NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Level 2 Appeal
Foundation for Resilient Societies, Inc.

TPL-007-1 - Transmission System Planned Performance for Geomagnetic Disturbance Events
(Project 2013-03 Geomagnetic Disturbance Mitigation)

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NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

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In accordance with Section 8.2 of the NERC Standard Processes Manual ("SPM"), notice is hereby provided that the Level 2 Appeals Panel shall meet via teleconference on **June 29, 2015 at 1:00 p.m. Eastern time** to hear the Level 2 Appeal of Foundation for Resilient Societies, Inc. (the "Appellant"). The meeting of the Level 2 Appeals Panel shall be open to the public in "listen only" mode using the dial-in information provided above.

On January 4, 2015, the Appellant submitted a Level 1 Appeal related to the development of proposed Reliability Standard TPL-007-1 (Project 2013-03 Geomagnetic Disturbance Mitigation), to which NERC responded on February 18, 2015. On February 26, 2015, the Appellant initiated a Level 2 Appeal.

In accordance with Section 8 of the SPM, the review of the Level 2 Appeals Panel shall be limited to those issues that implicate a procedural action or inaction involving the processes or procedures described in the SPM. Issues relating to the technical content of a Reliability Standards action are outside the scope of the appeals process. In particular, the Level 2 Appeals Panel shall consider:

1. whether the Appellant is an entity with "directly and materially affected interests" with respect to the development or approval of proposed Reliability Standard TPL-007-1;

2. whether the Appellant has been or will be adversely affected by any procedural action or inaction related to the development or approval of proposed Reliability Standard TPL-007-1; and

3. whether the purported procedural action(s) or inaction(s) described by the Appellant relate to the NERC Reliability Standards processes as defined in the SPM, and not the technical content of the Reliability Standards action.

The Level 2 Appeals Panel shall not consider any expansion of the scope of the appeal that was not presented in the Level 1 Appeal.

In accordance with Section 8.2 of the SPM, the Level 2 Appeals Panel may find for the Appellant and remand the issue to the Standards Committee with a statement of the issues and facts in regard to which fair and equitable action was not taken, or may find against the Appellant with a statement of the facts that demonstrate fair and equitable treatment of the Appellant and its objections. The panel may not revise, approve, disapprove, or adopt a Reliability Standard, as these responsibilities remain with the ballot pool and Board of Trustees.

The Appellant's Level 1 Appeal complaint, NERC's response, and other relevant materials are posted **here**.

Section 8.2 of the SPM provides an opportunity for entities that are directly and materially affected by the procedural action(s) or inaction(s) referenced in the Appellant's Level 1 Appeal complaint to present their concerns to the Level 2 Appeals Panel. The Level 2 Appeals Panel will accept written comments from such entities until **8:00 p.m. Eastern time on June 8, 2015**. Comments should be submitted to **spmappeal@nerc.net**. Comments submitted to the Level 2 Appeals Panel shall be made a part of the public record of this appeal.

For more information or assistance, please email **SPMAppeal@nerc.net**.

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Suite 600, North Tower
Atlanta, GA 30326
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Agenda
Meeting of Level 2 Appeals Panel
Level 2 Appeal of Foundation for Resilient Societies, Inc.
TPL-007-1 - Transmission System Planned Performance for Geomagnetic Disturbance Events
(Project 2013-03 Geomagnetic Disturbance Mitigation)

June 29, 2015 | 1:00 – 4:00 p.m. Eastern
Teleconference: (855) 331-9631| Conference ID/Passcode: 48631574

Introduction and Guidelines for Conduct

NERC Antitrust Compliance Guidelines and Public Announcement

Presentation of Arguments

1. **Appellant Foundation for Resilient Societies, Inc. (30 minutes)**
2. **Response by Chair of Project 2013-03 Geomagnetic Disturbances Standard Drafting Team (or His Designee) (30 minutes)**
3. **Discussion of Response to Level 1 Appeal by NERC Senior Director of Standards (30 minutes)**

Questions

Consideration of Written Comments Submitted by Other Affected Parties

Deliberations

Antitrust Compliance Guidelines

I. General

It is NERC's policy and practice to obey the antitrust laws and to avoid all conduct that unreasonably restrains competition. This policy requires the avoidance of any conduct that violates, or that might appear to violate, the antitrust laws. Among other things, the antitrust laws forbid any agreement between or among competitors regarding prices, availability of service, product design, terms of sale, division of markets, allocation of customers or any other activity that unreasonably restrains competition.

It is the responsibility of every NERC participant and employee who may in any way affect NERC's compliance with the antitrust laws to carry out this commitment.

