to perform harmonics analysis are not in wide availability in the industry. PacifiCorp supports the suggestion of MidAmerican and the MRO NERC Standards Review Forum in the last comment period that "R4, GMD Vulnerability Assessment...not be implemented until after guidance for the industry is readily available or the date provided in the implementation plan whichever is later."<br><br>2. The VRF for Requirement R2 has been changed from Medium to High. This change is for consistency with the corresponding requirement in TPL-001-4, which was raised to High in response to FERC directive. PacifiCorp does not support changing the VRF from Medium to High. The planning requirement of TPL-001-4 is not analogous since it is planning that is consistently done by the industry. The industry does not have enough experience with GMD events and their impact on the BES to support a high VRF for this requirement. |
| **Response:** | | |

| Organization | Yes or No | Question 1 Comment |
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| 1. The SDT has reviewed your comment and acknowledges the tools to perform detailed harmonics analysis are not in wide availability in the industry. However, replacement of all protective relays or outaging all relays in the power flow case are extreme reactions to the uncertainty associated with harmonics. The SDT believes that reasonable engineering judgment can be exercised to identify protection equipment that may be vulnerable to misoperation in the Benchmark GMD event and therefore, should be outaged in the power flow analysis. Loss of reactive compensation that has a high likelihood of tripping due to harmonics is an event that must be evaluated as part of the GMD Vulnerability Assessment because it is a known risk from GMD. Supporting technical guidance is available in the NERC GMD TF GMD Planning Guide (section 4.2 and 4.3) and the 2012 Interim Report (section 6.4).<br><br>2. The change of the VRF from Medium to High is to provide consistency with the VRF for approved standard TPL-001-4 Requirement R1 which is being revised to comply with FERC directives. See NERC filing dated August 29, 2014 (RM12-1-000). NERC guidelines require consistency among Reliability Standards. | | |
| Volkmann Consulting, Inc | No | The SDT has not justified this dramatic of change in the threshold |
| **Response:** The justification for the change in the thermal assessment threshold is included in the Screening Criterion for Transformer Thermal Assessment whitepaper which is included on the GMD Standard page on the NERC website. | | |
| JEA | Yes | We believe that this further supports the conclusion that GMD will not be a significant issue to the FRCC region and possible other regions and therefore those areas that have a high likely hood of not being affected should be exempted until there is harder evidence to support such action. |
| **Response:** The potential impacts of GIC are not limited to transformer hot spot heating but more importantly, to transformer var absorption, voltage stability and harmonics issues. The SDT does not have a technically supportable basis to propose an exemption from the requirements of the standard to any portion of the North American transmission system. | | |
| Bonneville Power Administration | Yes | 1. The Transformer Thermal Impact Assessment white paper's Background section states: Stage 2 Standard(s) that require applicable entities to conduct assessments of the potential impact of benchmark GMD events on their systems. |

| Organization | Yes or No | Question 1 Comment |
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| | | If the assessments identify potential impacts, the Standard(s) will require the applicable entity to develop and implement a plan to mitigate the risk. TPL-007-1 is a new Reliability Standard to specifically address the Stage 2 directives in Order No. 779. This is also stated as the Purpose/Industry Need on the project page. BPA suggests that the SDT align the stated purpose of the standard to the language of R7, to develop a Corrective Action Plan addressing how the performance requirements will be met.<br><br>2. BPA believes the table on page 8 of the Screening Criterion for Transformer Thermal Assessment should be labeled Table 2 as it is referenced in the preceding sentence. |
| **Response:**<br><br>1. The SDT believes the purpose section of TPL-007 is clear and appropriately worded to describe the reliability objective of the planning standard.<br><br>2. The SDT thanks the commenter for identifying the labeling error in the Screening Criterion for Transformer Thermal Assessment whitepaper. The table has been corrected. | | |
| Pepco Holdings Inc. | Yes | The 75 amps per phase maybe too high and result in overheating for some transformers. The criteria could be 50 amps per phase for all transformers or variable depending upon the transformer design type. The following limits are proposed: For 3 - phase core form transformers with a 3 limb core:<br><br>i. 30 - 50 Amps / phase for base current<br><br>ii. 100 Amps / phase for short duration GIC pulses<br><br>For transformers that have other than a 3 - phase, 3 - limb core: |

| Organization | Yes or No | Question 1 Comment |
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| | | i. 20 Amps / phase for base current.<br>ii. 50 Amps / phase for short - duration GIC pulses |
| **Response:** The SDT has reviewed the comment and has based its determination of the threshold on analysis that is explained in the Screening Criterion for Transformer Thermal Assessment whitepaper. The suggested alternative thresholds cannot be implemented since they are presented without technical justification. | | |
| Public Service Enterprise Group | Yes | While we agree with the changes, as they would appear to provide a more realistic basis for screening criteria for thermal assessment, we suggest some clarification discussion may be helpful for the paragraph at the top of page 3 of the Screening Criterion document, particularly related to the reference to bulk oil temperature of 80°C. In initial reading this appeared to perhaps be an 80°C temperature rise, applied with an ambient of 30°C to give the top oil temperature limit of 110°C seen in Table 1. On closer reading it appears it may be the actual bulk oil temperature for the full load rating in an example transformer in the thermal models. To clarify, a brief description referencing where the 80°C bulk oil temperature comes from would be helpful. |
| **Response:** The SDT has reviewed your comment and will revise the explanation of the reference to the bulk oil temperature of $80^{\circ}$C, which is the bulk oil temperature for the full load rating, as follows:<br>Consequently, with the most conservative thermal models known at this point in time, the peak metallic hot spot temperature obtained with the benchmark GMD event waveshape assuming an effective GIC magnitude of 75 A per phase will result in a peak temperature between 104°C and 150°C when the bulk oil temperature is 80°C (full load bulk oil temperature). The upper boundary of 150°C falls well below the metallic hot spot 200°C threshold for short-time emergency loading suggested in IEEE Std C57.91-2011 [5] (see Table 1). | | |

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| Northeast Utilities | Yes | Clarification is needed on whether or not the 75 A per phase is referring to AC or DC currents. Should we divide the current measured/calculated in the neutral by 3 since there are 3 phases, or is this some sort of current injection from GIC on the transformer for phase A, B or C? |
| **Response:** The SDT has reviewed the comment and confirms that the 75 A is effective dc current per phase. | | |
| Interested Parties on NERC Standard TPL-007-1 | No | Group Comments on NERC Standard TPL-007-1 - Transmission System Planned Performance for Geomagnetic Disturbance Events November 21, 2014<br><br>Draft standard TPL-007-1, "Transmission System Planned Performance for Geomagnetic Disturbance Events," is not a science-based standard. Instead, the apparent purpose of standard TPL-007-1 is to achieve a preferred policy outcome of the North American Electric Reliability Corporation (NERC) and its electric utility members: avoidance of installation of hardware-based protection against solar storms. The draft standard achieves this apparent purpose through a series of scientific contrivances that are largely unsupported by real-world data. Potential casualties in the millions and economic losses in trillions of dollars from severe solar storms instead demand the most prudent science-based standard.<br><br>A 2010 series of comprehensive technical reports, "Electromagnetic Pulse: Effects on the U.S. Power Grid" produced by Oak Ridge National Laboratory for the Federal Energy Regulatory Commission in joint sponsorship with the Department of Energy and the Department of Homeland Security found that a major geomagnetic storm "could interrupt power to as many as 130 million people in the United States alone, requiring several years to recover." |

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| | | A 2013 report produced by insurance company Lloyd's and Atmospheric and Environmental Research, "Solar Storm Risk to the North American Electric Grid," found that:<br><br>"A Carrington-level, extreme geomagnetic storm is almost inevitable in the future. While the probability of an extreme storm occurring is relatively low at any given time, it is almost inevitable that one will occur eventually. Historical auroral records suggest a return period of 50 years for Quebec-level storms and 150 years for very extreme storms, such as the Carrington Event that occurred 154 years ago."<br><br>"The total U.S. population at risk of extended power outage from a Carrington-level storm is between 20-40 million, with durations of 16 days to 1-2 years. The duration of outages will depend largely on the availability of spare replacement transformers. If new transformers need to be ordered, the lead-time is likely to be a minimum of five months. The total economic cost for such a scenario is estimated at $0.6-2.6 trillion USD."<br><br>A 2014 paper published in the Space Weather Journal, "Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment" by C. J. Schrijver, R. Dobbins, W. Murtagh, and S.M. Petrinec found:<br><br>"We find that claims rates are elevated on days with elevated geomagnetic activity by approximately 20% for the top 5%, and by about 10%for the top third of most active days ranked by daily maximum variability of the geomagnetic field."<br><br>"The overall fraction of all insurance claims statistically associated with the effects of geomagnetic activity is 4%." |

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| | | ”We find no significant dependence of the claims frequencies statistically associated with geomagnetic activity on geomagnetic latitude.”<br><br>Given the extreme societal impact of a major solar storm and large projected economic losses, it is vital that any study by NERC in support of standard TPL-007 be of the highest scientific caliber and rigorously supported by real-world data. The unsigned white papers of the NERC Standard Drafting Team fail scientific scrutiny for the following reasons:<br><br>1. The NERC Standard Drafting Team contrived a “Benchmark Geomagnetic Disturbance (GMD) Event” that relies on data from Northern Europe during a short time period with no major solar storms instead of using observed magnetometer and Geomagnetically Induced Current (GIC) data from the United States and Canada over a longer time period with larger storms. This inapplicable and incomplete data is used to extrapolate the magnitude of the largest solar storm that might be expected in 100 years-the so-called “benchmark event.” The magnitude of the “benchmark event” was calculated using a scientifically unproven “hotspot” conjecture that averaged the expected storm magnitude downward by an apparent factor of 2-3. This downward averaging used data collected from a square area only 500 kilometers in width, despite expected impact of a severe solar storm over most of Canada and the United States.<br><br>2. The NERC Standard Drafting Team contrived a table of “Geomagnetic Field Scaling Factors” that adjust the “benchmark event” downward by significant mathematical factors dependent on geomagnetic latitude. For example, the downward adjustment is 0.5 for Toronto at 54 degrees geomagnetic latitude, 0.3 for New York City at 51 degrees geomagnetic latitude, and 0.2 for Dallas at 43 degrees geomagnetic latitude. These adjustment factors are presented in the |

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| | | whitepaper in a manner that does not allow independent examination and validation.<br><br>3. The NERC Standard Drafting Team first contrived a limit of 15 amps of GIC for exemption of high voltage transformers from thermal impact assessment based on limited testing of a few transformers. When the draft standard failed to pass the second ballot, the NERC Standard Drafting Team contrived a new limit of 75 amps of GIC for exemption of transformers from thermal impact assessment, again based on limited testing of a few transformers. The most recent version of the "Screening Criterion for Transformer Thermal Impact Assessment" whitepaper uses measurements from limited tests of only three transformers to develop a model that purports to show all transformers could be exempt from the thermal impact assessment requirement. It is scientifically fallacious to extrapolate limited test results of idiosyncratic transformer designs to an installed base of transformers containing hundreds of diverse designs.<br><br>The above described contrivances of the NERC Standard Drafting Team are unlikely to withstand comparison to real-world data from the United States and Canada. Some public GIC data exists for the United States and Canada, but the NERC Standard Drafting Team did not reference this data in their unsigned whitepaper "Benchmark Geomagnetic Disturbance Event Description." Some public disclosures of transformer failures during and shortly after solar storms exist for the United States and Canada, but the NERC Standard Drafting Team did not reference this data in their unsigned whitepaper "Screening Criterion for Transformer Thermal Impact Assessment."<br><br>NERC is in possession of two transformer failure databases. This data should be released for scientific study and used by the NERC Standard Drafting Team to develop a data-validated Screening Criterion for Transformer Thermal Impact |

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| | | Assessment. The NERC Standard Drafting Team failed to conduct appropriate field tests and collect relevant data on transformer failures, contrary to Section 6.0 of the NERC Standards Processes Manual, “Processes for Conducting Field Tests and Collecting and Analyzing Data.”<br><br>U.S. and Canadian electric utilities are in possession of GIC data from over 100 monitoring locations, including several decades of data from the EPRI SUNBURST system. This GIC data should be released for scientific study and used by the NERC Standard Drafting Team to develop a data-validated Benchmark Geomagnetic Disturbance Event. The NERC Standard Drafting Team failed to conduct appropriate field tests and collect relevant data on measured GIC, contrary to Section 6.0 of the NERC Standards Processes Manual, “Processes for Conducting Field Tests and Collecting and Analyzing Data.”<br><br>The NERC whitepaper “Benchmark Geomagnetic Disturbance Event Description” contains “Appendix II - Scaling the Benchmark GMD Event,” a system of formulas and tables to adjust the Benchmark GMD Event to local conditions for network impact modeling. Multiple comments have been submitted to the Standard Drafting Team showing that the NERC formulas and tables are inconsistent with real-world observations during solar storms within the United States. While the NERC Standard Processes Manual requires that the Standard Drafting Team “shall make an effort to resolve each objection that is related to the topic under review,” the Team has failed to explain why its methodology is inconsistent with measured real-world data.<br><br>Even the most rudimentary comparison of measured GIC data to the NERC “Geomagnetic Field Scaling Factors” shows the methodology of “Appendix II-Scaling the Benchmark GMD Event” of whitepaper “Benchmark Geomagnetic |

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| | | Disturbance Event Description" is flawed. For example, this comment submitted in standard-setting by Manitoba Hydro:<br><br>"GMD Event of Sept 11-13, 2014 - EPRI SUNBURST GIC data over this period suggests that the physics of a GMD are still unknown, in particular the proposed geoelectric field cut-off is most likely invalid. Based on the SUNBURST data for this period in time one transformer neutral current at Grand Rapids Manitoba (above 60 degrees geomagnetic latitude) the northern most SUNBURST site just on the southern edge of the auroral zone only reached a peak GIC of 5.3 Amps where as two sites below 45 degrees geomagnetic latitude (southern USA) reached peak GIC's of 24.5 Amps and 20.2 Amps."<br><br>In the above instance, if the NERC "Geomagnetic Field Scaling Factors" were correct and all other factors were equal, the measured GIC amplitude at 45 degrees geomagnetic latitude should have been 1 Amp (5.3 Amps times scaling factor of 0.2). Were other GIC data to be made publicly available, it is exceedingly likely that the "Geomagnetic Field Scaling Factors" would be invalidated, except as statistical averages that do not account for extreme events. Notably, the above observation of Manitoba Hydro is consistent with the published finding of C. J. Schrijver, et. al. that "We find no significant dependence of the claims frequencies statistically associated with geomagnetic activity on geomagnetic latitude."<br><br>The EPRI SUNBURST database of GIC data referenced in the above Manitoba Hydro comment should be made available for independent scientific study and should be used by the NERC Standard Drafting Team to correct its methodologies.<br><br>American National Standards Institute (ANSI)-compliant standards are required by the NERC Standard Processes Manual. Because the sustainability of the Bulk |

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| | | Power System is essential to protect and promptly restore operation of all other critical infrastructures, it is essential that NERC utilize all relevant safety and reliability-related data supporting assessments of geomagnetic disturbance impacts on "critical equipment" and benefits of hardware protective equipment. Other ANSI standards depend upon and appropriately utilize safety-related data on relationships between structural design or protective equipment and the effective mitigation of earthquakes, hurricanes, maritime accidents, airplane crashes, train derailments, and car crashes.<br><br>Given the large loss of life and significant economic losses that could occur in the aftermath of a severe solar storm, and the scientific uncertainly around the magnitude of a 1-in-100 solar storm, the NERC Standard Drafting Team should have incorporated substantial safety factors in the standard requirements. However, the apparent safety factor for the "Benchmark GMD Event" appears to be only 1.4 (8 V/km geoelectric field used for assessments vs. 5.77 V/km estimated).<br><br>The NERC Standard Processes Manual requires that the NERC Reliability Standards Staff shall coordinate a "quality review" of the proposed standard. Any competent quality review would have detected inconsistencies between the methodologies of the "Benchmark Geomagnetic Disturbance Event Description" and real world data submitted in comments to the Standard Drafting Team. Moreover, any competent quality review would have required that the Standard Drafting Team use real-world data from the United States and Canada, rather than Northern Europe, in developing the methodologies of the "Benchmark Geomagnetic Disturbance Event Description" and "Screening Criterion for Transformer Thermal Impact Assessment." |

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| | | Draft standard TPL-007-1 does not currently require GIC monitoring of all high voltage transformers nor recording of failures during and after solar storms. These requirements should be added given the still-developing scientific understanding of geomagnetic disturbance phenomena and its impact on high voltage transformers and other critical equipment.<br><br>Going forward, data on observed GIC and transformer failures during solar storms should be publicly released for continuing scientific study. NERC can and should substitute a science-based standard to model the benefits and impacts on grid reliability of protective hardware to prevent long-term blackouts due to solar geomagnetic storms.<br><br>Submitted by:<br><br>Thomas S. Popik<br>Chairman<br>Foundation for Resilient Societies<br><br>William R. Harris<br>International Lawyer<br>Secretary, Foundation for Resilient Societies<br><br>Dr. George H. Baker<br>Professor Emeritus,<br>James Madison University<br>Director, Foundation for Resilient Societies<br><br>Representative Andrea Boland<br>Maine State Legislature |

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| | | Sanford, ME (D)<br><br>Dr. William R. Graham<br>Chair of Congressional EMP Commission and former Assistant to the President for Science and Technology<br>Director, Foundation for Resilient Societies<br><br>William H. Joyce<br>Chairman and CEO<br>Advanced Fusion Systems<br><br>John G. Kappenman<br>Owner and Principal Consultant<br>Storm Analysis Consultants, Inc. |

**Response:** The SDT thanks the contributors for participating in the standards development process and for the detailed comments.

1. Observational data for years 1993-2013 were used in the generation of the geoelectric field statistics. This is an extensive data set that covers almost two solar cycles and includes major storms such as the famous Halloween storm of October 2003. It is important to note that the averaging process does not assume the existence of ionospheric hotspots. The geoelectric field is characterized in regional scales without making any assumptions about the actual field structure. Localized hotspots, if they exist, will be reduced in amplitude in the averaging process as we are interested in regional-scale rather than point wise enhancements in the field. Large-scale spatially coherent enhancements are not reduced in amplitude in the averaging process.

2. The geomagnetic latitude scaling factor is based on results presented in peer-reviewed scientific literature (Pulkkinen et al., 2012; Ngwira et al., 2013; Thomson et al., 2011). The results are based on publicly available data from worldwide distribution of geomagnetic observatories. Consequently, all necessary data are available for independent examination and validation of the results.

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| 3. The SDT revised the thermal screening criterion from 15 A per phase to 75 A per phase after conducting extensive simulation of the benchmark GMD event on the most conservative thermal models known to date. The revision was also based on input from transformer manufacturer and industry SMEs. The justification is documented in the thermal screening criterion white paper.<br><br>References:<br><br>Pulkkinen, A., E. Bernabeu, J. Eichner, C. Beggan and A. Thomson, Generation of 100-year geomagnetically induced current scenarios, Space Weather, Vol. 10, S04003, doi:10.1029/2011SW000750, 2012.<br><br>Ngwira, C., A. Pulkkinen, F. Wilder, and G. Crowley, Extended study of extreme geoelectric field event scenarios for geomagnetically induced current applications, Space Weather, Vol. 11, 121–131, doi:10.1002/swe.20021, 2013.<br><br>Thomson, A., S. Reay, and E. Dawson. Quantifying extreme behavior in geomagnetic activity, Space Weather, 9, S10001, doi:10.1029/2011SW000696, 2011. | | |
| SmartSenseCom, Inc. | No | See Comment below at Section 1(b). SMARTSENSECOM, INC. COMMENTS ON PROPOSED STANDARD TPL-007-1<br><br>In recognition of the potentially severe, wide-spread impact of GMDs on the reliable operation of the Bulk-Power System, FERC directed NERC in Order No. 779 to develop and submit for approval proposed Reliability Standards that address the impact of GMDs on the reliable operation of the Bulk-Power System. In this, the second stage of that standards-setting effort, the Commission directed NERC to create standards that provide comprehensive protections to the Bulk-Power System by requiring applicable entities to protect their facilities against a benchmark GMD event. |

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| | | In particular, FERC directed NERC to require owners and operators to develop and implement a plan to protect the reliability of the Bulk-Power System, with strategies for protecting against the potential impact of a GMD based on the age, condition, technical specifications, or location of specific equipment, and include means such as automatic current blocking or the isolation of equipment that is not cost effective to retrofit. Moreover, FERC identified certain issues that it expected NERC to consider and explain how the standards addressed those issues. See Order No. 779 at Â¶ 4. Among the issues identified by FERC was Order No. 779's finding that GMDs can cause "half-cycle saturation" of high-voltage Bulk-Power System transformers, which can lead to increased consumption of reactive power and creation of disruptive harmonics that can cause the sudden collapse of the Bulk-Power System. FERC also found that half-cycle saturation from GICs may severely damage Bulk-Power System transformers. While the proposed standard addresses and explains transformer heating and damage with a model, NERC ignores the issues of harmonic generation and reactive power consumption caused by a GMD event that have caused grid collapse in the past.<br><br>FERC has also been very clear to NERC that it considered the "collection, dissemination, and use of GIC monitoring data" to be a critical component of these Second Stage GMD Reliability Standards "because such efforts could be useful in the development of GMD mitigation methods or to validate GMD models." See Order No. 797-A, 149 FERC Â¶ 61,027 at Â¶27. However, the proposed standard fails to tie the actions required under the standard to any actual grid conditions. In its place, the proposed standard relies entirely upon an untested system model with several suspect inputs and with no means for model verification and no affirmative requirement for real-time monitoring data as a means to enable GMD mitigation. |

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| | | It has been nearly eighteen months since Order No. 779 and this comment cycle represents NERC's last opportunity to correct its course before it files TPL-007-1 with FERC. Based on the considerable volume of scientific evidence and the capabilities of modern measurement and control technology to serve as a mitigation method, the proposed standard is technically unsound and fails to adequately address FERC's directives. Rather than risk the operation of the grid on the perfection of an untested model, NERC should have provided requirements for the collection and dissemination of GMD information, such as data collected from real-time current and harmonic monitoring equipment, to ensure that the Bulk-Power System is able to ride-through system disturbances. NERC should include these measures inTPL-007-1 or be prepared for a likely FERC remand - leaving the Bulk-Power System exposed to the risk of GMD while NERC addresses the matters that it ought to have considered at this stage of the process.<br><br>1. TPL-007-1 Should be Modified to Account for the Impact of System Harmonics and VAR Consumption and Mitigate the Risk Created by Reliance On Untested System ModelsIn Order No. 779, FERC found that GMDs cause half-cycle saturation of Bulk-Power System transformers, which can lead to transformer damage, increased consumption of reactive power, and creation of disruptive harmonics that can cause the sudden collapse of the Bulk-Power System. Whereas TPL-007-1 takes pains to model transformer thermal heating effects, the proposed standard does not adequately address the risks posed by harmonic injection and VAR consumption. Failure to deal directly with the effects of harmonics and VAR consumption is irresponsible given the empirical evidence of their impact upon system reliability during GMD events. Real-time monitoring, as called for by FERC, would provide the real-time operating information necessary to account for - and mitigate - these negative system effects. Real-time |

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| | | monitoring information would also remedy the vulnerability created by standard's "model-only" approach to the GMD threat and provide a means to iteratively improve any model over time.<br><br>A. Failure to Account for Harmonics and VAR Consumption. In the presence of a GIC, a saturated transformer becomes a reactive energy sink, acting as an unexpected inductive load on the system, and behaves more like a shunt reactor. Consequently, transformer differential protective relays may trip and remove the transformer from service because of the disproportionately large primary current being drawn and consumed by the saturated transformer. System VAR support devices, such as capacitor banks and SVCs, become particularly critical during such conditions in order to offset the undesired behavior of GIC-affected transformers. The magnetizing current pulse of a GIC-inflicted transformer injects substantial harmonics into the power system.<br><br>VAR support devices are a low impedance path for harmonic currents and subsequently these devices begin to draw large currents too. A power flow "tug-of-war" ensues between the saturated transformers and VAR support devices. The sustenance of the VAR support devices is paramount as their failure may result in system voltage instability and collapse. However, harmonics doom these devices on multiple counts. For example, the large harmonic currents being consumed by capacitor banks may affect other components in the device that cannot withstand such high magnitude currents and result in damage and the unwanted tripping of the capacitor bank. Additionally, harmonics often result in the improper operation of protective equipment, such as overcurrent relays. Therefore, harmonics are ultimately predisposing system VAR support components to failure and increasing the vulnerability of the grid to voltage instability and collapse. See Duplessis, The Use of Intensity Modulated Optical |

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| | | Sensing Technology to Identify and Measure Impacts of GIC on the Power System (attached).<br><br>Accounting for GIC-related harmonic impacts is also essential considering that where GICs have caused significant power outages, harmonics have been identified as the primary system failure mode through the improper tripping of protection relays in known GMD events. For example, the 1989 Quebec blackout was traced to improper protective device tripping influenced by the GIC-induced where seven large static VAR compensators were improperly tripped offline by relays. See Department of Homeland Security, Impacts of Severe Space Weather on the Electric Grid, Section 4.4. In light of FERC's directive to address and explain how the standard address these issues, it is clear that TPL-007-1 be modified to directly account for the reactive power and harmonic effects of GMD events.<br><br>B. Over-Reliance on Untested Models. The core of the proposed standard is a series of models designed to approximate the "worst-case" scenarios of a GMD event which are, in turn, used to determine system vulnerability and whether corrective action is required. This "model-only" approach is technically insufficient and leaves the grid open to unnecessary risk. Moreover, no mechanism exists in the standards to validate the GMD models through the use of actual operating data.<br><br>First, genuine concerns exist regarding whether the "worst-case" GMD scenario is actually being modeled or whether the model substantially underrepresents the threat. For example, according to empirically-based arguments of John Kappenman and William Radasky in their White Paper submitted to the NERC earlier this year, the NERC Benchmark model underestimates the resulting electric fields by factors of 2x to 5x. Kappenman et al., Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in |

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| | | this NERC GMD Standard. The thermal heating model also relies upon a 75 amps per phase assumption (equivalent to total neutral GIC of 225 amps) as the modeled parameter. As shown in the Oak Ridge Study, it was found that at as little as 90 amps (or 30 amps per phase) there is risk of permanent transformer damage. See, e.g., Oak Ridge National Laboratory, FERC EMP GIC Metatech Report 319 at 4-8 ("Oak Ridge Study"). Indeed, the Oak Ridge Study found that a 30 amps per phase level is the approximate GIC withstand threshold for the Salem nuclear plant GSU transformer and possibly for others of similar less robust design in the legacy population of U.S. EHV transformers. See Oak Ridge Study at Table 4-1 (finding 53% of the Nation's 345kV transformers at risk of permanent damage at a 30 amps per phase GIC level). In addition, the system model specified in Requirement 2 should also be run on the assumption that all VAR support components on the system (e.g., capacitor banks, SVCs, etc.) become inactive (i.e., removed from service by undesired operation of protective devices caused by the harmonics that GIC affected transformers are injecting into the system).<br><br>That the models appear to substantially under-estimate the expected GMD impact is critical as it the models alone - under the proposed standard - that drive the vulnerability assessments and corrective action plans that require owners and operators to implement appropriate strategies. As written, these models have the effect of greatly reducing the scope of the protective requirements that will be implemented, potentially allowing sizable portions of the grid to be wholly unprotected and subject to cascading blackouts despite the adoption of standards. The extensive analysis and findings of the Kappenman-Radasky White Paper and the Oak Ridge Study suggest that the modeling approach elected by NERC is technically unsound, does not accurately assess a "worst case" scenario |

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| | | as it purports to do, and, in any event, should not be the sole basis for the standard's applicability.<br><br>Second, the proposed standard provides no means to validate or update the standard's models in light of actual operating data. This amounts to little more than a gambler's wager that the model will adequately protect the Bulk-Power System from a substantial GMD event, when it has never actually been tested. As the model is designed, actual operating data has no means to influence or override actions based upon the model. This is inappropriate. As discussed above, it is likely that the model developed will underestimate the effects of a GMD event. To rely on a model to simulate actual equipment performance over a range of potential GMD disturbances, it is essential that that model must not only contain adequate information (i.e. - an accurate up-front estimate), but that it must also correspond to actual reported field values. NERC should modify the standard to provide that actual operating data be used to regularly verify and improve the model.<br><br>C. The Solution - Collect, Disseminate, and Use Real-Time Reactive Power and Harmonic Content Information to Mitigate GMD Impacts. While the standard's model-based approach to GMD mitigation efforts may have some limited utility as a first step towards identifying vulnerabilities and developing forward-looking correction action plans, the standard would provide far better protection with a requirement for the collection and use of accurate, real-time data regarding current, reactive power consumption, and system harmonics. Real-time data should underpin any GMD mitigation efforts, substantially reducing the risk of outages and damage to critical equipment in the event of a GMD, and would also improve the reliability of system models. Modern grid measurement and control technologies are capable and readily deployable to mitigate GMD events. |

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| | | First, real-time monitoring enables protective devices to be efficiently managed during a GIC event, initiating control signals that enable devices to "ride-through" GMD where they may otherwise trip offline during a period of normal operation. In these instances, the detection of harmonic content could be used to sense transformer saturation and override normal protective device trip settings in order to maintain key equipment online and not be "fooled" into tripping by the harmonics generated by the event. Given the diversity of protective devices for equipment used throughout the Bulk-Power System, a technically preferable approach would be to actively manage protection schemes based upon real-time operating data. Regarding the system's VAR response, if system voltage becomes unstable when VAR support is inhibited during a GIC event, operators would have an available solution through the identification of atypical harmonics, which can be associated with a GIC event, and this information used as a trigger to implement alternate protective schemes for VAR support components for the duration of the GIC event.<br><br>Second, if a GMD event is detected through the monitoring of systemic VAR consumption and harmonic content at key points in the network (which may include current monitoring on vulnerable transformer neutrals and monitoring of harmonics and VAR consumption on phases), this real-time monitoring data could be used to draw down, and ultimately cease, GMD operating procedures as the GMD event passes. Moreover, the VAR and harmonic derived from real-time operation information may also be used to trigger operating procedures, which is necessary given that the existing operational standard relies on space weather forecasts as the trigger for the implementation of operating procedures, despite the substantial error rates associated with these forecasts. Since GMD procedures impose transmission constraints that do not permit wholesale energy markets or system dispatch to achieve the most efficient use of available |

| Organization | Yes or No | Question 1 Comment |
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| | | resources, ultimately affecting the prices paid by consumers, NERC should seek to minimize the frequency and duration of mitigation efforts. Real-time monitoring of harmonic content and reactive power would enable a more efficient approach to recognizing and reacting to GMD events, harmonizing the Phase I and Phase II standards and providing greater overall protection to the grid.<br><br>Further, real-time monitoring information must be used to validate models that are used to inform the means by which owners and operators will prepare for, and react to, GMD events. Currently, the models presented in the standard are the sole means to trigger the implementation of protection measures and the availability of actual operating data that questions the model's outputs have no means to override the model-based approach. The use of actual operating data to verify the standard's model would improve the accuracy of model verifications needed to support reliability. A better approach would be to use modeling and real-time monitoring in tandem to constantly verify and enhance the model, while still maintaining protections for "missed" events that the model is likely to inevitably overlook. The people of the United States should not have the ongoing Bulk-Power System reliability put at risk by an unverified model.<br><br>NERC should use its authority to insure that real operating data will, over time, be employed to verify and improve any reference model and that real operating data will be employed as a means to ensure ongoing system reliability when events render the reference model unequal to its protective task (which evidence suggests will happen). The proposed standard should be modified to require the collection, dissemination, and use of real-time voltage and current monitoring data which will provide the reactive power and harmonic content information necessary to effectively and efficiently manage the system in response to GMDs. |

| Organization | Yes or No | Question 1 Comment |
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| | | 2. Conclusion. FERC was clear in its direction to NERC that the collection, dissemination, and use of real-time GIC monitoring data was a critical component of these Second Stage GMD Reliability Standards “because such efforts could be useful in the development of GMD mitigation methods or to validate GMD models.” See Order No. 797-A, 149 FERC Â¶ 61,027 at Â¶ 27. FERC also was clear that harmonic content and reactive power consumption created by GMD events constituted serious threats to system reliability that must be addressed. Order No. 779 at Â¶ 7.The draft standard offered by NERC simply fails to meet the needs identified by FERC - which are amply supported by the record established in these proceedings - a reasonable person could reach no other conclusion.<br><br>To create a reasonable and prudent standard, NERC needs to address the reactive power and harmonic generation aspects of GMD events, and it needs to provide for verification and improvement of the model included in the draft standard. The only route to meeting those needs that is supported by the evidentiary based findings and FERC’s directives is a mandate for the collection, dissemination, and use of real-time GIC current and harmonic data to drive protection schemes. With clearly articulated requirements for such data, NERC can fill the gaps in the current standard and provide a means by which to adequately protect the Bulk-Power system.<br><br>Respectfully submitted,/s/Christopher J. Vizas<br>Aaron M. Gregory<br>SMARTSENSECOM, INC.<br>cvizas@smartsensecom.com<br>agregory@smartsensecom.com<br>Date: November 21, 2014 |

| Organization | Yes or No | Question 1 Comment |
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| **Response:** The SDT thanks the commenter for participating in the standards development process. The following response is provided:<br>1. TPL-007 addresses impacts from GMD-related harmonics and var consumption. The proposed standard requires planning entities to conduct a GMD Vulnerability Assessment that includes steady state power flow analysis and supporting study or studies using the models specified in Requirement R2 that account for the effects of GIC. Table 1 further defines the planning event to include "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".<br>2. The SDT agrees that monitoring is a valuable component for many mitigation approaches and will further enhance system level understanding of GMD impacts. Monitoring is addressed in technical supporting material including the GMD Planning Guide and the 2012 GMD Report.<br>3. The benchmark GMD event has been technically justified in the supporting white paper. Assertions that plane wave methods systematically underestimate geoelectric field calculations are technically unsubstantiated. Earth impedance models published by the USGS have an element of uncertainty (as they may result in either overestimation or underestimation of geoelectric fields), and the SDT agrees that they should be updated as necessary with the use of good quality geomagnetic field and GIC measurements made at consistent data acquisition rates.<br>4. The standard addresses the risk of widespread transformer damage and uncontrolled cascading wide area blackouts. The standard is not intended to address the performance of individual transformers with known design deficiencies or in poor operating conditions.<br>5. The SDT agrees with the commenters' examples of use of real-time monitoring and effective operating procedures. The comments are consistent with technical references such as the GMD Planning Guide. Other approaches may be equally or more effective in addressing impacts identified in GMD Vulnerability Assessments. Consequently, the proposed standard should provide responsible entities with flexibility to meet specified performance criteria and not prescribe specific approaches. | | |

| Organization | Yes or No | Question 1 Comment |
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| 6. The SDT agrees that the benchmark GMD event and earth impedance models should be periodically reviewed and updated with additional information and data; this can be accomplished outside of the reliability standard using a process such as the periodic review of standards that is required under NERC Rules of Procedure. | | |
| John Kappenman, Storm Analysis Consultants | | Regarding NERC Draft Standard on Transformer Thermal Impact Assessments (comment appended to end of this report) |
| **Response:** A central point made in the comments is that delta winding heating due to harmonics has not been adequately considered by the SDT and that thermally this is a bigger concern than metallic part hot spot heating. Comments pertaining to tertiary winding harmonic heating are based on the assumption that delta winding currents can be calculated using the turns ratio between primary and tertiary winding. This assumption is incorrect when a transformer is under saturation. Therefore, the concerns regarding delta windings being a limiting problem from a thermal point of view are unwarranted. The criteria developed by the SDT uses state-of-the-art analysis methods and measurement-supported transformer models. | | |
| SERC PSS<br>Ameren | Yes | We appreciate the standard drafting team's efforts at reducing the potential scope of transformers needing to be evaluated, as well as streamlining the evaluation process. |
| ACES Standards Collaborators | Yes | We would like to thank the SDT for reviewing the screening criterion for transformer thermal assessments and increasing it to 75 A per phase or greater. |
| Colorado Springs Utilities | Yes | CSU agrees that this is a trend in the right direction.  Thank you for all of your efforts in evaluating this threshold! |
| Ingleside Cogeneration LP | Yes | Ingleside Cogeneration L.P. (ICLP) finds that both the transformer screening criterion and look-up tables are welcome updates to the GMD initiative.  In our view, they reflect the best available knowledge surrounding the impact of geomagnetically induced currents on susceptible BES transformers.  We |

| Organization | Yes or No | Question 1 Comment |
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| | | recognize that some stakeholders prefer a far more conservative approach to GMD-resiliency, but the experience with the phenomena over the last several decades does not justify the costs. That may change as our familiarity with GMD grows over time, but for now, these dollars are best spent on more pressing reliability issues. |
| Manitoba Hydro | Yes | The drafting team has greatly improved the standard by moving the threshold from 15A to 75A per phase. The screening criterion included in Table 1 (of the Screening Criterion for Transformer Thermal Assessment) makes it very easy to determine whether the metallic hot spot temperature of 200C is exceeded. |
| California ISO | Yes | The California ISO supports the comments of the Standards Review Committee. |
| American Electric Power | Yes | |
| Public Utility District No. 2 of Grant County, WA | Yes | |
| Texas Reliability Entity, Inc | Yes | |
| Bureau of Reclamation | Yes | |
| Seattle City Light | Yes | |
| Oncor Electric Delivery LLC | Yes | |

| Organization | Yes or No | Question 1 Comment |
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| South Carolina Electric & Gas | Yes | |
| Exelon and its Affiliates | Yes | |
| American Transmission Company | Yes | |
| Electric Reliability Council of Texas, Inc. | Yes | |
| Iberdrola USA | Yes | |
| Northeast Power Coordinating Council | Yes | |
| Con Edison, Inc. | Yes | |
| MRO NERC Standards Review Forum | Yes | |
| OG&E | Yes | |
| Duke Energy | Yes | |
| LCRA Transmission Services Corporation | Yes | |

| Organization | Yes or No | Question 1 Comment |
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| David Kiguel | Yes | |
| Puget Sound Energy, Inc. | Yes | |
| Avista Utilities | Yes | |
| Tacoma Power | Yes | |
| Idaho Power Company | Yes | |
| DTE Electric | | No Comment |

**2. TPL-007-1. Do you agree with the changes made to TPL-007-1? If not, please provide technical justification for your disagreement and suggested language changes**

**Summary Consideration:** The SDT thanks all commenters. The following changes have been made to the proposed standard:

- Corrected VRF terminology in Requirement R1.
- Added technical guidance to the applications guidelines section for Requirement R2 to address underground pipe-type transmission cable.
- Revised the rationale box for Requirement R7 to more clearly indicate necessary considerations in developing a Corrective Action Plan.
- Revised R6 to clarify that the 24-month timeline for R6 is based on receipt of GIC information provided in Requirement R5 part 5.1. R6 now states:

R6. 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 75 A per phase or greater. The 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.

Response to specific comments follows.

| Organization | Yes or No | Question 2 Comment |
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| Northeast Power Coordinating Council | No | 1. The Standard Drafting Team responded to our concerns on the omission of modeling for shielded, underground pipe-type transmission lines in the last posting with the following (posted in the Consideration of Comments): ”The SDT agrees that underground pipe-type cables should not be modeled as GIC sources. GIC, induced in the pipe, will circulate through the pipe, cathodic protection and ground return circuit, but it is probably an order of magnitude lower than what be induced in an unshielded transmission circuit. However, the cables will carry GIC induced elsewhere (overhead circuits) and must be included in the dc network (but not as dc sources) as well as the load flow base case. The SDT will refer that issue to NERC technical committees with the suggestion to address this modeling issue in future revision of the GMD Planning Guide.” Current modeling methods associate the driving force of GICs to impact all transmission lines according to location and length, but not with regard to their status as underground or overhead. However, the ability of GMDs to induce currents in underground lines is highly questionable, as their surrounding pipe type structures would be expected to act as a Faraday Cage, completely isolating the cables from a GMD event. It is expected that the overall GIC response for an underground pipe-type cable system would be significantly reduced in comparison to its overhead counterpart. There is no method currently available to create this model or differentiate underground shielded lines with contributions of zero or severely attenuated magnitudes of GIC. Therefore, the current modeling software cannot be used to gauge the impact of GMDs, and the true extent and impact of GMDs cannot be accurately assessed. The Drafting Team should consider excluding underground pipe-type cable from the standard. Referring this issue to the NERC technical committees is not sufficient. The technical committees may not implement the suggestion that all underground pipe-type cables are zero GIC sources. This suggestion has also not been implemented by the GIC modeling application developer(s). |

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| | | 2. Additionally, it has been raised on previous postings that the GMD Benchmark is much more severe than what has been observed in Hydro-Quebec's historical record. The parameters behind Attachment 1 and Table 1 are not adequately justified. A preliminary evaluation that applied the GMD Event Benchmark of 4 to 8 V/km on Hydro-Quebec's System necessitates unjustified investment to satisfy extraordinary system conditions that have never been experienced. The GMD Benchmark gets a maximum value of 8 V/km for the 60 degree geomagnetic latitude, above which the value is constant. We would like to propose the SDT to apply the constant value to a lower geomagnetic latitude. This would allow for a constant value of E (V/km) for all Quebec and Canada but lower than in the actual Benchmark without affecting most United States entities. This proposal would respect the actual standard's structure and provide a more realistic value. |

**Response:**

1. Thank you for your comment and amplifying information. The SDT maintains that underground pipe-type transmission lines are a necessary component of the dc network and therefore cannot be excluded from the proposed standard. The following has been added to the guidelines and technical basis section for R2:

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.

Commercially available modeling software allows setting the induced geoelectric field on any transmission circuit to a user-defined value (near zero in this case).

2. The SDT maintains that the 100-year benchmark is an appropriate reference storm for GMD Vulnerability Assessments due the potential for wide area impacts from GMD events. It is recognized that the benchmark GMD event is of greater magnitude that historically recorded storms such as the March 1989 event.

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| Con Edison, Inc. | No | The Standard Drafting Team responded to concerns on the omission of modeling for shielded, underground pipe-type transmission lines with the following: ”The SDT agrees that underground pipe-type cables should not be modeled as GIC sources. GIC, induced in the pipe, will circulate through the pipe, cathodic protection and ground return circuit, but it is probably an order of magnitude lower than what be induced in an unshielded transmission circuit. However, the cables will carry GIC induced elsewhere (overhead circuits) and must be included in the dc network (but not as dc sources) as well as the load flow base case. The SDT will refer that issue to NERC technical committees with the suggestion to address this modeling issue in future revision of the GMD Planning Guide.” Referring this issue to the NERC technical committees is not sufficient; the technical committees may not implement the suggestion that all underground pipe-type cables are zero GIC sources. This suggestion has also not been implemented by the GIC modeling application developer(s). The ability of GMDs to induce currents in underground lines is highly questionable, as their surrounding pipe-type structures would be expected to act as a Faraday cage, completely isolating the cables from a GMD event. In view of the impact that this enhancement would have on the evaluation of GIC currents in portions of the NPCC region, we request that the issue be captured in Attachment 1 or in the Application Guideline associated with TPL-007-1. |
| **Response:** Thank you for your comment and amplifying information. The SDT added the following to the guidelines and technical basis section for R2:<br><br>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. | | |

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| MRO NERC Standards Review Forum | No | 1. Page 11, Table 1 -Steady State Planning Events. The NSRF suggest that the SDT provide a tool or guidance on the method of determining Reactive Power compensation devices and other Transmission Facilities that are removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event. If a tool cannot be provided in a timely fashion. We suggest language be added to the implementation plan that provides R4, GMD Vulnerability Assessment, will not be implemented until after guidance for the industry is readily available or the date provided in the implementation plan whichever is later. The Planning Application Guide's Sections 4.2 and 4.3 specifically mention the unavailability of tools and difficulty in performing an accurate harmonic assessment but does not provide resolution or recommendation on how to accurately address the concern. The statement from Section 4-3 is referenced below. "The industry has limited availability of appropriate software tools to perform the harmonic analysis. General purpose electromagnetic transients programs can be used, via their frequency domain initial conditions solution capability. However, building network models that provide reasonable representation of harmonic characteristics, particularly damping, across a broad frequency range requires considerable modeling effort and expert knowledge. Use of simplistic models would result in highly unpredictable results." Additionally, there needs to be a clearer definition of how the steady state planning analysis due to GMD event harmonics is to be performed. Is it the intent of the standard to study the removal of all impacted Transmission Facilities and Reactive Power compensation devices simultaneously, sequentially, or individually as a result of Protection operation or Misoperation due to harmonics?<br><br>2. The Planning Application Guide references the "NERC Transformer Modeling Guide" in several places as a reference for more information on how to perform the study. The "NERC Transformer Modeling Guide" is shown in the citations as still forthcoming. Further, The NSRF does not believe it is feasible to implement a |

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| | | full harmonic analysis in the implementation timeframe for TPL-007. In a very broad view, the standard requires a specific analysis that the industry doesn't have the skill set or tools to perform. This is acknowledged by the supporting documents. The reference document cited as a resource to further explain how to perform the studies has not been created yet.<br><br>3. Page 20, Table of Compliance Elements - VRF for R2. The NSRF does not agree with the change to the VRF for R2 from "Medium" to "High". The VRF of "High" for R2 is not in line with the NERC VRF writing guide. |
| **Response:**<br><br>1. The SDT has reviewed your comment and acknowledges the tools to perform detailed harmonics analysis are not in wide availability in the industry. However, the SDT believes that reasonable engineering judgment can be exercised to identify protection equipment that may be vulnerable to misoperation in the Benchmark GMD event and therefore, should be outaged in the power flow analysis. As written, the standard provides flexibility for planners to apply engineering judgment and is appropriately supported by technical resources including the NERC GMD TF GMD Planning Guide (section 4.2 and 4.3) and the 2012 Interim Report (section 6.4). A prescriptive tool or method as suggested by the commenter would not be effective in application to all planning entities. Furthermore, the SDT does not support making implementation of Requirement R4 contingent upon development of a prescriptive tool for GMD harmonics analysis.<br><br>2. While the NERC GMD TF continues to develop a Transformer Modeling Guide which is expected to be available in 2015, there are sufficient technical resources available now to conduct a GMD Vulnerability Assessment.<br><br>3. The change of the VRF from Medium to High conforms to FERC and NERC guidelines requiring consistency among Reliability Standards (see guideline 3 in the VRF/VSL justification posted on the project page). TPL-001-4 Requirement R1 is an analogous requirement which is being revised from Medium to High to comply with FERC directives. See NERC filing dated August 29, 2014 (RM12-1-000). | | |
| Associated Electric Cooperative, Inc. | No | 1. Transformer Modeling Guide - An acceptable implementation time cannot be accurately determined or agreed upon without the availability or experience with |

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| | | resources that are mandatory with currently drafted requirements. AECI respectfully requests one of the following.<br>(a)Modify the implementation plan to specifically state that transformer thermal assessment time requirements are dependent on the availability of a technically sound modeling guide, -or-<br>(b) include exception within the deadline that considers an inability to attain necessary tools or resources to complete this portion of the study, -or-<br>(c) provide technically reasoned response on why the SDT disagrees with this approach.<br>2. DC Model Coordination - The current implementation plan does not consider the logistical steps inherent in model coordination and the compliance risk associated with failing to determine specific deadlines for both internal and external models. This concern cannot be mitigated during the planning coordinator phase when considering that the issue exists between two planning coordinator areas. AECI respectfully requests: Modify the implementation plan for DC model coordination to include a deadline for internal model development, and additional time for external model development through coordination with neighbors. The end result could be the exact same amount of time allotted for this phase, but with a staggered approach to promote good modeling practices between entities.<br>3. Contingency Mitigation Using Load Shed - AECI appreciates the SDT responsiveness to prior comment concerning the use of load shed as a mitigation to meet BES performance. However, the current language lacks clarity regarding the minimization of Load Loss or Firm Transmission Service. AECI respectfully requests the following. Modify Table 1, Steady State Performance Footnotes - Please clarify “The likelihood and magnitude of Load loss or curtailment of Firm Transmission Service should be minimized.” How should a transmission planner |

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| | | apply this language in the development of MW thresholds used to determine the validity of a mitigation option? |
| **Response:**<br>1. Technical resources necessary to perform the thermal impact assessment are available. Consequently, the SDT does not agree with the commenter's suggestion to modify TPL-007 or the Implementation Plan. The technical justification is provided in the thermal impact assessment white paper posted on the project page.<br>2. With respect to the issue of dc Model coordination, the SDT believes the addition of a specific milestone to the implementation plan for model coordination would add complexity and is not the most efficient approach to accomplish the objective. The preferred approach is to leave the sequencing of the development of the respective internal and external models in the hands of the planning entities.<br>3. Similarly, regarding the request for more specificity on the limits of acceptable load loss or firm service curtailment, the SDT's intent is to provide flexibility for planning entities to determine acceptable thresholds for load loss, if any, based on system and planning considerations. The commenter recommended modifying Table 1 footnotes; a suggested change was not provided for consideration. | | |
| PPL NERC Registered Affiliates | No | R7 gives the Responsible Entity determined by the PC/TP the sole authority to develop a Corrective Action Program (CAP) that may include, "Installation, modification, retirement, or removal of Transmission and generation Facilities and any associated equipment." There is no provision for the equipment owner to have the opportunity to demonstrate there may be a better, more cost-effective system to remedy the problem. The SDT stated in the 11/5/14 teleconference with the NAGF SRT that these are not excessive powers, since they involve only making a plan, not an implementation order. The NERC Glossary definition of a CAP, however, is, "A list of actions and an associated timetable for implementation [emphasis added] to remedy a specific problem." The statements, "will be met," in R7 and, "actions needed," in R7.1 make it additionally clear that TPL-007-1 CAPs aren't just discussion-starting lists of |

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| | | possibilities; they do in fact constitute implementation orders. Giving the Responsible Entity such sweeping powers over equipment owned by others is particularly problematic for GOs in a deregulated market where the GO may never be able to recover the cost (potentially millions of dollars) of the modified, retired or removed equipment. Moreover, the standard should provide the recipient of a Corrective Action Plan that continues to disagree with the Responsible Entity's decision with recourse to challenge the determination. To that end, we suggest that a subsection 7.3.2 be added providing that, "If disagreement between the recipient of the Corrective Action Plan and the Responsible Entity continues after the foregoing process, the recipient may seek resolution of the dispute by NERC and/or FERC." |
| **Response:** The SDT disagrees with the comment that the planning entities have sole authority to develop a Corrective Action Plan. The development of a Corrective Action Plan is generally done via a collaborative process with the asset owners or in consultation with internal customers for vertically integrated entities. The SDT did not intend to establish requirements for the implementation of the Corrective Action Plan in this standard because the implementation would be addressed in processes that are outside of the standards process. | | |
| ACES Standards Collaborators | No | 1. We recommend that the SDT remove all references to the TP and require the PC to be the responsible entity.<br><br>2. We continue to have concerns that the applicability section includes transformers that may not be a part of the BES. This standard should apply only to BES Facilities.<br><br>3. We have concerns with the increased violation risk factor for Requirement R2 from medium to high. We disagree that a requirement for the maintenance of system models should be classified as a high VRF. Requirement R2 is lacking a specific timeframe on how often these models must be maintained. Moreover, the lack of maintaining a model will not result in a cascading, separation, or instability event. We recommend moving the VRF back to medium, because it is |

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| | | an administrative task that should not result in monetary penalties up to $1 million per violation.<br>(4) Thank you for the opportunity to comment. |
| **Response:**<br>1. The SDT considered refinement of the applicable entities in the standard but determined that the variation in the relationships between PCs and TPs in the North American systems prevented a single construct for applying the standard.<br>2. With regard to the issue of non-BES transformers, the SDT believes that exclusion of some non-BES transformers will provide incorrect results in the Benchmark GMD Vulnerability Assessment. Therefore, the SDT has set the equipment applicability to help ensure that accurate results are maintained.<br>3. The change of the VRF from Medium to High is to provide 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. | | |
| DTE Electric | No | This draft Standard does not address in any detail the coordination and installation of any necessary mitigation measures (such as GIC reduction devices) once vulnerable transformers are identified. The Planning Coordinator/Transmission Planner would seem to be the entities best suited to determine where and what mitigation measures are put in place. R6.3 requires the transformer owner to describe mitigation actions, but the PC/TP would be better equipped to study and specify area mitigation strategies in cooperation with the transformer owners. |
| **Response:** The development of a Corrective Action Plan is generally done via a collaborative process with the asset owners or in consultation with internal customers for vertically integrated entities. The SDT believes Requirement R7 Part 7.3 and R6 Part 6.4 provide for the information exchange needed for this coordination. | | |

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| SmartSenseCom, Inc. | No | See below White Paper in support of Comment Submitted. PDF submitted separately. The Use of Intensity Modulated Optical Sensing Technology to Identify and Measure Impacts of GIC on the Power System. Jill Duplessis, SmartSenseCom, Inc., Washington, D.C. jduplessis@smartsensecom.com U.S.A.<br><br>Abstract: This paper describes the phenomenon of geomagnetically induced currents ("GIC"), a geomagnetic disturbance's potential impact on transformers and the electric power system, and FERC/NERC regulation regarding utility responsibility. The paper then introduces intensity modulated optical sensing technology, explains how this technology has been adapted to measure voltage, current, phase and other characteristics of electric phenomena, and answers why this adaptable core technology provides a comprehensive solution to identifying and measuring the impacts of GIC. |
| **Response:** The SDT recognizes this is submitted in support of SmartSenseCom's comments in Q1 and has responded accordingly. | | |
| Colorado Springs Utilities | No | Thank you for all of your efforts and your comments. We know that this is a very complex issue that unfortunately receives excessive political publicity. We really appreciate the SDT's efforts. The following are some the SDT's comments in response to some feedback we provided during the last posting.<br><br>"Field tests are governed by Section 6 of the Standards Process Manual (SPM). As described, these programs are conducted prior to formal comment periods to inform the standard development effort. SDT members have collectively conducted multiple GMD studies in many regions and applied their expertise to the development of the requirements and implementation plan. "<br><br>CSU still has concerns over the carte blanc approach to rolling this standard out. Are we going to get the desired result as every entity applies this standard? We still have concerns that we will not. If there have been field tests and multiple studies it seems that there would be some conclusions or thresholds that could |

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| | | be used to provide additional applicability criteria. Is it really true that every entity in the United States needs to create these models, run these studies and assessments?<br><br>There were no general applicability conclusions that would produce the data needed to focus the scope of GMD impacts into specific regions or entities with particular footprint profiles? We anticipate excessive and unnecessary resource expenditure in performing the requirements of this standard. We still have concerns that there will be significant modifications needed to the process as it is rolled out without a pilot program. Shorting the implementation period and including additional pilots we feel would yield substantial results in resource savings and additional applicability criteria. |
| **Response:** The SDT believes that all applicable entities need to perform the analyses required in the standard. The expected impacts of the Benchmark GMD event will vary widely across the North American system due to various factors, such as geomagnetic flexibility, earth conductivity, system topology, etc. The SDT believes that it has incorporated those considerations into the requirements of the standard. | | |
| LCRA Transmission Services Corporation | No | LCRA TSC comments on requirement R5 - To clarify cases where this requirement should apply, LCRA TSC suggests the following: Each responsible entity, as determined in Requirement R1, shall provide GIC flow information (where the maximum effective GIC value is 75 A per phase or greater) 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. |
| **Response:** The SDT believes that it is important for the entities doing the GIC calculations to provide maximum effective GIC information (part 5.1) for all applicable BES power transformers, so that the asset owner can understand the proximity of their transformers to the 75 A per phase limit. The asset owner may choose to perform thermal analysis even though the transformer may be below the threshold due to its history, for example. The suggested change would not meet the objective. | | |

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| David Kiguel | No | 1. The responses to my comments in the previous posting give me no comfort. I am sure the SDT has been "cost conscious" in developing the standard. However, without a serious cost/benefit assessment there is no way of quantifying such claim. Saying that a cost/benefit analysis was not in the project scope as defined in the SAR is mistaken. The SC has, in principle, approved the CEAP project and there is no need to state explicitly in the SAR that a Cost Effective Assessment shall be performed.<br><br>2. I do not agree with the VRF change from Medium to High in Requirement 2. The High VRF definition that applies in this case (planning time frame) is a requirement that, if violated, could, under emergency, abnormal, or restorative conditions anticipated by the preparations, directly cause or contribute to bulk power system instability, separation, or a cascading sequence of failures, or could place the bulk power system at an unacceptable risk of instability, separation, or cascading failures, or could hinder restoration to a normal condition. The Medium VRF definition is a requirement that, if violated, could, under emergency, abnormal, or restorative conditions anticipated by the preparations, directly affect the electrical state or capability of the bulk power system, or the ability to effectively monitor, control, or restore the bulk power system, but is unlikely, under emergency, abnormal, or restoration conditions anticipated by the preparations, to lead to bulk power system instability, separation, or cascading failures, nor to hinder restoration to a normal condition. I believe, violation of a System Models requirement should be Medium at best. |
| **Response:**<br><br>1. The SDT is aware of several preliminary studies that have been performed by various entities in the North American system that basically carry out the calculations contemplated by the standard. Those studies underscore the difficulty of performing a detailed cost/benefit analysis in that the mitigation strategies for potentially vulnerable facilities are not immediately evident and require additional iterative studies. Relative to the benefits of GMD mitigation, it is equally difficult to project the scope (and costs) of a | | |

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| voltage collapse and blackout without the detailed studies that will be required by the standard. The SDT suggests that a cost/benefit analysis will only become meaningful once the standard has been in place and entities are conducting GMD Vulnerability Assessments.<br><br>2. The change of the VRF from Medium to High is to provide 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. | | |
| Puget Sound Energy, Inc.<br><br>Public Utility District No. 2 of Grant County, WA | No | The proposed TPL-007 standard has no requirement to share GIC modeling data with neighboring PCs or other PCs in close electrical proximity. For a medium system like ours, we rely on the adjacent systems having adjacent PCs for major bulk transmission. Without appropriate modeling information from adjacent PCs GIC study results our assessments of the vulnerability of our system for GIC will be optimistic and misleading. While the standard requires us to share flawed study results with our neighboring PCs it does not address requirements to share GIC modeling data needed to correct the study deficiencies. |
| **Response:** Requirements to provide the data for power system modeling and analysis are covered under other standards. The SDT believes these requirements and planning processes are sufficient to perform GMD Vulnerability Assessments. | | |
| OMU | No | Small entities will be required to develop and maintain models for low frequency events that have not been proved to have a high impact on a system of our magnitude. |
| **Response:** GMD events are known to have potential impact on the interconnected transmission system. Consequently, the applicability of TPL-007 is not determined by an entity's size. | | |
| Volkmann Consulting, Inc | No | The SDT has not technically justified the Benchmark event case, both spatial averaging and scaling factor. The recent Chinese paper outline the event of a GMD event in 2005. The China paper indicates that they experiences a field of 0.67V / km. The NERC Benchmark scaling factors would have only yielded a field |

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| | | of 0.03V / km. Thus the NERC Benchmark scaling method is off by a factor of 22 times. |
| **Response:** Technical justification is provided in the benchmark GMD event white paper. The commenter's suggestion that the scaling factors do not agree by a factor of 22 with geoelectric fields in a cited paper is incorrect. Equation (2) from TPL-007 attachment 1 specifies a lower bound on the scaling factor. This lower bound scaling factor was not applied in the commenter's calculation resulting in a lower value for geoelectric field. | | |
| Avista Utilities | No | Please consider inserting language that clearly states the following:<br>1. That GIC/GMD is a regional phenomenon and as such requires that the data provided for modeling GIC/GMD be regional in scope. For example, to properly model GIC/GMD in WECC ALL WECC utilities shall provide GIC/GMD modeling data.<br>2. Utilities shall submit Latitude & Longitude of substations (including associated buses) in order to support accurate GIC/GMD modeling.<br>Comment: Presently there is an enormous amount of opposition to providing location data to WECC for use in power flow base cases for the purposes of modeling GIC/GMD. The excuse used is that the TPL-07 standard does not require that data (with additional security concerns about providing location data). Specifically stating the modeling data needs along with the requirement to submit said data will go a long way towards getting GIC/GMD modeling completed. |
| **Response:** The SDT does not agree with the assertion that it is necessary to model an entire Interconnection in order to accurately determine the GIC flows in a given system. Because the drivers of GIC flow in a system (e.g. system topology) tend to be more localized, modeling 2-3 buses into the neighboring system is sufficient to obtain accurate results [1],[2].<br>1. Thomas Overbye, et al, “Power Grid Sensitivity Analysis of Geomagnetically Induced Currents”, IEEE Transactions on Power Systems, Vol. 28, No. 4, November 2013. | | |

| 2. NERC GIC Application Guide | | |
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| ReliabilityFirst | No | ReliabilityFirst votes in the Affirmative and believes the TPL-007-1 standard enhances reliability and establishes requirements for Transmission system planned performance during geomagnetic disturbance (GMD) events. ReliabilityFirst offers the following comments for consideration:<br><br>Requirement R7 - ReliabilityFirst still believes Requirement R7 should require the Entity to not only develop a Corrective Action Plan (CAP) but require the Entity to "Implement" it as well. ReliabilityFirst agrees that other processes outside of the standards process, such as internal investment processes for a vertically integrated entity, or regional planning processes for RTOs, regulatory processes that vary from jurisdiction to jurisdiction, etc., are factors that are considered when developing a CAP, but once the CAP is developed the entity needs to implement it. Also, in FERC Order 706, the Commission makes it clear that when discussing the CIP standards (specifically Technical Feasibility Exceptions), that an Entity is required to "develop and implement" mitigation steps, mitigation plans and remediation plans. Even though the Order does not explicitly mention the term CAP, we believe mitigation steps, mitigation plans and remediation plans are in the same vain and context of a CAP. As you can see, the implementation piece is an important component in which the Commission highlighted. Listed below are examples from the Order:<br><br>FERC Order 706, paragraph 187 "As mentioned above, in the CIP NOPR, the Commission proposed a three step structure to require accountability when a responsible entity relies on technical feasibility as the basis for an exception. This proposed structure would require a responsible entity to: (1) develop and implement interim mitigation steps to address the vulnerabilities associated with each exception; (2) develop and implement a remediation plan..." |

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| | | FERC Order 706, paragraph 192 "With some minor refinements discussed below, the Commission adopts the CIP NOPR proposal for a three step structure to require accountability when a responsible entity relies on technical feasibility as the basis for an exception. We address mitigation and remediation in this section and direct the ERO to develop: (1) a requirement that the responsible entity must develop, document and implement a mitigation plan..." . Furthermore, FERC Order 706, paragraph 217 states "However, we disagree with Northern Indiana that penalties should be waived within the time when an approved remediation plan is being implemented, as proper implementation of the plan itself constitutes a necessary element of compliance." The Commission believes "proper implementation of the plan itself constitutes a necessary element of compliance" which bolsters our recommendation to include the "implementation" piece within Requirement R7. |
| **Response:** The development of a Corrective Action Plan is generally done via a collaborative process with the asset owners or in consultation with internal customers for vertically integrated entities. Specific implementation is addressed in processes that are outside of the standards process. This approach is appropriate for a planning standard and respects the diversity of mitigating measures that are possible to meet performance requirements during a benchmark GMD event. These measures may include operating procedures, hardware mitigation, or equipment upgrades, which involve various entities, timelines, and coordinating actions among collaborating stakeholders. TPL-007 maintains accountability for meeting performance through R7 part 7.2, which specifies that the planning entity must review corrective actions in subsequent GMD Vulnerability Assessments until performance requirements are met. | | |
| California ISO | No | 1. The California ISO recommends that a new requirement be added to the TPL-007-1 Standard requiring: Generator Owners and Transmission Owners shall be required to provide necessary transformer data for the GIC-models to the Planning Coordinators and Transmission Planners. The California ISO recommends the above requirement recognizing that the source of the transformer data and GIC-model data is generally the Transmission Owners and |

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| | | Generator Owners. This recommended additional requirement for TOs and GOs would ensure that the data needed to conduct the studies is provided to Planning Coordinators and Transmission Planners.<br><br>2. In addition, the California ISO supports the following portion of the Standards Review Committee's comments on this question: The SRC appreciates the revisions provided in Requirement R6, but recommends that the ability of entities to collaborate and coordinate on the performance of jointly-owned equipment be further clarified. The following revisions are proposed:<br><br>R6. Each Transmission Owner and Generator Owner shall conduct a thermal impact assessment for its solely owned applicable Bulk Electric System power transformers where the maximum effective geomagnetically-induced current (GIC) value provided in Requirement R5 part 5.1 is 75 A per phase or greater. For jointly-owned applicable Bulk Electric System power transformers where the maximum effective geomagnetically-induced current (GIC) value provided in Requirement R5 part 5.1 is 75 A or greater per phase, the joint Transmission Owners and/or Generator Owners shall coordinate to ensure that thermal impact assessment for such jointly-owned applicable equipment is performed and documented results are provided to all joint owners for each jointly-owned applicable Bulk Power System power transformer. The thermal impact assessment shall: [Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]<br><br>6.1. Be based on the effective GIC flow information provided in Requirement R5;<br><br>6.2. Document assumptions used in the analysis;<br><br>6.3. Describe suggested actions and supporting analysis to mitigate the impact of GICs, if any; and |

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| | | 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.<br><br>Corresponding revisions for associated measures and VSLs are also recommended.<br><br>3. Implementation times for the first cycle of the standard are uncoordinated. More specifically, Requirement R5 would be effective after 24 months, but compliance therewith requires data from Requirement R4, which is effective after 60 months. The SRC respectfully recommends that these implementation timeframes be revisited and revised.<br><br>4. Table 1 states that Protection Systems may trip due to effects of harmonics and that the analysis shall consider removal of equipment that may be susceptible. Specifically, Table 1 provides: ”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”. However, the GMD Planning Guide at Sections 2.1.4, 4.2 and 4.3, does not discuss how to assess “Misoperation due to harmonics”. The harmonics content would be created by the GIC event, but it is not clear how calculation and evaluation of harmonics load flow or its effects on reactive devices. We recommend the following be added to Table 1: TOs to provide PCs with transmission equipment harmonic current vulnerability data if asked. |

**Response:**

1. Requirements to provide the data for power system modeling and analysis are covered under other standards. The SDT believes these requirements and planning processes are sufficient to perform GMD Vulnerability Assessments and include Generator Owners and Transmission Owners as suggested by the commenter.

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| 2. The SDT considered the proposed wording to Requirement R6 for jointly-owned transformers. As written, the requirement does not preclude coordination among joint owners in conducting a thermal impact assessment. The suggested change was not accepted by the SDT because it weakens the overall requirement and makes responsibility for the required action unclear.<br><br>3. The GIC calculations specified in Requirement R5 can be performed by the planning entity once dc models have been developed in Requirement R2. It is not necessary or correct to make the requirement to provide GIC flow information effective after the requirement to conduct a GMD Vulnerability Assessment becomes effective.<br><br>4. The SDT believes the suggested language for Table 1 is not sufficiently clear on what may be needed by the planner and could result in an unintended requirement being placed on owners. As written, Table 1 provides planning entities with flexibility to apply reasonable engineering judgment to identify protection equipment that may be vulnerable to misoperation in the Benchmark GMD event and therefore, should be outaged in the power flow analysis. Data for power system modeling and analysis are covered under other standards which could be used by the planner to support TPL-007 requirements. | | |
| Electric Reliability Council of Texas | No | 1. The SRC appreciates revisions that have been made to the Standard in response to its comments, but respectfully submits that additional revisions are necessary as discussed below.<br><br>The SRC reiterates the importance of recognizing the source of modeling data, which is generally the applicable Transmission Owner and Generator Owner. This addition is recommended to ensure that the data needed to conduct the studies is provided. The below revisions are proposed:<br><br>R1. Each Planning Coordinator and the Transmission Planners, Transmission Owners, and Generator Owners within its Planning Coordinator Area shall delineate the individual and joint responsibilities of the Planning Coordinator and these entities in the Planning Coordinator's planning area for maintaining models and performing the studies needed to complete GMD Vulnerability Assessment(s). [Violation Risk Factor: Low] [Time Horizon: Long-term Planning] |

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| | | M1. Each Planning Coordinator and the Transmission Planners, Transmission Owners, and Generator Owners within its Planning Coordinator Area shall provide documentation on roles and responsibilities, such as meeting minutes, agreements, and copies of procedures or protocols in effect that identifies that an agreement has been reached on individual and joint responsibilities for maintaining models and performing the studies needed to complete GMD Vulnerability Assessment(s) in accordance with Requirement R1.Corresponding revisions to VSLs are also recommended.<br><br>2. The SRC appreciates the revisions provided in Requirement R6, but recommends that the ability of entities to collaborate and coordinate on the performance of jointly-owned equipment be further clarified. The following revisions are proposed:<br><br>R6. Each Transmission Owner and Generator Owner shall conduct a thermal impact assessment for its solely owned applicable Bulk Electric System power transformers where the maximum effective geomagnetically-induced current (GIC) value provided in Requirement R5 part 5.1 is 75 A per phase or greater. For jointly-owned applicable Bulk Electric System power transformers where the maximum effective geomagnetically-induced current (GIC) value provided in Requirement R5 part 5.1 is 75 A or greater per phase, the joint Transmission Owners and/or Generator Owners shall coordinate to ensure that thermal impact assessment for such jointly-owned applicable equipment is performed and documented results are provided to all joint owners for each jointly-owned applicable Bulk Power System power transformer. The thermal impact assessment shall: [Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]<br><br>6.1. Be based on the effective GIC flow information provided in Requirement R5; |

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| | | 6.2. Document assumptions used in the analysis;<br><br>6.3. Describe suggested actions and supporting analysis to mitigate the impact of GICs, if any; and<br><br>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.<br><br>Corresponding revisions for associated measures and VSLs are also recommended.<br><br>3. Implementation times for the first cycle of the standard are uncoordinated. More specifically, Requirement R5 would be effective after 24 months, but compliance therewith requires data from Requirement R4, which is effective after 60 months. The SRC respectfully recommends that these implementation timeframes be revisited and revised.<br><br>4. Table 1 states that Protection Systems may trip due to effects of harmonics and that the analysis shall consider removal of equipment that may be susceptible. Specifically, Table 1 provides: ”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”. However, the GMD Planning Guide at Sections 2.1.4, 4.2 and 4.3, does not discuss how to assess “Misoperation due to harmonics”. The harmonics content would be created by the GIC event, but it is not clear how calculation and evaluation of harmonics load flow or its effects on reactive devices. We recommend the following be added to Table 1: TOs to provide PCs with transmission equipment harmonic current vulnerability data if asked. |
| 1. Requirements to provide the data for power system modeling and analysis are covered under other standards. The SDT believes these requirements and planning processes are sufficient to perform GMD Vulnerability Assessments, and include Generator Owners and Transmission Owners as suggested by the commenter. | | |

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| 2. The SDT considered the proposed wording to Requirement R6 for jointly-owned transformers. As written, the requirement does not preclude coordination among joint owners in conducting a thermal impact assessment. The suggested change was not accepted by the SDT because it weakens the overall requirement and makes responsibility for the required action unclear.<br><br>3. The GIC calculations specified in Requirement R5 can be performed by the planning entity once dc models have been developed in Requirement R2. It is not necessary or correct to make the requirement to provide GIC flow information effective after the requirement to conduct a GMD Vulnerability Assessment becomes effective.<br><br>4. The SDT believes the suggested language for Table 1 is not sufficiently clear on what may be needed by the planner and could result in an unintended requirement being placed on owners. As written, Table 1 provides planning entities with flexibility to apply reasonable engineering judgment to identify protection equipment that may be vulnerable to misoperation in the Benchmark GMD event and therefore, should be outaged in the power flow analysis. Data for power system modeling and analysis are covered under other standards which could be used by the planner to support TPL-007 requirements. | | |
| Texas Reliability Entity, Inc | No | Comments:<br><br>1. Requirement R3: Texas Reliability Entity, Inc. (Texas RE) requests the SDT consider and respond to the concern that GMD criteria in the proposed standard for steady state voltage performance is different than the steady state voltage performance criteria in other TPL standards or the SOL methodology. GMD events will typically not be transient in nature so adopting the steady state approach is preferable as it would simplify the studies if the voltage criteria between GMD events and other planning events were the same.<br><br>2. Requirement R7: Texas RE intends to vote negative on this proposed standard solely on the basis that we remain unconvinced that the proposed standard meets the intent of FERC Order 779. Paragraph 79 for the following reasons:<br><br>(A) Reliance on the definition of Corrective Action Plans (CAP) in the NERC Glossary in lieu of including language in the requirement appears insufficient to address the FERC statement that a Reliability Standard require owners and |

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| | | operators of the BPS to "develop and implement a plan to protect against instability, uncontrolled separation, or cascading failures of the Bulk-Power System, caused by damage to critical or vulnerable Bulk-Power System equipment, or otherwise, as a result of a benchmark GMD event." While Texas RE agrees that requiring the development of a CAP in Requirement R7 meets part of the FERC directive, R7 falls short as there is no language in the requirement (and therefore the standard) that addresses completion of the CAP. The CAP definition calls for an associated timetable but does not address completion. Coupled with the language in R7.2, that the CAP be reviewed in subsequent GMD Vulnerability Assessments, it is conceivable that a CAP may never get completed as timetables can be revised and extended as long as the deficiency is addressed in future Vulnerability Assessments. Without a completion requirement, a demonstrable reliability risk to the BES may persist in perpetuity. Texas RE recommends the SDT revise Requirement R7.2 as follows: "Be completed prior to the next GMD Vulnerability Assessments unless granted an extension by the Planning Coordinator."<br><br>(B) The language in R7.1 does not appear to adequately address the FERC statement that "Owners and operators of the Bulk-Power System cannot limit their plans to considering operational procedures or enhanced training, but must, subject to the vulnerabilities identified in the assessments, contain strategies for protecting against the potential impact of any benchmark GMD event based on factors such as the age, condition, technical specifications, system configuration, or location of specific equipment." While R7.1 lists examples of actions needed to achieve required System performance, it does not expressly restrict a CAP from only including revision of operating procedures or training. In addition, Table 1 language regarding planned system adjustments such as transmission configuration changes and redispatch of generation, or the reliance on manual load shed, seem to contradict the FERC language regarding the limiting plans to considering operational procedures. Texas RE suggests the revising the language |

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| | | of R7.1 as follows: "Corrective actions shall not be limited to considering operational procedures or enhanced training, but may include:" Alternatively, Texas RE suggests the addition of language to the Application Guidelines for Requirement R7 reinforcing FERC's concern that CAPs "must, subject to the vulnerabilities identified in the assessments, contain strategies for protecting against the potential impact of any benchmark GMD event based on factors such as the age, condition, technical specifications, system configuration, or location of specific equipment."<br><br>3. Compliance Monitoring Process Section: Evidence Retention. Texas RE remains concerned about the evidence retention period of five years for the entire standard.<br><br>(A) Texas RE reiterates the recommendation that the CAP should be retained until it is completed. The SDT responded to Texas RE's first such recommendation with the following response: "The evidence retention period of 5 years supports the compliance program and will provide the necessary information for evaluating compliance with the standard. The SDT does not believe it is necessary to have a different retention period for the CAP because a CAP must be developed for every GMD Vulnerability Assessment where the system does not meet required performance." With a periodic study period of five years, a CAP may extend significantly beyond the five-year window, especially in cases where equipment replacement or retrofit may be required. A retention period of five years could make it difficult to demonstrate compliance and could potentially place a burden on the entity as they will be asked to "provide other evidence to show that it was compliant for the full time period since the last audit." Texas RE recommends the SDT revise the retention language to state responsible entities shall retain evidence on CAPs until completion.<br><br>(B) Texas RE also recommends revising the evidence retention to cover the period of two GMDVAs. The limited evidence retention period has an impact on |

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| | | determination of VSLs, and therefore assessment of penalty. Determining when the responsible entity completed a GMDVA will be difficult to ascertain if evidence of the last GMDVA is not retained. |

**Response:**

1. The SDT provided flexibility to the planning entities to establish steady state voltage performance criteria that may differ from those used in other planning analyses due to the nature of GMD events. A planning entity is not precluded from using the same steady state voltage criteria for GMD Vulnerability Assessments and other planning events.

2(A). The SDT does not agree with the suggested change to requirement R7 that would specify completion requirements for Corrective Action Plans. As written, the standard provides the necessary flexibility for developing viable timelines for mitigation actions which may come in various forms such as operating procedures, hardware mitigation, or equipment upgrades. Although flexible, the proposed standard also holds planning entities accountable for meeting system performance requirements by requiring the CAP to be reviewed in subsequent GMD Vulnerability Assessments. This provides for various mechanisms of accountability to be employed to obtain assurance of implementation. The SDT believes this is an appropriate approach for a planning standard with diverse mitigation options, and that it is the most effective and efficient way to meet the reliability objectives.

2(B). The SDT has revised the rationale box for Requirement R7 to address the concern.

Rationale for Requirement 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.

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| 3. Evidence retention periods were revised as recommended by Texas RE in the third posting. | | |
| Bureau of Reclamation | No | The Bureau of Reclamation does not agree that a Responsible Entity should have the power to obligate Transmission Owners (TOs) or Generator Owners (GOs) to take actions under a Corrective Action Plan (CAP) under R7 unless the TOs and GOs agree to the CAP. A mere requirement to respond to comments is not sufficient to ensure that costs will not outweigh anticipated reliability benefits under a results-based approach. Reclamation continues to believe that R7 should require the affected Transmission Owner and Generator Owner to agree on actions and timeframes in a CAP. |
| **Response:** The SDT did not intend to establish requirements for the implementation of the Corrective Action Plan in this standard because the implementation would be addressed in processes that are outside of the standards process. The standard requires the preparation of a Corrective Action Plan (CAP) for situations where system performance cannot be met during the Benchmark GMD conditions. However, as with other TPL standards, the standard does not address the specific execution of the CAP or obligations of other entities. As written the requirement is clear, results-based, and reflects the correct functional entities per the NERC functional model. The suggested wording to require TO and GO agreement on actions in the CAP would result in a weaker requirement that does not meet NERC guidelines for quality. Nonetheless, the SDT believes that development of the GMD Corrective Action Plan will require a collaborative process outside of this standard. To do otherwise would grant additional authority to the planning entities that was not intended and which they do not possess today. | | |
| Northeast Utilities | No | 1. NU supports NPCC's comments as they relate to the consideration of the impact of Underground Pipe-type cables. NU seeks clarification on if SDT evaluated Solid Dielectric type cables. If not, why.<br><br>2. The proposed standard is written presents the potential for competition conflicts under FERC Order 1000 for Requirement 4.3, 6.4, 7.3. Clarification to this effect should be captured in either the requirements themselves or the application guidelines to mitigate any potential conflicts. |

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| **Response:**<br>1. The SDT maintains that underground pipe-type transmission lines are a necessary component of the dc network and therefore cannot be excluded from the proposed standard. The following has been added to the guidelines and technical basis section for R2:<br>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.<br>Evaluation of specific dc characteristics is modeling issue that should be addressed further in modeling guidance and not as part of the standards development process.<br>2. FERC Order No. 1000 established requirements for transmission cost allocation and transmission planning reforms. Information sharing required by the proposed standard is necessary for reliability and can be accomplished without presenting any market or competition-related concerns. Furthermore, the proposed standard is consistent with Order No. 672. | | |
| Foundation for Resilient Societies | No | Supplemental Comments of the Foundation for Resilient Societies on NERC Standard TPL-007-1Transmission System Planned Performance for Geomagnetic Disturbance Events<br>November 21, 2014<br>The Foundation for Resilient Societies, Inc. [hereinafter “Resilient Societies”] separately files today, November 21, 2014 Group Comments that assert multiple failures, both procedural and substantive, that result in material noncompliance with ANSI Procedural Due Process, and with NERC’s Standard Processes Manual Version 3, effective on June 26, 2013.<br>In this separate Supplemental Comment, Resilient Societies incorporates as its concerns the material in comments on NERC Standard TPL-007-1 submitted by John Kappenman and William Radasky (July 30, 2014); John Kappenman and Curtis |

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| | | Birnbach (October 10, 2014); John Kappenman (2 comments dated November 21, 2014); and EMPrimus (November 21, 2014).<br><br>We reserve the right to utilize all other comments filed in the development of this standard in a Stage 1 Appeal under NERC's Standard Processes Manual Version 3. In particular but not in limitation, we assert that NERC fails to collect and make available to all GMD Task Force participants and to utilize essential relevant data, thereby causing an unscientific, systemically biased benchmark model that will discourage cost-effective hardware protection of the Bulk Power System; that NERC fails to fulfill the obligations under ANSI standards and under the Standard Processes Manual to address and where possible to resolve on their merits criticisms of the NERC Benchmark GMD Event model. Moreover, if the NERC Director of Standards and Standards Department fail to exercise the "quality control" demanded by the Standard Processes Manual, this will also become an appealable error if the standard submitted on October 27 and released on October 29, 2014 becomes the final standard for the NERC ballot body.<br><br>Moreover, an essential element of quality control for NERC standard development and standard promulgation is that the Standard comply with the lawful Order or Orders of the Federal Energy Regulatory Commission. To date, no element of the standard performs the cost-benefit mandate of FERC Order. No. 779.<br><br>Resilient Societies hereby refers the Standards Drafting Team and the NERC Standards Department to the filing today, November 21, 2014 of Item 31 in Maine Public Utilities Commission Docket 2013-00415. This filing is publicly downloadable. Appendix A to this filing of as Draft Report to the Maine PUC on geomagnetic disturbance and EMP mitigation includes an assessment of avoided costs, hence financial benefits of installing neutral ground blocking devices, including a range of several devices (Central Maine Power) to as many as 18 neutral ground blocking, and GIC monitors (EMPrimus Report, November 12, 2014, Appendix A in the Maine PUC filing of November 21, 2014). Cost-benefit analysis |

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| | | could and should be applied on a regional basis, in the NERC model and with criteria for application by NERC registered entities. NERC has failed to fulfill its mandate, with the foreseeable effect of suppressing public awareness of the benefits resulting from blockage of GICs to entry through high voltage transmission lines into the Bulk Power System. Another foreseeable result is economic harm to those companies that have invested capital in the development of GMD hardware protection devices and GIC monitors. We incorporate by reference the materials in Maine PUC Docket 2013-00415, Items 30 and 31, filed and publicly retrievable online in November 2014.<br><br>Finally, we express concern that the combination of NERC Standards in Phase 1 and in Phase 2, providing no mandatory GIC monitor installations and data sharing with Regional Coordinators, and with state and federal operations centers, effectively precludes time-urgent mitigation during severe solar storms despite timely reports to the White House Situation Room.<br><br>NERC has effectively created insuperable barriers to fulfill the purposes of FERC Order No. 779. Without significant improvements that encourage situational awareness by Generator Operators and near-real-time data to mitigate the impacts of solar geomagnetic storms, the only extra high voltage transformers that can be reliably protected will be those with installed hardware protection. Yet this defective standard will provide false reassurance that no hardware protection is required. Also, the scientifically defective NERC model may also preclude regional cost recoveries for protective equipment, by falsely claiming that no protective equipment is required under the assessment methodologies in the standard.<br><br>Hence irreparable harm to the reliability of the Bulk Power System, and to the residents of North America, is a foreseeable result of the process and substantive result of this standard.<br><br>Respectfully submitted by: |

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| | | Submitted by:<br><br>Thomas S. Popik<br>Chairman<br>Foundation for Resilient Societies<br><br>William R. Harris<br>International Lawyer<br><br>Secretary, Foundation for Resilient Societies |

**Response:** Thank you for your comments and for your continued participation in the standards development process. The SDT has reviewed your comments.

1. NERC and the Standards Drafting Team have followed the NERC Standards Process Manual, which is approved by ANSI, throughout the development of TPL-007. The drafting team has made a good faith effort to resolve all objections to the proposed standard and responded in writing to submitted comments. For these reasons, no procedural failures have occurred in the development of TPL-007.

2. Thank you for bringing attention to the draft report in Maine PUC docket 2013-00415. The SDT solicited stakeholder comments on cost considerations and has proposed a standard that provides performance requirements but is not prescriptive on mitigation strategies or technologies. This SDT believes this approach, which is consistent with other planning standards, is the most cost effective means to accomplish the reliability objectives and is technology-neutral. Further, this approach complies with Order No. 779. Paragraph 28 states: "We expect that NERC and industry will consider the costs and benefits of particular mitigation measures as NERC develops the technically-justified Second Stage GMD Reliability Standards." NERC and the industry have considered the costs and benefits associated with TPL-007-1. Order No. 779 does not include a "cost-benefit mandate." Indeed, the Commission disagreed that section 215 of the FPA requires a particular cost-benefit showing.