Antitrust laws are complex and subject to court interpretation that can vary over time and from one court to another. The purpose of these guidelines is to alert NERC participants and employees to potential antitrust problems and to set forth policies to be followed with respect to activities that may involve antitrust considerations. In some instances, the NERC policy contained in these guidelines is stricter than the applicable antitrust laws. Any NERC participant or employee who is uncertain about the legal ramifications of a particular course of conduct or who has doubts or concerns about whether NERC's antitrust compliance policy is implicated in any situation should consult NERC's General Counsel immediately.

II. Prohibited Activities

Participants in NERC activities (including those of its committees and subgroups) should refrain from the following when acting in their capacity as participants in NERC activities (e.g., at NERC meetings, conference calls and in informal discussions):

- Discussions involving pricing information, especially margin (profit) and internal cost information and participants' expectations as to their future prices or internal costs.
- Discussions of a participant's marketing strategies.
- Discussions regarding how customers and geographical areas are to be divided among competitors.
- Discussions concerning the exclusion of competitors from markets.
- Discussions concerning boycotting or group refusals to deal with competitors, vendors or suppliers.

- Any other matters that do not clearly fall within these guidelines should be reviewed with NERC's General Counsel before being discussed.

III. Activities That Are Permitted

From time to time decisions or actions of NERC (including those of its committees and subgroups) may have a negative impact on particular entities and thus in that sense adversely impact competition. Decisions and actions by NERC (including its committees and subgroups) should only be undertaken for the purpose of promoting and maintaining the reliability and adequacy of the bulk power system. If you do not have a legitimate purpose consistent with this objective for discussing a matter, please refrain from discussing the matter during NERC meetings and in other NERC-related communications.

You should also ensure that NERC procedures, including those set forth in NERC's Certificate of Incorporation, Bylaws, and Rules of Procedure are followed in conducting NERC business.

In addition, all discussions in NERC meetings and other NERC-related communications should be within the scope of the mandate for or assignment to the particular NERC committee or subgroup, as well as within the scope of the published agenda for the meeting.

No decisions should be made nor any actions taken in NERC activities for the purpose of giving an industry participant or group of participants a competitive advantage over other participants. In particular, decisions with respect to setting, revising, or assessing compliance with NERC reliability standards should not be influenced by anti-competitive motivations.

Subject to the foregoing restrictions, participants in NERC activities may discuss:

- Reliability matters relating to the bulk power system, including operation and planning matters such as establishing or revising reliability standards, special operating procedures, operating transfer capabilities, and plans for new facilities.
- Matters relating to the impact of reliability standards for the bulk power system on electricity markets, and the impact of electricity market operations on the reliability of the bulk power system.
- Proposed filings or other communications with state or federal regulatory authorities or other governmental entities.

Matters relating to the internal governance, management and operation of NERC, such as nominations for vacant committee positions, budgeting and assessments, and employment matters; and procedural matters such as planning and scheduling meetings.

Guidelines for Conduct of Level 2 Appeals Panel
TPL-007-1
Transmission System Planned Performance for Geomagnetic Disturbance Events
(Project 2013-03 Geomagnetic Disturbance Mitigation)

Background

Under Section 8 of the NERC Standard Processes Manual ("SPM"), any entity that has or will be adversely affected by any procedural action or inaction related to the development of a Reliability Standard shall have the right to file an appeal. The appeals process consists of two levels: a Level 1 Appeal, before the NERC Senior Director of Standards; and Level 2 Appeal, before a five-member panel appointed by the NERC Board of Trustees.

On January 4, 2015 (amended January 5, 2015), the Foundation for Resilient Societies, Inc. (the "Foundation" or the "Appellant") initiated a Level 1 Appeal related to the development of proposed Reliability Standard TPL-007-1 by filing a complaint (the "Complaint") to the NERC Senior Director of Standards. On February 18, 2015, NERC responded to the Level 1 Appeal. On February 26, 2015, Foundation initiated a Level 2 Appeal by letter addressed to the NERC Senior Director of Standards.

Proposed Reliability Standard TPL-007-1 was filed with the Federal Energy Regulatory Commission for approval on January 21, 2015.

Selection of Panel

In accordance with Section 8.2 of the SPM, the Senior Director of Standards shall convene a Level 2 Appeals Panel. This panel shall consist of five members appointed by the Board of Trustees. The members shall have no direct affiliation with the participants in the appeal.

The NERC Board of Trustees has appointed the following members to the Level 2 Appeals Panel by written resolution dated March 31, 2015:

- Ken Peterson, Chair
- Fred Gorbet
- Paul Barber
- Dave Goulding
- Doug Jaeger

Adoption of Guidelines and Setting of Meeting Date

The Level 2 Appeals Panel met on May 5, 2015 to establish a time to hear Foundation's Level 2 Appeal and to adopt these Guidelines for Conduct.