3. The approved Stage 1 standard, EOP-010-1, addresses operating plans, processes, and procedures for mitigation of GMD events. Proposed standard TPL-007 requires entities to develop mitigation plans to address identified impacts from the benchmark GMD event but does not impose prescriptive mitigation strategies. The SDT's approach allows applicable entities to decide how to mitigate

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| GMD vulnerabilities on their systems. GIC monitoring may be a component of an entities mitigation plan as discussed in technical supporting material including the GMD TF GMD Planning Guide and the 2012 GMD Report. | | |
| Iberdrola USA | Yes | The NERC drafting committee has done an excellent job creating the TPL-007-1 standard.  Iberdrola USA has two areas that we are requesting further explanation on.<br><br>1. Please provide additional clarity on the amount devices removed from service as part of Table 1.  A whitepaper or footnote on identification, number of devices and design considerations would be helpful.  For example, consideration of Wye grounded capacitor banks with electromechanical relays vs. microprocessor controlled/protected ungrounded capacitor banks and they amount to remove.<br><br>2.  The development of Corrective Action Plans has the same date as the completion of the GMD assessment.  It would be helpful to lay out when the facilities/equipment identified in CAPs would need to be in-service.  It is impossible to have a CAP that needs facility installations to be completed at the same time as an assessment has just identified the issues. |
| **Response:**<br><br>1. The SDT has reviewed your comment and does not believe that a footnote or additional white paper are appropriate. As written, the standard provides flexibility for planners to apply engineering judgment and is appropriately supported by technical resources including the NERC GMD TF GMD Planning Guide (section 4.2 and 4.3) and the 2012 GMD Interim Report (Section 6.4). A prescriptive tool or method as suggested by the commenter would not be effective in application to all planning entities.<br><br>2. The proposed standard does not specify a completion date for corrective actions because there may be a variety of factors for a planning entity to consider in evaluating the various mitigation strategies. The planning entity has flexibility to include an appropriate timeline in the Corrective Action Plan. | | |
| OG&E | Yes | The changes in the Standard to date are a significant improvement over the prior versions.  That being said, the Standard still places a substantial burden on |

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| | | Transmission Planners whose operating areas are not located in areas that, due to latitude and soil types, are not generally considered vulnerable to GMD. There should be some screening criteria for GMD vulnerability that would not require burdensome iterative studies for TPs whose facilities are not located in geographical areas not generally considered impacted by GMD events. |
| **Response:** The SDT does not have sufficient data to be able to propose an exemption from the requirements of the standard to any portion of the North American transmission system. | | |
| Duke Energy | Yes | Duke Energy suggests adding the following provision in the rationale box of R5 that is in the rationale box of R6: "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." |
| **Response:** The SDT has reviewed the comment and will modify the Rationale for Requirement R5 as follows:<br><br>Rationale for Requirement R5:<br>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.<br><br>The maximum effective GIC value provided in Part 5.1 is used for transformer thermal impact assessment.<br><br>GIC(t) provided in Part 5.2 ~~is~~ 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:<br>http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-DisturbanceMitigation.aspx | | |

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| 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.<br><br>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. | | |
| SERC PSS | Yes | While we agree with the changes made to the draft standard, we still believe that the magnitude of the benchmark GMD event is too great. We also remain concerned with respect to the amount of resources which will be needed to complete the necessary modeling and assessment work. The comments expressed herein represent a consensus of the views of the above-named members of the SERC EC Planning Standards Subcommittee only and should not be construed as the position of SERC Reliability Corporation, its board, or its officers. |
| **Response:** The SDT responds that the Benchmark GMD event was established based on a statistical analysis of actual magnetometer readings over a span of 20 years. Due to the potential wide-area impact of GMD events, the SDT believes a 100-year scenario is an appropriate benchmark. | | |
| Bonneville Power Administration | Yes | 1. BPA requests that R4.3 be clarified. Completion of the vulnerability assessment starts the 90 day clock for distribution of the results to adjacents. If another functional entity (not an RC, adjacent PC or TP) submits a written request for the results, say 100 days after completion, is the responsible entity at risk of a compliance violation because they were unable to provide the assessment within the 90 day required time frame? BPA suggests the 90 calendar day requirement be bifurcated from the requirement to respond to a written request from a functional entity.<br><br>2. Proposed revisions: |

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| | | R5. Each 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]<br><br>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.<br><br>5.2. The GIC flow information shall also include the effective GIC time series, GIC(t), (calculated using the benchmark GMD event described in Attachment 1), in response to a written request from any Transmission Owner and Generator Owner with applicable facilities in the planning area. The GIC(t) shall be provided within 90 calendar days of receipt of the written request. 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.<br><br>BPA requests the above clarifying changes be made to R5 and parts 5.1 and 5.2. We believe the changes clarify the required actions in R5 and parts 5.1 and 5.2 without compromising SDT intent.<br><br>R5 - “Applicable facilities” are defined in section 4.2 of the standard so the struck sentence seems redundant and confusing.<br><br>5.1 - Please strike second sentence as TO, GO and applicable facilities are already called out in the actual requirement (R5). |

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| | | 5.2 - Since the 90 day clock begins ticking after determination of the maximum effective GIC value in 5.1, changes requested reflect this.<br><br>3 - BPA is concerned that, under extreme conditions, R7 may require entities to implement Corrective Action Plans that require shutting down or islanding their transmission systems, in order to meet the performance requirements of Table 1.<br><br>4 - BPA also suggests adding a comma to R 7.1, third bullet, following the word, "Procedures."<br><br>5 - Table 1 - Steady State Planning Events under the Event column indicates that facilities removed as a result of protection system operation or misoperation due to harmonics during GMD event need to be modeled. There seem to be three options to perform the required assessment: 1. Perform harmonic studies to justify not taking the var devices outage analysis or 2. Replace all mechanical relays with microprocessor relays that have the capability to block harmonics or 3. Remove all SVCs or shunt caps and perform the assessment. BPA believes Option 1 is not practical for the Transmission Planner to perform harmonic analysis for the entire system due to lack of tools and expertise. Option 2 is an expensive solution for a one in a hundred year event. Utilities do not build for extreme contingencies such as a one in ten probability event. Removing all reactive devices under Option 3 defeats the purpose of installing these reactive devices. BPA suggests that this low probability extreme GMD event be evaluated under normal system conditions, not under system contingency events.<br><br>6 - Additionally, the SDT provided this response to BPA's comment during the last period: "The SDT agrees with comments on the limitations of commercial tools. TPL-007 requirements can be met with existing tools and techniques." BPA requests the GMD taskforce provide any existing tool(s), such as a spreadsheet calculator, with the functionality to evaluate the thermal, reactive, or harmonic, impact of GIC on a transformer and identify the tool(s) required to perform harmonics analysis of reactive elements such as shunt capacitors and SVCs. These |

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| | | study tools are described as available, but it is not clear what they actually are and BPA would like to be certain that any assessments done are done so in a constant manor by all infrastructure owners that that this standard applies to. |
| **Response:**<br>1. The SDT has reviewed the comment regarding R4.3 and believes that the requirement as written is clear. The comment refers to requests that are outside the 90 day period. Such requests should be easy to fulfill, given that the analysis would have already been complete.<br>2. The SDT is averse to making the change to R5 because it would change the intent of the SDT. While non-BES transformers are to be included in the modeling and GIC calculation, the intent is to have the network analysis and potential mitigation only apply to BES transformers. Therefore, using the Applicable Facilities definition would change the SDT intent.<br>Regarding the suggested changes to 5.1 and 5.2, the SDT added the second sentence in 5.1 based on previous comments to provide additional clarity. The suggested comment to 5.2 is addressed in the Rationale for Requirement R5.<br>3. The CAP developed under R7 must address how the performance requirements of Table 1 will be met. A CAP that requires shutting down or islanding the transmission system would not meet the requirements of Table 1.<br>4. Regarding the suggested edit to 7.1, we will implement that suggestion.<br>5. Replacement of all protective relays or outaging all relays in the power flow case are extreme reactions to the uncertainty associated with harmonics. The SDT believes that some reasonable engineering judgment can be exercised by protection engineers to identify protection equipment that may be vulnerable to misoperation in the Benchmark GMD event and therefore, should be outaged in the power flow analysis. Loss of reactive compensation that has a high likelihood of tripping due to harmonics is an event that must be evaluated as part of the GMD Vulnerability Assessment because it is a known risk from GMD.<br>6. The SDT acknowledges the tools to perform detailed harmonics analysis are not in wide availability in the industry. As written, the standard provides flexibility for planners to apply engineering judgment and is appropriately supported by technical resources including the NERC GMD TF GMD Planning Guide (section 4.2 and 4.3) and the 2012 Interim Report (section 6.4). | | |
| Manitoba Hydro | Yes | On the whole, changes made to TPL-007-1 were errata with the exception of the thermal assessment screening criteria. The suggested changes are acceptable. In |

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| | | previous comment forms, the SDT proposed the following question, which was missing in this comment form. Manitoba Hydro believes there still are outstanding issues needing to be addressed. Manitoba Hydro has two main concerns with the proposed standard that prevent it from voting affirmative:<br><br>1. Thermal Assessments not tied back to GMD Vulnerability Assessment - The SDT has explained in the rationale to R6 the fact that issues identified in the thermal impact assessment should be included in the GMD vulnerability assessment and corrective action plan, however, there needs to be corresponding language in the requirements to make this action occur. This approach is important because the Planning Coordinator is in the best position to take a wide area view to determine if the suggested actions by the TO/GO are appropriate to add to the Corrective Action Plan or whether other actions should be taken. Suggested changes:<br><br>- Requirement R6.4: Remove "performed and" from this requirement as it is redundant. Requirement R6 already requires the TO and GO to conduct the assessment.- Add a new requirement R4.4: "The study or studies shall include the results from the thermal impact assessment performed in Requirement R6 and determine whether the System meets the performance requirements in Table 1." Transformers that have been determined to be vulnerable should be tripped as part of the Event in table to determine ability to meet performance requirements. If performance is not met, the PC should determine the appropriate Corrective Action Plan, which includes investigating any of the TO/GO's suggested actions from the thermal impact assessment.<br><br>- Revise the Event description in Table to: "Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation or Misoperation due to harmonics or thermal overload during the GMD event." This clarifies the intent of the SDT to ensure that event includes |

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| | | simultaneous loss of all devices including those identified in the thermal assessment.<br><br>2. Lack of Harmonic Analysis Tools may make the Event in Table 1 too severe - At present, there are no harmonic analysis tools that are capable of efficiently modeling the Planning Coordinator area to determine the impacts of harmonics on Protection Systems and other Transmission Facilities (eg. HVdc converters). These tools may develop over the five-year implementation period of the GMD standard, however there are no guarantees. In the absence of harmonic analysis, the SDT wants the Event in Table 1 to include simultaneous loss of all Reactive Power compensation devices and other Transmission Facilities. This is potentially too severe an event to develop a Corrective Action Plan for. Manitoba Hydro is willing to include the analysis of such an event but would recommend that it be a categorized as an extreme event (as per TPL-001-4). If Cascading occurs, then an evaluation of possible actions designed to reduce the likelihood or mitigate the consequences of the event shall be conducted. The event in Table 1 should be modified to possibly two (credible event and an extreme event) or a note could be added to the event such as: - Note 4: In the absence of a harmonic assessment, complete simultaneous loss of all Reactive Power compensation and other Transmission Facilities is considered an extreme event and If Cascading occurs, then an evaluation of possible actions designed to reduce the likelihood or mitigate the consequences of the event shall be conducted. At minimum, loss of all Reactive Power compensation and other Transmission Facilities vulnerable to Protection System operation or Misoperation within a single substation shall be removed during the GMD event plus any transformers determined to be overloaded in a thermal impact assessment. |
| **Response:**<br><br>1. The SDT does not support adding prescriptive language to the standard for how the thermal assessment results are incorporated into the GMD VA and believes the rationale box is sufficient. The entity responsible for performing a GMD VA must consider the | | |

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| information provided in Requirement R6. A GMD VA is defined as: *Documented evaluation of potential susceptibility to voltage collapse, Cascading, or localized damage of equipment due to geomagnetic disturbances.* The following is part of the rationale box for R6:<br>*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.*<br>2. Regarding the comments on harmonics analysis, the SDT acknowledges the tools to perform detailed harmonics analysis are not in wide availability in the industry. However, replacement of all protective relays or outaging all relays in the power flow case are extreme reactions to the uncertainty associated with harmonics. The SDT believes that reasonable engineering judgment can be exercised to identify protection equipment that may be vulnerable to misoperation in the Benchmark GMD event and therefore, should be outaged in the power flow analysis. | | |
| American Electric Power | Yes | It is unclear from the current wording whether the 24 month timing of completion of R6 begins with a) the receipt of the information in R5.1 or b) the receipt of information requested under R5.2. AEP recommends the SDT clarify within the standard. |
| **Response:** The SDT has clarified that the 24-month timeline for R6 is based on receipt of GIC information provided in Requirement R5 part 5.1. See summary consideration for the revised language. | | |
| Public Service Enterprise Group | Yes | It would be helpful to understand whether the GMD Vulnerability Assessment will be factored into such items as generation interconnection requests or transmission expansion planning, and if so, how it will be incorporated. In other words, will a GMD Vulnerablity Assessment be added to traditional planning studies (i.e., load flow, dynamic, and short circuit)? Also, is additional GMD-related modelling data expected to be requested from assest owners? For example, transformer thermal capabilities, grounding resistance, transformer type (shell/core) are not requested presently. |

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| **Response:** The SDT does not have additional insights into the potential uses of the GMD VA. Planning entities may need to obtain GMD-related modeling information such as resistances for dc network model. | | |
| Ameren | Yes | While we agree with most of the changes made to the draft standard, we still believe that the magnitude of the benchmark GMD event is too great. In addition, we also remain concerned about the amount of resources, which will be needed to complete the necessary modeling and assessment work. |
| **Response:** The SDT responds that the Benchmark GMD event was established based on a statistical analysis of actual magnetometer readings over a span 20 years. Due to the potential wide-area impact of GMD events, the SDT believes a 100-year scenario is an appropriate benchmark. The SDT appreciates industry input throughout the standard development process to reach the right balance of resources to meet the reliability objectives of TPL-007. | | |
| Tacoma Power | Yes | Tacoma Power appreciates the opportunity to comment and had the following comments regarding VSLs for the standard. The implementation for R5 allows 24 months to implement, and 90 days to respond to a request, but the difference between a lower and medium VSL is only 10 days. We suggest using the same grading as in MOD027-1 of 90, 180, and 270 days. Requirement R6 allows 24 months to complete the study, but the difference between a lower and medium VSL is just 2 months. We suggest using the same grading as in MOD-030 of 3,6, and 9 months. |
| **Response:** The SDT does not agree with the proposed VSL changes. Timely completion of Requirements R5 and R6 are necessary for executing the GMD Vulnerability Assessments within a 60-month period. The VSLs in the proposed standard are consistent with other standards. | | |
| Seminole Electric Cooperative, Inc | | 1. Seminole requests the drafting team explain in more detail why the resistivity values were calculated via geometric mean calculation as opposed to arithmetic mean calculation if you are just dealing with one category of values (i.e. with the same units) for the Florida peninsula? Seminole cannot determine from the |

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| | | short write-up provided by USGS via the drafting team shortly before ballot closing what all of the factors are that went into some of the resistivity mean calculations, e.g., are the factors just resistivity values or was layer thickness included.<br><br>2. Seminole requests more data on how the interim layer for layers 1 and 2 was calculated. The short write-up provided by USGS via the drafting team shortly before ballot closing does not appear to include this information.<br><br>3. Seminole requests the drafting team provide a Florida ground model illustration that includes the naming of the layers akin to what USGS has posted for other regions. It appears that layer four is the upper mantle, but it is unclear what are the other layers.<br><br>4. Seminole reiterates its request that the drafting team perform a CEAP for this Standard.<br><br>5. Seminole requests the drafting team post this Standard for a full additional comment period of 45 days. The full time period is needed, especially for Florida, as the Florida beta factor was revised by the drafting team from 0.94 to 0.74. In addition, the amps per phase amount cited in Requirement R5 was revised from 15 A to 75 A. Such major revisions reflect the need for additional review by the drafting team and balloting members.<br><br>6. Seminole has concern on whether the drafting team followed the NERC Standard Drafting Procedure by not providing the Florida ground model information at the time of balloting as stated in the proposed Standard. The Florida ground model information was not distributed until approximately ten (10) days after posting via a webinar, which left Florida utilities approximately 15 days to review and comment. Seminole believes that all information that the Standard depends on needs to be posted at the time of ballot in order to meet the ANSI Standards which NERC is attempting to emulate along with the NERC |

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| | | Standard Drafting Process. A review of USGS Regional Conductivity Maps webpage, linked to in the Standard, shows that on November 14, 2014 that Florida's data has still not been posted on the website.<br><br>7. Seminole proposed that NERC include the opportunity for "regions" to "test outâ€? the TPL-007-1. By that, Seminole means that certain "regions" would perform the initial analyses for TPL-007-1 and if none of the transformers within a "region" had GIC values above 75 A/phase in accordance with Requirement R5, then entities would not need to perform studies again for those transformers in that "region" until NERC/FERC developed reasons why the circumstances have changed and a study needs to be performed again, i.e., no requirement to perform the study every 5-years unless circumstances have changed. As far as what a "region" constitutes, Seminole suggests that a "region" be defined as a NERC Region, e.g., FRCC, TRE, SPP RE, etc. |

**Response:**

1-3. These comments have been referred to USGS individuals who are qualified to address them. A technical basis for the Florida ground model description was provided by USGS and cited available information and reports. The standard allows entities to use justified alternative ground models in GMD Vulnerability Assessments, which provides a means for entities to obtain more refined or exact models for their specific location.

4. The SDT is aware of several preliminary studies that have been performed by various entities in the North American system that basically carry out the calculations contemplated by the standard. Those studies underscore the difficulty of performing a detailed cost/benefit analysis in that the mitigation strategies for potentially vulnerable facilities are not immediately evident and require additional iterative studies. Relative to the benefits of GMD mitigation, it is equally difficult to project the scope (and costs) of a voltage collapse and blackout without the detailed studies that will be required by the standard. The SDT suggests that a cost/benefit analysis will only become meaningful once the standard has been in place and entities are conducting GMD Vulnerability Assessments.

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| 5. NERC, the SDT, and Standards Committee (SC) liaison obtained SC authorization for shortened comment period to meet a regulatory deadline after providing notification to stakeholders as required by the Standards Process Manual.<br>6. TPL-007 has been developed in accordance with NERC Standards Process Manual. The SDT reiterates that the beta scaling factor is a default based on publicly available information. The standard allows entities to use justified alternative ground models in GMD Vulnerability Assessments.<br>7. System changes that are best understood by the planner may affect GMD Vulnerability Assessment results. The proposed standard is consistent with other standards in requiring periodic reevaluation. Additionally, the 75A per phase criterion applies to transformer thermal impacts but does not indicate immunity to potential system voltage or harmonic impacts. | | |
| SPP Standards Review Group | | We have a concern about clarity for Requirement R3 in reference to Table 1. In the actual requirement, it mentions having criteria for acceptable System steady state voltage performance in reference to the benchmark GMD event described in Attachment 1. However in the Rationale Box, we're not sure what's the signifigance of Table 1. Also, you mention in the Rationale Box for Requirment R4 (the last sentence) "Performance criteria are specified in Table 1". We ask the drafting team to provide more detail and clarity on the impact of Table 1 on the development of performance criteria in the Rationale Boxes for Requirements R3 and R4. |
| **Response:** Requirement R3 specifies that the designated planning entity will establish steady state voltage performance criteria for GMD planning. Table 1 provides details on the GMD planning event. The performance criteria and planning event are components of the GMD Vulnerability Assessment specified in Requirement R4. | | |
| Seattle City Light | Yes | Seattle City Light appreciates the efforts of the Drafting Team to include language supporting regional-scale studies, which will be essential to achieving a sound understanding of GMD effects in WECC. |
| Ingleside Cogeneration LP | Yes | As with many other respondents to the previous draft of TPL-007-1, ICLP is trusting that Compliance Enforcement Authorities will apply reasonable |

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| | | consideration of the state of scientific understanding of the GMD phenomena during audits. Even though the requirements are written in a zero-tolerance fashion, it is our understanding that FERC recognizes that performance expectations will evolve as our cumulative experience grows over time. It would be inappropriate for CEAs to assess penalties for action or non-action that no Registered Entity could possibly anticipate. We are willing to proceed based upon our perception that the ERO will implement this Standard in a fair and even-handed way - but suggest that it may not be easy to keep that reputation if trust is violated. |
| **Response:** The SDT agrees with the comment and trusts that compliance will understand the "state of the art" regarding the ability to perform these analyses. | | |
| John Kappenman, Storm Analysis Consultants<br>and<br>Curtis Birnbach, Advanced Fusion Systems | | Comments Regarding NERC Draft Standard on GIC Observations and NERC Geo-Electric Field Modelling Inaccuracies<br>(appended to this report) |
| **Response:** The commenters use the terms/concepts of models and input data interchangeably. The commenters assert that the models used by the SDT are flawed and consistently under predict the geoelectric field. This is simply not the case. The models and simulation techniques used to develop the benchmark GMD event are known throughout the scientific community as being state-of-the-art. The input data (e.g., earth models) that were used in the analysis represent the best available in the public domain. The models, methodology and input data that were used to develop the benchmark event have been detailed in numerous white papers and electronic data files and have been made available to the public. However, the details of the models and input data used to develop the response by the commenters have not been described or made available to the SDT for review; thus, limiting the ability of the SDT to perform an independent review of the commenter's simulation results and analysis. | | |

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| The commenters suggest that the way to overcome the perceived modeling errors is to examine GIC data that are available throughout the United States and Canada. As noted previously, the simulation methods used by the SDT are not in error; however, without local geomagnetic field measurements, exact information on the power system at the exact time of the measurements, and consistent data acquisition rates, GIC measurements alone cannot provide any usable information regarding the accuracy of models, simulation methods or input data that are used to perform GMD vulnerability assessments or to develop severe GMD event scenarios. See previous comment response regarding the detailed information that is required to perform validation of models and input data. | | |
| Representative Andrea Boland<br><br>Sanford, Maine | | Supplemental Comment (appended to this report) |
| **Response:** Thank you for participating in the standards development process and sharing your insights. | | |
| Gale Nordling,<br><br>EMPrimus | | NERC Geomagnetic and Geoelectric Field Benchmark Model and Recommendations (appended to this report) |
| **Response:**<br><br>1. Thank you for your continued participation in the standards development process. The SDT has responded to prior comments.<br><br>2A. The SDT revised the thermal screening criterion from 15 A per phase to 75 A per phase after conducting extensive simulation of the benchmark GMD event on the most conservative thermal models known to date. The revision was also based on input from transformer manufacturer and industry SMEs. The justification is documented in the thermal screening criterion white paper.<br>2B. The 75 A per phase criterion in Requirement R6 applies to transformer thermal impact assessment only.<br><br>3. The commenter's suggestion that the scaling factors do not agree by a factor of 22 with geoelectric fields in a cited paper is incorrect. Equation (2) from TPL-007 attachment 1 specifies a lower bound on the scaling factor. This lower bound scaling factor was not applied in the commenter's calculation resulting in a lower value for geoelectric field.<br><br>4. TPL-007 addresses impacts to the Bulk-Power System from GMD-related harmonics, which conforms to the scope of the standard as established in the Standard Authorization Request and FERC Order No. 779 (P. 2). Table 1 defines the planning event to include | | |

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| "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". | | |
| South Carolina Electric & Gas | Yes | |
| Oncor Electric Delivery LLC | Yes | |
| South Carolina Electric & Gas | Yes | |
| Exelon and its Affiliates | Yes | |
| American Transmission Company | Yes | |
| Pepco Holdings Inc. | Yes | |
| Idaho Power Company | Yes | |
| PacifiCorp | | See response to #1. |

**END OF REPORT**

## Mark Olson

**From:** Gale Nordling <gnordling@emprimus.com>
**Sent:** Thursday, November 20, 2014 3:36 PM
**To:** Mark Olson; Mark Lauby; Thomas Burgess; Mark Rossi; John Moura
**Subject:** NERC Geomagnetic and Geoelectric Field Benchmark Model and Recommendations
**Attachments:** Chinese paper on GIC Curents Liu et al 2014.pdf; GMD Correlated Equipment Insurance Claims.pdf; PESGM2013-000013_Generators.pdf; NERC Formula Compared to China Data rev 1.xlsx

New studies and papers bring significant clarity and information relevant to the proposed NERC GMD standards. Please accept the following comments for additional changes to NERC GMD Benchmark Model as recently revised:

1. We renew all previous comments and objections.

2. Changing transformer thermal screening criteria to 75 amps/phase from 15 amps/phase would not meet industry best practices for grid operation because:
   a. Some transformers have a GIC rating under 75 amps/phase
   b. The standard would suggest there is little or no damage to electrical equipment until you reach 75 amps/phase of GIC. The Luis Marti paper attached suggests rotor damage due to harmonics when GIC reaches levels of 50 or more amps/phase.

3. The NERC Benchmark formula modified further for latitude and soil does not give results that are anywhere near actual data. In fact a calculation that we have made (see attached Excel spreadsheet) for actual data recorded in China (see attached Chinese paper) would suggest the NERC Benchmark formula understates the actual geoelectric field by a <u>factor</u> of 22 (not 22%). For the Benchmark Model to be used to determine grid reliability and mitigation for public health and safety (and national security), the Benchmark Model must be consistent with actual data.

4. The Benchmark Model does very little to address harmonics and damage to both customer equipment and to utility equipment. Attached is a recent study done by Lockheed Martin, Zurich and NOAA in which claims for damage to customers were correlated to GMD events during the period of 2000-2010. The study shows in excess of $2 Billion of damage per year in the US due to low level solar storms (due to harmonics). The solar storms for this period are nowhere near in size to either the Carrington event or even the 1989 Quebec solar event. This would suggest that utilities on a regular year to year basis are in violation of IEEE 519 for both FERC approved wholesale contracts and for power delivered to customers. Customers on the distribution side are being damaged every year by harmonics. The NERC proposed standards don't address this virtually at all, and don't deal with either the ordinary year to year solar storms or the severe solar superstorms on the damage to customers and the violations of IEEE 519. This new study also found little or no difference in damage due to latitude which would suggest the NERC standard is wrong on latitude adjustments as well. Latitude adjustments must also be justified by actual data. This new study also changes the issue of harmonics from a low frequency (ie one in 50 or 100 year event) to an every year event which must be addressed for all levels of solar storm.

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RESEARCH ARTICLE OPEN ACCESS

# Observations and modeling of GIC in the Chinese large-scale high-voltage power networks

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**ABSTRACT**

During geomagnetic storms, the geomagnetically induced currents (GIC) cause bias fluxes in transformers, resulting in half-cycle saturation. Severely distorted exciting currents, which contain significant amounts of harmonics, threaten the safe operation of equipment and even the whole power system. In this paper, we compare GIC data measured in transformer neutrals and magnetic recordings in China, and show that the GIC amplitudes can be quite large even in mid-low latitude areas. The GIC in the Chinese Northwest 750 kV Power Grid are modeled based on the plane wave assumption. The results show that GIC flowing in some transformers exceed 30 A/phase during strong geomagnetic storms. GIC are thus not only a high-latitude problem but networks in middle and low latitudes can be impacted as well, which needs careful attention.

**Key words.** electric circuit – geomagnetically induced currents (GIC) – modelling – engineering – space weather

## 1. Introduction

During strong space weather storms, which are caused by the activity of the Sun, the Earth's magnetic field is intensely disturbed by the space current system in the magnetosphere and ionosphere. The electric fields induced by time variations of the geomagnetic field drive geomagnetically induced currents (GIC) in electric power transmission networks. The frequencies of GIC are in the range of 0.0001 ~ 0.1 Hz. Such quasi-DC currents cause bias fluxes in transformers, which result in half-cycle saturation due to the nonlinear response of the core material (e.g., Kappenman & Albertson 1990; Molinski 2002; Kappenman 2007). The sharply increased magnetizing current with serious waveform distortion may lead to temperature rise and vibration in transformers, reactive power fluctuations, voltage sag, protection relay malfunction, and possibly even a collapse of the whole power system (e.g., Kappenman 1996; Bolduc 2002).

Large GIC are usually considered to occur at high latitudes such as North America and Scandinavia, where tripping problems and even blackouts of power systems due to GIC have been experienced (Bolduc 2002; Pulkkinen et al. 2005; Wik et al. 2009). Large currents in transformer neutrals have been monitored in the Chinese high-voltage power system many times during geomagnetic storms although China is a mid-low-latitude country. At the same time, transformers have had abnormal noise and vibration. Those events have been shown to be caused by GIC based on analyses of simultaneous magnetic data and GIC recordings (Liu & Xie 2005; Liu et al. 2009a). The power grids are using higher voltages, longer transmission distances, and larger capacity with the developing economy in China. So, the risk that the power systems would suffer from GIC problems may obviously increase. The Chinese Northwest 750 kV power grid has long transmission lines with small resistances making it prone to large GIC during geomagnetic storms. Thus it is important to model GIC particularly in that network.

## 2. GIC observations in Chinese high-voltage power grid

We acquire GIC data through the neutral point of the transformer at the Ling'ao nuclear power plant (22.6° N, 114.6° E) in the Guangdong Province. Besides, geomagnetic field data are collected from the Zhaoqing Geomagnetic Observatory (23.1° N, 112.3° E) which is not very far from Ling'ao. Figure1 shows the neutral point current (top panel), the horizontal component of the geomagnetic field (bottom panel), and its variation rate (middle panel) during the magnetic storms on 7–8 (a) and 9–10 (b) November 2004. The occurrence times of the current peaks match with those of the geomagnetic field variation rate. It is confirmed that there is no HVDC (high-voltage direct current) monopole operation during that time. So it is reasonable to believe that the currents are really GIC induced by geomagnetic storms. The maximum value of GIC is up to 75.5 A/3 phases, which is much higher than the DC bias caused by monopole operation of HVDC.

## 3. Modeling GIC in power grids

The modeling of GIC in a power grid can be divided into two steps (e.g., Pirjola 2000): step 1, calculating the geoelectric field induced by a magnetic storm; step 2, calculating the GIC in the power grid. The effect of the induced geoelectric field is equivalent to voltage sources in the transmission lines, which enables converting the GIC calculation into a circuit problem in step 2.

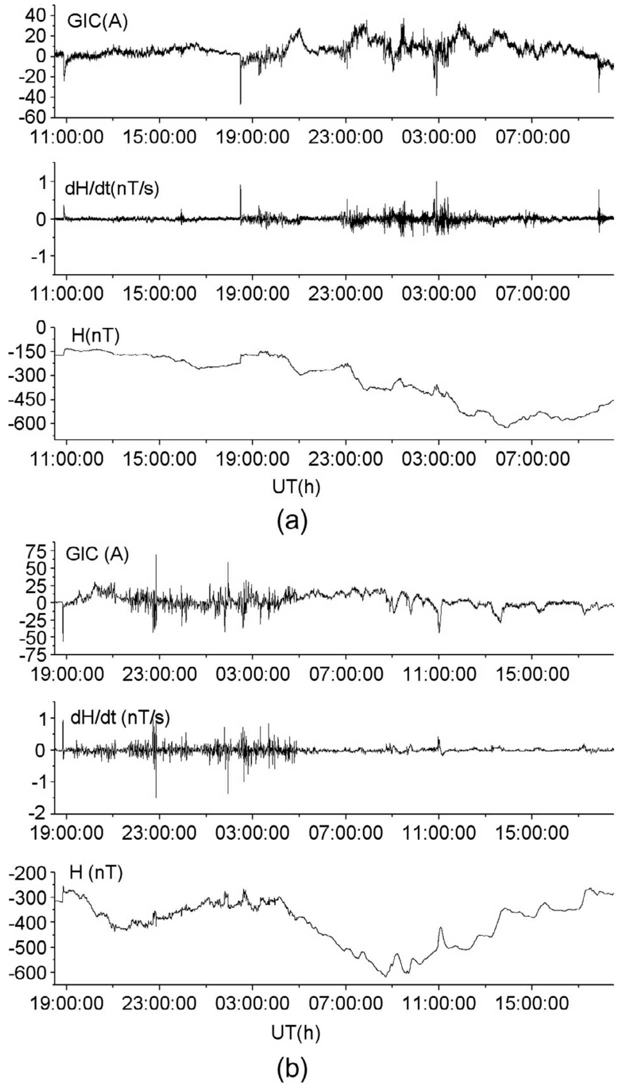


**Fig. 1.** GIC data at the Ling'ao nuclear power plant on 7–8 (a) and 9–10 (b) November 2004. The horizontal component of the geomagnetic field and its variation rate are also shown based on data from the Zhaoqing Geomagnetic Observatory.

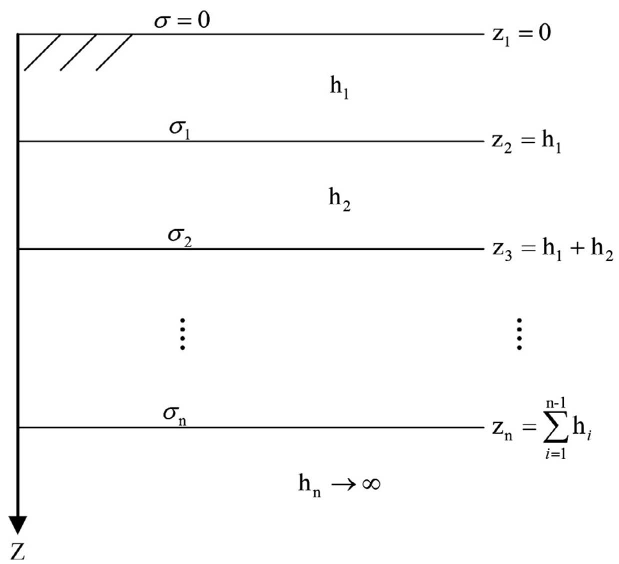


**Fig. 2.** Layered Earth model for calculating the induced geoelectric field.

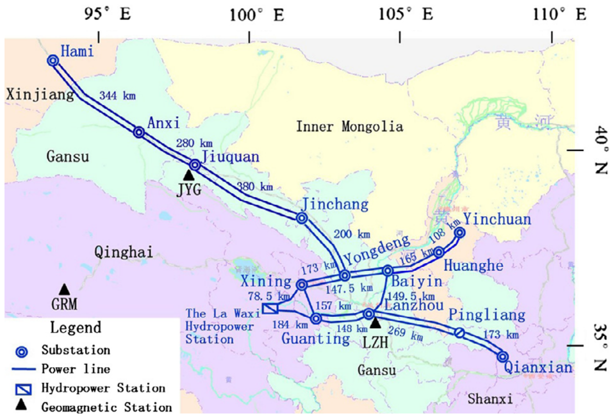


**Fig. 3.** Chinese Northwest 750 kV power grid. Three geomagnetic observatories (GRM, LZH, and JYG) are also shown on the map. (The WMQ observatory is not located in the area of this map.)

**Table 1.** Locations of geomagnetic observatories in the area of the Chinese Northwest 750 kV power grid.

| Name | Longitude (°E) | Latitude (°N) |
|---|---|---|
| WMQ | 87.7 | 43.8 |
| GRM | 94.9 | 36.4 |
| LZH | 103.8 | 36.1 |
| JYG | 98.2 | 39.8 |

### 3.1. Calculating the electric field using a layered earth model

We use the standard conventional Cartesian geomagnetic coordinate system in which the $x$, $y$ and $z$ axes point northwards, eastwards, and downwards, respectively. According to the plane wave assumption (e.g., Boteler 1999), the relation between perpendicular horizontal components of the geoelectric ($E$) and geomagnetic ($B$) fields at the earth's surface can be expressed as

$$E_x(\omega) = \frac{1}{\mu_0} B_y(\omega) Z(\omega), \tag{1}$$

$$E_y(\omega) = -\frac{1}{\mu_0} B_x(\omega) Z(\omega), \tag{2}$$

where $\mu_0$ is the vacuum permeability and $Z$ is surface impedance of the earth which depends on the conductivity structure of the earth and on the angular frequency $\omega$.

In a previous study about GIC in China, Liu et al. (2009b) used a uniform half-space model for the earth. However, one-dimensional layered earth models are more accurate descriptions for the real situations. Figure 2 shows a layered earth model which contains $n$ layers with conductivities $\sigma_1$, $\sigma_2$, …, $\sigma_n$ and thicknesses $h_1$, $h_2$, …, $h_n \to \infty$.

The thickness of the bottom layer is $h_n \to \infty$, and $E_x = 0$ and $B_y = 0$ when $z \to \infty$. Hence the impedance at the top of the layer of the $n$th layer is

$$Z_n = \mu_0 \frac{E_x}{B_y} = \frac{j\omega\mu_0}{k_n} = \sqrt{\frac{j\omega\mu_0}{\sigma_n}}, \tag{3}$$

where $k_n$ is the propagation constant given by $k_n = \sqrt{j\omega\mu_0\sigma_n}$. The impedance at the top of the layer within the $m$th layer ($m = 1, 2, \ldots, n-1$) can be expressed as

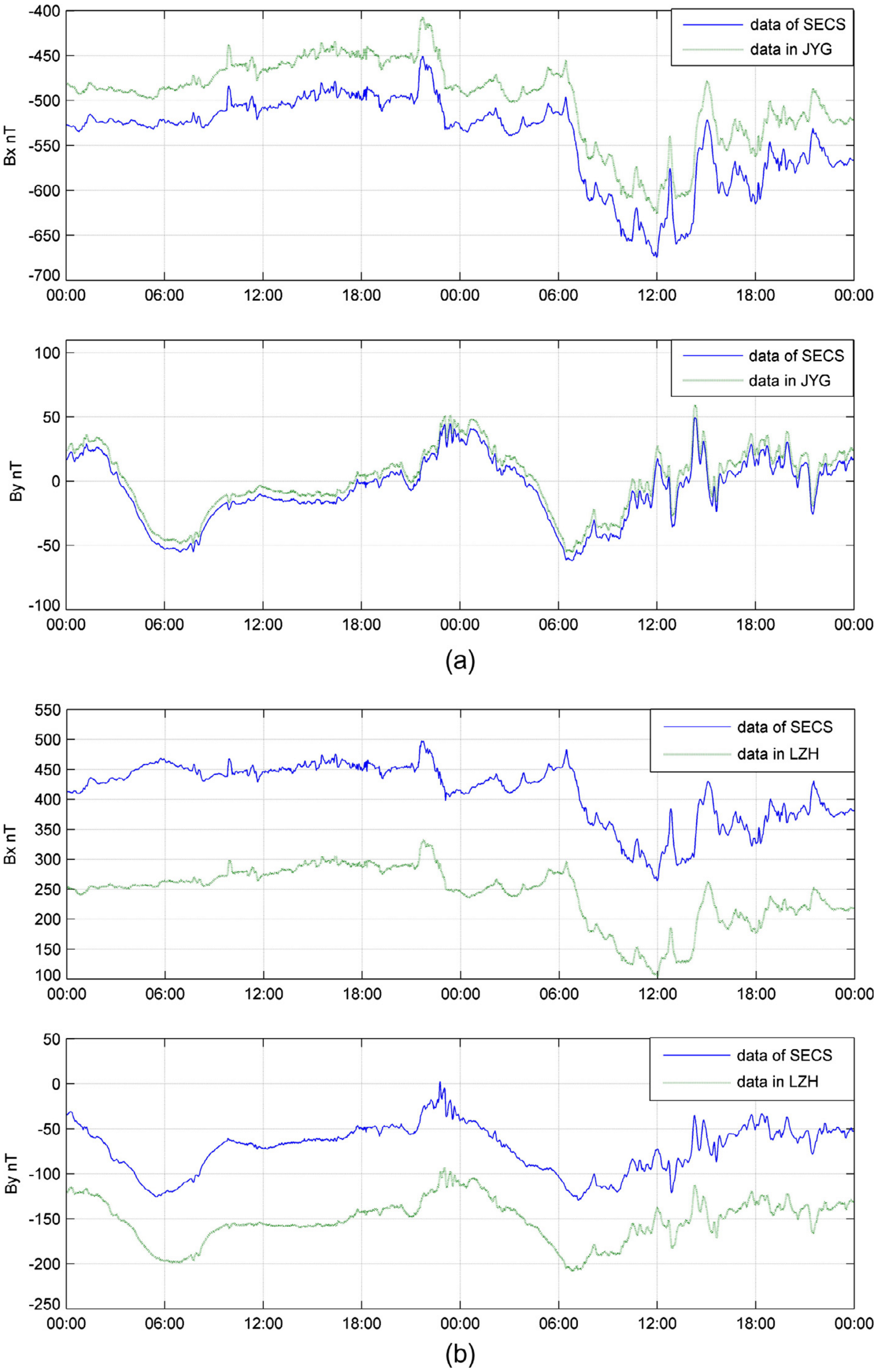


**Fig. 4.** Measured magnetic data and the SECS-derived magnetic data on 29–30 May 2005. The horizontal axis is the UT time in hours (a) magnetic data from JYG observatory and the SECS-derived magnetic data for Jiuquan substation and (b) magnetic data from LZH observatory and the SECS-derived magnetic data for Yongdeng substation.

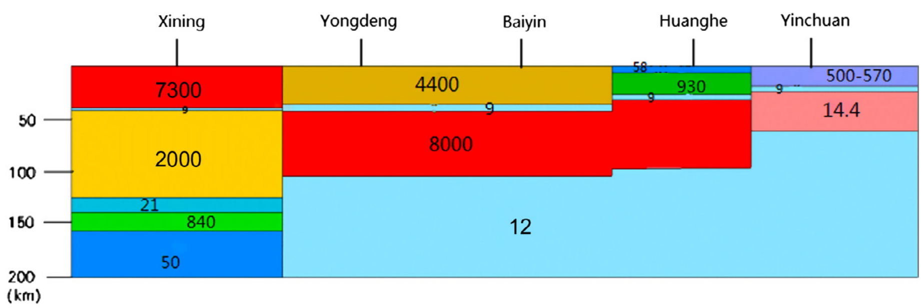


**Fig. 5.** Resistivity for the section Xining-Yinchuan along 750 kV power transmission lines.

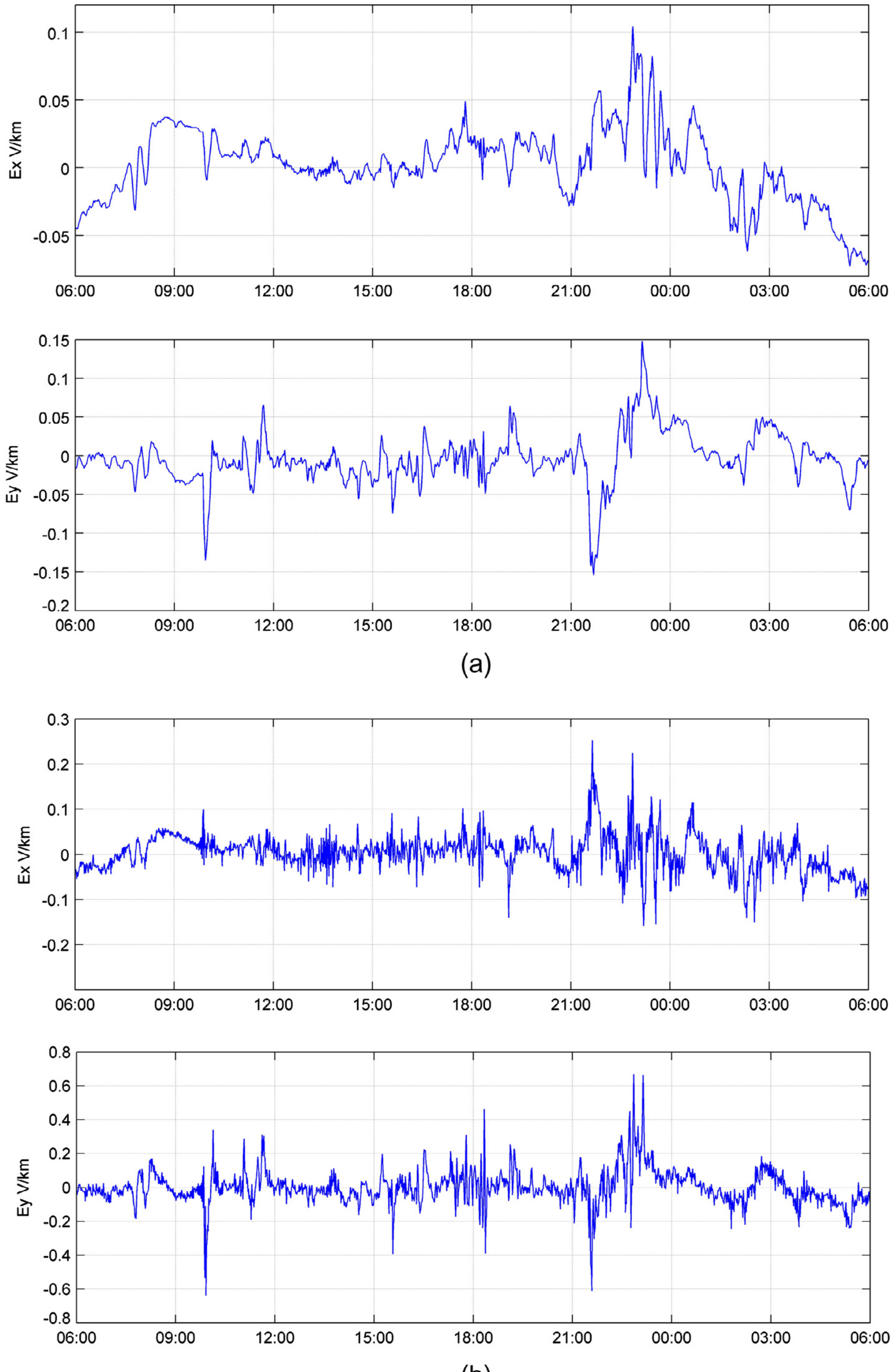


**Fig. 6.** Calculated geoelectric fields at two sites (Jiuquan and Yongdeng) of the Chinese Northwest 750 kV power grid on 29–30 May 2005. The horizontal axis is the UT time in hours (a) E-Jiuquan and (b) E-Yongdeng.

$$Z_m = Z_{0m}\frac{1 - L_{m+1}e^{-2k_m h_m}}{1 + L_{m+1}e^{-2k_m h_m}} \quad (4)$$

where $k_m = \sqrt{j\omega\mu_0\sigma_m}$ and $Z_{0m} = \frac{jw\mu_0}{k_m}$ and $L_{m+1} = \frac{Z_{0m}-Z_{m+1}}{Z_{0m}+Z_{m+1}}$.

In the model, the bottom of $m$th layer is the top of $(m + 1)$th layer, so equation (4) can be seen as a recursive formula for the impedance at the top of each layer, through which we can calculate the surface impedance of the Earth $Z$. The geoelectric field in frequency domain can be calculated from geomagnetic data according to equations (1) and (2). Then the result has to be inverse Fourier transformed back to the time domain.

### 3.2. Calculating GIC

The frequencies of GIC are very low from the view point of power systems. Thus the GIC can be treated as a direct current. The effect of the geoelectric field on a power grid is equivalent to a set of voltage sources in the transmission lines between the substations. The value of the voltage is the integral of the electric field along the line, i.e.:

$$V_{AB} = \int_A^B \vec{E} \cdot \overleftarrow{\mathrm{d}l}\,. \quad (5)$$

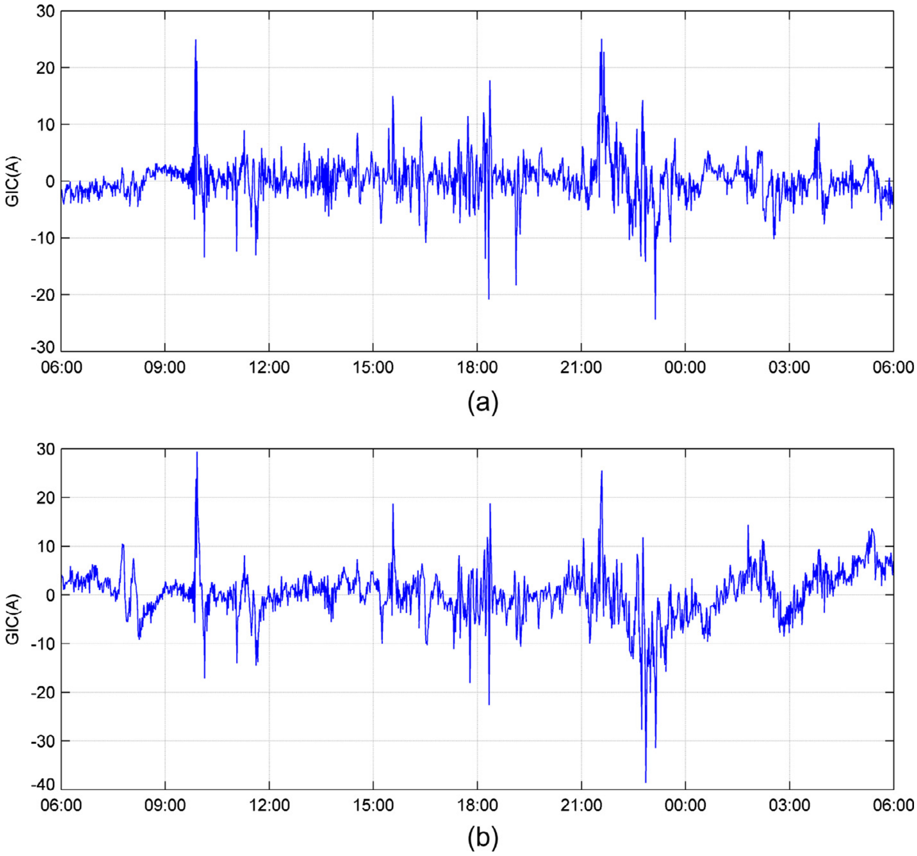


**Fig. 7.** Calculated GIC at two sites (Jiuquan and Yongdeng) of the Chinese Northwest 750 kV power grid on 29–30 May 2005. The horizontal axis is the UT time in hours (a) calculated GIC at Jiuquan substation and (b) calculated GIC at Youngdeng substation.

If the geoelectric field is uniform, the integrals are independent of the paths. Therefore equation (5) can be simplified to

$$V_{AB} = L_{AB}(E_x \sin\theta + E_y \cos\theta) \qquad (6)$$

Where $L_{AB}$ is the direct distance between nodes $A$ and $B$; $\theta$ is the "compass angles" i.e. clockwise from geographic North.

The GIC flowing from the power grid to the earth can be expressed as a column matrix **I**, which has the following formula (e.g., Pirjola & Lehtinen 1985)

$$\mathbf{I} = (\mathbf{1} + \mathbf{YZ})^{-1}\mathbf{J}, \qquad (7)$$

where **1** is a unit (identity) matrix; **Y** and **Z** are the network admittance matrix and the earthing impedance matrix respectively. The elements of column matrix **J** are defined by

$$J_i = \sum_{j=1, j\neq i}^{N} \frac{V_{ij}}{R_{ij}}. \qquad (8)$$

The matrix **J** gives the GIC between the power grid and the earth in the case of ideal groundings, i.e. the grounding resistances are zero making **Z** a zero matrix.

## 4. Modeling GIC in Chinese Northwest 750 kV power grid

The problem of GIC should be considered more serious in the Chinese Northwest 750 kV power grid because of the high voltage implying low transmission line resistances and because of the low earth conductivity increasing geoelectric field values. The power grid (shown in Fig. 3) for which GIC calculations are made in this paper is mainly located in the Gansu Province in the Northwest of China. We ignore the lower voltage part connected to the 750 kV power grid when modeling the GIC, because the resistances of that part are much larger, and so it is considered to have little influence on GIC flowing in the 750 kV system.

### 4.1. Geoelectric field calculation

We use data of the geomagnetic storm on 29–30 May 2005. The power grid is very large, extending more than 2 000 km in an east-west direction and 1 500 km in a North-South direction, so the geomagnetic variations cannot be considered to be the same all over the network. The magnetic data from four geomagnetic observatories, whose locations are shown in Figure 3 and in Table 1, are used to calculate the geoelectric field. The local magnetic data are interpolated by using the spherical elementary current systems (SECS) method (Amm 1997). The method uses geomagnetic field data to inverse the ionosphere equivalent current according to which the geomagnetic field data of every location can be calculated. Therefore the interpolation of magnetic data at different locations during a storm can be acquired. As examples, Figure 4a shows the measured data from JYG and the SECS-derived magnetic data for Jiuquan Substation, and Figure 4b shows the measured data from LZH and the SECS-derived magnetic data for Yongdeng Substation on 29–30 May 2005. It can be seen that the differences between measured magnetic data and the SECS-derived

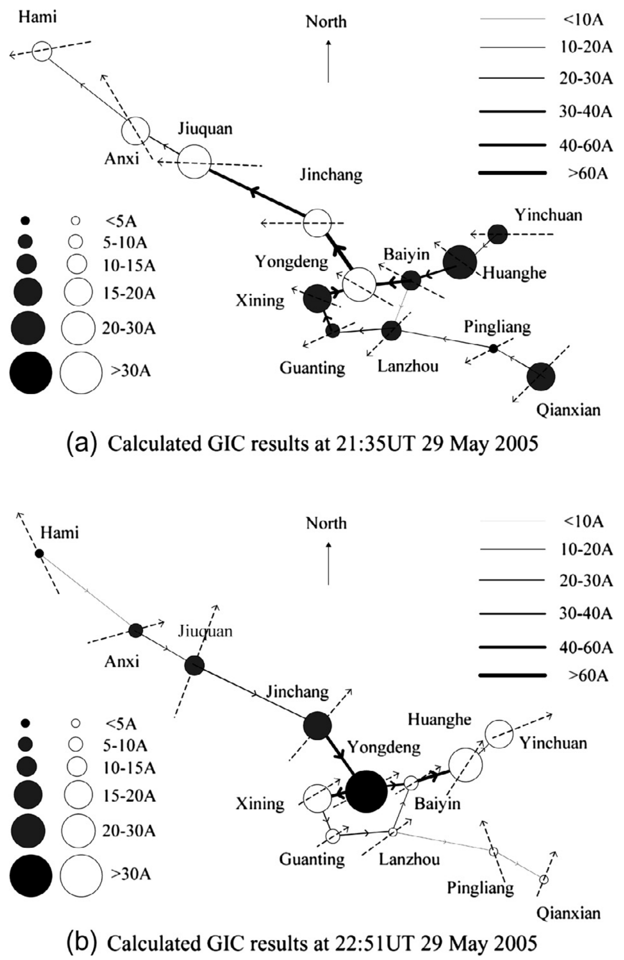


**Fig. 8.** Snapshots at 21:35 on 29 May 2005 (a) and at 22:51UT on 29 May 2005 (b) of calculated GIC at different sites of the Chinese Northwest 750 kV power grid. The solid circle represents that the GIC flow into the power network from ground, the hollow one means that GIC flow into the ground. The dashed line with an arrow represents the direction of electric field at that substation.

data are little except for the base line values which have no effect on the induced electric fields.

The earth conductivities are quite different across the power grid considered, so the geoelectric field values are calculated segment by segment according to the local magnetic data and the local layered earth model. In other words, we utilize the piecewise layered earth model. The earth resistivity in the region where the Chinese Northwest 750 kV power grid is located was provided by Prof. Liu Guo-Xing, a geologist at the Jilin University (private communication). Figure 5 shows a section of the earth resistivity in Ω·m from Xining to Yinchuan along the 750 kV power lines (see Fig. 3). The resistances of some places are given within a range such as 500–570 at Yinchuan in Figure 5. The upper limit values were used to calculate the induced electric fields because they stand for the most disadvantageous situation to the power grid.

As mentioned, the geoelectric fields have been calculated all over the Chinese Northwest 750 kV system based on the Piecewise layered earth models during the geomagnetic storm on 29–30 May 2005. As examples, Figure 6 shows the geoelectric field at Jiuquan and Yongdeng (whose locations are shown in Fig. 3). Our calculation results indicate that the largest $E_x$ value is 0.36 V/km and the largest $E_y$ value is 0.668 V/km in the area of the Northwest 750 kV grid during the geomagnetic storm considered. It is also shown by Figure 6 that the electric fields calculated for Yongdeng and Jiugan are quite different because the Earth conductivity at Yongdeng is much lower than that at Jiuquan.

### 4.2. GIC calculation

The GIC through all neutral points of the transformers to the Earth and in all transmission lines of the Chinese Northwest 750 kV network have been calculated. Figure 7 shows the GIC through two typical substations: Jiuquan and Yondeng (also referred to in Fig. 6). The largest GIC at Jiuquan is 25.08 A/phase at 21:35 UT on 29 May 2005, and the largest GIC at Yongdeng is 38.63 A/phase at 22:51 UT on 29 May 2005.

As snapshots, Figure 8 shows the GIC through every node and line at 21:35 UT (panel a) and at 22:51UT (panel b) on 29 May 2005 when the GIC through some of the nodes reach their peaks. It can be seen that the largest GIC through a neutral point is 38.63 A/phase, which is obtained at theYongdeng substation at 22:51 as already mentioned above (see also Fig. 7). The peak GIC through a transmission line is 68.84 A/phase, which occurs in the line from Yongdeng to Jinchang at 21:35 UT. It should be note that there is one single-phase transformer bank in a 750 kV substation except Guanting and Yinchuan where the number of transformer banks is two.

## 5. Conclusions

The high-voltage power grid in China may experience large GIC during geomagnetic storms, which has been concluded from monitoring the current through the neutral point at Ling'ao nuclear power plant. The GIC in the Chinese Northwest 750 kV power grid during a specific geomagnetic storm have been modeled based on calculating the geoelectric field using the piecewise layered earth models. It can be seen from the results that some sites are sensitive to geomagnetic storms, and the magnitude of GIC can be quite large (> 30 A/phase) during strong geomagnetic storms. Our studies thus clearly demonstrate that GIC are not only a high-latitude problem but networks in middle and low latitudes can be impacted as well. Factors increasing GIC risks in China include the large size of the power network, the small resistances of the transmission lines, and the high resistivity of the earth.

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# Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment

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**Abstract.** Geomagnetically induced currents are known to induce disturbances in the electric power grid. Here, we perform a statistical analysis of 11,242 insurance claims from 2000 through 2010 for equipment losses and related business interruptions in North-American commercial organizations that are associated with damage to, or malfunction of, electrical and electronic equipment. We find that claims rates are elevated on days with elevated geomagnetic activity by approximately 20% for the top 5%, and by about 10% for the top third of most active days ranked by daily maximum variability of the geomagnetic field. When focusing on the claims explicitly attributed to electrical surges (amounting to more than half the total sample), we find that the dependence of claims rates on geomagnetic activity mirrors that of major disturbances in the U.S. high-voltage electric power grid. The claims statistics thus reveal that large-scale geomagnetic variability couples into the low-voltage power distribution network and that related power-quality variations can cause malfunctions and failures in electrical and electronic devices that, in turn, lead to an estimated 500 claims per average year within North America. We discuss the possible magnitude of the full economic impact associated with quality variations in electrical power associated with space weather.

## 1. Introduction

Large explosions that expel hot, magnetized gases on the Sun can, should they eventually envelop Earth, effect severe disturbances in the geomagnetic field. These, in turn, cause geomagnetically induced currents (GICs) to run through the surface layers of the Earth and through conducting infrastructures in and on these, including the electrical power grids. The storm-related GICs run on a background of daily variations associated with solar (X)(E)UV irradiation that itself is variable through its dependence on both quiescent and flaring processes.

The strongest GIC events are known to have impacted the power grid on occasion [see, e.g., *Kappenman et al.*, 1997; *Boteler et al.*, 1998; *Arslan Erinmez et al.*, 2002; *Kappenman*, 2005; *Wik et al.*, 2009]. Among the best-known of such impacts is the 1989 Hydro-Québec blackout [e.g., *Bolduc*, 2002; *Béland and Small*, 2004]. Impacts are likely strongest at mid to high geomagnetic latitudes, but low-latitude regions also appear susceptible [*Gaunt*, 2013].

The potential for severe impacts on the high-voltage power grid and thereby on society that depends on it has been assessed in studies by government, academic, and insurance industry working groups [e.g., *Space Studies Board*, 2008; *FEMA*, 2010; *Kappenman*, 2010; *Hapgood*, 2011; *JASON*, 2011]. How costly such potential major grid failures would be remains to be determined, but impacts of many billions of dollars have been suggested [e.g., *Space Studies Board*, 2008; *JASON*, 2011].

Non-catastrophic GIC effects on the high-voltage electrical grid percolate into financial consequences for the power market [*Forbes and St. Cyr*, 2004, 2008, 2010] leading to price variations on the bulk electrical power market on the order of a few percent [*Forbes and St. Cyr*, 2004].

*Schrijver and Mitchell* [2013] quantified the susceptibility of the U.S. high-voltage power grid to severe, yet not extreme, space storms, leading to power outages and power-quality variations related to voltage sags and frequency changes. They find, "with more than 3$\sigma$ significance, that approximately 4% of the disturbances in the US power grid reported to the US Department of Energy are attributable to strong geomagnetic activity and its associated geomagnetically induced currents."

The effects of GICs on the high-voltage power grid can, in turn, affect the low-voltage distribution networks and, in principle, might impact electrical and electronic systems of users of those regional and local networks. A first indication that this does indeed happen was reported on in association with tests conducted by the Idaho National Laboratory (INL) and the Defense Threat Reduction Agency (DTRA). They reported [*Wise and Benjamin*, 2013] that "INL and DTRA used the lab's unique power grid and a pair of 138kV core form, 2 winding substation transformers, which had been in-service at INL since the 1950s, to perform the first full-scale testing to replicate conditions electric utilities could experience from geomagnetic disturbances." In these experiments, the researchers could study how the artificial GIC-like currents resulted in harmonics on the power lines that can affect the power transmission and distribution equipment. These "tests demonstrated that geomagnetic-induced harmonics are strong enough to penetrate many power line filters and cause temporary resets to computer power supplies and disruption to electronic equipment, such as uninterruptible power supplies".

In parallel to that experiment, we collected information on insurance claims submitted to Zurich North-America (NA) for damage to, or outages of, electrical and electronic systems from all types of industries for a comparison with geomagnetic variability. Here, we report on the results of a retrospective cohort exposure analysis of the impact of geomagnetic variability on the frequency of insurance claims. In this analysis, we contrast insurance claims frequencies on "high-exposure" dates (i.e., dates of high geomagnetic activity) with a control sample of "low-exposure" dates (i.e., dates with essentially quiescent space weather conditions), carefully matching each high-exposure date to a

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[2]Zurich Services Corporation, Schaumburg, IL, USA
[3]Space Weather Prediction Center, Boulder, CO, USA

control sample nearby in time so that we may assume no systematic changes in conditions other than space weather occurred between the exposure dates and their controls (thus compensating for seasonal weather changes and other trends and cycles).

For comparison purposes we repeat the analysis of the frequency of disturbances in the high-voltage electrical power grid as performed by *Schrijver and Mitchell* [2013] for the same date range and with matching criteria for threshold setting and for the selection of the control samples. In Section 1 we describe the insurance claim data, the metric of geomagnetic variability used, and the grid-disturbance information. The procedure to test for any impacts of space weather on insurance claims and the high-voltage power grid is presented and applied in Section 3. We summarize our conclusions in Section 4 where we also discuss the challenges in translating the statistics on claims and disturbances into an economic impact.

## 2. Data

### 2.1. Insurance claim data

We compiled a list of all insurance claims filed by commercial organizations to Zurich NA relating to costs incurred for electrical and electronic systems for the 11-year interval from 2000/01/01 through 2010/12/31. Available for our study were the date of the event to which the claim referred, the state or province within which the event occurred, a brief description of the affected equipment, and a top-level assessment of the probable cause. Information that might lead to identification of the insured parties was not disclosed.

Zurich NA estimates that it has a market share of approximately 8% in North America for policies covering commercially-used electrical and electronic equipment and contingency business interruptions related to their failure to function properly during the study period. Using that information as a multiplier suggests that overall some 12,800 claims are filed per average year related to electrical/electronic equipment problems in North-American businesses. The data available for this study cannot reveal impacts on uninsured or self-insured organizations or impacts in events of which the costs fall below the policy deductable.

The 11-year period under study has the same duration as that characteristic of the solar magnetic activity cycle. Fig. 1 shows that the start of this period coincides with the maximum in the annual sunspot number for 2000, followed by a decline into an extended minimum period in 2008 and 2009, ending with the rise of sunspot number into the start of the next cycle.

The full sample of claims, regardless of attribution, for which an electrical or electronic system was involved includes 11,242 entries. We refer to this complete set as set $A$.

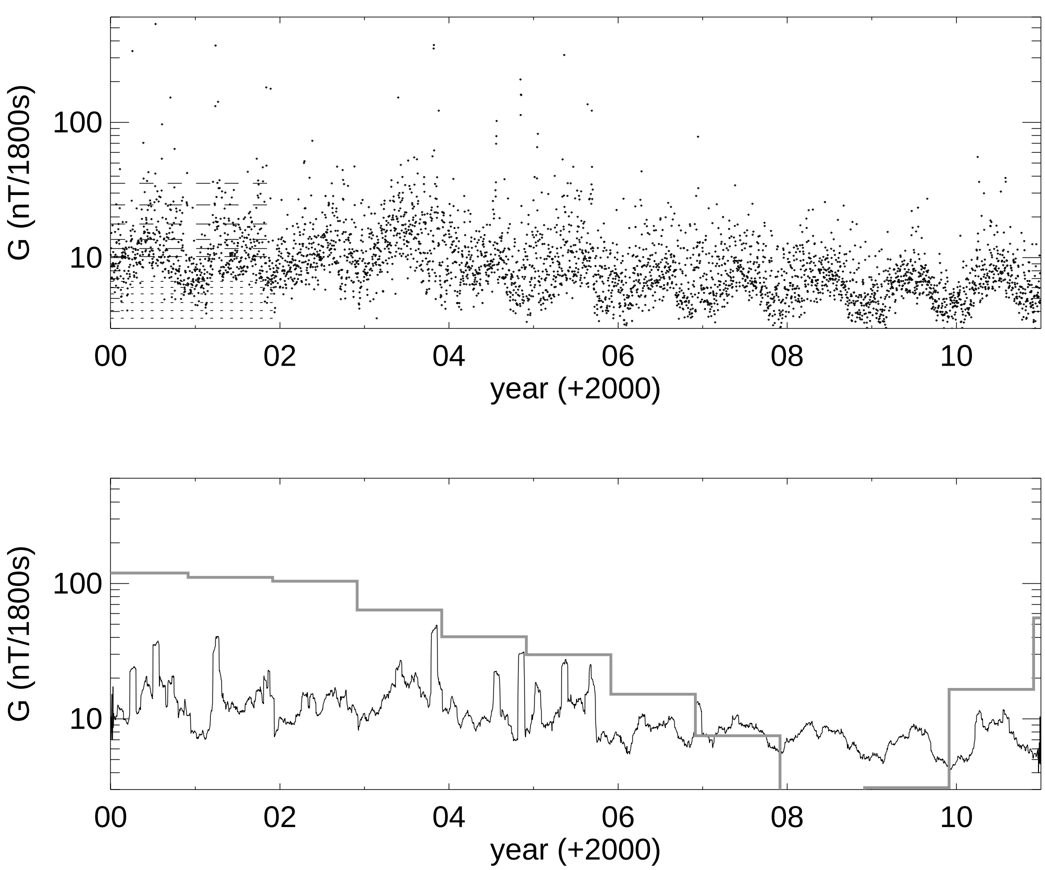


**Figure 1.** *Daily values $G \equiv max(|dB/dt|)$ based on 30-min. intervals (dots; nT/1800s) characterizing geomagnetic variability for the contiguous United States versus time (in years since 2000). The 27-d running mean is shown by the solid line. The levels for the 98, 95, 90, 82, 75, and 67 percentiles of the entire sample are shown by dashed lines (sorting downward from the top value of $G$) and dotted lines (sorting upward from the minimum value of the daily geomagnetic variability as expressed by $G \equiv max(|dB/dt|)$). The grey histogram shows the annual mean sunspot number.*

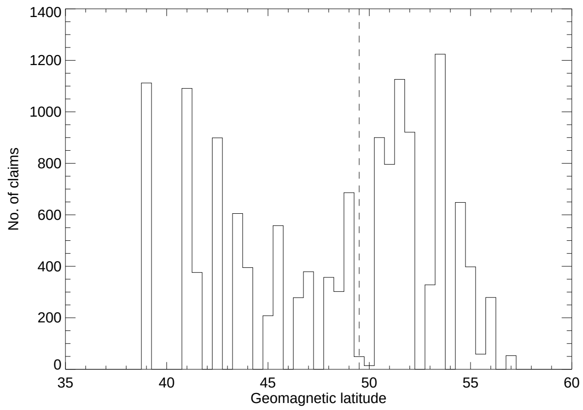


**Figure 2.** *Number of insurance claims sorted by geomagnetic latitude (using the central geographical location of the state) in 0.5° bins. The dashed line at 49.5° is near the median geomagnetic latitude of the sample (at 49.3°), separating what this paper refers to as high-latitude from low-latitude states.*

Claims that were attributed to causes that were in all likelihood not associated with space weather phenomena were deleted from set $A$ to form set $B$ (with 8,151 entries remaining after review of the Accident Narrative description of each line item). Such omitted claims included attributions to water leaks and flooding, stolen or lost equipment, vandalism or other intentional damage, vehicle damage or vehicular accidents, animal intrusions (raccoons, squirrels, birds, etc.), obvious mechanical damage, and obvious weather damage (ice storm damage, hurricane/windstorm damage, etc.). The probable causes for the events making up set $B$ were limited to the following categories (sorted by the occurrence frequency, given in percent): Misc: Electrical surge (59%); Apparatus, Miscellaneous Electrical - Breaking (30%); Apparatus, Miscellaneous Electrical - Arcing (4.1%); Electronics - Breaking (1.6%); Apparatus, Miscellaneous Electrical - Overheating (1.4%); Transformers - Arcing (0.9%); Electronics - Arcing (0.6%); Transformers - Breaking (0.5%); Generators - Breaking (0.4%); Apparatus, Electronics - Overheating (0.3%); Generators - Arcing (0.2%); Generators - Overheating (0.2%); and Transformers - Overheating (0.1%).

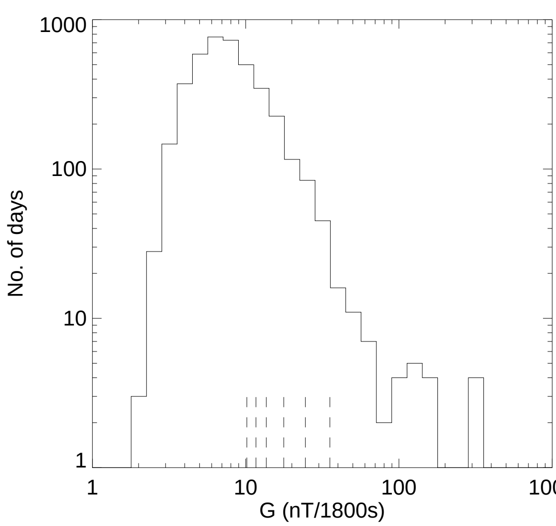


**Figure 3.** *Histogram of the number of days between 2000/01/01 and 2010/12/31 with values of $G \equiv max(|dB/dt|)$ in logarithmically spaced intervals as shown on the horizontal axis. The 98, 95, 90, 82, 75, and 67 percentiles (ranking $G$ from low to high) are shown by dashed lines.*

Fig. 2 shows the number of claims received as a function of the mean geomagnetic latitude for the state within which the claim was recorded. Based on this histogram, we divided the claims into categories of comparable size for high and low geomagnetic latitudes along a separation at 49.°5 north geomagnetic latitude to enable testing for a dependence on proximity to the auroral zones. We note that we do not have access to information about the latitudinal distribution of insured assets, only on the claims received. Hence, we can only assess any dependence of insurance claims on latitude in a relative sense, comparing excess relative claims frequencies for claims above and below the median geomagnetic latitudes, as discussed in Sect. 3.

### 2.2. Geomagnetic data

Geomagnetically-induced currents are driven by changes in the geomagnetic field. These changes are caused by the interaction of the variable, magnetized solar wind with the geomagnetic field and by the insolation of Earth's atmosphere that varies globally with solar activity and locally owing to the Earth's daily rotation and annual revolution in its orbit around the Sun. A variety of geomagnetic activity indices is available to characterize geomagnetic field variability [e.g., *Jursa*, 1985]. These indices are sensitive to different aspects of the variable geomagnetic-ionospheric current systems as they may differentially filter or weight storm-time variations (Dst), disturbance-daily variations (Ds), or solar quiet daily variations (known as the Sq field), and may weight differentially by (geomagnetic) latitude. Here, we are interested not in any particular driver of

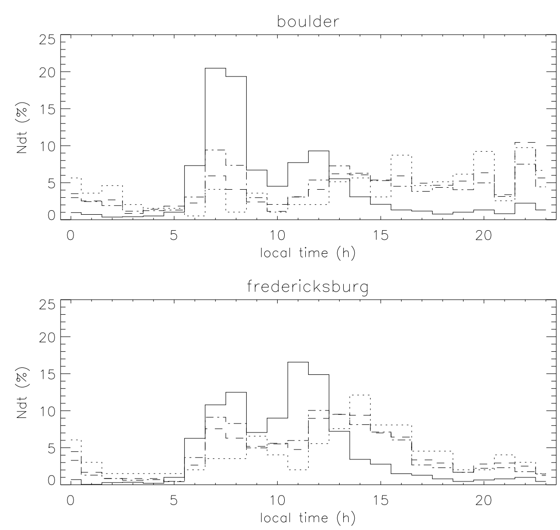


**Figure 4.** *Normalized histograms of the local times for which the values of $G \equiv max(|dB/dt|)$ reach their daily maximum (top: Boulder; bottom: Fredericksburg). The solid histogram shows the distribution for daily peaks for all dates with $G$ values in the lower half of the distribution, i.e., for generally quiescent conditions. The dotted, dashed, and dashed-dotted histograms show the distributions for dates with high $G$ values, for thresholds set at the 95, 82, and 67 percentiles of the set of values for $G$, respectively.*

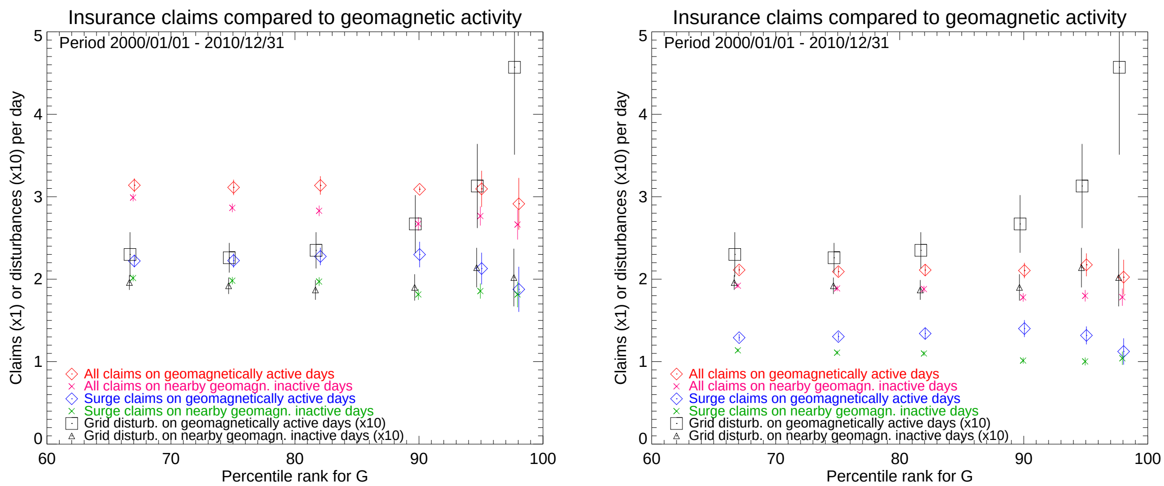


**Figure 5.** *Claims per day for the full sample of insurance claims (set A left) and the sample from which claims likely unrelated to any space weather influence have been removed (set B, right). Each panel shows mean incident claim frequencies $n_i \pm \sigma_c$ (diamonds) for the most geomagnetically active dates, specifically for the 98, 95, 90, 82, 75, and 67 percentiles of the distribution of daily values of $G \equiv max(|dB/dt|)$ sorted from low to high (shown with slight horizontal offsets to avoid overlap in the symbols and bars showing the standard deviations for the mean values). The asterisks show the associated claim frequencies $n_c \pm \sigma_c$, for the control samples. The panels also show the frequencies of reported high-voltage power-grid disturbances (diamonds and triangles for geomagnetically active dates and for control dates, respectively), multiplied by 10 for easier comparison, using the same exposure-control sampling and applied to the same date range as that used for the insurance claims.*

changes in the geomagnetic field but rather need a metric of the rate of change in the strength of the surface magnetic field as that is the primary driver of geomagnetically-induced currents.

To quantify the variability in the geomagnetic field we use the same metric as *Schrijver and Mitchell* [2013] based on the minute-by-minute geomagnetic field measurements from the Boulder (BOU) and Fredericksburg (FRD) stations (available via http://ottawa.intermagnet.org): we use these measurements to compute the daily maximum value, $G$, of $|dB/dt|$ over 30-min. intervals, using the mean value for the two stations. We selected this metric recognizing a need to use a more regional metric than the often-used global metrics, but also recognizing that the available geomagnetic and insurance claims data have poor geographical resolution so that a focus on a metric responsive to relatively low-order geomagnetic variability was appropriate. We chose a time base short enough to be sensitive to rapid changes in the geomagnetic field, but long enough that it is also sensitive to sustained changes over the course of over some tens of minutes. For the purpose of this study, we chose to use a single metric of geomagnetic variability, but with the conclusion of our pilot study revealing a dependence of damage to electrical and electronic equipment on space weather conditions, a multi-parameter follow up study is clearly warranted, ideally also with more information on insurance claims, than could be achieved with what we have access to for this exploratory study.

The BOU and FRD stations are located along the central latitudinal axis of the U.S.. The averaging of their measurements somewhat emphasizes the eastern U.S. as do the grid and population that uses that. Because the insurance claims use dates based on local time we compute the daily $G$ values based on date boundaries of U.S. central time. Fig. 3 shows the distribution of values of $G$, while also showing the levels of the percentiles for the rank-sorted value of $G$ used as threshold values for a series of sub-samples in the following sections.

Figure 4 shows the local times at which the maximum variations in the geomagnetic field occur during 30-min. intervals. The most pronounced peak in the distribution for geomagnetically quiet days (solid histogram) occurs around $7-8$ o'clock local time, i.e., a few hours after sunrise, and a second peak occurs around local noon. The histograms for the subsets of geomagnetically active days for which $G$ values exceed thresholds set at 67, 82, and 95 percentiles of the sample are much broader, even more so for the Boulder station than for the Fredericksburg station. From the perspective of the present study, it is important to note that the majority of the peak times for our metric of geomagnetic variability occurs within the economically most active window from 7 to 18 hours local time; for example, at the 82-percentile of geomagnetic variability in $G$, 54% and 77% of the peak variability occur in that time span for Boulder and Fredericksburg, respectively.

From a general physics perspective, we note that periods of markedly enhanced geomagnetic activity ride on top of a daily background variation of the ionospheric current systes (largely associated with the "solar quiet" modulations, referred to as the Sq field) that is induced to a large extent by solar irradiation of the atmosphere of the rotating Earth, including the variable coronal components associated with active-region gradual evolution and impulsive solar flaring. We do not attempt to separate the impacts of these drivers in this study, both because we do not have information on the local times for which the problems occurred that lead to the insurance claims, and because the power grid is sensitive to the total variability in the geomagnetic field regardless of cause.

The daily $G$ values are shown versus time in Fig. 1, along with a 27-d running mean and (as a grey histogram) the yearly sunspot number. As expected, the $G$ value shows strong upward excursions particularly during the sunspot maximum. Note the annual modulation in $G$ with generally lower values in the northern-hemispheric winter months than in the summer months.

### 2.3. Power-grid disturbances

In parallel to the analysis of the insurance claims statistics, we also analyze the frequencies of disturbances in the U.S. high-voltage power grid. *Schrijver and Mitchell* [2013] compiled a list of "system disturbances" published by the North American Electric Reliability Corporation (NERC: available since 1992) and by the Office of Electricity Delivery and Energy Reliability of the Department of Energy (DOE; available since 2000). This information is compiled by NERC for a region with over 300 million electric power customers throughout the U.S.A. and in Ontario and New Brunswick in Canada, connected by more than 340,000 km of high-voltage transmission lines delivering power generated in some 18,000 power plants within the U.S. [*JASON*, 2011]. The reported disturbances include, among others, "electric service interruptions, voltage reductions, acts of sabotage, unusual occurrences that can affect the reliability of the bulk electric systems, and fuel problems." We use the complete set of disturbances reported from 2000/01/01 through 2010/12/31 regardless of attributed cause. We refer to *Schrijver and Mitchell* [2013] for more details.

## 3. Testing for the impact of space weather

In order to quantify effects of geomagnetic variability on the frequency of insurance claims filed for electrical and electronic equipment we need to carefully control for a multitude of variables that include trends in solar activity, the structure and operation of the power grid (including, for example, scheduled maintenance and inspection), various societal and technological factors changing over the years, as well as the costs and procedures related to the insurance industry, and, of course, weather and seasonal trends related to the insolation angle and the varying tilt of the Earth's magnetic field relative to the incoming solar wind throughout the year.

There are many parameters that may influence the ionospheric current systems, the quality and continuity of electrical power, and the malfunctioning of equipment running on electrical power. We may not presume that we could identify and obtain all such parameters, or that all power grid segments and all equipment would respond similarly to changes in these parameters. We therefore do not attempt a multi-parameter correlation study, but instead apply a retrospective cohort exposure study with tightly matched controls very similar to that applied by Schrijver and Mitchell (2013).

This type of exposure study is based on pairing dates of exposure, i.e., of elevated geomagnetic activity, with control dates of low geomagnetic activity shortly before or after each of the dates of exposure, selected from within a fairly narrow window in time during which we expect no substantial systematic variation in ionospheric conditions, weather, the operations of the grid, or the equipment powered by the grid. Our results are based on a comparison of claims counts on exposure dates relative to claims counts on matching sets of nearby control dates. This minimizes the impacts of trends (including "confounders") in any of the potential factors that affect the claims statistics or geomagnetic variability, including the daily variations in quiet-Sun irradiance and the seasonal variations as Earth orbits the Sun, the solar cycle, and the structure and operation of the electrical power network. This is a standard method as used in, e.g., epidemiology. We refer to Wacholder et al. (1992, and references therein) for a discussion on this method particularly regarding ensuring of time comparability of the "exposed" and control samples, to Schulz and Grimes (2002) for a discussion on the comparison of cohort studies as applied here versus case-control studies, and to Grimes and Schulz (2005) for a discussion of selection biases in samples and their controls (specifically their example on pp. 1429-1430).

We define a series of values of geomagnetic variability in order to form sets of dates including different ranges of exposure, i.e., of geomagnetic variability, so that each high exposure date is matched by representative low exposure dates as controls. We create exposure sets by selecting a series of threshold levels corresponding to percentages of all dates with the most intense geomagnetic activity as measured by the metric $G$. Specifically, we determined the values of $G$ for which geomagnetic activity, sorted from least active upward, includes 67%, 75%, 82%, 90%, 95%, and 98% of all dates in our study period. For each threshold value we selected the dates with $G$ exceeding that threshold (with possible further selection criteria as described below). For each percentile set we compute the mean daily rate of incident claims, $n_i$, as well as the standard deviation on the mean, $\sigma_i$, as determined from the events in the day-by-day claims list.

In order to form tightly matched control samples for low "exposure", we then select 3 dates within a 27-d period centered on each of the selected high-activity days. The 27-d period, also known as the Bartels period, is that characteristic of a full rotation of the solar large-scale field as viewed from the orbiting Earth; $G$ values within that period sample geomagnetic variability as induced during one full solar rotation. This window for control sample selection is tighter than that used by *Schrijver and Mitchell* [2013] who used 100-day windows centered on dates with reported grid disturbances. For the present study we selected a narrower window to put even stronger limits on the potential effects of any possible long-term trends in factors that might influence claims statistics or geomagnetic variability. We note that there is no substantive change in our main conclusions for control windows at least up to 100 days in duration.

The three dates selected from within this 27-d interval are those with the lowest value of $G$ smoothed with a 3-day running mean. We determine the mean claim rate, $n_c$, for this control set and the associated standard deviation in the mean, $\sigma_c$.

Fig. 5 shows the resulting daily frequency of claims and the standard deviations in the mean, $n_i \pm \sigma_i$, for the selected percentiles, both for the full sample $A$ (left panel) and for sample $B$ (right panel) from which claims were omitted that were attributed to causes not likely associated directly or indirectly with geomagnetic activity. For all percentile sets we see that the claim frequencies $n_i$ on geomagnetically active days exceed the frequencies $n_c$ for the control dates.

The frequency distributions of insurance claims are not Poisson distributions, as can be seen in the example in Fig. 6 (left panel): compared to a Poisson distribution of the same mean, the claims distributions on geomagnetically active dates, $N_{\mathrm{B,a,75}}$ and for control days, $N_{\mathrm{B,c,75}}$, are skewed to have a peak frequency at lower numbers and a raised tail at higher numbers; a Kolmogorov-Smirnov (KS) test suggests that the probability that $N_{\mathrm{B,c,75}}$ is consistent with a Poisson distribution with the same mean is 0.01 for this example. The elevated tail of the distribution relative to a Poisson distribution suggests some correlation between claims events, which is of interest from an actuarial perspective as it suggests a nonlinear response of the power system to space weather that we cannot investigate further here owing to the signal to noise ratio of the results given our sample.

For the case shown in Fig. 6 for the 25% most geomagnetically active dates in set $B$, a KS test shows that the probability that $N_{\mathrm{B,a,75}}$ and $N_{\mathrm{B,c,75}}$ are drawn from the same parent distribution is of order $10^{-14}$, i.e. extremely unlikely.

The numbers that we are ultimately interested in are the excess frequencies of claims on geomagnetically active

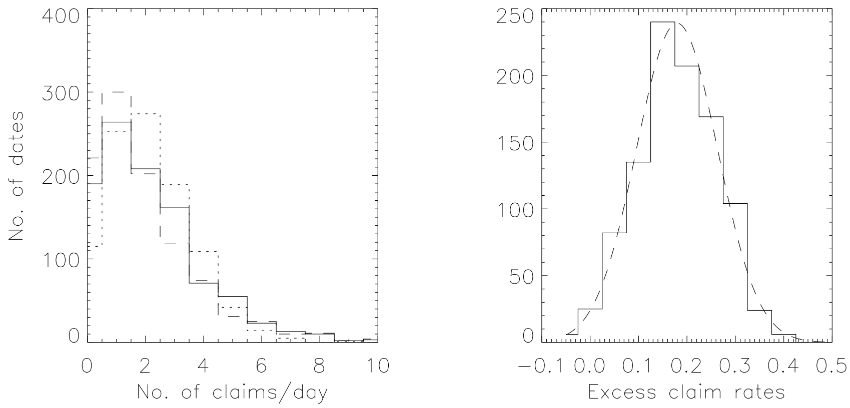


**Figure 6.** *(left) Distribution of the number of claims per geomagnetically active day for set* B *for the top 25% of* $G$ *values (solid) compared to that for the distribution of control dates (divided by 3 to yield the same total number of dates; dashed). For comparison, the expected histogram for a random Poisson distribution with the same mean as that for the geomagnetically active days is also shown (dotted). (right) Distribution (solid) of excess daily claim frequencies during geomagnetically active days (defined as in the left panel) over those on control dates determined by repeated random sampling from the observations (known as the bootstrap method), compared to a Gaussian distribution (dashed) with the same mean and standard deviation.*

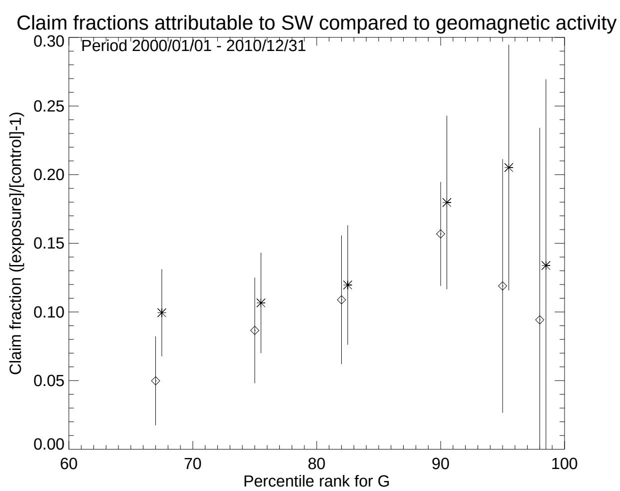


**Figure 7.** *Relative excess claim frequencies statistically associated with geomagnetic activity (difference between claim frequencies on geomagnetically active dates and the frequencies on control dates as shown in Fig. 5, i.e.,* $(n_i - n_c)/n_c$ *for the full sample (A; diamonds) and for the sample (B; asterisks) from which claims were removed attributable to apparently non-space-weather related causes.*

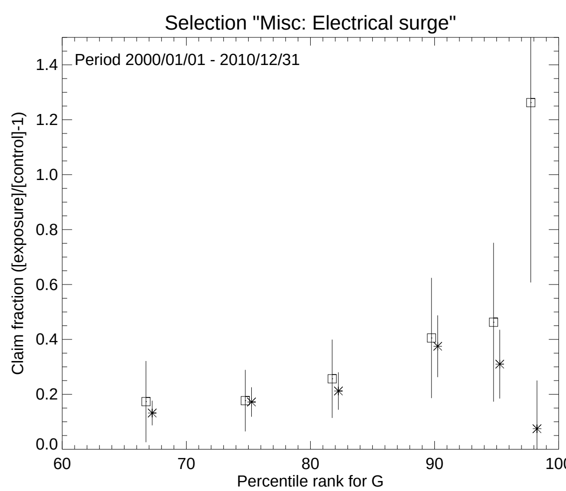


**Figure 8.** *Same as Fig. 7 but for sample* B *limited to those claims attributed to "Misc.: Electrical surge" (asterisks) (for 57% of the cases in that sample), compared to the fraction of high-voltage power-grid disturbances statistically associated with geomagnetic activity (squares).*

dates over those on the control dates, and their uncertainty. For the above data set, we find and excess daily claims rate of $(n_{\rm B,i} - n_{\rm B,c}) \pm \sigma_{\rm B} = 0.20 \pm 0.08$. The uncertainty $\sigma_{\rm B}$ is in this case determined by repeated random sampling of the claims sample for exposure and control dates, and subsequently determining the standard deviation in a large sample of resulting excess frequencies (using the so-called bootstrap method). The distribution of excess frequencies (shown in the righthand panel of Fig. 6) is essentially Gaussian, so that the metric of the standard deviation gives a useful value to specify the uncertainty. We note that the value of $\sigma_{\rm B}$ is comparable to the value $\sigma_{a,c} = (\sigma_{\rm a}^2 + \sigma_{\rm b}^2)^{1/2}$ derived by combining the standard deviations for the numbers of claims per day for geomagnetically active dates and the control dates, which in this case equals $\sigma_{a,c} = 0.07$. Thus, despite the skewness of the claim count distributions relative to a Poisson distribution as shown in the example in the left panel of Fig. 6, the effect of that on the uncertainty in the excess claims rate is relatively small. For this reason, we show the standard deviations on the mean frequencies in Figs. 5-10 as a useful visual indicator of the significance of the differences in mean frequencies.

Fig. 7 shows the relative excess claims frequencies, i.e., the relative differences $r_e = (n_i - n_c)/n_c$ between the claim frequencies on geomagnetically active dates and those on the control dates, thus quantifying the claim fraction statistically associated with elevated geomagnetic activity. The uncertainties shown are computed as $\sigma_e =$

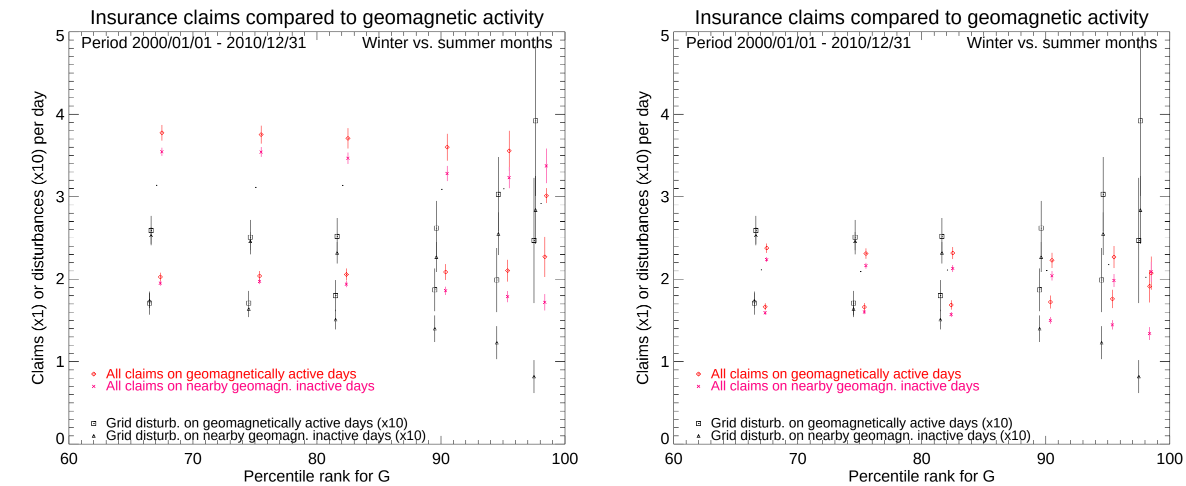


**Figure 9.** *As Fig. 5 but separating the winter half year (October through March) from the summer half year (April through September), for the full sample of insurance claims (set* A*, left) and the sample from which claims likely unrelated to any space weather influence have been removed (set* B*, right). Values for the summer months are shown offset slightly towards the left of the percentiles tested (98, 95, 90, 82, 75, and 67) while values for the winter months are offset to the right. Values for the winter season are systematically higher than those for summer months.*

$(\sigma_i^2/n_i^2 + \sigma_c^2/n_c^2)^{1/2}\, r_e$, i.e., using the approximation of normally distributed uncertainties, warranted by the arguments above. We note that the relative rate of claims statistically associated with space weather is slightly higher for sample $B$ than for the full set $A$ consistent with the hypothesis that the claims omitted from sample $A$ to form sample $B$ were indeed preferentially unaffected by geomagnetic activity. Most importantly, we note that the rate of claims statistically associated with geomagnetic activity increases with the magnitude of that activity.

About 59% of the claims in sample $B$ attribute the case of the problem to "Misc.: Electrical surge", so that we can be certain that some variation in the quality or continuity of electrical power was involved. Fig. 8 shows the relative excess claims rate $(n_i - n_c)/n_c$ as function of threshold for geomagnetic activity. We compare these results with the same metric, based on identical selection procedures, for the frequency of disturbances in the high-voltage power grid (squares). We note that these two metrics, one for interference with commercial electrical/electronic equipment and one for high-voltage power, agree within the uncertainties, with the possible exception of the infrequent highest geomagnetic activity (98 percentile) although there the statistical uncertainties on the mean frequencies are so large that the difference is less than 2 standard deviations in the mean values.

To quantify the significance of the excess claims frequencies on geomagnetically active days we perform a non-parametric Kolmogorov-Smirnov (KS) test of the null hypothesis that the claims events on active and on control days could be drawn from the same parent sample. The resulting $p$ values from the KS test, summarized in Table 1, show that it is extremely unlikely that our conclusion that geomagnetic activity has an impact on insurance claims could be based on chance, except for the highest percentiles

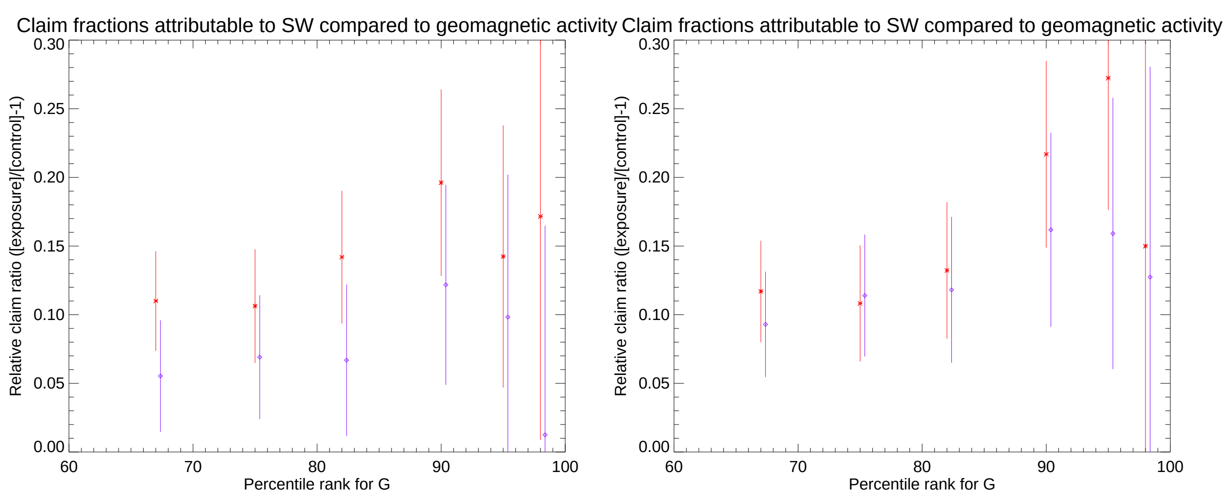


**Figure 10.** *Relative excess claim frequencies* $(n_i - n_c)/n_i$ *on geomagnetically active dates relative to those on control dates for geomagnetic latitudes below* $49.^\circ 5\,N$ *(asterisks, red) compared to those for higher latitudes (diamonds, purple; offset slightly to the right) for the percentiles tested (98, 95, 90, 82, 75, and 67). The lefthand panel shows the results for the full sample (A), and the righthand panel shows these for sample B from which apparently non-space-weather related events were removed (see Section 2.1).*

**Table 1.** Probability ($p$) values based on a Kolmogorov-Smirnov test that the observed sets of claims numbers on geomagnetically active dates and on control dates are drawn from the same parent distribution, for date sets with the geomagnetic activity metric $G$ exceeding the percentile threshold in the distribution of values.

| Percentile | All claims | | Attr. to electr. surges | |
|---|---|---|---|---|
| | set $A$ | set $B$ | set $A$ | set $B$ |
| 67 | $2.\times10^{-10}$ | $2.\times10^{-19}$ | $1.\times10^{-27}$ | 0 |
| 75 | $3.\times10^{-7}$ | $4.\times10^{-14}$ | $8.\times10^{-20}$ | $4.\times10^{-35}$ |
| 82 | 0.0004 | $2.\times10^{-7}$ | $1.\times10^{-13}$ | $6.\times10^{-24}$ |
| 90 | 0.010 | 0.0002 | $1.\times10^{-7}$ | $8.\times10^{-13}$ |
| 95 | 0.05 | 0.013 | 0.0001 | $2.\times10^{-7}$ |
| 98 | 0.33 | 0.06 | 0.003 | 0.0001 |

in which the small sample sizes result in larger uncertainties. We note that the $p$ values tend to decrease when we eliminate claims most likely unaffected by space weather (contrasting set $A$ with $B$) and when we limit either set to events attributed to electrical surges: biasing the sample tested towards issues more likely associated with power-grid variability increases the significance of our findings that there is an impact of space weather.

Fig. 9 shows insurance claims differentiated by season: the frequencies of both insurance claims and power-grid disturbances are higher in the winter months than in the summer months, but the excess claim frequencies statistically associated with geomagnetic activity follow similar trends as for the full date range. The same is true when looking at the subset of events attributed to surges in the low-voltage power distribution grid.

Figure 11 shows a similar diagram to that on left-hand side of Fig. 9, now differentiating between the equinox periods and the solstice periods. Note that although the claims frequencies for the solstice periods are higher than those for the equinox periods, that difference is mainly a consequence of background (control) frequencies: the fractional excess frequencies on geomagnetically active days relative to the control dates are larger around the equinoxes than around the solstices.

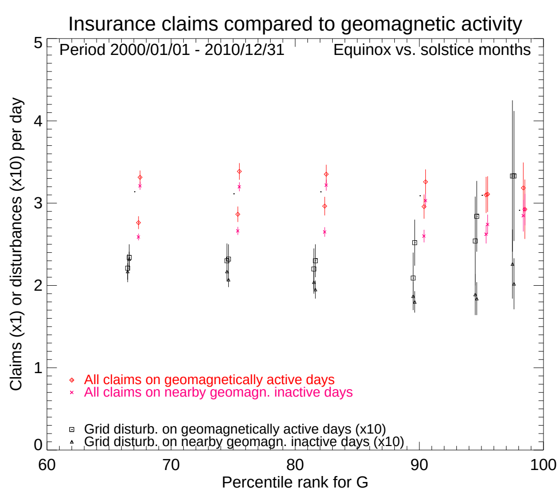


**Figure 11.** *As Fig. 9 but separating the months around the equinoxes (February-April and August-October) from the complementing months around the solstices, for the full sample of insurance claims (set* A*). Values for the equinox periods are shown offset slightly towards the left of the percentiles tested (98, 95, 90, 82, 75, and 67) while values for the solstice months are offset to the right. Mean claims frequencies for the solstice periods are systematically higher than those for equinox periods, but the frequencies for high-G days in excess of the control sample frequencies is slightly larger around the equinoxes than around the solstices.*

Fig. 10 shows the comparison of claim ratios of geomagnetically active dates relative to control dates for states with high versus low geomagnetic latitude, revealing no significant contrast (based on uncertainties computed as described above for Fig. 7).

## 4. Discussion and conclusions

We perform a statistical study of North-American insurance claims for malfunctions of electronic and electrical equipment and for business interruptions related to such malfunctions. We find that there is a significant increase in claim frequencies in association with elevated variability in the geomagnetic field, comparable in magnitude to the increase in occurrence frequencies of space weather-related disturbances in the high-voltage power grid. In summary:

- The fraction of insurance claims statistically associated with geomagnetic variability tends to increase with increasing activity from about $5-10\%$ of claims for the top third of most active days to approximately 20% for the most active few percent of days.
- The overall fraction of all insurance claims statistically associated with the effects of geomagnetic activity is $\approx 4\%$. With a market share of about 8% for Zurich NA in this area, we estimate that some 500 claims per year are involved overall in North America.
- Disturbances in the high-voltage power grid statistically associated with geomagnetic activity show a comparable frequency dependence on geomagnetic activity as do insurance claims.
- We find no significant dependence of the claims frequencies statistically associated with geomagnetic activity on geomagnetic latitude.

For our study, we use a quantity that measures the rate of change of the geomagnetic field regardless of what drives that. Having established an impact of space weather on users of the electric power grid, a next step would be to see if it can be established what the relative importance of various drivers is (including variability in the ring current, electrojetc, substorm dynamics, solar insolation of the rotating Earth, ...), but that requires information on the times and locations of the impacts that is not available to us.

The claims data available to us do not allow a direct estimate of the financial impacts on industry of the malfunctioning equipment and the business interruptions attributable to such malfunctions: we do not have access to the specific policy conditions from which each individual claim originated, so have no information on deductable amounts, whether (contingency) business interruptions were claimed or covered or were excluded from the policy, whether current value or replacement costs were covered, etc. Moreover, the full impact on society goes well beyond insured assets and business interruptions, of course, as business interruptions percolate through the complex of economic networks well outside of direct effects on the party submitting a claim. A sound assessment of the economic impact of space weather through the electrical power systems is a major challenge, but we can make a rough order-of-magnitude estimate based on existing other studies as follows.

The majority (59% in sample B) of the insurance claims studied here are explicitly attributed to "Misc.: electrical surge", which are predominantly associated with quality or continuity of electrical power in the low-voltage distribution networks to which the electrical and electronic components are coupled. Many of the other stated causes (see

Section 2.1) may well be related to that, too, but we cannot be certain given the brevity of the attributions and the way in which these particular data are collected and recorded. Knowing that in most cases the damage on which the insurance claims are based is attributable to perturbations in the low-voltage distribution systems, however, suggests that we can look to a study that attempted to quantify the economic impact of such perturbations on society.

That study, performed for the Consortium for Electric Infrastructure to Support a Digital Society" (CEIDS) [*Lineweber and McNulty*, 2001], focused on the three sectors in the US economy that are particularly influenced by electric power disturbances: the digital economy (including telecommunications), the continuous process manufacturing (including metals, chemicals, and paper), and the fabrication and essential services sector (which includes transportation and water and gas utilities). These three sectors contribute approximately 40% of the US Gross Domestic Product (GDP).

*Lineweber and McNulty* [2001] obtained information from a sampling of 985 out of a total of about 2 million businesses in these three sectors. The surveys assessed impact by "direct costing" by combining statistics on grid disturbances and estimates of costs of outage scenarios via questionnaires completed by business officials. Information was gathered on grid disturbances of any type or duration, thus resulting in a rather complete assessment of the economic impact. The resulting numbers were corrected for any later actions to make up for lost productivity (actions with their own types of benefits or costs).

For a typical year (excluding, for example, years with scheduled rolling blackouts due to chronic shortages in electric power supply), the total annual loss to outages in the sectors studied is estimated to be $46 billion, and to power quality phenomena almost $7 billion. Extrapolating from there to the impact on all businesses in the US from all electric power disturbances results in impacts ranging from $119 billion/year to $188 billion/year (for about year-2000 economic conditions).

Combining the findings of that impact quantification of all problems associated with electrical power with our present study on insurance claims suggests that, for an average year, the economic impact of power-quality variations related to elevated geomagnetic activity may be a few percent of the total impact, or several billion dollars annually. That very rough estimate obviously needs a rigorous follow-up assessment, but its magnitude suggests that such a detailed, multi-disciplinary study is well worth doing.

**Acknowledgments.** We are grateful to the three reviewers of our manuscript for their guidance to improve the presentation of our results. This work was supported by Lockheed Martin Independent Research funds (CJS, SMP). The results presented in this paper rely on data collected at magnetic observatories. We thank the national institutes that support them and INTERMAGNET for promoting high standards of magnetic observatory practice (www.intermagnet.org). The insurance claims data are accessible at http://www.lmsal.com/∼schryver/claims/claims.csv.

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# Generator Thermal Stress during a Geomagnetic Disturbance

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***Abstract*— this paper investigates the operating condition of the generator during a Geomagnetic Disturbance (GMD). Generators are sensitive to harmonics and negative sequence currents, caused by the half-cycle saturation of the generator step-up transformer due to Geomagnetically Induced Current. Such harmonic currents can cause rotor heating, alarming, and the loss of generation.**

**Based on the time-domain simulation in the EMTP, this study investigates the order and magnitude of the harmonics which impact the generator, and determines the rotor heating level due to such harmonics, at various levels of the GIC. The study reveals that the generator can reach its thermal capability limit at moderate GIC levels. However, the existing standards, e.g., IEEE Standards C50.12 and C50.13, fail to account for such operating conditions, and the corresponding recommendations underestimate the rotor heating level. As such, the negative sequence relays may not accurately operate under GMDs. A modification to the standards is also required which is proposed in this study.**

***Index Terms*-- Generator, Power Transformer, Geomagnetically Induced Current, Negative Sequence Relay.**

## I. INTRODUCTION

Geomagnetic disturbance or Solar Magnetic Storm refers to the phenomena caused by the solar flare and coronal mass ejection activities. Due to explosion on the sun surface, a large amount of the charged particles, which is also known as the solar wind, is released to the space. If the solar wind strikes the earth, it distorts the dc magnetic field of the earth and a slowly varying voltage is induced in the earth and on the power transmission lines. The induced dc voltage is discharged to ground through the grounded neutral of the power transformers and generates a quasi-dc current which is referred to as Geomagnetically Induced Current (GIC). The GIC biases the transformer core in one direction, and causes a half-cycle saturation. The saturation of transformers in turn increases the reactive power demand which endangers the power system stability. Furthermore, the unidirectional saturation of transformers creates harmonics which can cause several adverse consequences in the power system [1]-[3]. The Hydro-Quebec power system blackout and the failure of a Generator Step-Up (GSU) transformer in Salem nuclear plant, New Jersey, on March 13, 1989 are examples of the consequences of a GMD event [4]-[6].

The operation condition of generators is also influenced by the GIC. During a GMD, the increase of the reactive power demand due to the saturation of the system transformers should be compensated by the generators. As such, the generator field current increases to respond to the increase of the VAR demand. This in turn may raise another concern that the VAR generation limit of the generator can be reached, and the generator is not able to further inject reactive power to the system and regulate the system voltage.

Generators are sensitive to harmonics and the fundamental frequency negative sequence current. The negative sequence current due to the voltage imbalance induces a twice frequency in the rotor, and causes rotor heating [7]. Similarly, the current harmonics induce eddy current in the rotor surface, and produce additional power loss and excessive rotor heating [7]. Another undesired impact of harmonics and negative sequence currents is the generation of the oscillatory torque and vibration of the generator. As such, the mechanical parts of the generator are subjected to mechanical stress and the risk of damage. During the past GMD events, several abnormal conditions associated with the generators have been reported [3]. However, a quantitative investigation of the magnitude of the generator negative sequence current and the current harmonics under a geomagnetic disturbance has not been carried out.

In this paper, the magnitude and the order of the harmonics generated by the saturated transformer due to GIC are determined. Based on the time-domain simulation of a generation unit including the generator, the connected 500kV GSU transformer, and the transmission line, the harmonics and the negative sequence current impressed on the generator are obtained. This study reveals that the generator can reach its

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thermal capability limit at moderate GIC levels and the available standards do not address this issue.

## II. Saturation of GSU Transformer due to GIC

When the GSU transformer is subjected to GIC, the dc current generates a dc flux offset in the core and results in a shift in the core flux, Fig. 1. The ac flux due to the system voltage is superimposed on the dc flux. If the peak of the total flux enters the saturation region of the core magnetization characteristic, the transformer is driven into a half-cycle saturation, as shown in Fig. 1. The normal transformer magnetizing current ImAC, which is small under symmetric excitation condition, increases to the unidirectional magnetizing current ImGIC, under the GIC conditions.

Fig. 2 depicts the frequency spectrum of the magnetizing current of a typical three-phase 500kV-750 MVA power transformer, when the transformer is subjected to the GIC magnitude of 100A at the neutral point of the transformer. This current corresponds to 33.3 A/phase GIC, since the geomagnetic disturbance induces the same magnitude of GIC on the three phases. Due to both unsymmetrical excitation and the core nonlinearity, the magnetizing current contains both even and odd harmonics. The frequency spectrum of Fig. 2 also reveals that the magnitudes of the harmonics are comparable with the fundamental component. Furthermore, the magnitude of the dominant harmonics gradually decreases as the order of harmonics increases. Fig. 3 shows the total harmonic distortion (THD) of the magnetizing current which exceeds 200% at the lower levels of GIC and decreases at higher GIC levels. The flow of the harmonics in the power system creates power loss, can overload the capacitor banks, increases the possibility of the resonance in the power system, and may cause mal-operation of the protective relays due to the distorted voltage and current signals.

In addition to the harmonic generation, the fundamental frequency component of the magnetizing current significantly increases with the applied GIC. Therefore, when a power system is exposed to a GMD event, the reactive power demand of the system increases. This in turn degrades the system voltage regulation and can endanger the system voltage stability. Under such conditions, maintaining the capacitor banks in service is a requirement, while they can be under stress due to the imposed harmonics. This implies that the protection settings need to be properly chosen to keep the capacitor bank in service as for as the impressed stress does not damage the capacitor.

## III. System under Study and the Equipment Models

Fig. 4 illustrates the system under study. The generation unit includes a 26kV-892.4MVA turbo generator and the corresponding step-up transformer. The parameters of the generator are given in the Appendix. The GSU transformer is a transformer bank consisting of three single-phase units. The three-phase transformer is rated 525/26kV – 920 MVA, with a short circuit impedance of %14. The winding connection of the transformer is delta on the generator side and grounded wye on the high-voltage side. The generation unit is connected to the power grid through a 500kV transmission

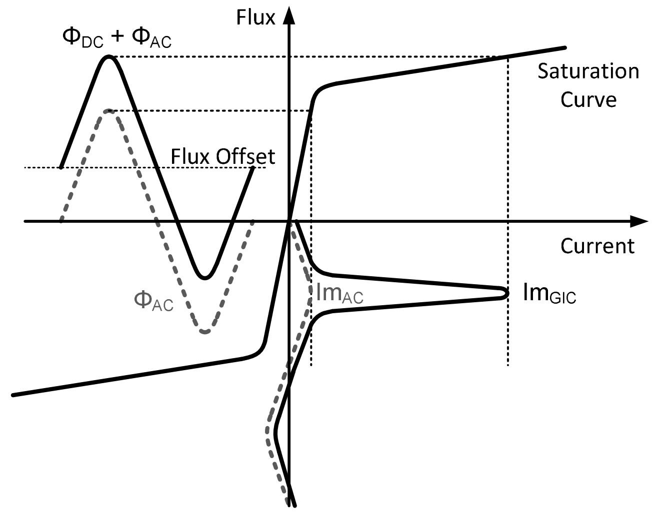


Fig. 1. Half-cycle saturation of the transformer core due to GIC

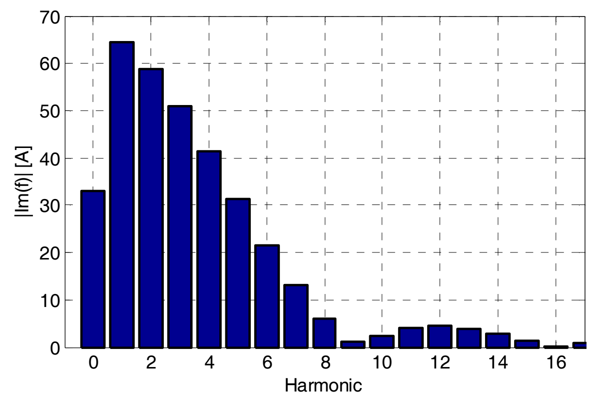


Fig. 2. Harmonics of the transformer magnetizing current at GIC=33.3 A/phase (100A at the neutral of the transformer)

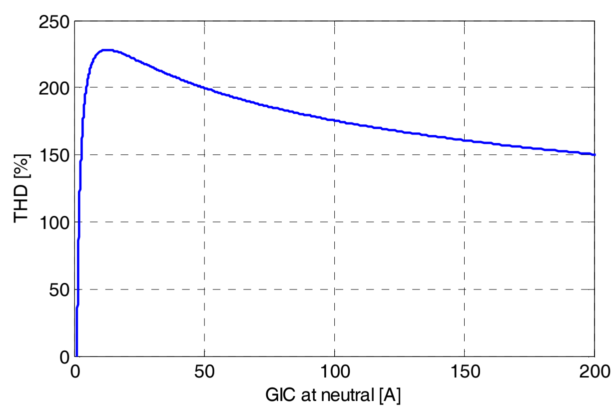


Fig. 3. Total Harmonic Distortion (THD) of the transformer magnetizing current under various GIC levels seen at the transformer neutral

line with the length of 170km and the parameters given in the Appendix. The transmission line is modeled based on a frequency-dependent representation, which takes into account the actual configuration of the conductors. The line is not transposed and therefore, represents an unbalanced voltage at the GSU transformer high voltage terminals. The 500kV power grid is represented by a thevenin equivalent with the

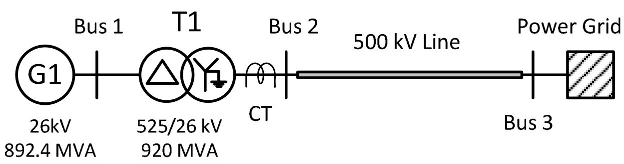


Fig. 4. System under study

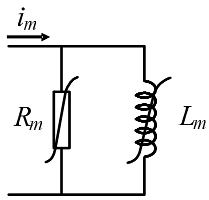


Fig. 5. Transformer core model with a dynamic core loss resistance

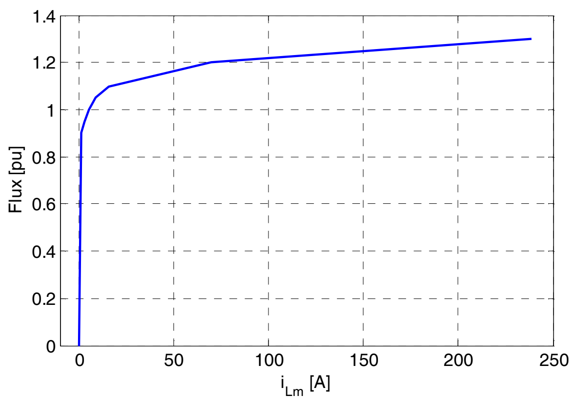


Fig. 6. Saturation curve of the GSU transformer

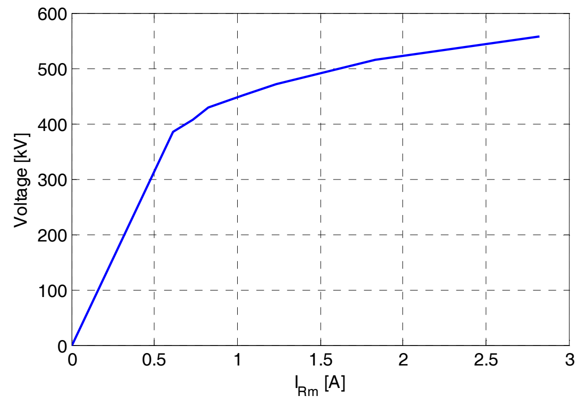


Fig. 7. Characteristic of the dynamic core loss resistance of the GSU transformer

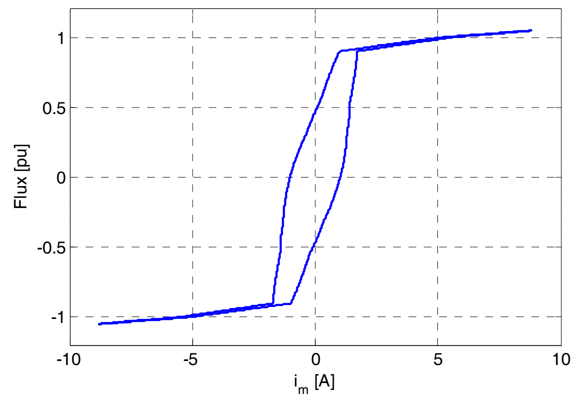


Fig. 8. Overall characteristic of the GSU transformer core at 1.1pu excitation based on the dynamic core loss model of Fig. 5 and the characteristics of Figs. 6 and 7.

equivalent impedance deduced based on the short circuit level of 50kA, at Bus 3, Fig. 4.

The main component of the system for the GIC studies is the transformer. The GSU transformer consists of three single-phase units. The transformer core is represented based on a nonlinear inductance in parallel with a nonlinear dynamic core loss resistance, Fig. 5. Figs 6 and 7 illustrate the characteristics of the nonlinear inductance and the dynamic core loss resistance, respectively. These characteristics are obtained such that the transformer no-load test current and core loss are accurately duplicated. Unlike the conventional transformer models in which the core loss resistance is constant, Fig. 7 indicates that as the excitation level increases the core loss resistance, i.e., the slope of the characteristic, decreases. Based on the characteristics of Figs. 6 and 7, Fig. 8 shows the overall characteristic of the core model of Fig. 5, which is close to an actual hysteresis core characteristic. Fig. 8 illustrates the core characteristic at the excitation level of 1.1pu.

## IV. Generator Rotor Heating due to GIC

During a geomagnetic disturbance, the saturation of power transformers causes the system imbalance and generates harmonics. Such abnormal voltage and currents subject the generator to thermal and mechanical stresses. The generators are usually protected by the negative-sequence relays which operate based on an inverse-time characteristic to maintain a permissible $I^2t$=*constant* thermal capability curve.

IEEE Standards C50.12 and C50.13 [9]-[10] provide recommendations for the negative-sequence capability of the salient-pole and cylindrical synchronous generators, respectively. For a turbo cylindrical generator, the permissible continuous negative sequence is deduced as

$$I_2 = 8-(MVA-350)/300, \qquad (1)$$

where $I_2$ is the permissible value in per-unit of the rated generator current, and *MVA* is the rated power of the generator in megavolt-ampere. Accordingly, the permissible continuous negative sequence for the generator under study is 6.2%.

The standards C50.12 and C50.13 also provide the guideline to take into account the impacts of the stator harmonic currents on the rotor heating. The recommendations are based on finding an equivalent negative sequence current which generates the same heat as that produced by the actual negative sequence and all the harmonics. The standards require that the equivalent negative sequence current shall not exceed the value calculated in (1). Furthermore, if 25% of the permissible current (1) is exceeded, the manufacturer shall be notified about the expected harmonics during the design or to determine whether or not the generator can withstand the harmonic heating. The equivalent negative sequence current is calculated as [9], [10],

$$I_{2eq} = \sqrt{I_2^{\,2} + \sum_n \sqrt{\frac{n+i}{2}} I_n^{\,2}}\,, \qquad (2)$$

where,

$i = +1$ when $n = 5, 11, 17, etc.,$

$i = -1$ when $n = 7, 13, 19, etc.$

Equation (2) is based on the fact that under continuous operating conditions, the system harmonic currents only include the odd harmonics of the fundamental frequency. In addition, the triplen harmonics appear as zero sequence currents and are eliminated by the delta winding of the GSU transformers. As such, the harmonic orders n=6k-1, k=1, 2, …, are negative sequence, and the associate air gap fluxes rotate in the opposite direction of the generator rotation. Therefore, the frequency of the induced eddy current on the rotor surface is the sum of the fundamental frequency and the harmonic frequency. On the other hand, harmonics n=6k+1, k=1, 2, …, are positive sequence harmonics and induces one order lower frequency on the rotor.

However, during a geomagnetic disturbance, both even and odd harmonics present in the generator current. Consequently, for the GIC analysis, equation (2) requires to be modified and extended to both even and odd harmonics, considering that

Negative sequence harmonics: $n = 3k-1, \quad k=1, 2,\ldots,$

Positive sequence harmonics: $n = 3k+1, \quad k=1, 2, \ldots \qquad (3)$

Since the GMD is a slowly varying event which can prolong for a few hours, the unbalanced condition and the generated harmonics caused by GIC can be considered in the context of the continuous capability of the generator. The IEEE Standard C37.102 on the protection of the AC generators [11] recommends that a relay is provided with a sensitive alarm and the negative sequence pickup range 0.03–0.20 pu to notify the operator when such a setting is exceeded.

As a case study, it is assumed that the system of Fig. 4 initially operates under normal conditions and generator $G_1$ delivers 800MW to the grid. Under such a condition, various levels of GIC are applied to the GSU transformer, and the generator negative sequence current and the current harmonics are calculated. The CPU time with a 2.53GHz dual-CPU computer is 4.3sec for obtaining the steady-state condition of each GIC level. Under the neutral GIC of 200A, Fig. 9 shows the simulated waveforms of the transformer magnetizing currents, and Fig. 10 depicts the harmonic components of the generator current. Due to the balanced GIC flowing in all phases, the dc current magnitude of the phase current is one third of the GIC observed at the neutral point of the GSU transformer. Fig. 10 indicates that the second harmonic is the dominant one, and the 4$^{th}$ and the 7$^{th}$ harmonics are also present in the generator current.

Table I summarizes the calculated fundamental component ($I_2$) and the effective negative sequence current ($I_{2eq}$) of the generator for various levels of the neutral GIC, in the range of 100A to 300A. Such a GIC range is considered as the moderate level of GMD. Based on the permissible negative sequence current of 6.19%, Table I reveals that at the moderate neutral GIC of 150A and higher, the effective negative sequence current exceeds the capability limit of the generator and can cause damage to the generator rotor. Even if the negative sequence relay of the generator filters the harmonics, the fundamental frequency of the negative sequence current (I2) is within the alarming range (higher than 3%) at the significantly lower GIC levels.

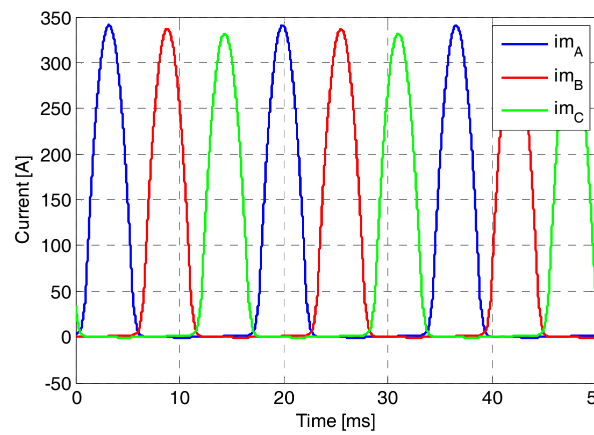


Fig. 9. Generator current harmonics under GIC of 200A at the neutral of the GSU transformer

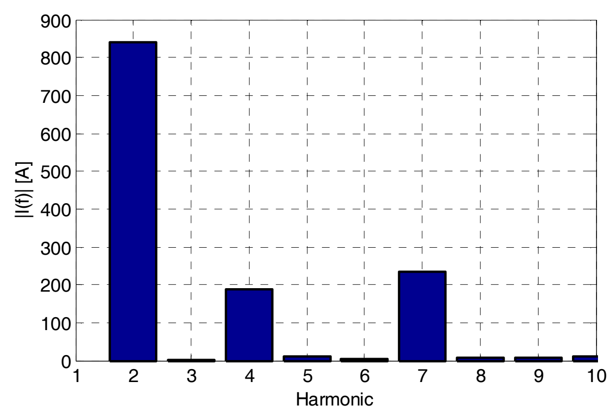


Fig. 10. Generator current harmonics under the transformer neutral GIC of 200A

TABLE I

FUNDAMENTAL FREQUENCY AND EFFECTIVE NEGATIVE SEQUENCE CURRENTS WHICH CAUSE ROTOR HEATING AT VARIOUS GIC LEVELS (PERMISSIBLE $I_{2EQ}$=6.19%)

| GIC at neutral (A) | HV bus voltage THD (%) | $I_2$ (%) | $I_{2eq}$ (%) |
|---|---|---|---|
| 100 | 1.38 | 4.28 | 5.37 |
| 150 | 2.24 | 4.39 | 6.20 |
| 200 | 2.71 | 4.41 | 6.78 |
| 250 | 2.51 | 4.58 | 7.48 |
| 300 | 2.13 | 4.71 | 8.07 |

## V. CONCLUSIONS

In this study, the magnitudes of the negative sequence current and the harmonic currents which impressed on the generator during a Geomagnetic Disturbance (GMD) are investigated. The harmonics are generated by the half-cycle saturation of the GSU transformer due to the GIC. Such harmonic currents cause rotor heating, can result in the mal-operation of protective relays, and the loss of generation.

Based on the time-domain simulation, this study indicates that the relevant IEEE standards C50.12 and C50.13 require modifications to take into account the even harmonics of the generator current during a GMD event. The standards underestimate the effective negative sequence current which contributes to the rotor heating. Such an effective current determines the capability limit of the generator to withstand the fundamental negative sequence and harmonic currents and is a basis for the associated relay settings. The simulation results reveal that the generator capability limit can be exceeded at moderate GIC levels, e.g. 50A/phase, and the rotor damage is likely during a severe GMD event.

## VI. APPENDIX

The generator data are based on the benchmark [8] as follows,

| Parameter | Value |
|---|---|
| $X_d$ | *1.79 pu* |
| $X'_d$ | *0.169 pu* |
| $X''_d$ | *0.135 pu* |
| $X_q$ | *1.71 pu* |
| $X'_q$ | *0.228 pu* |
| $X''_q$ | *0.2 pu* |
| $T'_{do}$ | *4.3 s* |
| $T''_{do}$ | *0.032 s* |
| $T'_{qo}$ | *0.85 s* |
| $T''_{qo}$ | *0.05 s* |
| $X_l$ | *0.13 pu* |
| $R_l$ | *0.0 pu* |

The transmission line data in per unit of 100 MVA and 500 kV are as follows. Subscripts 1 and 0 stand for positive and zero sequence impedances, respectively.

| Parameter | Value |
|---|---|
| $R_1$ | *0.00189647 pu* |
| $X_1$ | *0.0214564 pu* |
| $B_1$ | *2.23483961 pu* |
| $R_0$ | *0.022752 pu* |
| $X_0$ | *0.074057 pu* |
| $B_0$ | *0.952363 pu* |

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China Data Compared to Draft NERC Std

| | | | |
|---|---|---|---|
| Geomagnetic Lattitude | 12.7 | deg | (furthest north point<br>geomagnetic Lattituc |
| Alpha Latitude Scaling Factor | 0.00431 | | extrapolatede with f |
| Beta Soil Factor | 0.9 | | No value supplied so |
| E from NERC Formula (V/km) | 0.03 | V/km | NERC Std for a One |
| Observed E (V/km) in China | 0.67 | V/km | 29 - 30 May 2005 Str<br>or 0.2 nT/s) Not a Or |
| Ratio = Obs (2005) / NERC Field | 22 | | This ratio is comparir<br>a severe One Hundre |

in China grid is 12.7 degrees
de)

ormula 0.001*EXP(0.115*12.7)

assumed a high value of 0.9

Hundred Year Storm (i.e. 4,800 nT/min)

om, Weak K7 Strom, dB/dt = 30 nT/min (
ne Hundred Year Storm

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**SUPPLEMENTAL COMMENT OF REP. ANDREA BOLAND**

I'd like to add the following, on behalf of the people of Maine and the 182 of the 185 members of the Maine State Legislature who voted to have the Maine PUC provide a report on the best information available to advise the Maine Legislature on the vulnerabilities of the Maine electric grid and the options available for protecting it. Hearings and work sessions before the Joint Committee on Energy, Utilities and Technology, on this legislation showed the electric utilities and ISO-New England to first be in denial of any real problem from GMD, and then be startlingly unable to answer many technical and operational questions posed to them b committee members. They repeatedly referred to NERC as the authority they follow, so their weak presentation diminished the confidence we might otherwise have had in NERC's own expertise and guidance. The engineer representative from ISO-New England was particularly disappointing.

Unfortunately, the Maine PUC's work has continued to look towards the utilities and NERC standards for authoritative information, even in the face of the far more detailed examinations by nationally known experts that was presented to them, and despite Central Maine Power's own historical, real-world data that was made available to them in the committee meetings. In the last scheduled meeting of the study task force, we had two presentations. One, building off Power World modeling and real-world data, found it would be important to protect eighteen of our most important transformers with neutral ground blockers and GIC monitors to achieve a survivable level of protection. The Central Maine Power presentation found it was not necessary to do anything at all, using NERC benchmarks and suppositions; they did not use their own real-world data or give answers as to why they had not.

As a state legislator, in touch with many national experts on science and policy, I have worked at understanding the problem of poor or absent standards and their consequences for the protection of the electric grid. I have studied the potential protections available, and the very low costs for critical, tested equipment that could save the State of Maine from societal and economic collapse. The costs would be pennies per household per year for just about five years. Average legislators and lay people easily see the sense of installing such protective equipment, finding that, "If it's good enough for Idaho National Labs, it should be good enough for us." It's clearly very cheap insurance. The question we all have is, "Why is this job not getting done?" The answer seems to lie ultimately with NERC and a seemingly compromised FERC, as they seem to exert so much influence over the lives of Americans.

The states are within their rights to protect their own electric grids, and several are working to do it. They should not be subjected to lies and pretensions that can threaten to compromise their own processes. I'd like to ask, as a representative of the Maine public, that NERC either find the integrity to produce, in a timely way, the excellent work product that is expected of them, and live up to the duty entrusted to them, or get out of the way of those who are more conscientiously and expertly advising the electric utilities of the United States of America.

Respectfully submitted,

Andrea Boland

Representative Andrea Boland
Sanford, Maine

**Comments of John Kappenman, Storm Analysis Consultants & Curtis Birnbach, Advanced Fusion Systems Regarding NERC Draft Standard on GIC Observations and NERC Geo-Electric Field Modelling Inaccuracies**

Several comments have been provided to the NERC SDT by this commenter which the NERC SDT has failed to properly assess , interpret the data and analysis provided in these comments[1,2].

The NERC SDT claimed to have examined the Chester geo-electric field using Ottawa 5 second cadence data and concluded that the geo-electric field would be substantially larger than 1 V/km calculated using the NERC modeling methods from NRCan Ottawa 1 minute data. In the White Paper, the GIC observed at Chester and a detailed knowledge of the grid verifies that the actual geo-electric field was ~2 V/km during the May 4, 1998 storm. For reasons not explained by the NERC SDT, they failed to use the 10 second cadence magnetometer data actually measured at Chester but instead only used the high cadence data from Ottawa which was over 550kM west of Chester. This Chester data was provided in Figure 15 of the Kappenman/Radasky white paper which was submitted in July 2014 and the data and comments related to that data are provided in Figure 1 of this document.

At the time that the White Paper was submitted, NERC had not yet made publicly available their geo-electric field simulation model. Therefore it was not possible to independently test the NERC model results for the 10 second data at Chester and 1 minute data from Ottawa had to be used instead, which was publicly available. Because the NERC Model is now available, this model can now be used to calculate the geo-electric field at Chester using the Chester 10 second magnetometer data and provide an even more detailed examination of the degree of error that this model is producing versus actual observations. Figure 2 provides a comparison of the 10 sec cadence magnetometer data in the NERC model versus the previously discussed 1 minute data. As this comparison shows, the NERC model using the 10 sec data still provides only a geo-electric field peak of ~1 V/km, rather than the 2 V/km necessary to agree with actual GIC observations. As discussed in the White Paper, the NERC Model is understating the actual peak by nearly a factor of 2 at this location, a large uncertainty.

1. John Kappenman, William Radasky, "Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard" White Paper comments submitted on NERC Draft Standard TPL-007-1, July 2014.
2. Kappenman, Birnbach , Comments Submitted to NERC on October 10, 2014

Figure 1 – Figure from Kappenman/Radasky White Paper showing locally measured 10 sec magnetometer data from Chester versus the Ottawa 1 minute data around the critical 4:39UT time span

At Chester some limited 10 second cadence magnetometer data was also observed during this storm, and Figure 15 provides a plot of the delta Bx at Ottawa (1 minute data) compared with the Chester delta Bx (10 sec) during the electrojet intensification at time 4:39UT. As this comparison illustrates that at this critical time in the storm, the disturbances at both Ottawa and Chester were nearly identical in intensity.

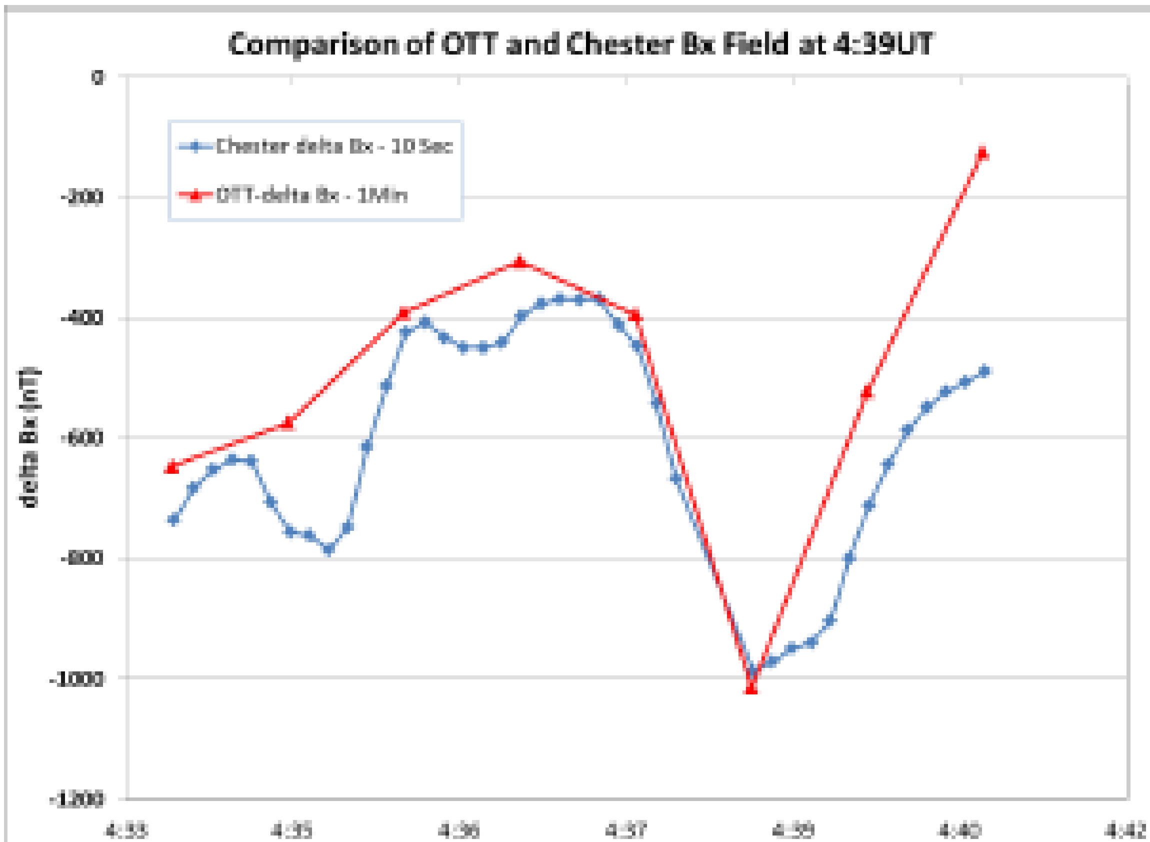
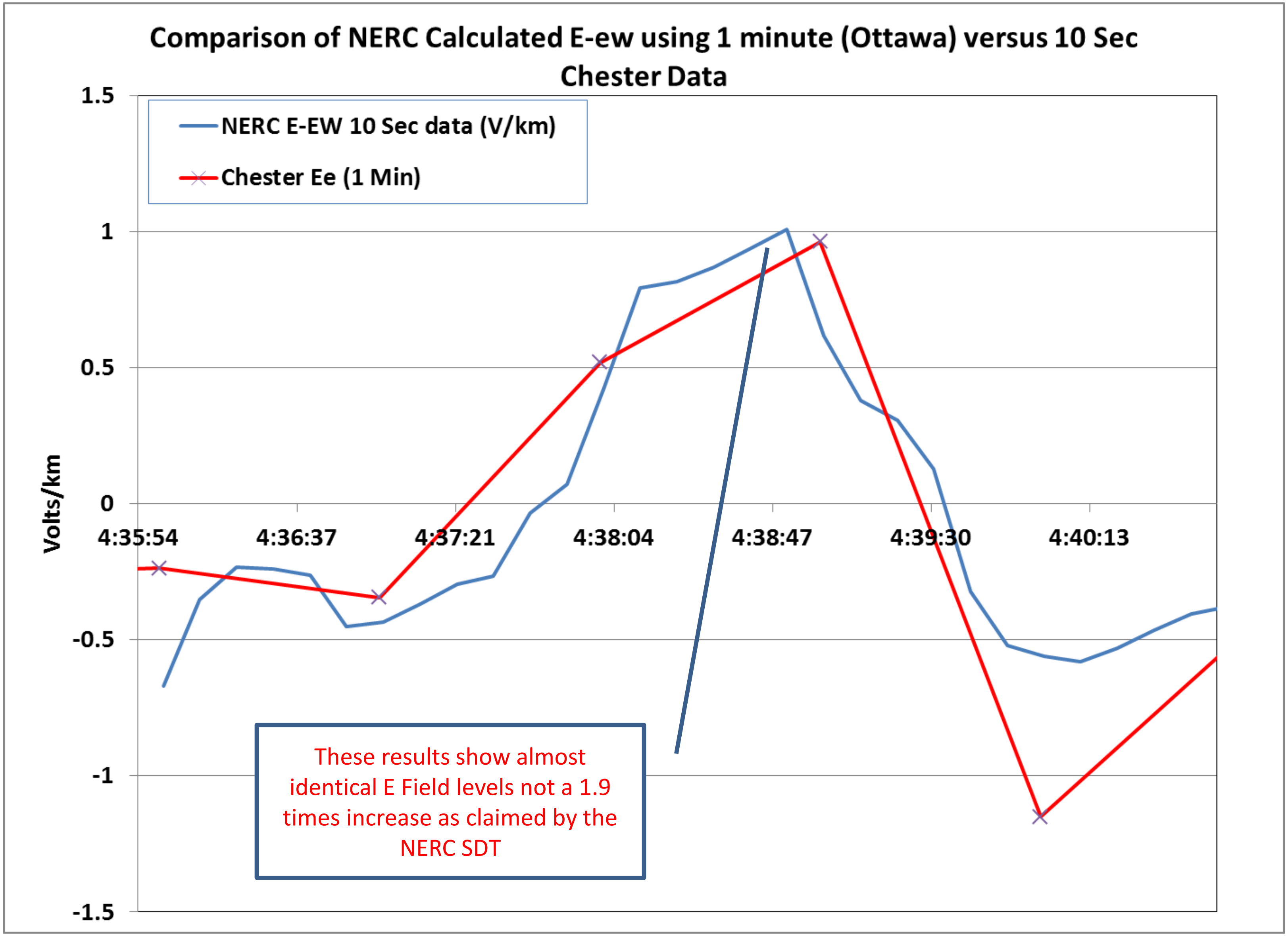



Figure 15 – Observation of Bx at Ottawa and Chester during peak impulse at time 4:39UT.

Figure 2 – Results of the NERC geo-electric field simulation model developed by Marti, et. al., with input of the 10 sec data over this study period.



The NERC SDT in their brief and inadequate response to the Kappenman/Radasky White Paper responded with the following sentence, as shown below:

> *"The method has been shown in numerous studies to accurately map the observed ground magnetic field to the geoelectric field and observed GIC (e.g., Trichtchenko et al., 2004; Viljanen et al., 2004; Viljanen et al., 2006; Pulkkinen et al., 2007; Wik et al., 2008)."*

These papers are all papers that Pulkkinen from the NERC SDT has co-authored and they also consistently confirm the same symptomatic geo-electric field simulation errors noted in the Kappenman/Radasky White Paper. In that for high dB/dt impulses, the calculated geo-electric field and resulting GIC simulations are severely understated. For example when looking at results published in the Viljanen, Pulkkinen 2004 publication noted above, the same greater than factor of 2 error shows up again in this paper as well. Figure 3 provides a model validation simulation which is Figure 8 from this paper[3]. In this figure, the intense GIC spike is highlighted in red and how the model results significantly diverge from measured GIC for these important intensifications. Figure 4 provides a plot of the observed geomagnetic field dB/dt for this same storm for an observatory close to the GIC observations and model validation provided in Figure 3. As this analysis clearly shows, at the peak dB/dt of ~500 nT/min, the Pulkkinen model diverges from reality by approximately a factor of 2 too low. This exhibits an identically similar pattern of error and low estimates as noted in Figures 31 and 32 of the Kappenman/Radasky White Paper when examining other published work of Pulkkinen. Hence the publications the NERC SDT has cited as being important to prove their model integrity, actually continue to show serious and pronounced systematic errors that have been made in their modeling approaches.

3. Fast computation of the geoelectric field using the method of elementary current systems and planar Earth models, A. Viljanen, A. Pulkkinen, O. Amm, R. Pirjola, T. Korja,*, and BEAR Working Group

Figure 3 – GIC Model validation from Viljanen, Pulkkinen paper with GIC modeling errors noted.

110 A. Viljanen et al.: Fast computation of the geoelectric field

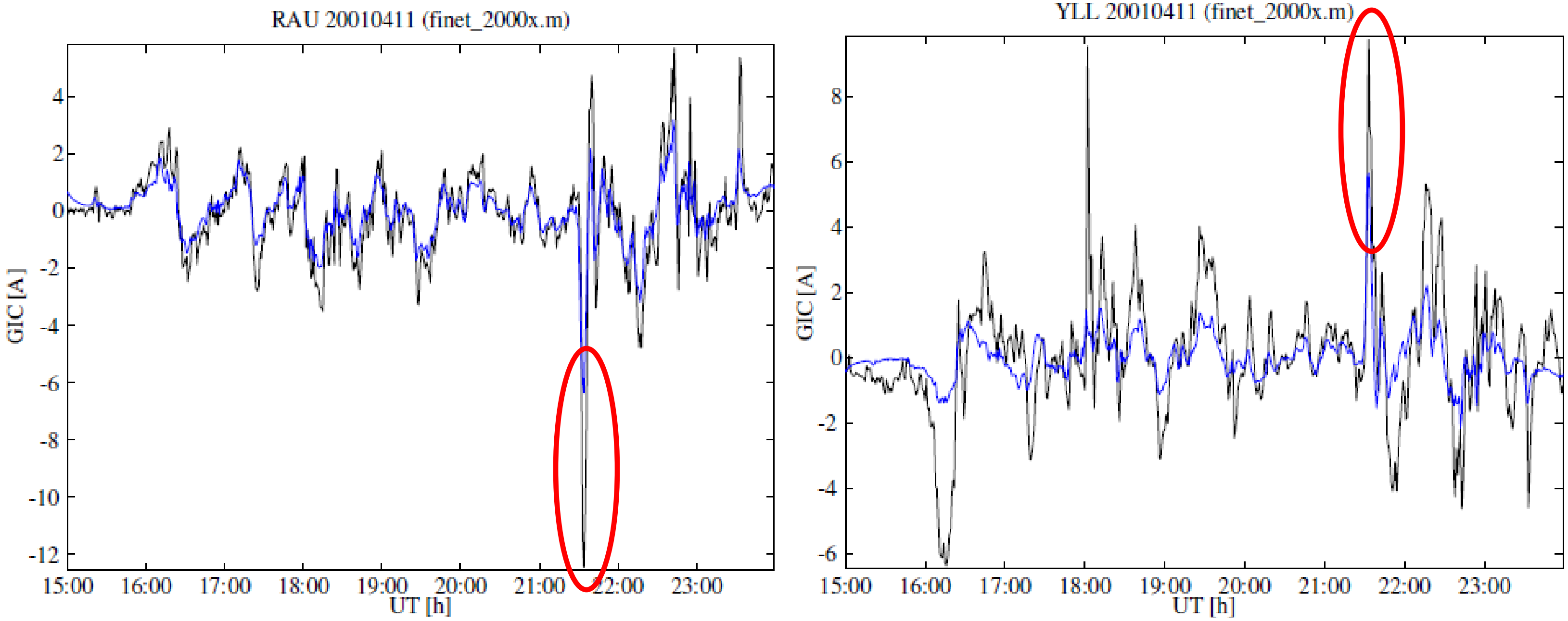
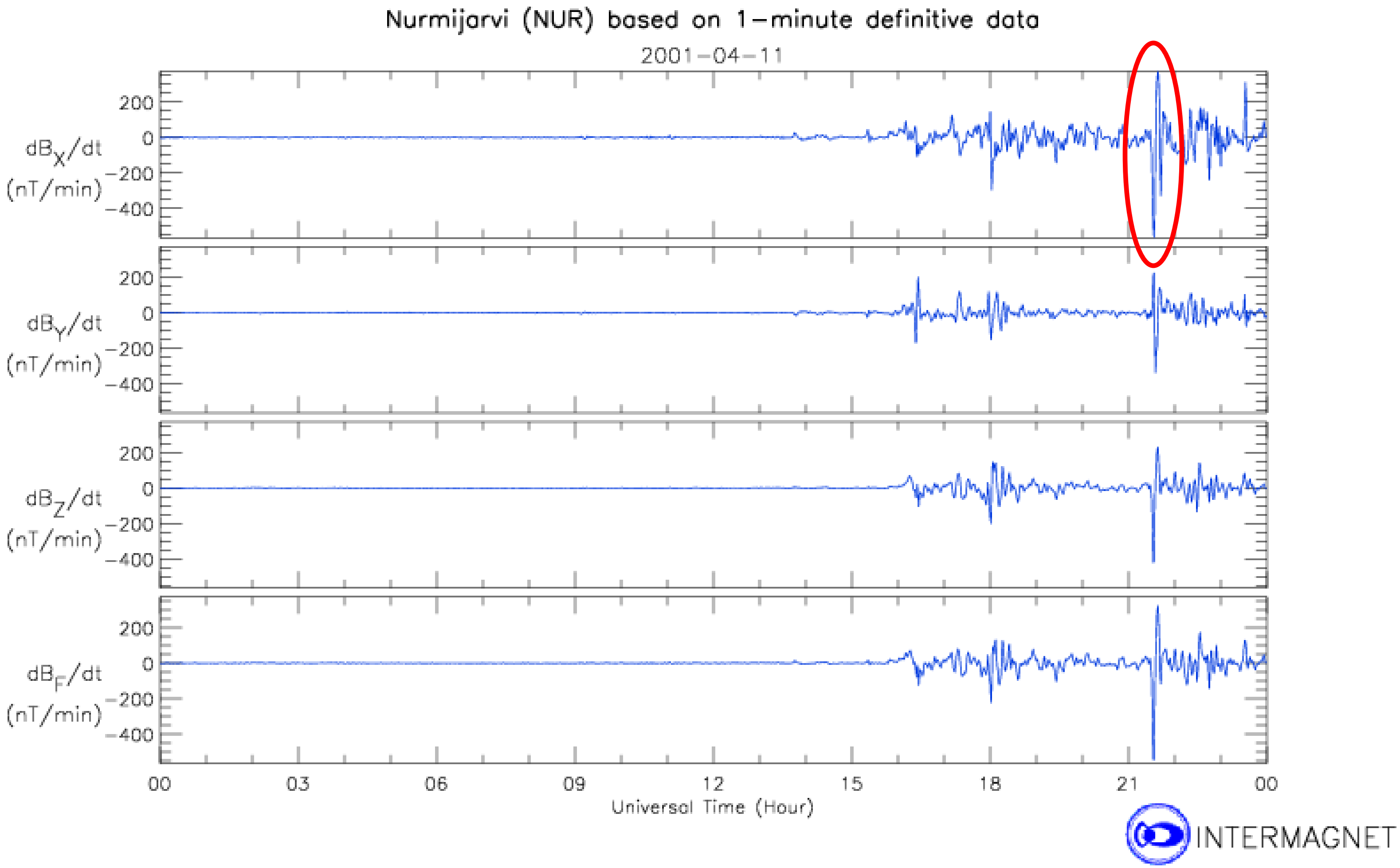



**Fig. 8.** Measured (black line) and modelled (blue line) geomagnetically induced currents at the Rauma (RAU) and Yllikkälä (YLL) 400 kV transformer stations on 11 April 2001.

Figure 4 – Corresponding observed dB/dt that are associated with the Viljanen, Pulkkinen paper with GIC modeling errors noted in Figure 3.



In regards to the comments provided in Oct 2014 by Kappenman/Birnbach, the NERC SDT provided this response:

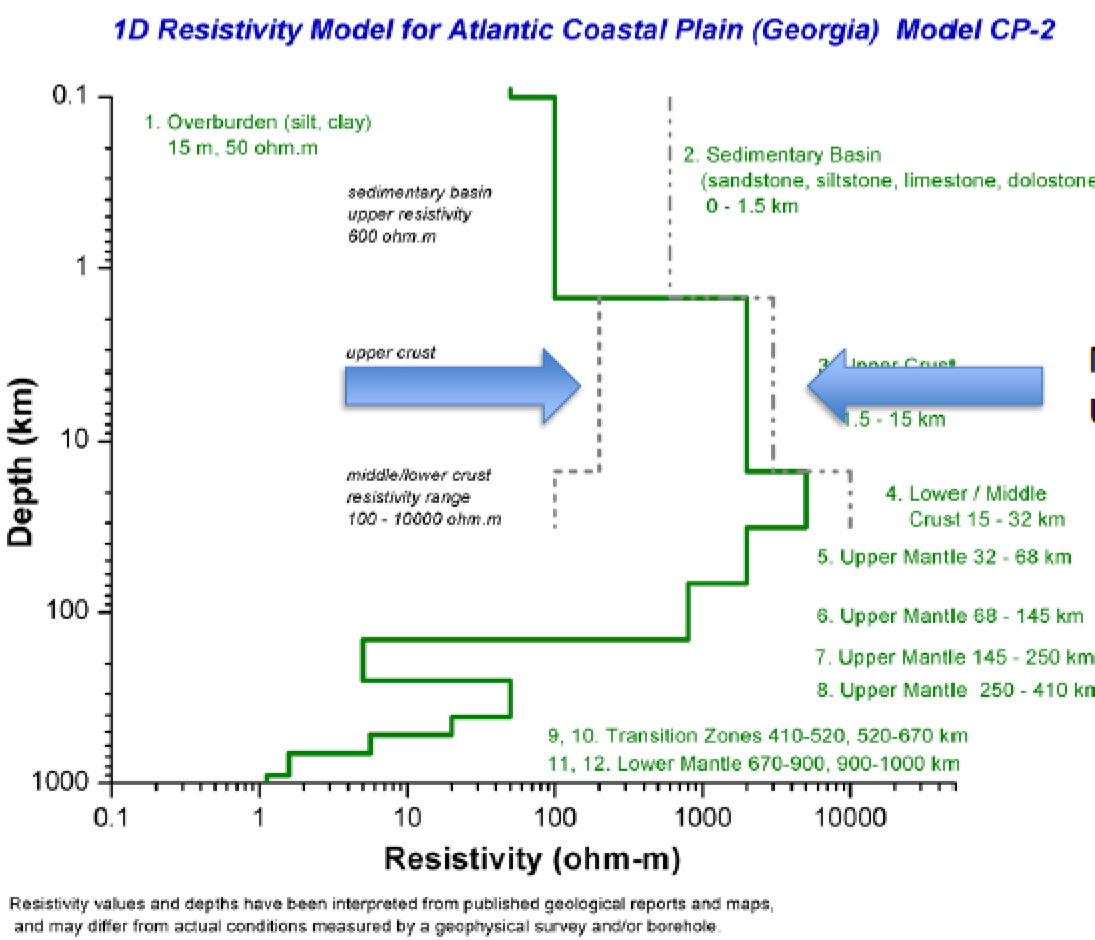
> *"The commenter's approach for using GIC data to calculate geoelectric fields is valid when an accurate power system model, ground conductivity model, specific power system configuration at the time of measurement, and high data rate magnetometer data is available. Calculations are not accurate without all elements. With limited data it is not feasible to develop a technically-justified benchmark using the commenter's approach."*

It should be noted that in the case of the Chester GIC data from May 4, 1998, the details on the transmission network are well known, there is also high cadence magnetometer data as well at the location of the GIC measurement. What had not been well confirmed is the accuracy of the ground model NERC proposed or the reliability of the geo-electric field simulation model that NERC has been using. This use of GIC data and Ohm's law to validate the ground model is a well-proven approach and it is simply not credible that the NERC SDT would raise any objection to this. Further it is fully possible just using GIC observations and knowledge of the power grid (which is precisely known) to calculate the actual driving geo-electric field even if there is some uncertainty as to the local geomagnetic field.

The NERC SDT notes that "*with limited data it is not feasible to develop a technically-justified benchmark*", but in contrast that is exactly what the NERC SDT has been doing in developing their Beta factors on un-validated ground conductivity models. In a NERC GMD Task Force meeting in Atlanta on Nov 14, 2013, Dr. Jennifer Gannon from the USGS provided a presentation on the US ground models she developed for NERC and in her presentation she pointed out the large scale uncertainty in these models. In Figure 5 is a slide from her presentation where she showed an example of the ground conductivity model uncertainty for the 1D models. In Figure 6, she provides a slide which showed a factor of 4 error range in the geo-electric field when looking at two different ground model formulations that are within the range of uncertainty. She further noted that this could only be addressed by the NERC members providing GIC observations as a way to test and validate these ground models to a lower range of uncertainty. This important validation task was never performed by NERC. Yet the NERC SDT drafted a standard which as shown in Figure 7 has determined ground conductivity model Beta factors that are defined to two significant digits after the decimal point. These Beta factors are an illusion of accuracy that the NERC SDT has put forward that is not realistic and cannot be scientifically substantiated. The only means to overcome these limitations are to begin examining the GIC observations that are available, an effort which the NERC SDT has continues to refuse to perform.

Figure 5 – Slide Presented by Jennifer Gannon USGS on Ground Conductivity Model Uncertainty on Nov 14, 2013

# 1D Conductivity




This is the 1-D conductivity model for an example region, CP2.

USGS science for a changing world

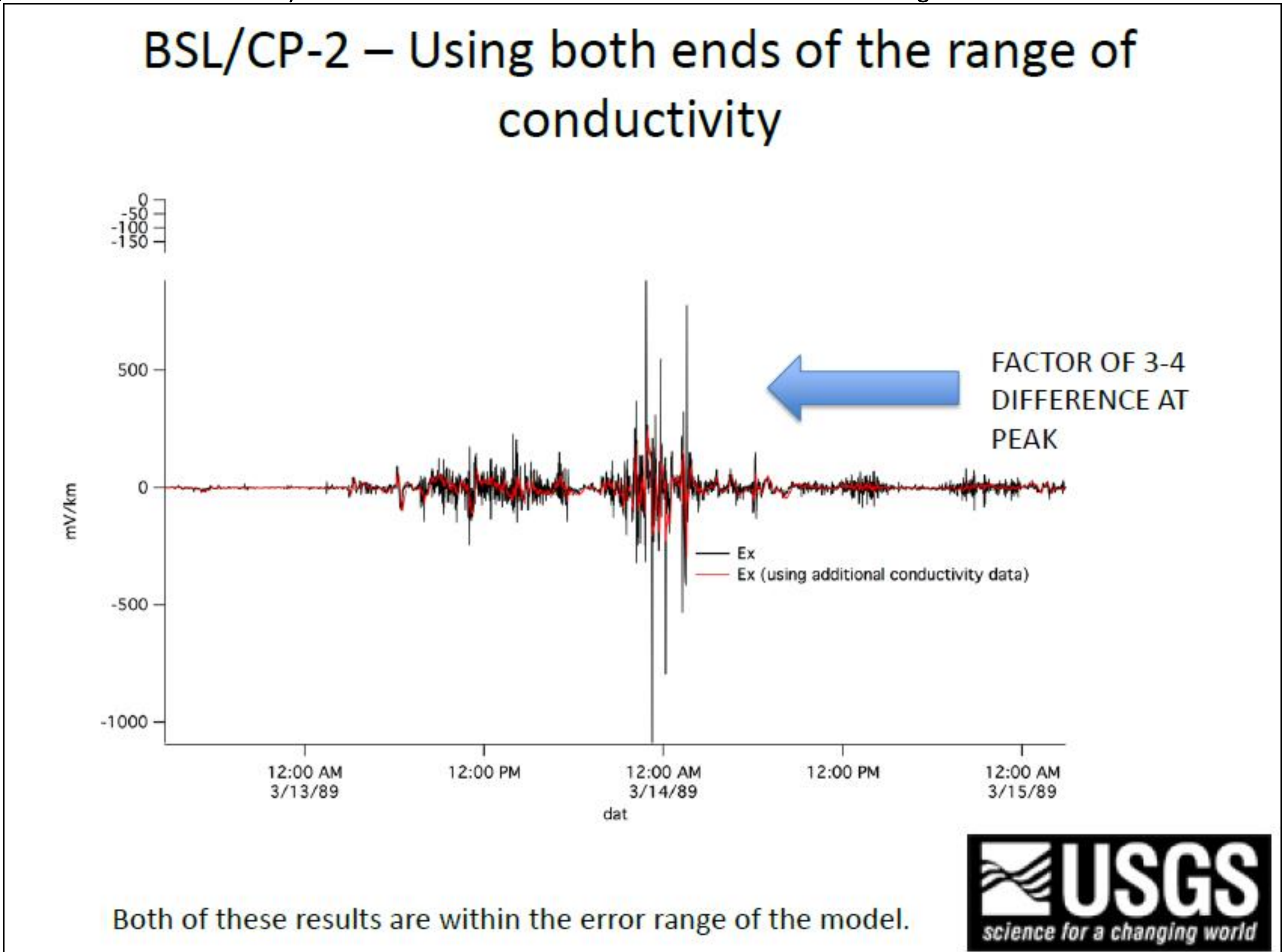



Figure 6 – Slide Presented by Jennifer Gannon USGS on Geo-Electric Field Error Range due to Ground Model Uncertainty

Figure 7 – NERC Draft Standard Benchmark Geo-electric field scaling factors

| Table II-2 Geoelectric Field Scaling Factors | |
|---|---|
| USGS Earth model | Scaling Factor ($\beta$) |
| 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 |
| CP3 | 0.94 |
| 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 |

**Comments of John Kappenman, Storm Analysis Consultants**
**Regarding NERC Draft Standard on Transformer Thermal Impact Assessments**

There are serious errors and omissions in the proposed revisions from the NERC GMD Standards Task Force in regard to increasing the GIC Threshold from 15 Amps/phase to 75 Amps/phase. Both Analytical analysis and actual observation data show that problem onsets could occur at much lower GIC levels.

Figure 1 is from the Recent NERC Screening Criteria publication which shows their results of screening several transformers for thermal increases due to GIC. It must be noted that these results all ignore important factors. The most important being that the Tertiary windings on the autotransformers are the most vulnerable portions of these transformers and that the testing that was performed was conducted in a manner to obscure or hide this vulnerability. He4nce it was not properly considered. In the case of the FinnGrid transformer, the Owners and Manufacturers noted that the transformer was considered to account for relatively high stray fluxes in the design stage[1,2]. Hence this transformer may have higher GIC tolerance than exists for almost all other US transformers that were not designed with GIC considerations and have been in service for many years. Further the FinnGrid transformer is a 5 Legged Core Design which is seldom used anywhere in the US electric grid. And also has higher GIC withstand than comparable single phase transformers which largely populate the 500 and 765kV grid.

Figure 2 provides a plot of NERC Table 1 from the same publication which of the Upper Bound of Peak Metallic Hot Spot Temps that are also shown in Figure 1. Figure 3 provides a revised plot which now includes the tertiary winding heating that was provided the NERC SDT in May 2014 comments[3]. These omitted winding heating curves when added provide much lower levels of GIC withstand than the proposed NERC revision of this standard.

1. M. Lahtinen, J. Elovaara: GIC occurrences and GIC test for 400 kV system transformer. IEEE Trans on Power Delivery, vol 17, no 2, April 2002, p555-561.
2. Nordman, Hasse, "GIC Test on a 400kV System Transformer", IEEE Transformer Standards Committee Meeting, GIC Tutorial, March,2010.
3. Kappenman, J.G., Section 2. – Analysis of Autotransformer Tertiary Winding Vulnerability, Comments filed with NERC, May 2014.

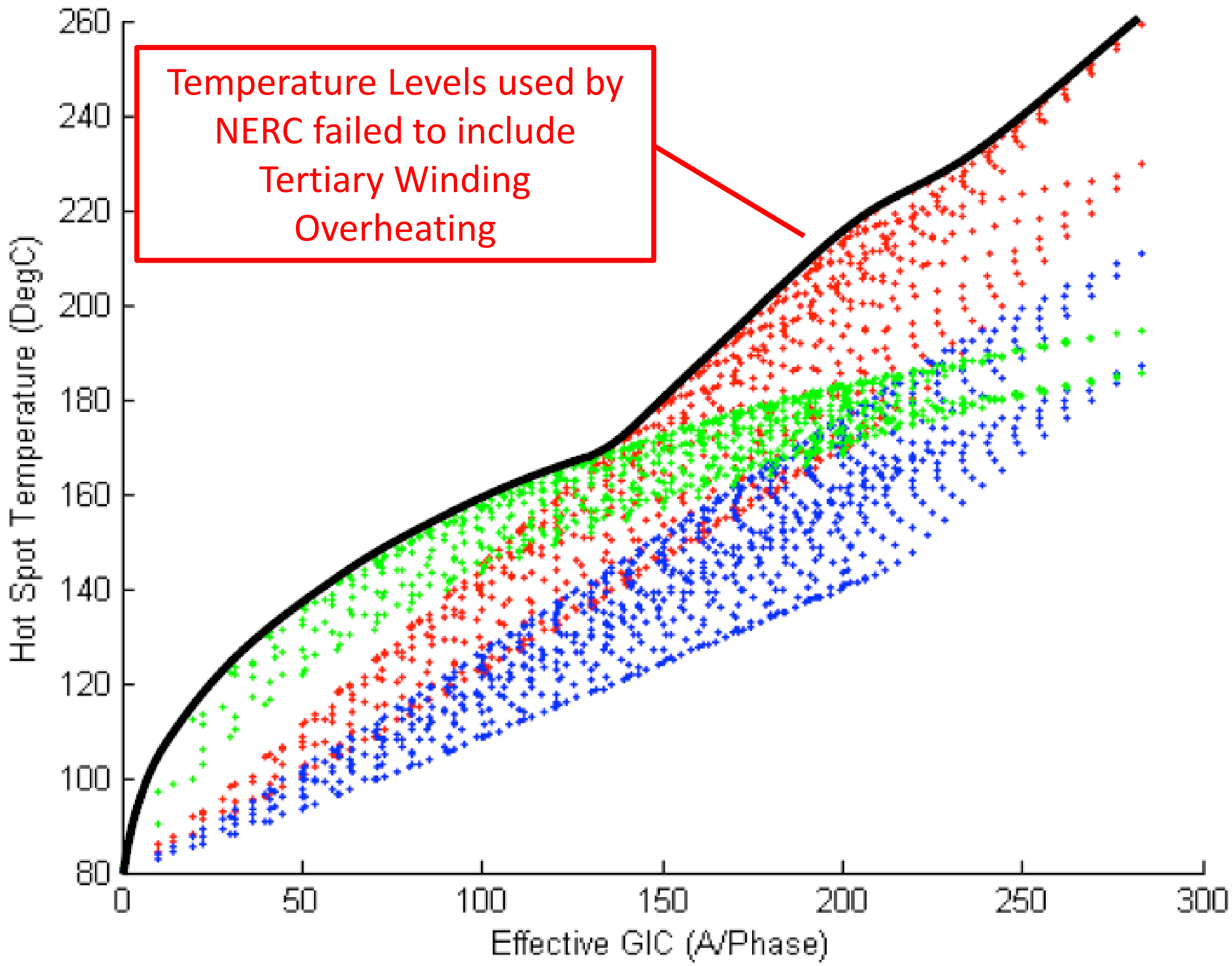



Figure 1: Metallic hot spot temperatures calculated using the benchmark GMD event. Red: Screening model [2]. Blue: Fingrid model [3]. Green: SoCo model [4].

Figure 2 – Plot of NERC Table 1 Upper Bound of Peak Metallic Hot Spot Temps

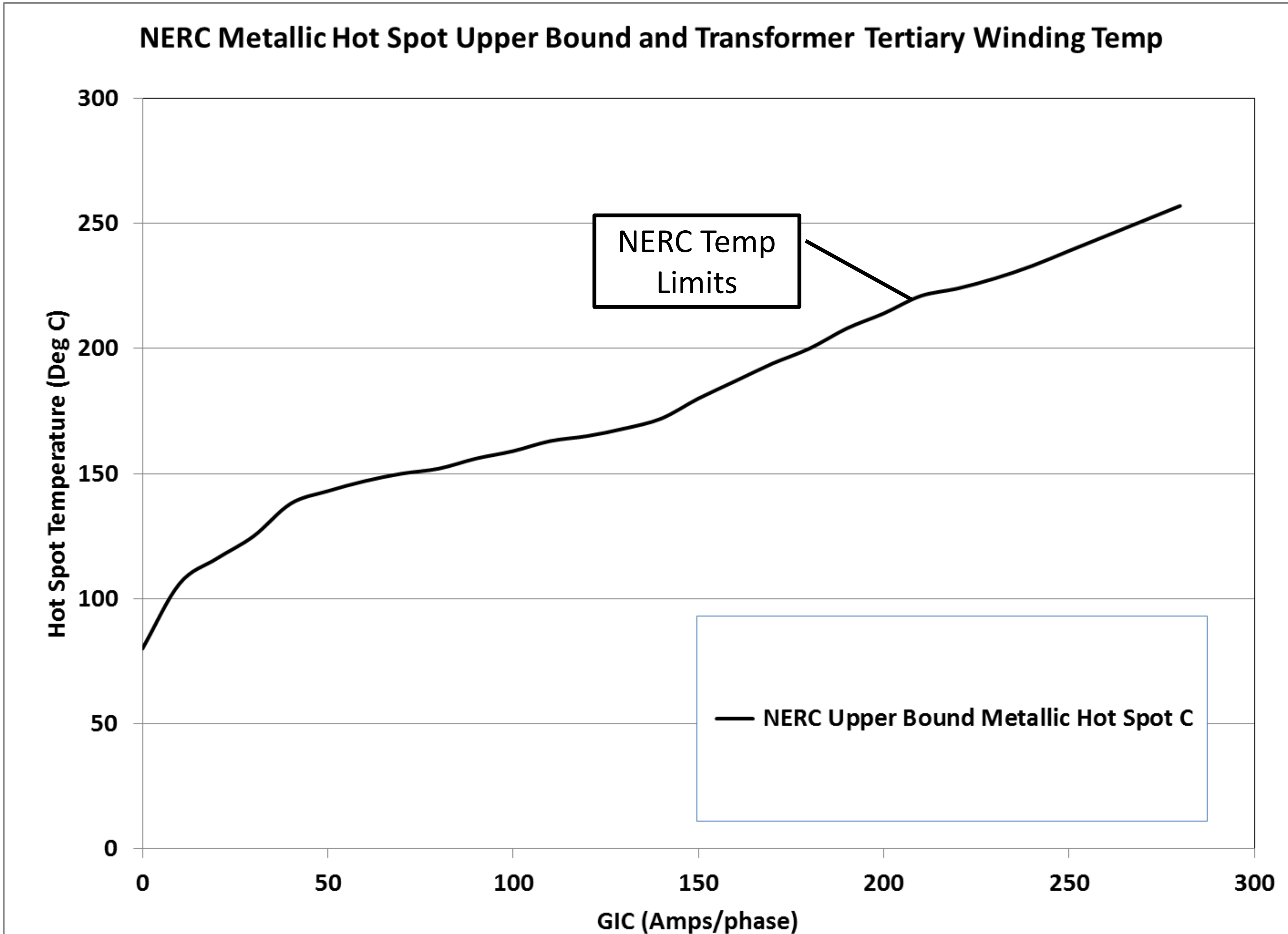
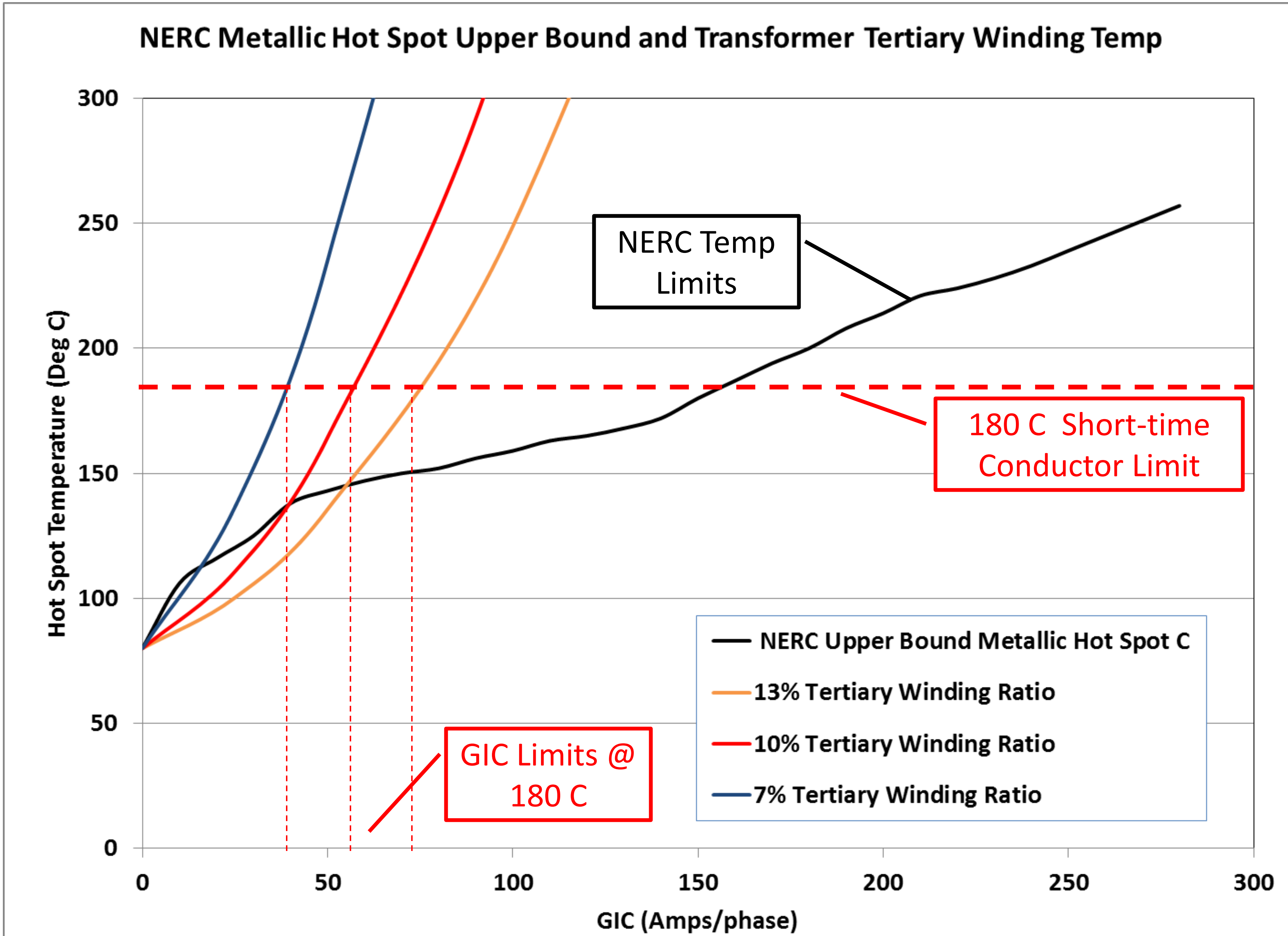


Figure 3 – Plot of NERC Table 1 & Ignored Tertiary Winding Conductor Temperatures



While much of the available monitored GIC and transformer behavior data is being concealed from independent and public review, some small amounts of details have shown heating impacts at lower GIC levels and at higher degrees of severity than the proposed NERC draft standards and screening criteria would anticipate. In reports provided by Allegheny Power, they reported heating and irreversible deleterious impacts at 8 of their 22 EHV 500kV transformers during the March 13, 1989 storm[4]. in subsequent storms where they increased monitoring on an accessible external transformer hot spot revealed by the March 1989 storm, they found significant heating issues that could be confirmed. Figure 4 is a plot of one such observation that occurred during a minor storm on May 10, 1992 at their Meadow Brook 500kV transformer which was a three phase shell form design (again not the most vulnerable transformer design). This plot clearly shows the temperature increasing to ~170 $^{o}$C in a matter of just a few minutes for an observed Neutral GIC which peaks out at 60 Amps (equivalent to 20 Amps/phase). Figure 5 provides other data samples of GIC dose and Transformer Heating Response. Again, the GIC is shown in Neutral GIC Amps and needs to be divided by 3 to convert to Amps/phase. As shown, the response is consistent and can therefore also be extrapolated to higher GIC levels[5,6].

This transformer GIC-Exposure / Temperature Response can be contrasted with the Asymptotic thermal response that is included in the NERC Screening Criteria publication. Figure 5 provides a copy of the asymptotic temperature plot ( Fig 6 from NERC screening publication) which is now also modified (in red) to show the temperature rise characteristics as actually observed in the Meadow Brook transformer. As this comparison clearly illustrates, the rate of heating is much more severe in the Meadowbrook transformer than what NERC is suggesting is the broad case for all transformers, especially for the large number of existing transformers that were not specifically built or designed to take into consideration any GIC-Tolerance Design Basis.

4. P.R.Gattens, R.M.Waggel, Ramsis Girgus, Robert Nevins,"Investigations of Transformer Overheating Due To Solar Magnetic Disturbances", IEEE Special Publication 90TH0291-5PWR, Effects of Solar- Geomagnetic Disturbances on Power Systems, July12,1989.
5. P. R. Gattens, Robert Langan, " Application of a Transformer Performance Analysis System", presented at Southeastern Electric Exchange, May 28, 1992.
6. Fagnan, Donald A., Phillip Gattens, "Measuring GIC in Power Systems", IEEE Special Publication 90TH0357-4-PWR, July 17, 1990.

Figure 4 – Plot of Observed GIC and Transformer Temperatures at Meadow Brook

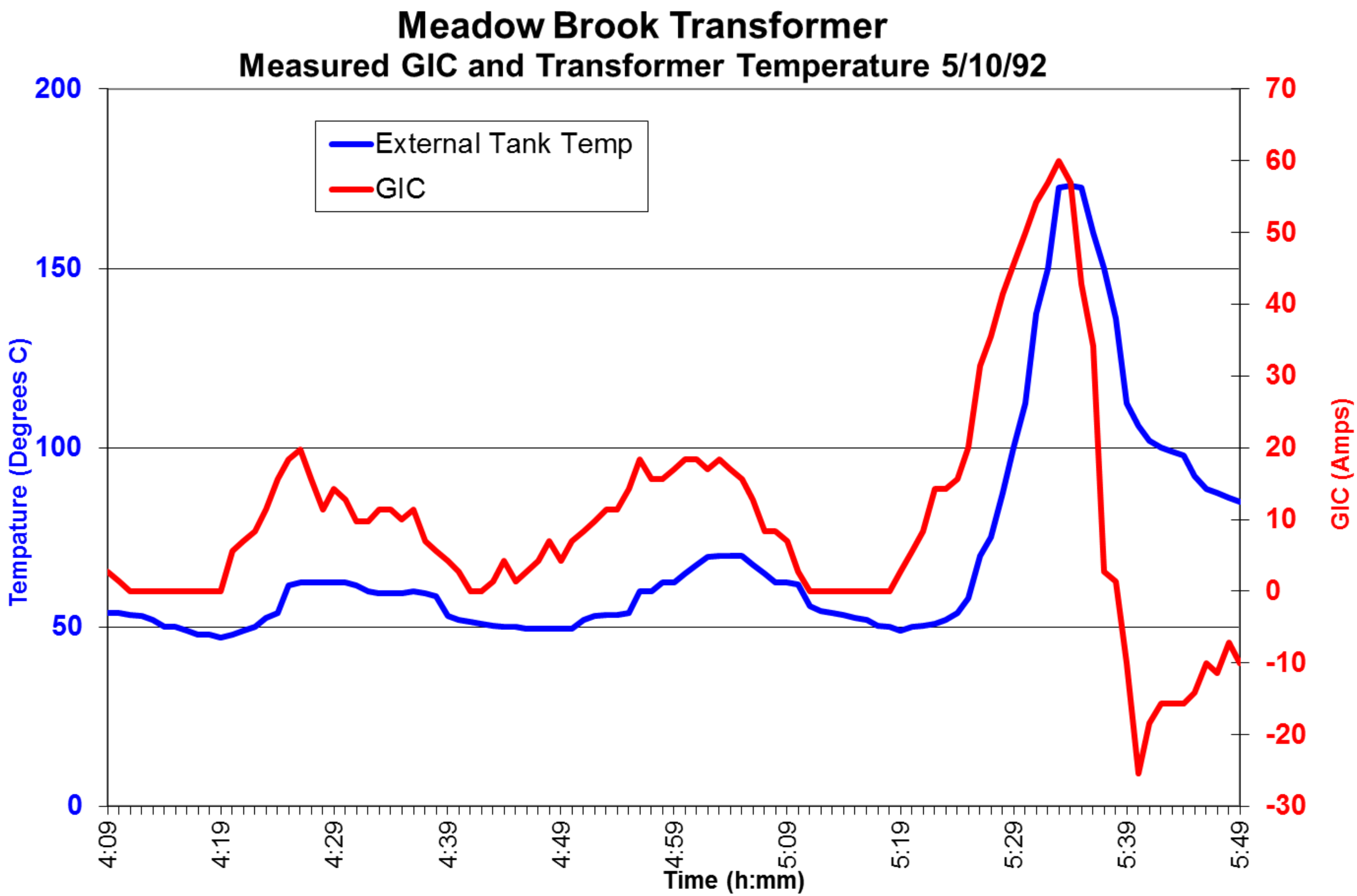


Figure 4 – Plot of Observed GIC and Transformer Temperatures at Meadow Brook

(Note to convert GIC Neutral to GIC Amps/phase, divide by 3)

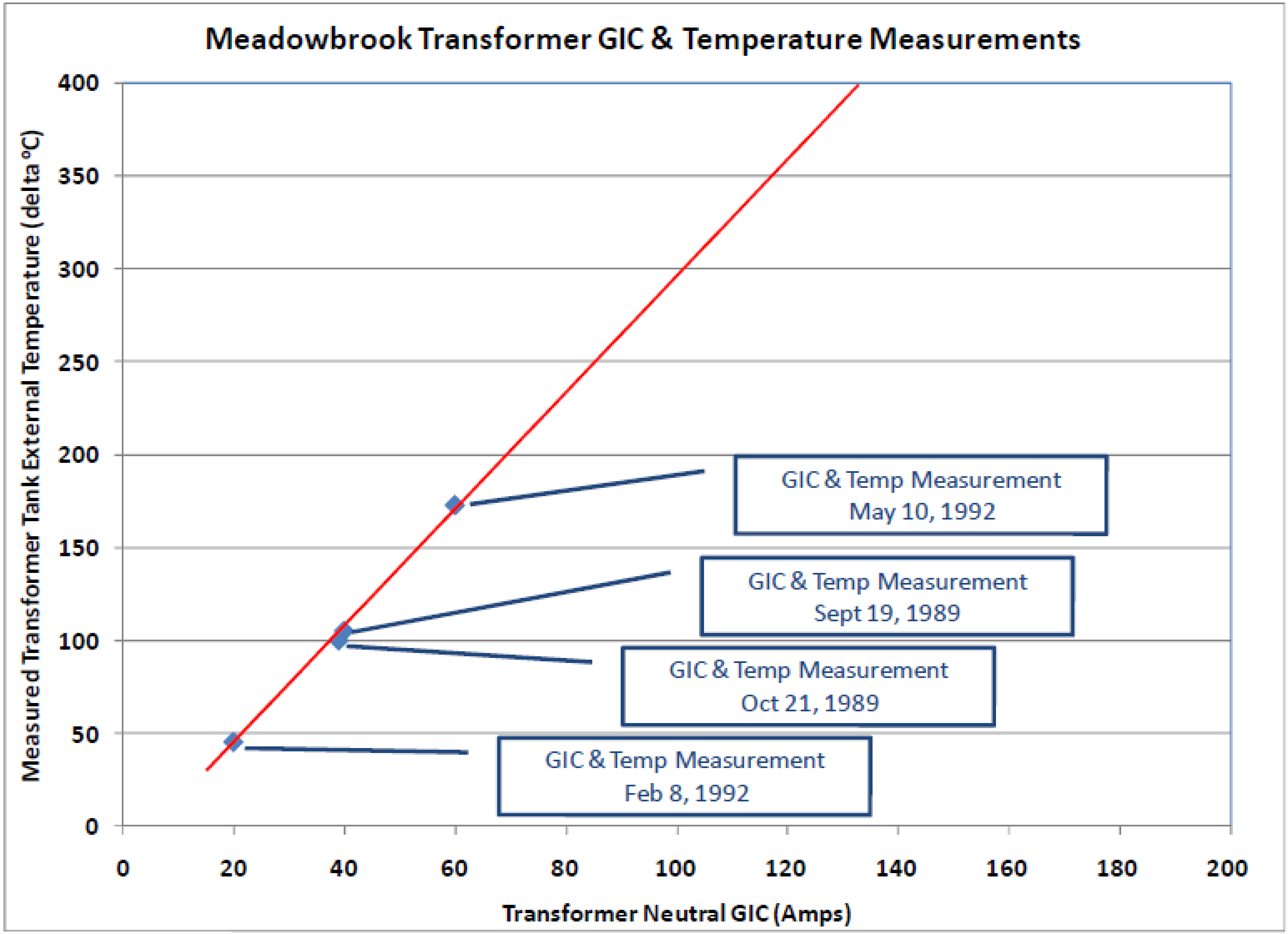



Figure 5-4 - Observation Points of GIC and Hot Spot temperatures and GIC-Temperature Trend Line.

Storm-R-112, August 2011

Figure 5 – NERC Asymptotic thermal response versus Meadow Brook actual

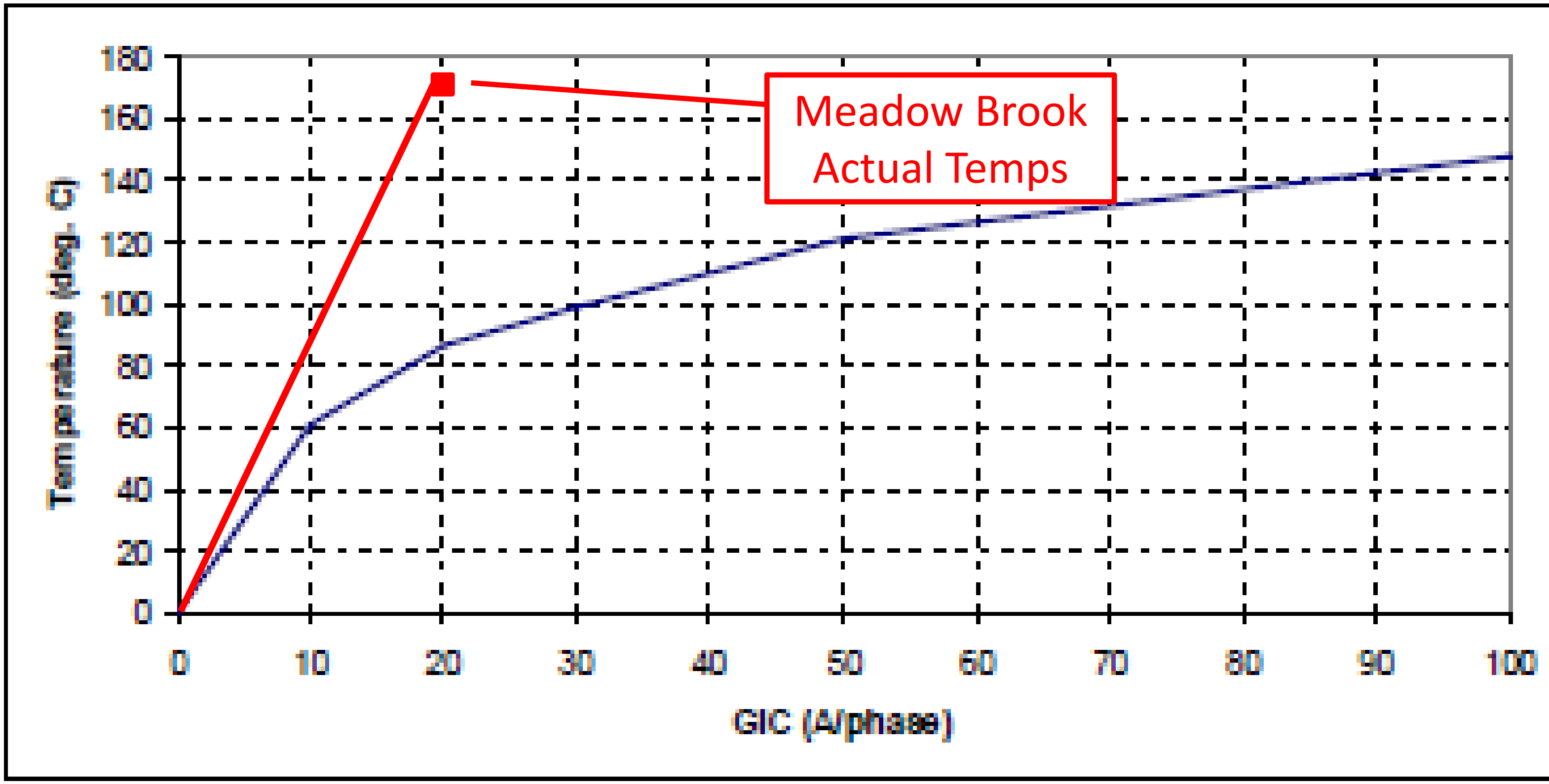



Figure 6: Asymptotic thermal response of the Flitch plate of a 400 kV 400 MVA single-phase core-type autotransformer.

To place the Meadow Brook transformer heating observations in a context that can also be applied to other existing transformers that never had a "GIC Design Basis", it is necessary to review some fundamentals in regards to GIC-caused overheating. The temperature rise experienced in any object (within the transformer and transformer tank) is affected by a number of factors, including:

- Magnitude of the Stray Flux
- Spectral content of the flux
- Magnitude and spectral content of harmonic currents in all windings of the transformer
- Orientation of the flux with respect to the major dimensions of the object
- Dimensions and mass of the object
- Material characteristics (for example permeability, conductivity)
- Heat transfer provided to the object (conduction and oil flow)

In addition to the above factors which relate only to thermal heating impacts, there are a number of other impacts that GIC could cause to a transformer which could damage and shorten its life. These include partial discharge breakdown (something that has been observed, but EPRI and industry have withheld available monitoring data) and also vibrational/mechanical failures to the transformer caused by GIC exposures.

**A Brief Overview of Possible Oil Flow Constraints**

In these cases and without sufficient oil flow, the temperature rise is capable of approaching ~400$^{o}$C or higher in a very brief period of time. While the Tank heating at Meadow Brook was associated with a spacer wood slab, the gas in oil analysis also indicated that "acetylene was probably generated by discharges not directly associated with the tank heating"[4]. Oil cooling constraints can arise from other sources, such as cooling triggered via top-oil or simulated hot-spot indicators which will not observe rapid hot-spot developments in unanticipated and very small locations in the transformer due to GIC-caused heating. Electrical Discharging also suggests processes that may still be poorly understood for GIC-exposure concerns.

GIC-caused over excitation of a transformer is an unusual mode of operation and present cooling controls on transformers are not reliably optimized to ensure proper cooling functions within the transformer when a sudden GIC exposure condition develops. For example the turn-on of oil pumps for cooling in many existing transformers is driven by a “simulated hot-spot” not actual hot-spot. The actual hot-spot can be quite different from normal loading when caused by GIC.

In the case of the Meadow Brook transformer a physical obstruction was the cause of oil flow constriction. But for all other exposed transformers, intense hot-spots can develop due to constraints on cooling system limitations as noted here. Therefore these types of existing control systems on transformers cannot be relied upon to ensure adequate oil flow and cooling conditions within the transformer and prevent the rapid transient development of intense hot-spots due to GIC exposures.

**A Brief Overview of Tertiary Winding Conductor Heating**

The examination of winding heating by the manufacturers and NERC has been limited to only consideration of transformer main windings which have full MVA rating and are much more physically massive than the much reduced MVA Tertiary windings of autotransformers which are also exposed to harmonics generated by the GIC flow in the transformer. Triplen harmonics will naturally circulate in these windings and at low levels of GIC can reach harmonic current levels which greatly exceed their rating leading to enormous losses and heating that is narrowly confined to this very small area within the transformer. Because of the small mass and area involved, it would be reasonable to expect higher temperature rises than noted in the NERC asymptotic charts that have been previously discussed. Further is it unclear whether a lightly load autotransformer which is experiencing a small tertiary winding heating problem would have sufficient oil flow to ensure safety of the winding.

**Conclusions**

The previous discussions only examined two of the large number of factors that could lead to deleterious impacts to large power transformers exposed to GIC. What has been illustrated in this discussion is the lack of a comprehensive understanding by both the NERC SDT and transformer manufacturers. This has also been coupled with efforts to withhold data and observations taken by the industry and EPRI specifically monitoring transformer impacts during geomagnetic storms. Hence the NERC efforts to increase the GIC safety threshold is being implemented without an adequate examination of all of the possible concerns.

**SMARTSENSECOM, INC. COMMENTS ON PROPOSED STANDARD TPL-007-1**

In recognition of the potentially severe, wide-spread impact of GMDs on the reliable operation of the Bulk-Power System, FERC directed NERC in Order No. 779 to develop and submit for approval proposed Reliability Standards that address the impact of GMDs on the reliable operation of the Bulk-Power System. In this, the second stage of that standards-setting effort, the Commission directed NERC to create standards that provide comprehensive protections to the Bulk-Power System by requiring applicable entities to protect their facilities against a benchmark GMD event.

In particular, FERC directed NERC to require owners and operators to develop and implement a plan to protect the reliability of the Bulk-Power System, with strategies for protecting against the potential impact of a GMD based on the age, condition, technical specifications, or location of specific equipment, and include means such as automatic current blocking or the isolation of equipment that is not cost effective to retrofit. Moreover, FERC identified certain issues that it expected NERC to consider and explain how the standards addressed those issues. *See* Order No. 779 at ¶ 4. Among the issues identified by FERC was Order No. 779's finding that GMDs can cause "half-cycle saturation" of high-voltage Bulk-Power System transformers, which can lead to increased consumption of reactive power and creation of disruptive harmonics that can cause the sudden collapse of the Bulk-Power System. FERC also found that half-cycle saturation from GICs may severely damage Bulk-Power System transformers. While the proposed standard addresses and explains transformer heating and damage with a model, NERC ignores the issues of harmonic generation and reactive power consumption caused by a GMD event that have caused grid collapse in the past.

FERC has also been very clear to NERC that it considered the "collection, dissemination, and use of GIC monitoring data" to be a critical component of these Second Stage GMD Reliability Standards "because such efforts could be useful in the development of GMD mitigation methods or to validate GMD models." *See* Order No. 797-A, 149 FERC ¶ 61,027 at ¶ 27. However, the proposed standard fails to tie the actions required under the standard to any actual grid conditions. In its place, the proposed standard relies entirely upon an untested system model with several suspect inputs and with no means for model verification and no affirmative requirement for real-time monitoring data as a means to enable GMD mitigation.

It has been nearly eighteen months since Order No. 779 and this comment cycle represents NERC's last opportunity to correct its course before it files TPL-007-1 with FERC. Based on the considerable volume of scientific evidence and the capabilities of modern measurement and control technology to serve as a mitigation method, the proposed standard is technically unsound and fails to adequately address FERC's directives. Rather than risk the operation of the grid on the perfection of an untested model, NERC should have provided requirements for the collection and dissemination of GMD information, such as data collected from real-time current and harmonic monitoring equipment, to ensure that the Bulk-Power System is able to ride-through system disturbances. NERC should include these measures in TPL-007-1 or be prepared for a likely FERC remand – leaving the Bulk-Power System exposed to the risk of GMD while NERC addresses the matters that it ought to have considered at this stage of the process.

## 1. TPL-007-1 Should be Modified to Account for the Impact of System Harmonics and VAR Consumption and Mitigate the Risk Created by Reliance On Untested System Models

In Order No. 779, FERC found that GMDs cause half-cycle saturation of Bulk-Power System transformers, which can lead to transformer damage, increased consumption of reactive power, and creation of disruptive harmonics that can cause the sudden collapse of the Bulk-Power System. Whereas TPL-007-1 takes pains to model transformer thermal heating effects, the proposed standard does not adequately address the risks posed by harmonic injection and VAR consumption. Failure to deal directly with the effects of harmonics and VAR consumption is irresponsible given the empirical evidence of their impact upon system reliability during GMD events. Real-time monitoring, as called for by FERC, would provide the real-time operating information necessary to account for – and mitigate – these negative system effects. Real-time monitoring information would also remedy the vulnerability created by standard's "model-only" approach to the GMD threat and provide a means to iteratively improve any model over time.

### *A. Failure to Account for Harmonics and VAR Consumption*

In the presence of a GIC, a saturated transformer becomes a reactive energy sink, acting as an unexpected inductive load on the system, and behaves more like a shunt reactor.

Consequently, transformer differential protective relays may trip and remove the transformer from service because of the disproportionately large primary current being drawn and consumed by the saturated transformer. System VAR support devices, such as capacitor banks and SVCs, become particularly critical during such conditions in order to offset the undesired behavior of GIC-affected transformers. The magnetizing current pulse of a GIC-inflicted transformer injects substantial harmonics into the power system.

VAR support devices are a low impedance path for harmonic currents and subsequently these devices begin to draw large currents too. A power flow "tug-of-war" ensues between the saturated transformers and VAR support devices. The sustenance of the VAR support devices is paramount as their failure may result in system voltage instability and collapse. However, harmonics doom these devices on multiple counts. For example, the large harmonic currents being consumed by capacitor banks may affect other components in the device that cannot withstand such high magnitude currents and result in damage and the unwanted tripping of the capacitor bank. Additionally, harmonics often result in the improper operation of protective equipment, such as overcurrent relays. Therefore, harmonics are ultimately predisposing system VAR support components to failure and increasing the vulnerability of the grid to voltage instability and collapse. See Duplessis, *The Use of Intensity Modulated Optical Sensing Technology to Identify and Measure Impacts of GIC on the Power System* (attached).

Accounting for GIC-related harmonic impacts is also essential considering that where GICs have caused significant power outages, harmonics have been identified as the primary system failure mode through the improper tripping of protection relays in known GMD events. For example, the 1989 Quebec blackout was traced to improper protective device tripping influenced by the GIC-induced where seven large static VAR compensators were improperly tripped offline by relays. See Department of Homeland Security, *Impacts of Severe Space Weather on the Electric Grid*, Section 4.4. In light of FERC's directive to address and explain how the standard address these issues, it is clear that TPL-007-1 be modified to directly account for the reactive power and harmonic effects of GMD events.

*B. Over-Reliance on Untested Models*

The core of the proposed standard is a series of models designed to approximate the "worst-case" scenarios of a GMD event which are, in turn, used to determine system vulnerability and whether corrective action is required. This "model-only" approach is technically insufficient and leaves the grid open to unnecessary risk. Moreover, no mechanism exists in the standards to validate the GMD models through the use of actual operating data.

First, genuine concerns exist regarding whether the "worst-case" GMD scenario is actually being modeled or whether the model substantially underrepresents the threat. For example, according to empirically-based arguments of John Kappenman and William Radasky in their White Paper submitted to the NERC earlier this year, the NERC Benchmark model under-estimates the resulting electric fields by factors of 2x to 5x. Kappenman *et al*., *Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard*. The thermal heating model also relies upon a 75 amps <u>per phase</u> assumption (equivalent to total neutral GIC of 225 amps) as the modeled parameter. As shown in the Oak Ridge Study, it was found that at as little as 90 amps (or 30 amps per phase) there is risk of permanent transformer damage. *See, e.g.*, Oak Ridge National Laboratory, FERC EMP-GIC Metatech Report 319 at 4-8 ("Oak Ridge Study"). Indeed, the Oak Ridge Study found that a 30 amps per phase level is the approximate GIC withstand threshold for the Salem nuclear plant GSU transformer and possibly for others of similar less robust design in the legacy population of U.S. EHV transformers. *See* Oak Ridge Study at Table 4-1 (finding 53% of the Nation's 345kV transformers at risk of permanent damage at a 30 amps <u>per phase</u> GIC level). In addition, the system model specified in Requirement 2 should also be run on the assumption that all VAR support components on the system (e.g., capacitor banks, SVCs, etc.) become inactive (i.e., removed from service by undesired operation of protective devices caused by the harmonics that GIC affected transformers are injecting into the system).

That the models appear to substantially under-estimate the expected GMD impact is critical as it the models alone – under the proposed standard – that drive the vulnerability assessments and corrective action plans that require owners and operators to implement appropriate strategies. As written, these models have the effect of greatly reducing the scope of the protective requirements that will be implemented, potentially allowing sizable portions of the grid to be wholly unprotected and subject to cascading blackouts despite the adoption of standards. The extensive analysis and findings of the Kappenman-Radasky White Paper and the Oak Ridge Study suggest that the modeling approach elected by NERC is technically unsound, does not accurately assess a "worst case" scenario as it purports to do, and, in any event, should not be the sole basis for the standard's applicability.

Second, the proposed standard provides no means to validate or update the standard's models in light of actual operating data. This amounts to little more than a gambler's wager that the model will adequately protect the Bulk-Power System from a substantial GMD event, when it has never actually been tested. As the model is designed, actual operating data has no means to influence or override actions based upon the model. This is inappropriate. As discussed above, it is likely that the model developed will underestimate the effects of a GMD event. To rely on a model to simulate actual equipment performance over a range of potential GMD disturbances, it is essential that that model must not only contain adequate information (i.e. – an accurate up-front estimate), but that it must also correspond to actual reported field values. NERC should modify the standard to provide that actual operating data be used to regularly verify and improve the model.

*C. The Solution – Collect, Disseminate, and Use Real-Time Reactive Power and Harmonic Content Information to Mitigate GMD Impacts*

While the standard's model-based approach to GMD mitigation efforts may have some limited utility as a first step towards identifying vulnerabilities and developing forward-looking correction action plans, the standard would provide far better protection with a requirement for the collection and use of accurate, real-time data regarding current, reactive power consumption, and system harmonics. Real-time data should underpin any GMD mitigation efforts, substantially reducing the risk of outages and damage to critical equipment in the event of a GMD, and would also improve the reliability of system models. Modern grid measurement and control technologies are capable and readily deployable to mitigate GMD events.

First, real-time monitoring enables protective devices to be efficiently managed during a GIC event, initiating control signals that enable devices to "ride-through" GMD where they may otherwise trip offline during a period of normal operation. In these instances, the detection of harmonic content could be used to sense transformer saturation and override normal protective device trip settings in order to maintain key equipment online and not be "fooled" into tripping by the harmonics generated by the event. Given the diversity of protective devices for equipment used throughout the Bulk-Power System, a technically preferable approach would be to actively manage protection schemes based upon real-time operating data. Regarding the system's VAR response, if system voltage becomes unstable when VAR support is inhibited during a GIC event, operators would have an available solution through the identification of atypical harmonics, which can be associated with a GIC event, and this information used as a trigger to implement alternate protective schemes for VAR support components for the duration of the GIC event.

Second, if a GMD event is detected through the monitoring of systemic VAR consumption and harmonic content at key points in the network (which may include current monitoring on vulnerable transformer neutrals and monitoring of harmonics and VAR consumption on phases), this real-time monitoring data could be used to draw down, and ultimately cease, GMD operating procedures as the GMD event passes. Moreover, the VAR and harmonic derived from real-time operation information may also be used to trigger operating procedures, which is necessary given that the existing operational standard relies on space weather forecasts as the trigger for the implementation of operating procedures, despite the substantial error rates associated with these forecasts. Since GMD procedures impose transmission constraints that do not permit wholesale energy markets or system dispatch to achieve the most efficient use of available resources, ultimately affecting the prices paid by consumers, NERC should seek to minimize the frequency and duration of mitigation efforts. Real-time monitoring of harmonic content and reactive power would enable a more efficient approach to recognizing and reacting to GMD events, harmonizing the Phase I and Phase II standards and providing greater overall protection to the grid.

Further, real-time monitoring information must be used to validate models that are used to inform the means by which owners and operators will prepare for, and react to, GMD events. Currently, the models presented in the standard are the sole means to trigger the implementation of protection measures and the availability of actual operating data that questions the model's outputs have no means to override the model-based approach. The use of actual operating data to verify the standard's model would improve the accuracy of model verifications needed to support reliability. A better approach would be to use modeling and real-time monitoring in tandem to constantly verify and enhance the model, while still maintaining protections for "missed" events that the model is likely to inevitably overlook. The people of the United States should not have the ongoing Bulk-Power System reliability put at risk by an unverified model.

NERC should use its authority to insure that real operating data will, over time, be employed to verify and improve any reference model and that real operating data will be employed as a means to ensure ongoing system reliability when events render the reference model unequal to its protective task (which evidence suggests will happen). The proposed standard should be modified to require the collection, dissemination, and use of real-time voltage and current monitoring data which will provide the reactive power and harmonic content information necessary to effectively and efficiently manage the system in response to GMDs.

## 2. Conclusion

FERC was clear in its direction to NERC that the collection, dissemination, and use of real-time GIC monitoring data was a critical component of these Second Stage GMD Reliability Standards "because such efforts could be useful in the development of GMD mitigation methods or to validate GMD models." See Order No. 797-A, 149 FERC ¶ 61,027 at ¶ 27. FERC also was clear that harmonic content and reactive power consumption created by GMD events constituted serious threats to system reliability that must be addressed. Order No. 779 at ¶ 7. The draft standard offered by NERC simply fails to meet the needs identified by FERC – which are amply supported by the record established in these proceedings – a reasonable person could reach no other conclusion.

To create a reasonable and prudent standard, NERC needs to address the reactive power and harmonic generation aspects of GMD events, and it needs to provide for verification and improvement of the model included in the draft standard. The only route to meeting those needs that is supported by the evidentiary based findings and FERC's directives is a mandate for the collection, dissemination, and use of real-time GIC current and harmonic data to drive protection schemes. With clearly articulated requirements for such data, NERC can fill the gaps in the current standard and provide a means by which to adequately protect the Bulk-Power system.

Respectfully submitted,

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**The Use of Intensity Modulated Optical Sensing Technology to Identify and Measure Impacts of GIC on the Power System**

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**Abstract**

This paper describes the phenomenon of geomagnetically induced currents ("GIC"), a geomagnetic disturbance's potential impact on transformers and the electric power system, and FERC/NERC regulation regarding utility responsibility. The paper then introduces intensity modulated optical sensing technology, explains how this technology has been adapted to measure voltage, current, phase and other characteristics of electric phenomena, and answers why this adaptable core technology provides a comprehensive solution to identifying and measuring the impacts of GIC.

**Introduction**

The phenomenon of geomagnetically induced currents ("GIC") has been well documented[1] and is summarized herein. Because of the catastrophic impacts a major solar storm, which precipitates GIC flow, can have on electric power grid operations and its components, the Federal Energy Regulatory Commission (FERC) issued an order in May 2013 requiring the North American Electric Reliability Corporation (NERC) to create reliability standards to address the Geomagnetic Disturbance (GMD) threat.

This paper reviews the mechanism by which the loss of reactive power occurs due to GIC and how it could lead to system voltage collapse, which is central to FERC's concerns. However, the main impetus for writing this paper is to introduce a technology that brings true system visibility within reach of utility asset managers and system operators. This visibility is paramount to the success of managing GIC effects. Practically, it is impossible to manage something you cannot measure; for example, how can you know whether the reaction is appropriate for the problem if the latter is not quantified? Increased system visibility also validates the effectiveness of strategies to block GIC.

Managing and blocking are the two mitigation approaches for dealing with GIC. Managing GIC in real time involves fast, responsive operating procedures. While modeling efforts will aid in predetermining operating steps that will help to minimize outages and limit damage to critical equipment in the presence of GIC, accurate, real-time system visibility reveals the necessity of these operating steps or need for more during each unique GMD event and guides the operator (manual or automatic) with respect to when these steps must be implemented (and when the danger is gone). Afterwards, this increased visibility will help improve the predefined thresholds of system switching and VAR support components used during GIC induced events.

Alternatively, blocking GIC can be done through several means, including the installation of a GIC neutral blocking capacitor on the neutral of a susceptible transformer, resistive grounding of the transformer

[1] W. Hagman, "Space Weather in Solar Cycle 24: Is the Power Grid at Risk?", IEEE PES Boston Chapter & IEEE Com Society Boston Chapter Joint Lecture, April 16, 2013, references.

(although this will require a higher surge arrester rating), and series capacitor blocking in transmission lines.

The technology that delivers the system visibility required to effectively manage and mitigate the threat of GMD is called Intensity Modulated ("IM") Optical Sensing. It was developed by the Naval Research Laboratory for use by the United States Navy in mission-critical applications which presented with very hostile measuring environments. IM optical sensing devices solve the measuring challenges to which other optical devices and traditional instrument transformer devices succumb, including those present during geomagnetic storms. Furthermore, the measuring capabilities of IM optical sensing devices transcend the capabilities of traditional devices. The remarkable stability of an IM optical monitoring systems in harsh measuring conditions, its higher accuracy, broadband measuring capabilities, and its real-time delivery of power system information are key to delivering a more resilient electric power grid, even and particularly in the grips of such High Impact Low Frequency events as GMD.

**Geomagnetically Induced Currents**

Geomagnetic storms are associated with activity on the sun's surface, namely sunspots and solar flares. Solar flares result in electromagnetic radiation (coronal mass ejections (CME), x-rays and charged particles) forming a plasma cloud or "gust of solar wind" that can reach earth in as little as eight minutes. Depending on its orientation, the magnetic field produced by the current within this plasma cloud can interact with the earth's magnetic field, causing it to fluctuate, and result in a geomagnetic storm.

Geomagnetically induced currents ("GICs") are caused when the "auroral electrojet", currents that follow high altitude circular paths around the earth's geomagnetic poles in the magnetosphere at altitudes of about 100 kilometers, becomes 'energized' and subjects portions of the earth's nonhomogeneous, conductive surface to slow, time-varying fluctuations in Earth's normally unchanging magnetic field. [1][2] By Faraday's Law of Induction, these time-varying magnetic field fluctuations induce electric fields in the earth which give rise to potential differences (ESPs – earth surface potentials) between grounding points. The distances over which a resulting electric field's effects may be felt can be quite large. The field, then, essentially behaves as an ideal voltage source between rather remote neutral ground connections of transformers in a power system, causing a GIC to flow through these transformers, connected power system lines and neutral ground points.

A power system's susceptibility to geomagnetic storms varies and is dependent upon several contributing elements, including:

- The characteristics of the transformers on the system, which serve as the entry (and exit points) for GIC flow, such as:
    - Transformer winding construction: Any transformer with a grounded-wye connection is susceptible to having quasi-DC current flow through its windings; an autotransformer (whereby the high- and low-voltage windings are common, or shared) permits GIC to

[2] John G. Kappenman, 'Geomagnetic Disturbances and Impacts upon Power System Operation,' The Electric Power Engineering Handbook, Chapter 4.9, 4-151., 2001.

pass through to the high-voltage power lines, while a delta-wye transformer does not [Figure 1].

  - Transformer core construction: The core design determines the magnetic reluctance of the DC flux path which influences the magnitude of the DC flux shift that will occur in the core. A 3-phase, 3-legged core form transformer, with an order of magnitude higher reluctance to the DC Amp-turns in the 'core – tank' magnetic circuit than other core types, is least vulnerable to GIC. Most problems are associated with single phase core or shell form units, 3-phase shell form designs or 3-phase, 5-legged core form designs.[3]
  - Transformer ground construction: Transformers on extra high voltage (EHV) transmission systems are more vulnerable than others because those systems are very solidly grounded, creating a low-resistive, desirable path for the flow of GIC. Incidentally, many EHV transformers are not 3-phase, 3-legged core form designs.

- The geographical location, specifically the magnetic latitude, of the power system: The closer the power segment is to the earth's magnetic poles generally means the nearer it is to the auroral electrojet currents, and consequently, the greater the effect.[4] Note, however, that the lines of magnetic latitude do not map exactly with geographic latitude as the north and south magnetic poles are offset from Earth's spin axis poles. Therefore, the East coast geographic mid-latitude is more vulnerable than the West coast geographic mid-latitude as the former is closer to the magnetic pole.[4]
- Earth ground conductivity: Power systems in areas of low conductivity, such as regions of igneous rock geology (common in NE and Canada), are the most vulnerable to the effects of intense geomagnetic activity because: (1) any geomagnetic disturbance will cause a larger gradient in the earth surface potential it induces in the ground (for example, 6 V/km or larger versus 1 – 2 V/km)[5] and (2) the relatively high resistance of igneous rock encourages more current to flow in alternative conductors such as power transmission lines situated above these geological formations (current will utilize any path available to it but favors the least resistive).[5] Earth's conductivity varies by as much as five orders of magnitude.[5] [Reference Figure 2.]
- Orientation of the power system lines (E-W versus N-S): The orientation of the power lines affects the induced currents. The gradients of earth surface potential are normally, though not always, greater in the east-west direction than in the north-south direction.[6]
- The length and connectivity of the power system lines: The longer the transmission lines the greater the vulnerability. Systems dependent upon remote generation sources linked by long transmission lines to deliver energy to load centers are particularly vulnerable. This is characteristic of Hydro Quebec's system in Quebec where much of its power is produced far from where it is consumed; for example, its James Bay generators are 1,000 km away from any

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[3] R. Girgis and K. Vedante, "Effects of GIC on Power Transformers and Power Systems," 2012 IEEE PES Transmission and Distribution Conference and Exposition, Orlando, FL, May 7-10, 2012.
[4] James A. Marusek, "Solar Storm Threat Analysis", Impact 2007, Bloomfield, Indiana
[5] John G. Kappenman, 'Geomagnetic Disturbances and Impacts upon Power System Operation,' The Electric Power Engineering Handbook, Chapter 4.9, 4-151., 2001.
[6] P.R. Barnes, D.T. Rizy, and B.W. McConnell, "Electric Utility Experience with Geomagnetic Disturbances," Oak Ridge National Lab, Nov. 25, 1991.

populated load center.[7] Since the GMD event that ravished their system in March 1989, Hydro Quebec has installed series capacitors on transmission lines which will block GIC flow.

- The strength of the geomagnetic storm: A more powerful solar storm increases the intensity of the auroral electrojet currents and can move these currents towards the earth's equator.

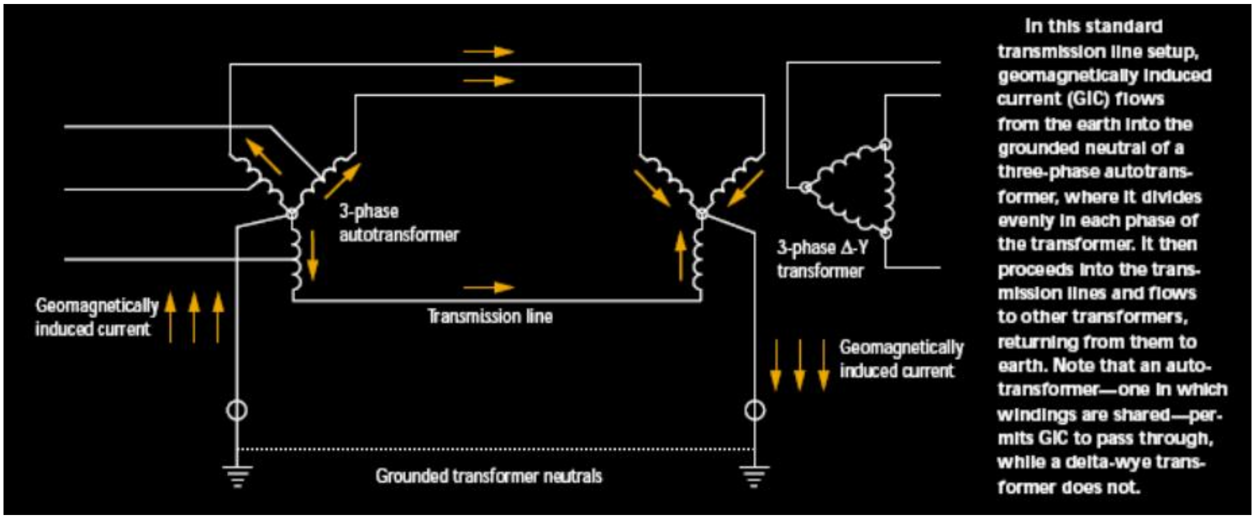


**FIGURE 1**
**Conducting Path for GICs[8]**

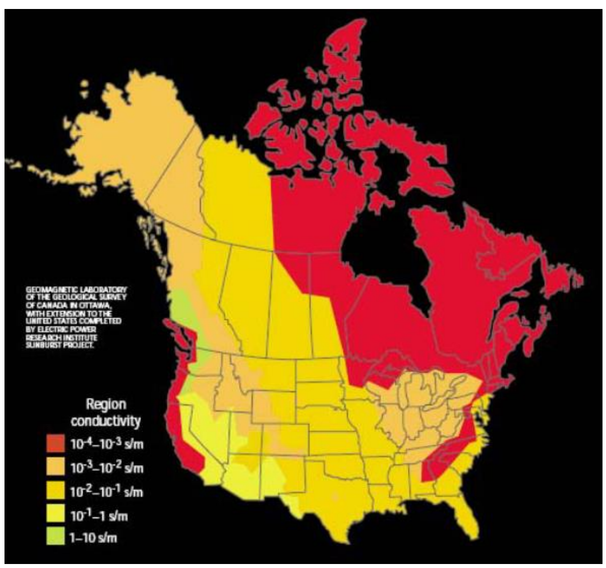


**FIGURE 2**
**Earth Conductivity in US & Canada[8]**

[7] M. Corey Goldman, "How one power grid kept lights on", Toronto Star, September 8, 2003, http://www.ontariotenants.ca/electricity/articles/2003/ts-03i08.phtml

[8] Tom S. Molinski, William E. Feero, and Ben L. Damsky, "Shielding Grids from Solar Storms", *IEEE Spectrum*, November 2000, pp. 55-60.

The impact of GIC on afflicted transformers and corresponding electric power systems is generally understood but the many variables that influence vulnerability and therefore the inconsistency in the resultant singular manifestations of GIC lends to a near impossible cumulative quantification of a geomagnetic storm's impact on power systems. Most impact quantifications up to now have been anecdotal.

**Potential Impact of GIC on Transformers and Electric Power Systems**

The source of nearly all of the operating and equipment problems attributed to a geomagnetic disturbance is the reaction of susceptible transformers in the presence of GIC. Therefore, the first order effects of GIC are those on the transformer and the second order effects of GIC are those on the power system.

First Order Effects of GIC

The exciting current of a transformer represents the continuous energy required to force "transformer action", in other words, make the transformer behave as a transformer. It is largely a reactive current (usually dominated by an inductive contribution known as the magnetizing current) and typically very small as transformers are very efficient devices, usually less than 1% of the transformer's rated operating current. Under normal, steady state conditions, the exciting current of a transformer is symmetrical (balanced between the positive and negative peaks of its waveform) as shown in Figure 3; the exciting current is shown in blue on the bottom vertical axis.

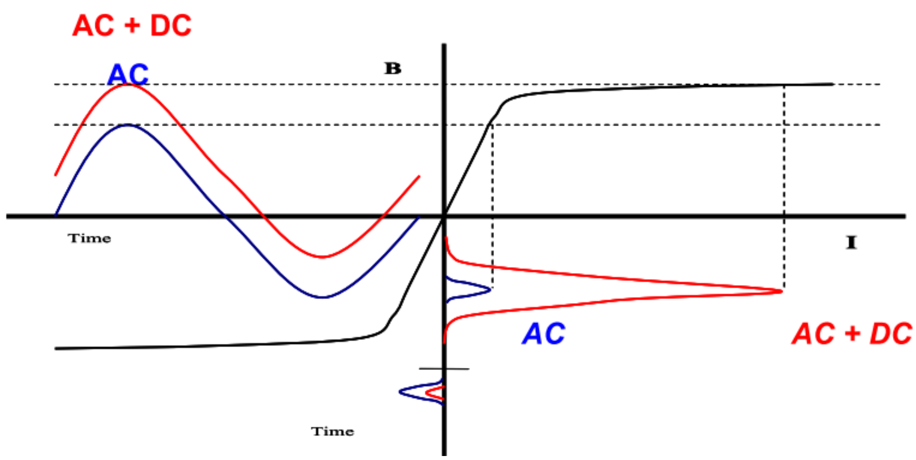


**FIGURE 3**
**Part Cycle, Semi Saturation of Transformer Cores[9]**

For economic motivations, the peak ac flux in the power transformer (given by the blue waveform on the left side of Figure 3) is designed to be close to the knee (or magnetic saturation point) of the magnetization curve (shown by the black curve in Figure 3) so that nearly the full magnetic capabilities of the transformer's core is used during operation. When a core operates below its saturation point, practically all of the magnetic flux created by the exciting current is contained in the core. The magnetic reluctance of the core is low because the core steel is an excellent conduit for magnetic flux.

[9] R. Girgis and K. Vedante, "Effects of GIC on Power Transformers and Power Systems," 2012 IEEE PES Transmission and Distribution Conference and Exposition, Orlando, FL, May 7-10, 2012.

Accordingly, the magnetization losses are low (i.e., a small $I_h$ in Figure 4) and the (shunt) magnetizing inductance is high, resulting in a very small magnetizing current, $I_m$. The exciting current is the vector sum of these current contributions, $I_h$ and $I_m$. The inductive volt-amperes-reactive (VAR) requirements of the transformer are very low. Moreover, with non-saturated core magnetization, the transformer voltage and current waveforms contain very low harmonic content.

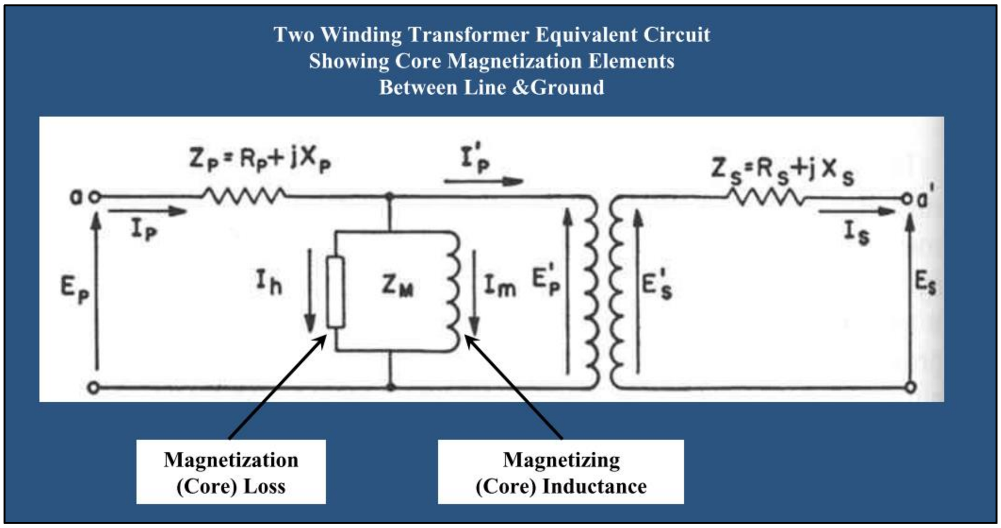


**FIGURE 4**
**Transformer Equivalent Circuit**[10]

During a GIC event, a quasi-dc current enters the ground connected neutral of the transformer and splits equally between phase windings (on multiple phase winding transformers). If the zero sequence reluctance of the transformer is low, the GIC biases the operating point on the magnetization curve to one side (see the top black dashed line in Figure 3). This bias causes the transformer to enter the saturation region in the half cycle in which the ac causes a flux in the same direction as the bias. This effect is known as half-cycle saturation.[11] When the core saturates, it has reached the limit of its ability to carry a magnetic field and any field beyond the limit "leaks" out of the core and passes through the space around the core (air/oil) as "leakage flux". While the magnetic reluctance of the core is still low, the reluctance of the portion of the magnetic circuit outside the core is high. This results in a much-lowered value of shunt inductance and a large shunt current ($I_m$) flows through the magnetizing branch. The inductive volt-amperes-reactive (VAR) requirements of the transformer can become very high (see the red exciting current pulse given a DC offset on the bottom vertical axis in Figure 3). With saturated core magnetization, the transformer voltage and current waveforms contain very high harmonic content.

[10] W. Hagman, "Space Weather in Solar Cycle 24: Is the Power Grid at Risk?", IEEE PES Boston Chapter & IEEE Com Society Boston Chapter Joint Lecture, April 16, 2013

[11] W. Chandrasena, P.G. McLaren, U.D. Annakkage, R.P. Jayasinghe, "Modeling GIC Effects on Power Systems: The Need to Model Magnetic Status of Transformers", 2003 IEEE Bologna Power Tech Conference, June 23 – 26, 2003, Bologna, Italy

Problems can occur with differential protective relays that are looking to see balanced primary and secondary currents, i.e., the transformer may trip as the primary current becomes disproportionately large (drawing increasingly more reactive current) compared to its secondary current.

Leakage flux is always present in a transformer that is carrying load. Because of the problems that it can otherwise cause, transformer manufacturers design and build their transformers such that the anticipated leakage flux is "managed" and has minimal impact on the long term operation and survivability of the transformer. Leakage flux, however, is never anticipated from the excitation of the transformer. The high peak magnetizing current pulse (red in Figure 3) produces correspondingly higher magnitudes of leakage flux (as given by the red waveform on the left side of Figure 3) that is also rich in harmonics.[12]

The influence of excessive leakage flux on the transformer is generally thermal. Leakage flux in transformers that links any conductive material (including transformer windings and structural parts) will cause induced currents which will result in almost immediate localized, unexpected, and severe heating due to resistive losses. Paint burning off transformer tank walls might be considered an asset owner's best news case example. Transformer designs that implement core bolts are a concern because should the stray flux link such bolts located at the bottom of the windings and cause the surrounding oil to heat to 140°C, this could result in bubble evolution that ultimately fails the transformer. For any given design, a finite element analysis will reveal the leakage flux paths and weaknesses, if any, in the design. If a transformer is lightly loaded, and therefore its operating leakage flux is light as compared to its full load rated flux, the unit may be able to handle the additional leakage flux introduced by GIC.

In summary, a saturated transformer becomes a reactive energy sink, an unexpected inductive load on the system, and behaves more like a shunt reactor.[13] Transformer differential protective relays may trip and remove the transformer from service. Excessive leakage flux can result in detrimental overheating, or in some designs, winding damage due to resulting high winding circulating currents. Separately, the magnetizing current pulse of a GIC inflicted transformer injects significant harmonics into the power system. The resultant impact of these changes in the transformer(s) constitutes the second order effects of GIC.

Second Order Effects of GIC

Many agree that the more concerning impacts of GIC are its indirect effects on the power system and its components. The influence of a transformer morphing into a shunt reactor on the power system is best understood after a review of shunt reactors and capacitors.

Shunt capacitor banks are used to offset inductive effects on the power system (to support voltage) while shunt reactors are used to offset the effects of capacitance on the system (to lower voltage). Typically, shunt capacitors are switched in during periods of high load, and shunt reactors are switched in during periods of light load. The same effects can be achieved, within rating limits, by varying the excitation of generators, i.e., operating them as "synchronous condensers". Static VAR compensators (SVC's), which combine capacitor banks and reactors also provide similar compensation and voltage

[12] R. Girgis and K. Vedante, "Effects of GIC on Power Transformers and Power Systems," 2012 IEEE PES Transmission and Distribution Conference and Exposition, Orlando, FL, May 7-10, 2012.
[13] It should be noted that upon removal of the DC current, a core will not remain in its saturated state while energized.

support, with very fast automated controls. Many power systems once had dedicated synchronous condensers (rotating machines). However, capacitor banks are cheaper and capacitor technology advanced to the point where reliability became excellent, so synchronous condensers were retired.[14]

Inductive reactance, which is expressed by, $X_L = 2\pi fL$, indicates that as inductance, L, goes down, inductive reactance drops. Saturated transformers have low shunt magnetizing inductance so they draw high currents; they look like shunt reactors on the system, dragging down the system voltage. Capacitive reactance is expressed by, $X_C = 1/(2\pi fC)$. From this, it is easy to see that a capacitor presents as an open circuit (infinite impedance) to DC current; thus the effectiveness of series capacitor blocking in very long transmission lines as a GIC mitigation strategy. Alternatively, as frequency goes up, capacitive reactance drops so capacitor banks have lower impedances to harmonics and draw larger currents when harmonics are present.

While saturated transformers draw large currents, forcing system voltage down (and potentially overloading long transmission lines), capacitor banks also draw large currents due to the presence of resultant harmonics, partially offsetting the inductive effects. Essentially, the saturated transformers are in a tug-of-war with the capacitors on the system. Modern shunt capacitors have very low loss and are therefore less susceptible to transient heating damage due to excess current. However, large currents may affect other components in capacitor bank installations, resulting in damage and unwanted tripping.[15] Voltage imbalance and overvoltage protection may also be "fooled" by harmonic voltage spikes and cause unwanted trips. Finally, overcurrent protection may also operate spuriously in the face of harmonic currents.[16] Similar issues may apply to SVC's. Harmonic filters for SVCs banks create parallel resonances which can exacerbate voltage disturbance issues and result in tripping of the protection devices. [13]

Rotating machines have fairly high thermal inertias, so generators operated as synchronous condensers have a higher probability of staying on line.[13] However, generators can also be affected by GIC currents. These effects include additional heating, damage to rotor components, increased mechanical vibrations and torsional stress due to oscillating rotor flux caused by increased negative sequence harmonic currents. The harmonic content of negative sequence currents can also cause relay alarming, erratic behavior or generator tripping.[17] If VAR resources are exhausted during a GMD event, specifically capacitive voltage support, voltage collapse can occur.

NERC's 2012 Special Reliability Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System provides a block diagram that illustrates the effects of GIC, culminating in a threat to system voltage and angle stability (Figure 5).

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[14] W. Hagman, "Space Weather in Solar Cycle 24: Is the Power Grid at Risk?", IEEE PES Boston Chapter & IEEE Com Society Boston Chapter Joint Lecture, April 16, 2013

[15] W. Hagman, "Space Weather in Solar Cycle 24: Is the Power Grid at Risk?", IEEE PES Boston Chapter & IEEE Com Society Boston Chapter Joint Lecture, April 16, 2013

[16] B. Bozoki et al., Working Group K-11 of the Substation Protection Subcommittee of the Power System Relaying Committee, IEEE PES, "The Effects of GIC on Protective Relaying," *IEEE Transactions on PowerDelivery*, Vol. 11, No. 2, April 1996, pp. 725-739.

[17] D. Wojtczak and M. Marz, "Geomagnetic Disturbances and the Transmission Grid" http://www.cce.umn.edu/documents/cpe-conferences/mipsycon-papers/2013/geomagneticdisturbancesandthetransmissiongrid.pdf

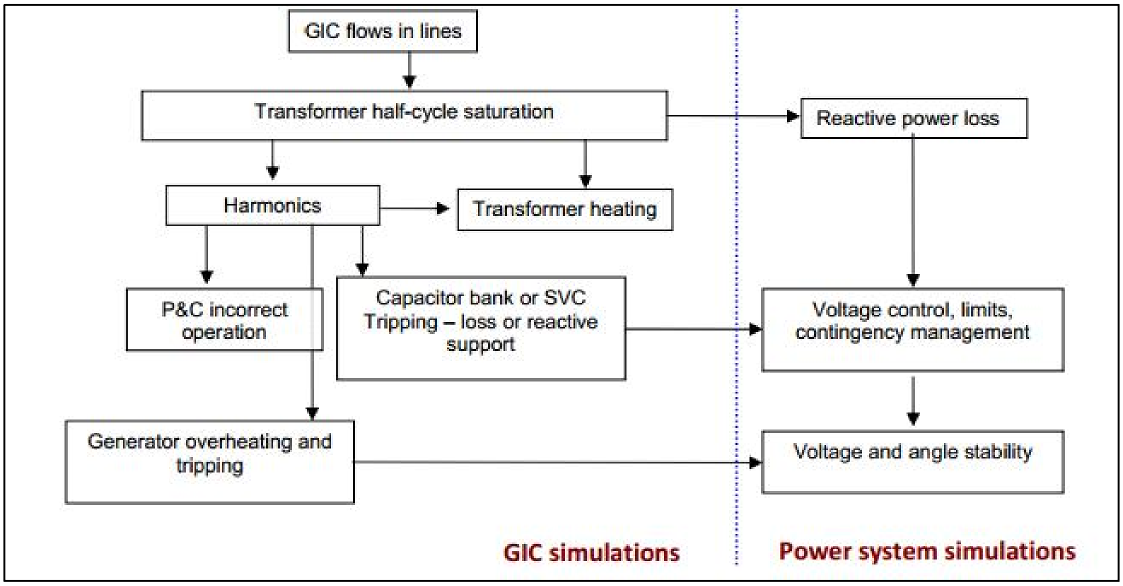


**FIGURE 5**
**From NERC: Effects of GIC in a High Voltage Transmission Network[18]**

<u>A Special Dispensation about the Effects of GIC on CTs (and protective relays)</u>;

It is important to have accurate measurements of system state during abnormal operating conditions. For these purposes, the industry has predominantly relied upon conventional instrument transformers (such as a current transformer ("CT"); a potential (or voltage) transformer, which may be inductive ("PT"/"VT") or capacitive ("CCVT"); or a combined current and voltage instrument transformer). An instrument transformer ("IT") is "intended to reproduce in its secondary circuit, in a definite and known proportion, the current or voltage of its primary circuit with the phase relations and waveforms substantially preserved."[19] The electromagnetically induced current or voltage waveform(s) in the secondary circuit(s) of the instrument transformer (IT) should then be of an easily measurable value for the metering or protective devices that are connected as the load, or "burden", on the IT.

In as much as a traditional, "ferromagnetic" IT has a magnetic core, instrument transformers are subject to influence from the presence of GIC much like a power transformer (discussed in the preceding sections). If an IT is pushed to a non-linear region of its saturation curve (i.e., its operating curve), due, for example, to a DC flux shift, the accuracy of the IT will significantly decline. While it is true that ITs typically operate at lower magnetization levels than power transformers because reading accuracy must be maintained in the face of large fault currents (i.e., they have more "built-in margin" on the curve), there is no way of knowing whether the magnitude of GIC in the system is yet enough to saturate the core (despite its margins), or if remanence was pre-existing in the core and already compromising the IT's performance. In short, there will always be uncertainty about the reliability of system state measurements provided by ferromagnetic instrument transformers during a GIC event. Moreover,

[18] North American Electric Reliability Corporation (NERC) Geomagnetic Disturbance Task Force (GMDTF) Interim Report, "Effects of Geomagnetic Disturbances on the Bulk Power System," February 2012, page 62. http://www.nerc.com/files/2012GMD.pdf
[19] "C37.110-2007 IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes", IEEE, New York, NY April 7, 2008.

when currents and voltages become rich in harmonics, even if the IT is not operating in a saturated state, the accuracy of the measurements will decline. Unfortunately, there is no on-line method of validating whether the instrument transformer is operating in a non-saturated state and, therefore, within its “window of accuracy” (i.e., the pseudo-linear region of its saturation curve at 60 Hz) or in a saturated state and, therefore, outside the realm in which it can accurately reproduce measurements.

Reference 20 provides more details about the variables that impact the performance of conventional instrument transformers.[20]

It is lastly noted that protective relays operate based only on their inputs. If a CT, for example, is supplying a distorted waveform due to the effects of harmonic saturation, the relay may respond in a different, and unwanted, way than it does to nearly sinusoidal inputs.[21]

**FERC/NERC Regulation**

Federal regulations designed to protect the nation’s electric grid from the potentially severe and widespread impact of a geomagnetic disturbance (GMD) are in the process of being adopted. Following several years of study, the Federal Energy Regulatory Commission (FERC) initiated a rulemaking in 2012, the first of its kind, directing NERC to develop and submit for approval Reliability Standards to protect the grid from the impact of GMDs.

In Order No. 779, FERC determined that the risk posed by GMD events, and the absence of Reliability Standards to address GMD events, posed a risk to system reliability that justified its precedent-setting order directive to NERC to develop Reliability Standards to address the issue. In order to expedite the standards-setting process, FERC ordered NERC to develop mandatory standards in two stages, both of which are now underway.

In the first stage, FERC directed NERC to submit Reliability Standards that required owners and operators of the bulk-power system to develop and implement operational procedures to mitigate the effects of GMDs to ensure grid reliability. These operational procedures were considered a “first step” to address the reliability gap and were approved by FERC in June 2014. These standards become mandatory on January 1, 2015.

In the second stage, FERC has directed NERC to provide more comprehensive protection by requiring entities to perform vulnerability assessments and develop appropriate mitigation strategies to protect their facilities against GMD events. These strategies include blocking GICs from entering the grid, instituting specification requirements for new equipment, and isolating equipment that is not cost effective to retrofit. In subsequent orders, FERC has reiterated its expectation that the second stage GMD standard include measures that address the collection, dissemination, and use of GIC data, by NERC, industry, or others, which may be used to develop or improve GMD mitigation methods or to validate GMD models.

Thus, FERC’s forthcoming standard is likely to require or strongly encourage the installation of GIC monitoring equipment as a means of assessing vulnerability and as the data source by which GIC

[20] J. Duplessis and J. Barker, “Intelligent Measurement for Grid Management and Control”, PACWorld Americas Conference, Raleigh, N.C., September 2013
[21] W. Hagman, “Space Weather in Solar Cycle 24: Is the Power Grid at Risk?”, IEEE PES Boston Chapter & IEEE Com Society Boston Chapter Joint Lecture, April 16, 2013

blocking or other protection schemes are to be implemented. The second stage standards including equipment-based GMD mitigation strategies are due to be filed by NERC in January 2015 and are likely to be approved by FERC in mid-2015.

**Intensity Modulated Optical Sensing Technology**

Intensity modulated optical sensing technology provides the full system visibility, accuracy and stability required to effectively mitigate GIC effects. This cannot be done with the grid's present information infrastructure comprised primarily of ferromagnetic type instrument transformers.

The fundamental solution to accurate information is to find a physical solution that can observe the system without being electrically coupled to the system, or measurand. This concept precludes any of the IT products either currently available or under development. Instead, it requires a completely new approach to measurement.

Starting in the late 90's, the electric power industry began to experiment with optical techniques that used interferometeric wave and phase modulation as the physical underpinnings of an electrically decoupled measurement system. Unfortunately, this equipment has generally failed in field applications due to its extreme sensitivity to temperature and EMI.

To solve this problem, a new approach based on recently declassified military applications has now been adapted to the needs of the electric power grid – thus achieving the objective of a highly accurate and reliable measurement device that is not electrically coupled to the measurand.

*How the technology works:*

The U.S. Naval Research Lab (NRL) has been a leader in optical sensing research for over 50 years. Similar to the power industry's experience with interferometric sensors[22], the Navy found that the acute temperature and EMI sensitivity of these devices caused them to fail in mission critical, field applications. To solve these problems, the NRL ultimately developed a highly stable, *intensity* modulated optical sensor that has no temperature sensitivity, no susceptibility to EMI, no frequency modulation, and has been proven to operate accurately in very harsh conditions for long periods of time. This technology, vetted over decades, has now been adapted to measure voltage, current, phase and other characteristics of electric phenomena, and can deliver accurate, stable and reliable performance in rigorous field applications on the power system.

An intensity modulated optical monitoring system consists of a transducer that is located within the force field it is measuring, a light source located some distance away, a fiber optic transmitting cable, at least one fiber collector or return cable, and power electronics.

A sensing element is held securely within the transducer; this is a material that is deliberately selected based upon the measuring application and which responds to changes in the force to which it is subjected. This force is characterized by a magnitude and frequency. In the case of acoustic measurements, and as shown in Figure 6, this material is a diaphragm. Physical displacement of the sensor is being directly measured but this movement is ultimately a function of the force (i.e., the measurand) acting upon it.

Light of a known intensity ($P_T$) from a light-emitting diode (LED) is coupled into an optical fiber for transmission to the sensing element where it is modulated in accordance with the state of the measurand.

[22] As gauged by general polled feedback

Reflected light of a varying intensity ($P_R$) is collected by at least one return fiber for transmission back to a photo-detector.

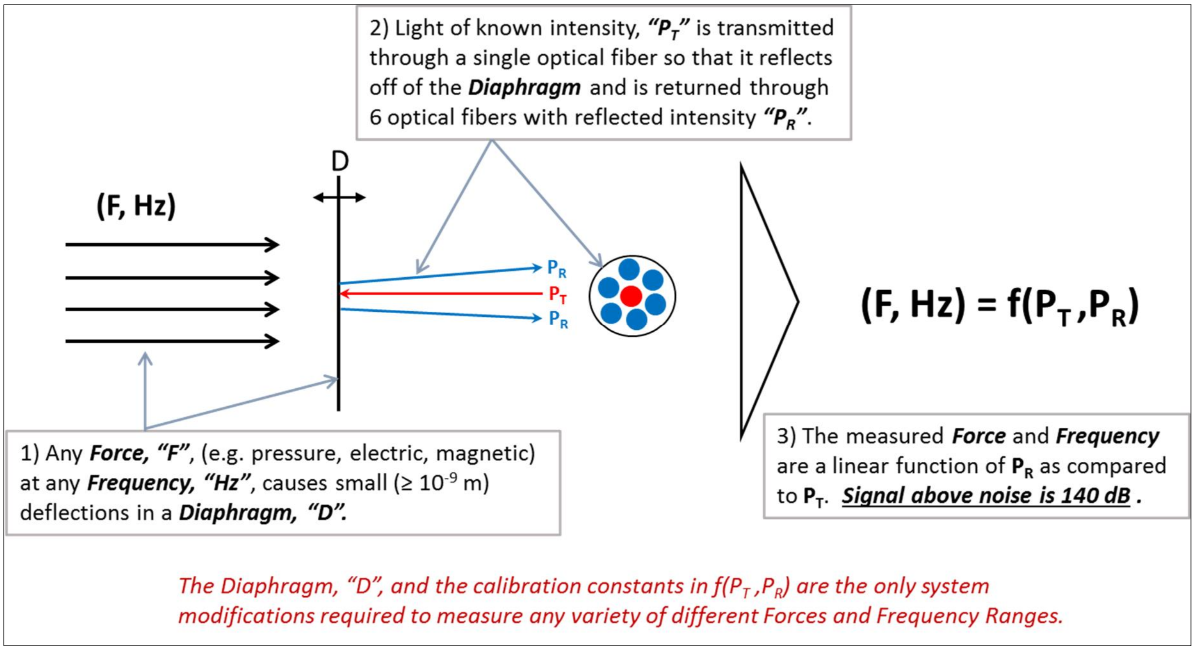


**Figure 6**
**Intensity Modulated Optical Sensing – Fundamental Concept**

The intensity of the light returned through the fiber correlates to the force exerted on the sensing element and the frequency with which it is changing. As an example, consider an acoustical measurement. As sound changes, the diaphragm moves and the resultant distance between the fiber probe and the diaphragm changes. Note that the fiber probe is stationary; it is the movement of the sensing element that alters the distance between the probe and the sensor. If that distance becomes smaller by way of displacement of the diaphragm towards the fiber probe, the reflectance changes and the intensity of the reflected light captured by the return fibers decreases (Figure 7). As the distance increases, more reflected light is captured by the return fibers and, consequently, $P_R$ increases (Figure 8).

One transmit fiber and only one return fiber is depicted in Figures 7 and 8. The use of multiple return fibers amplifies the sensitivity of this intensity modulated technology, resulting in the ability to detect displacement changes of the sensing element on the order of $10^{-9}$ meters.

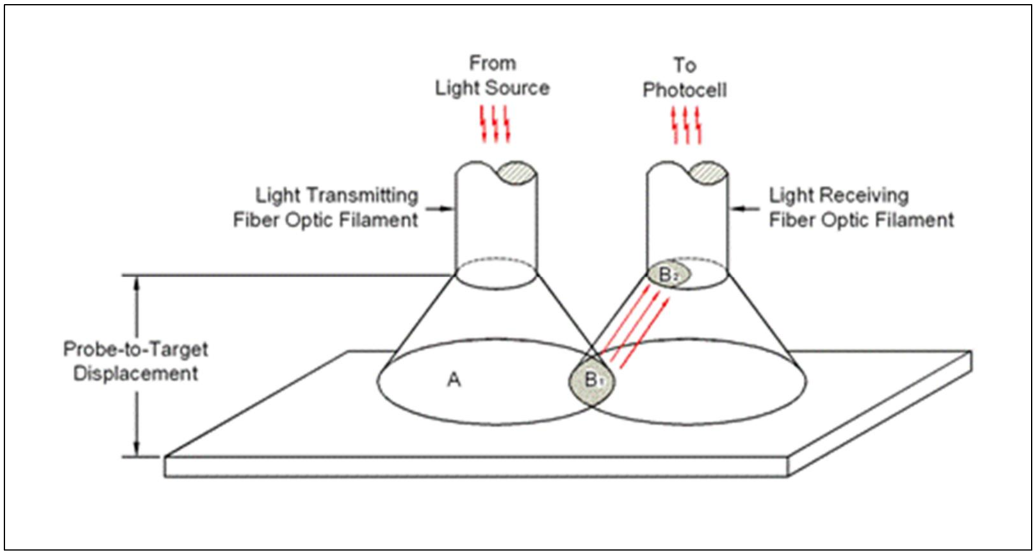


**FIGURE 7**[23]
**$P_R$ Decreases as Displacement between Probe and Diaphragm Decreases**

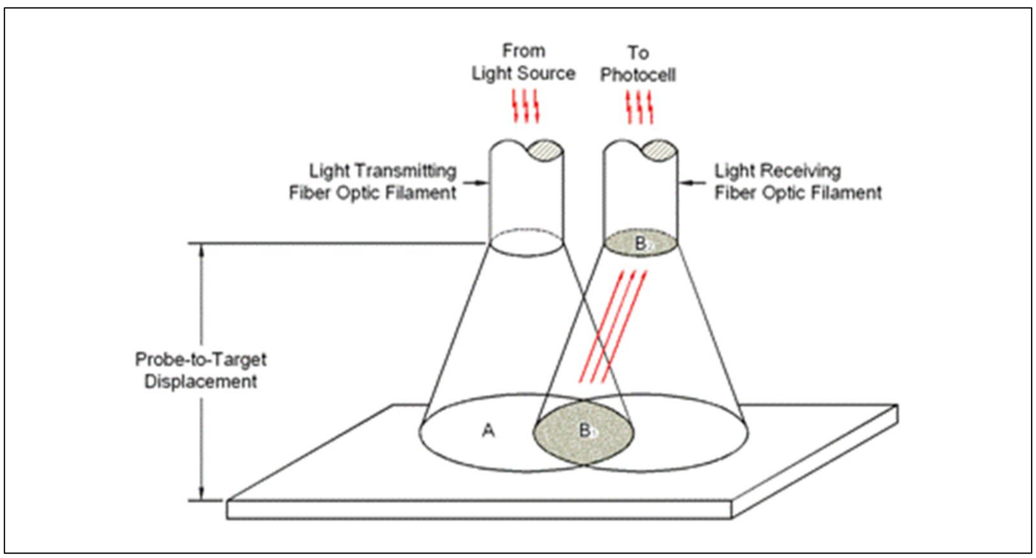


**FIGURE 8**[24]
**$P_R$ Increases as Displacement between Probe and Membrane Increases**

## Adaptation

*Adapting Intensity Modulated Optical Sensors to Measure Electrical Phenomena:*

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[23] Yury Pyekh, "Dynamic Terrain Following: NVCPD Scanning Technique Improvement", Fig. 3.7, Thesis Presented to the Academic Faculty of Georgia Institute of Technology, August 2010.
[24] Yury Pyekh, "Dynamic Terrain Following: NVCPD Scanning Technique Improvement", Fig. 3.8, Thesis Presented to the Academic Faculty of Georgia Institute of Technology, August 2010.

Laws of physics are used to adapt the intensity modulated (IM) optical sensors to measure current and voltage. For example, principles of Lorentz's Force are applied to build the IM optical (AC) current sensor.

A Lorentz force, given by F = BLI and illustrated in Figure 9, will result when a current (I) carrying conductor passes through a non-varying magnetic field with flux density, B for some length, L.

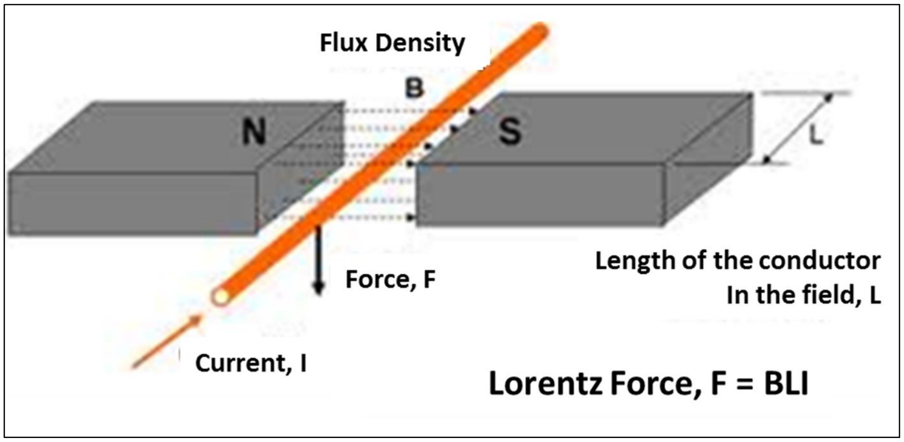


**FIGURE 9**
**Lorentz Law**

Accordingly, the current sensing element (Figure 10) connects to the line conductor; as current changes, variations in the Lorentz Force will result in the physical displacement of the sensing element. The intensity of light reflected back will therefore alter proportionally to the changes in the current.

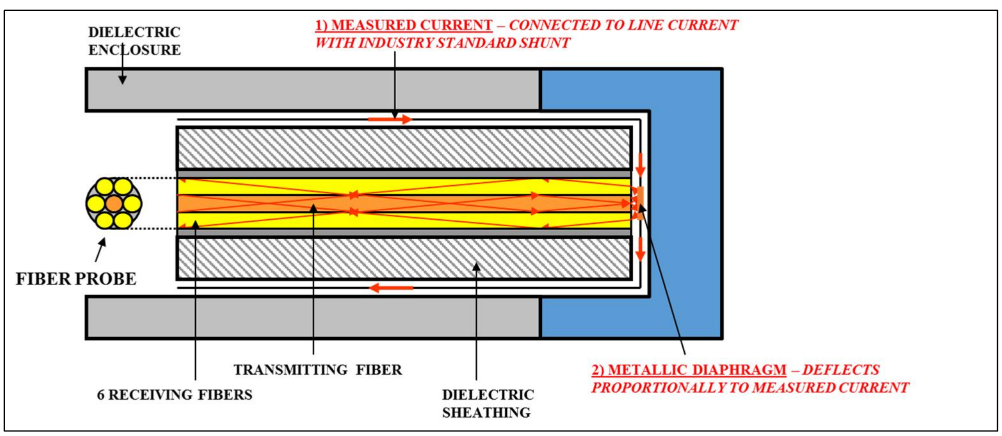


**FIGURE 10**
**Intensity Modulated Fiber Optic Current Sensor**

For voltage measurements, the selection of the sensing element is key. Here, a piezoelectric material is selected that has very stable physical characteristics that vary in a known way as the electric field in which the material is placed varies. A reflected surface affixed to the end of the sensing element will physically displace, therefore, as the material deflects relative to changes in the electric field.

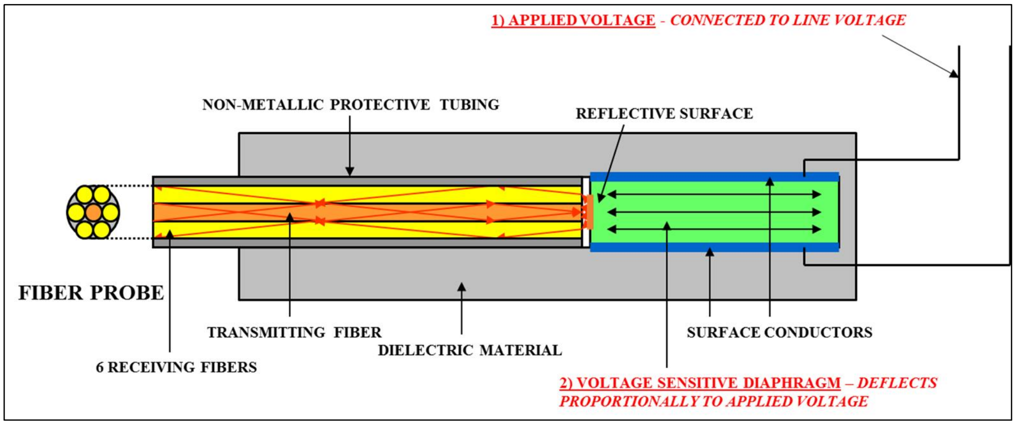


**FIGURE 11**
**Intensity Modulated Fiber Optic Voltage Sensor**

The IM optical current and voltage sensors are housed in a common transducer. The physical dimensions of these sensors are very small; the length of a sensor, its maximum dimension, is typically shorter than a few inches. This makes it possible to hold several sensors within one transducer, including IM optical temperature sensors.

IM optical sensing technology is adapted differently to measure DC current and voltage but is not discussed in this paper.

**Advantages**

*Accurate, Repeatable Measurement over an Extremely Wide Range of Values and Frequencies*

The fact that Intensity Modulated (IM) optical sensing is passive, non-ferromagnetic and non-interferometry based is central to why this technology delivers a step-change improvement in performance over both conventional instrument transformers and interferometry-based optical equipment.

First, because of its passivity, an IM optical transducer does not disturb the (power) system it observes. The sensing element is non-conductive and the transducer is electrically decoupled from the grid; light is the 'exchange medium' of the transducer and an electrical system is not altered by light. The transducer therefore 'sees' exactly what exists on the power system and this creates notably higher accuracy than what can be achieved by even the most accurate of metering class instrument transformers.

Second, because IM optical sensing is electrically de-coupled and is not ferromagnetic, traditional burdens have no influence on the transducer and the power system cannot negatively impact its measuring capability. IM optical sensors have no saturation curve; their equivalent operating "curve", and therefore performance, is perfectly linear throughout their wide measurement range. By removing variables introduced by system and burden influences, which have plagued the performance of conventional ITs in unpredictable ways for decades, the industry gains automatic assurances that the IM optical transducer is maintaining the accuracy it should at all times. This creates consistent accuracy and therefore, repeatability.

A third advantage of IM optical sensors' non-ferromagnetic based operation is that frequency has no influence on its measuring capabilities. While varying the frequency does alter the shape of a saturation curve that defines the operating characteristics of a conventional IT, it has no effect on the linear operating curve of an IM optical sensor. IM sensors can measure voltage and current at frequencies from quasi-DC to several thousand Hertz. There are no concerns about resonant frequencies associated with inductive and capacitive voltage transformers. This measuring technology therefore affords the power industry the opportunity to view a broad range of non-fundamental frequency components with the same accuracy as measurements at the fundamental frequency (50/60 Hz) and therefore, to perform incredibly insightful power quality studies.

While the pseudo-linear range of a conventional IT's saturation curve is not large, affording only an approximate 20 dB dynamic range, the linear range of operation of an IM optical sensor delivers an approximate >130 dB dynamic range. This means that a single IM optical current sensor, for example, can measure an extremely large fault current, and at once, an exceptionally small harmonic current with identical accuracy. An IM optical system's measuring range is only limited by its noise floor, which is much lower than any other conventional or non-conventional field measurement device that is currently available.

Figure 12 gives a visual representation of the range of (current/voltage) magnitudes over which a conventional IT will yield accurate measurements (the vertical height of the blue shaded area at 60 HZ) and the limiting influence of frequency on a conventional IT's accurate measuring capabilities (as given by the diminishing height of the blue-shaded area as the frequency decreases/increases). In contrast, the much broader, frequency independent, and notably more accurate measuring capabilities of an IM monitoring system are indicated by the encompassing white backdrop that frames the graph in Figure 12.

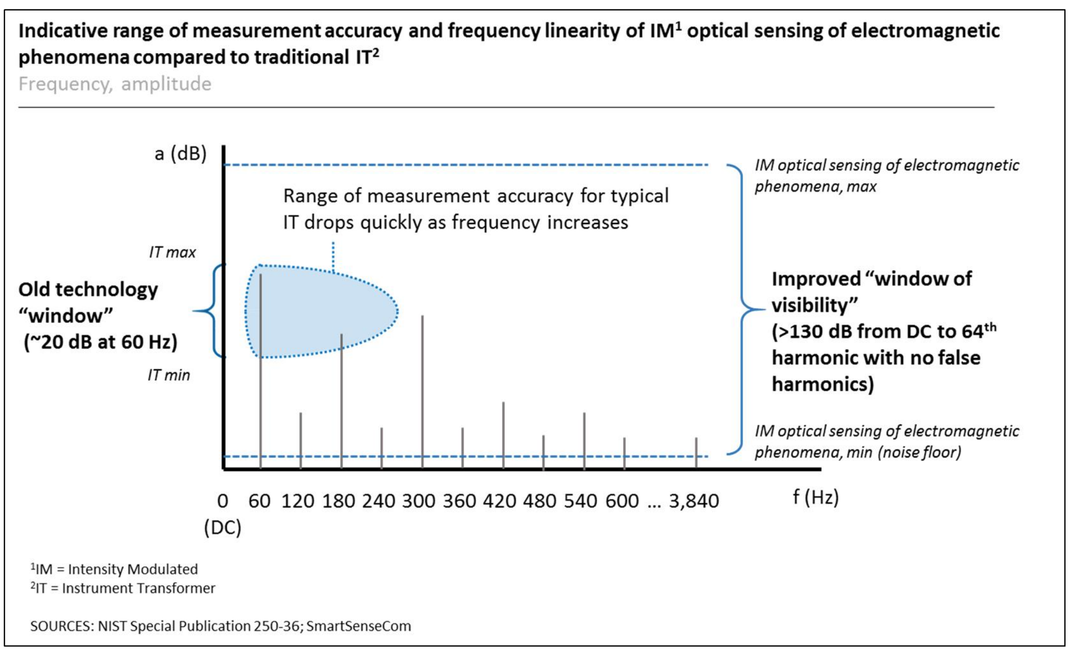


**FIGURE 12**
**Accuracy/ Linearity as a Function of Frequency**
**(For an IM Optical Monitoring System versus a Conventional IT)**

*Safety and Risk Reduction*

A separate, but equally important, advantage of passive IM optical sensors is safety and risk reduction in the unlikely event of the IM optical system's failure. With a conventional IT, the electrical grid extends all the way to the meter or protective device and the possibility exists for workers to be injured or even killed if they were to inadvertently come into contact with an open-circuited CT secondary. In contrast, the equivalent "secondary" side of an IM optical transducer is fiber optic cable carrying light. It presents no safety hazard. Moreover, should a conventional IT fail, it typically brings the circuit down with it, either due to catastrophic fire or a fault that trips the breaker. In comparison, the IM has no influence on the power system it is observing, and if it should fail, the power system would typically continue to operate as usual.

An additional benefit of being non-ferromagnetic is that periodic field testing to verify operating characteristics and insulation integrity is not necessary for an IM optical transducer. In fact, because an IM optical transducer is electrically decoupled from the grid, there is no requirement for the use of dielectric materials such as oil or SF6 in the device. The combination of these factors reduces O&M costs and expedites safe system restoration after outages.

**"IM" Optical Sensing as a Comprehensive Solution to Identifying and Measuring Impacts of GIC**

The concerns about GMD are justified and the effects of GIC well documented. The path forward becomes clear after reflection upon just a few of the industry comments about GIC:

- "Accurate estimation of the VAR consumption of the transformer during a GMD event is critical for proper mitigation of effects of GIC on power system stability."
- "Increase in VAR demand is one of the major concerns during a GMD event. The loss of reactive power could lead to system voltage collapse if it is not identified and managed properly."
- "…the magnetizing current pulse injects significant harmonics into the power system which can have a significant impact on shunt capacitor banks, SVCs and relays and could compromise the stability of the grid."

The GIC mitigation solution lies in the ability to quantify its effects in real time. The industry has not been able to do that up to now with the measuring devices available. IM optical monitoring systems change this.

An AC current and voltage IM optical transducer must be installed on the high-voltage side of a susceptible transformer. This will measure the VAR consumption of the transformer as well as any harmonics generated given the operating state of the transformer, well into the kHz range. A DC current IM optical transducer would be installed on the grounded neutral connection of the transformer. IM optical technology provides for accuracies of approximately one percent at low magnitude DC currents, 1 – 25A, allowing exacting correlation between DC currents and concurrently observed effects on the transformer (reactive energy consumption and harmonic profile).

Because of the many variables that contribute to the vulnerability of the transformer and connected power system, even given the same GIC magnitude, the transformer/system response is expected to be different. For this reason, it is not enough to install a simple DC current monitor, such as a Hall Effect sensor, on the neutral ground connection of a transformer. Even if one were to look past the instability of such devices, particularly at low DC current levels (< 25A), a DC measurement alone does not afford reliable predictability about the associated power system impact.

**Conclusion**

The negative impacts of geomagnetically induced currents (“GIC”) are understood at a high level. GIC flow negatively impacts certain power transformers causing half-cycle saturation that leads to increased demand for reactive power, generation of harmonics, and transformer heating. This in turn negatively impacts electric power transmission systems; at its worse, causing grid instability due to voltage collapse, misoperation of protection equipment (e.g., capacitor banks, overcurrent relays), damage to sensitive loads due to poor power quality, and/or thermal damage to the transformer. However, better system visibility is required to develop effective GIC mitigation strategies. For example, what is the actual change in reactive power and the harmonic generation profile at a specific location when GIC is present? How will the surrounding transmission system actually respond to these changes?

It is important to have accurate measurements of system state during abnormal operating conditions. Unfortunately, traditional ferromagnetic-type instrument transformers are at risk of being affected by GIC conditions too. There is no way of validating, in real time and while energized, whether an instrument transformer is saturated or not, so it is possible that information provided to protective devices may be riddled with error on the magnitude of over 12 percent. Moreover, classical instrument transformers do not have the ability to reproduce harmonics with any guaranteed accuracy (even when demagnetized) much beyond the 3$^{rd}$ harmonic.

The GMD/GIC phenomena is a prime example where the industry’s inability to sufficiently measure will leave it struggling to manage unless we embrace change. A solution to gain full (and stable!) system visibility was introduced. It is an optical solution called Intensity Modulated (IM) optical measuring; it resolves the grid’s present-day measuring inadequacies and is different than earlier optical techniques which, while promising, have proven to be unstable under field conditions due to extreme temperature instability and electromagnetic interference. An IM optical system was described along with some example adaptations for its use in measuring electrical phenomena. Advantages of IM optical transducers, rooted in their passivity and non-ferromagnetic characteristics, were enumerated. These include a step-change improvement in accuracy; hardening to otherwise influencing ‘environmental’ variables resulting in stability and consistency in measurements, and therefore, repeatability; the ability to observe the power system more comprehensively than ever before through one transducer; and significant enhancement in personnel and system safety.

The GIC mitigation solution lies in the ability to quantify its effects in real time. This can be accomplished through intensity modulated optical monitoring systems.

**Group Comments on NERC Standard TPL-007-1 – Transmission System Planned Performance for Geomagnetic Disturbance Events**

**November 21, 2014**

Draft standard TPL-007-1, "Transmission System Planned Performance for Geomagnetic Disturbance Events," is not a science-based standard. Instead, the apparent purpose of standard TPL-007-1 is to achieve a preferred policy outcome of the North American Electric Reliability Corporation (NERC) and its electric utility members: avoidance of installation of hardware-based protection against solar storms. The draft standard achieves this apparent purpose through a series of scientific contrivances that are largely unsupported by real-world data. Potential casualties in the millions and economic losses in trillions of dollars from severe solar storms instead demand the most prudent science-based standard.

A 2010 series of comprehensive technical reports, "Electromagnetic Pulse: Effects on the U.S. Power Grid"[1] produced by Oak Ridge National Laboratory for the Federal Energy Regulatory Commission in joint sponsorship with the Department of Energy and the Department of Homeland Security found that a major geomagnetic storm "could interrupt power to as many as 130 million people in the United States alone, requiring several years to recover."

A 2013 report produced by insurance company Lloyd's and Atmospheric and Environmental Research, "Solar Storm Risk to the North American Electric Grid,"[2] found that:

> "A Carrington-level, extreme geomagnetic storm is almost inevitable in the future. While the probability of an extreme storm occurring is relatively low at any given time, it is almost inevitable that one will occur eventually. Historical auroral records suggest a return period of 50 years for Quebec-level storms and 150 years for very extreme storms, such as the Carrington Event that occurred 154 years ago."
>
> "The total U.S. population at risk of extended power outage from a Carrington-level storm is between 20-40 million, with durations of 16 days to 1-2 years. The duration of outages will depend largely on the availability of spare replacement transformers. If new transformers need to be ordered, the lead-time is likely to be a minimum of five months. The total economic cost for such a scenario is estimated at $0.6-2.6 trillion USD."

A 2014 paper published in the Space Weather Journal, "Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment"[3] by C. J. Schrijver, R. Dobbins, W. Murtagh, and S.M. Petrinec found:

> "We find that claims rates are elevated on days with elevated geomagnetic activity by approximately 20% for the top 5%, and by about 10%for the top third of most active days ranked by daily maximum variability of the geomagnetic field."
>
> "The overall fraction of all insurance claims statistically associated with the effects of geomagnetic activity is 4%."

"We find no significant dependence of the claims frequencies statistically associated with geomagnetic activity on geomagnetic latitude."

Given the extreme societal impact of a major solar storm and large projected economic losses, it is vital that any study by NERC in support of standard TPL-007 be of the highest scientific caliber and rigorously supported by real-world data. The unsigned white papers of the NERC Standard Drafting Team fail scientific scrutiny for the following reasons:

1. The NERC Standard Drafting Team contrived a "Benchmark Geomagnetic Disturbance (GMD) Event"[4] that relies on data from Northern Europe during a short time period with no major solar storms instead of using observed magnetometer and Geomagnetically Induced Current (GIC) data from the United States and Canada over a longer time period with larger storms. This inapplicable and incomplete data is used to extrapolate the magnitude of the largest solar storm that might be expected in 100 years—the so-called "benchmark event." The magnitude of the "benchmark event" was calculated using a scientifically unproven "hotspot" conjecture that averaged the expected storm magnitude downward by an apparent factor of 2-3. This downward averaging used data collected from a square area only 500 kilometers in width, despite expected impact of a severe solar storm over most of Canada and the United States.
2. The NERC Standard Drafting Team contrived a table of "Geomagnetic Field Scaling Factors" that adjust the "benchmark event" downward by significant mathematical factors dependent on geomagnetic latitude. For example, the downward adjustment is 0.5 for Toronto at 54 degrees geomagnetic latitude, 0.3 for New York City at 51 degrees geomagnetic latitude, and 0.2 for Dallas at 43 degrees geomagnetic latitude. These adjustment factors are presented in the whitepaper in a manner that does not allow independent examination and validation.
3. The NERC Standard Drafting Team first contrived a limit of 15 amps of GIC for exemption of high voltage transformers from thermal impact assessment based on limited testing of a few transformers. When the draft standard failed to pass the second ballot, the NERC Standard Drafting Team contrived a new limit of 75 amps of GIC for exemption of transformers from thermal impact assessment, again based on limited testing of a few transformers. The most recent version of the "Screening Criterion for Transformer Thermal Impact Assessment"[5] whitepaper uses measurements from limited tests of only three transformers to develop a model that purports to show all transformers could be exempt from the thermal impact assessment requirement. It is scientifically fallacious to extrapolate limited test results of idiosyncratic transformer designs to an installed base of transformers containing hundreds of diverse designs.

The above described contrivances of the NERC Standard Drafting Team are unlikely to withstand comparison to real-world data from the United States and Canada. Some public GIC data exists for the United States and Canada, but the NERC Standard Drafting Team did not reference this data in their unsigned whitepaper “Benchmark Geomagnetic Disturbance Event Description.” Some public disclosures of transformer failures during and shortly after solar storms exist for the United States and Canada, but the NERC Standard Drafting Team did not reference this data in their unsigned whitepaper “Screening Criterion for Transformer Thermal Impact Assessment.”

NERC is in possession of two transformer failure databases.[6] [7] This data should be released for scientific study and used by the NERC Standard Drafting Team to develop a data-validated Screening Criterion for Transformer Thermal Impact Assessment. The NERC Standard Drafting Team failed to conduct appropriate field tests and collect relevant data on transformer failures, contrary to Section 6.0 of the NERC Standards Processes Manual, “Processes for Conducting Field Tests and Collecting and Analyzing Data.”[8]

U.S. and Canadian electric utilities are in possession of GIC data from over 100 monitoring locations, including several decades of data from the EPRI SUNBURST system.[9] This GIC data should be released for scientific study and used by the NERC Standard Drafting Team to develop a data-validated Benchmark Geomagnetic Disturbance Event. The NERC Standard Drafting Team failed to conduct appropriate field tests and collect relevant data on measured GIC, contrary to Section 6.0 of the NERC Standards Processes Manual, “Processes for Conducting Field Tests and Collecting and Analyzing Data.”[10]

The NERC whitepaper “Benchmark Geomagnetic Disturbance Event Description” contains “Appendix II – Scaling the Benchmark GMD Event,” a system of formulas and tables to adjust the Benchmark GMD Event to local conditions for network impact modeling. Multiple comments have been submitted to the Standard Drafting Team showing that the NERC formulas and tables are inconsistent with real-world observations during solar storms within the United States.[11] [12] [13] While the NERC Standard Processes Manual requires that the Standard Drafting Team “shall make an effort to resolve each objection that is related to the topic under review,” the Team has failed to explain why its methodology is inconsistent with measured real-world data.[14]

Even the most rudimentary comparison of measured GIC data to the NERC “Geomagnetic Field Scaling Factors” shows the methodology of “Appendix II—Scaling the Benchmark GMD Event” of whitepaper “Benchmark Geomagnetic Disturbance Event Description” is flawed. For example, this comment submitted in standard-setting by Manitoba Hydro:

> “GMD Event of Sept 11-13, 2014 - EPRI SUNBURST GIC data over this period suggests that the physics of a GMD are still unknown, in particular the proposed geoelectric field cut-off is most likely invalid. Based on the SUNBURST data for this period in time one transformer neutral current at Grand Rapids Manitoba (above 60 degrees geomagnetic latitude) the northern most SUNBURST site just on the southern edge of the auroral zone only reached a peak GIC of 5.3 Amps where as two sites below 45 degrees geomagnetic latitude (southern USA) reached peak GIC’s of 24.5 Amps and 20.2 Amps. “[15]

In the above instance, if the NERC "Geomagnetic Field Scaling Factors" were correct and all other factors were equal, the measured GIC amplitude at 45 degrees geomagnetic latitude should have been 1 Amp (5.3 Amps times scaling factor of 0.2). Were other GIC data to be made publicly available, it is exceedingly likely that the "Geomagnetic Field Scaling Factors" would be invalidated, except as statistical averages that do not account for extreme events. Notably, the above observation of Manitoba Hydro is consistent with the published finding of C. J. Schrijver, et. al. that "We find no significant dependence of the claims frequencies statistically associated with geomagnetic activity on geomagnetic latitude."

The EPRI SUNBURST database of GIC data referenced in the above Manitoba Hydro comment should be made available for independent scientific study and should be used by the NERC Standard Drafting Team to correct its methodologies.

American National Standards Institute (ANSI)-compliant standards[16] are required by the NERC Standard Processes Manual. Because the sustainability of the Bulk Power System is essential to protect and promptly restore operation of all other critical infrastructures, it is essential that NERC utilize all relevant safety and reliability-related data supporting assessments of geomagnetic disturbance impacts on "critical equipment" and benefits of hardware protective equipment. Other ANSI standards depend upon and appropriately utilize safety-related data on relationships between structural design or protective equipment and the effective mitigation of earthquakes, hurricanes, maritime accidents, airplane crashes, train derailments, and car crashes.

Given the large loss of life and significant economic losses that could occur in the aftermath of a severe solar storm, and the scientific uncertainly around the magnitude of a 1-in-100 solar storm, the NERC Standard Drafting Team should have incorporated substantial safety factors in the standard requirements. However, the apparent safety factor for the "Benchmark GMD Event" appears to be only 1.4 (8 V/km geoelectric field used for assessments vs. 5.77 V/km estimated).

The NERC Standard Processes Manual requires that the NERC Reliability Standards Staff shall coordinate a "quality review" of the proposed standard.[17] Any competent quality review would have detected inconsistencies between the methodologies of the "Benchmark Geomagnetic Disturbance Event Description" and real world data submitted in comments to the Standard Drafting Team. Moreover, any competent quality review would have required that the Standard Drafting Team use real-world data from the United States and Canada, rather than Northern Europe, in developing the methodologies of the "Benchmark Geomagnetic Disturbance Event Description" and "Screening Criterion for Transformer Thermal Impact Assessment."

Draft standard TPL-007-1 does not currently require GIC monitoring of all high voltage transformers nor recording of failures during and after solar storms.[18] These requirements should be added given the still-developing scientific understanding of geomagnetic disturbance phenomena and its impact on high voltage transformers and other critical equipment.

Going forward, data on observed GIC and transformer failures during solar storms should be publicly released for continuing scientific study. NERC can and should substitute a science-based standard to model the benefits and impacts on grid reliability of protective hardware to prevent long-term blackouts due to solar geomagnetic storms.

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**Supplemental Comments of the Foundation for Resilient Societies on NERC Standard TPL-007-1 Transmission System Planned Performance for Geomagnetic Disturbance Events November 21, 2014**

The Foundation for Resilient Societies, Inc. [hereinafter "Resilient Societies"] separately files today, November 21, 2014 Group Comments that assert multiple failures, both procedural and substantive, that result in material noncompliance with ANSI Procedural Due Process, and with NERC's Standard Processes Manual Version 3, effective on June 26, 2013.

In this separate Supplemental Comment, Resilient Societies incorporates as its concerns the material in comments on NERC Standard TPL-007-1 submitted by John Kappenman and William Radasky (July 30, 2014); John Kappenman and Curtis Birnbach (October 10, 2014); John Kappenman (2 comments dated November 21, 2014); and EMPrimus (November 21, 2014).

We reserve the right to utilize all other comments filed in the development of this standard in a Stage 1 Appeal under NERC's Standard Processes Manual Version 3. In particular but not in limitation, we assert that NERC fails to collect and make available to all GMD Task Force participants and to utilize essential relevant data, thereby causing an unscientific, systemically biased benchmark model that will discourage cost-effective hardware protection of the Bulk Power System; that NERC fails to fulfill the obligations under ANSI standards and under the Standard Processes Manual to address and where possible to resolve on their merits criticisms of the NERC Benchmark GMD Event model. Moreover, if the NERC Director of Standards and Standards Department fail to exercise the "quality control" demanded by the Standard Processes Manual, this will also become an appealable error if the standard submitted on October 27 and released on October 29, 2014 becomes the final standard for the NERC ballot body.

Moreover, an essential element of quality control for NERC standard development and standard promulgation is that the Standard comply with the lawful Order or Orders of the Federal Energy Regulatory Commission. To date, no element of the standard performs the cost-benefit mandate of FERC Order. No. 779.

Resilient Societies hereby refers the Standards Drafting Team and the NERC Standards Department to the filing today, November 21, 2014 of Item 31 in Maine Public Utilities Commission Docket 2013-00415. This filing is publicly downloadable. Appendix A to this filing of as Draft Report to the Maine PUC on geomagnetic disturbance and EMP mitigation includes an assessment of avoided costs, hence financial benefits of installing neutral ground blocking devices, including a range of several devices (Central Maine Power) to as many as 18 neutral ground blocking, and GIC monitors (EMPrimus Report, November 12, 2014, Appendix A in the Maine PUC filing of November 21, 2014). Cost-benefit analysis could and should be applied on a regional basis, in the NERC model and with criteria for application by NERC registered entities. NERC has failed to fulfill its mandate, with the foreseeable effect of suppressing public awareness of the benefits resulting from blockage of GICs to entry through high voltage transmission lines into the Bulk Power System. Another foreseeable result is economic harm to those companies that have invested capital in the development of GMD hardware protection devices and GIC monitors. We incorporate by reference the materials in Maine PUC Docket 2013-00415, Items 30 and 31, filed and publicly retrievable online in November 2014.

Finally, we express concern that the combination of NERC Standards in Phase 1 and in Phase 2, providing no mandatory GIC monitor installations and data sharing with Regional Coordinators, and with state and federal operations centers, effectively precludes time-urgent mitigation during severe solar storms despite timely reports to the White House Situation Room.

NERC has effectively created insuperable barriers to fulfill the purposes of FERC Order No. 779. Without significant improvements that encourage situational awareness by Generator Operators and near-real-time data to mitigate the impacts of solar geomagnetic storms, the only extra high voltage transformers that can be reliably protected will be those with installed hardware protection. Yet this defective standard will provide false reassurance that no hardware protection is required. Also, the scientifically defective NERC model may also preclude regional cost recoveries for protective equipment, by falsely claiming that no protective equipment is required under the assessment methodologies in the standard.

Hence irreparable harm to the reliability of the Bulk Power System, and to the residents of North America, is a foreseeable result of the process and substantive result of this standard.

Respectfully submitted by:

Submitted by:

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