Notice of Meeting and Posting of Materials

The Level 2 Appeals Panel shall meet to hear Foundation's Level 2 Appeal via teleconference at **1:00 p.m. Eastern time on Monday, June 29, 2015**.

In accordance with Section 8.2 of the SPM, NERC Reliability Standards staff shall post the Appellant's Complaint and other relevant materials on the Project 2013-03 Geomagnetic Disturbance Mitigation project page and provide at least 30 days' notice of the meeting of the Level 2 Appeals Panel.

The meeting of the Level 2 Appeals Panel shall be open to the public in "listen only" mode.

Submission of Written Comments

Section 8.2 of the SPM provides an opportunity for entities that are directly and materially affected by the procedural action(s) or inaction(s) referenced in the Appellant's Complaint to present their concerns to the Level 2 Appeals Panel. The Level 2 Appeals Panel will accept written comments from such entities until **8:00 p.m. Eastern time on June 8, 2015**. Comments should be submitted to spmappeal@nerc.net.

Comments submitted to the Level 2 Appeals Panel shall be made a part of the public record of this appeal.

Conduct of Meeting

Generally

Section 8 of the SPM describes the Reliability Standards appeals process generally as follows:

> Any entity that has directly and materially affected interests and that has been or will be adversely affected by any procedural action or inaction related to the development, approval, revision, reaffirmation, retirement or withdrawal of a Reliability Standard, definition, Variance, associated implementation plan, or Interpretation shall have the right to appeal. This appeals process applies only to the NERC Reliability Standards processes as defined in [the SPM], not to the technical content of the Reliability Standards action.
>
> The burden of proof to show adverse effect shall be on the appellant. Appeals shall be made in writing within 30 days of the date of the action purported to cause the adverse effect, except appeals for inaction, which may be made at any time. The final decisions of any appeal shall be documented in writing and made public.

Scope of Issues Considered
In accordance with Section 8 of the SPM, the review of the Level 2 Appeals Panel shall be limited to those issues that implicate a procedural action or inaction involving the processes or procedures described in the SPM. Issues relating to the technical content of a Reliability Standards action are outside the scope of the appeals process. In particular, the Level 2 Appeals Panel shall consider:

1. whether the Appellant is an entity with “directly and materially affected interests” with respect to the development or approval of proposed Reliability Standard TPL-007-1;
2. whether the Appellant has been or will be adversely affected by any procedural action or inaction related to the development or approval of proposed Reliability Standard TPL-007-1; and
3. whether the purported procedural action(s) or inaction(s) described by the Appellant relate to the NERC Reliability Standards processes as defined in the SPM, and not the technical content of the Reliability Standards action.

The Level 2 Appeals Panel shall not consider any expansion of the scope of the appeal that was not presented in the Level 1 Appeal. SPM § 8.2.

Conduct of Proceeding
At the beginning of the hearing, the Chair shall introduce the members of the Level 2 Appeals Panel. The parties shall be called upon to introduce themselves and their affiliations. The Chair will then refer the participants and observers to the NERC Antitrust Guidelines.

The parties shall present their objections or responses to the Level 2 Appeals Panel as follows:

<u>Appellant</u>: Foundation shall have 30 minutes to present its objections. The Appellant has the burden of demonstrating adverse effects.

<u>The Standard Drafting Team</u>: The Chair of Project 2013-03 Geomagnetic Disturbance Mitigation or his designee shall have 30 minutes to present the response of the Standard Drafting Team.

<u>The NERC Senior Director of Standards:</u> The NERC Senior Director of Standards shall have 30 minutes to present the findings contained in NERC’s February 18, 2015 response to the Appellant’s Level 1 Appeal.

Each party may adduce other pertinent arguments. Members of the Level 2 Appeals Panel may address questions to the parties at any time. The Level 2 Appeals Panel shall have the authority to limit any discussion that falls outside the scope of the appeal.

Consideration of Written Comments

The Chair of the Level 2 Appeals Panel shall identify the other affected entities that submitted comments for consideration by the panel. The Level 2 Appeals Panel shall consider such comments as part of its deliberations.

Deliberation

Following the conclusion of presentations and questions, the Chair shall dismiss the parties and any observers. The Level 2 Appeals Panel may deliberate immediately thereafter or at another time as it deems fit.

Decision

The Level 2 Appeals Panel shall issue a written decision. The Level 2 Appeals Panel may be assisted by NERC staff in preparing this written decision.

In accordance with Section 8.2 of the SPM, the Level 2 Appeals Panel:

- may find for the Appellant and remand the issue to the Standards Committee, with a statement of the issues and facts in regard to which fair and equitable action was not taken; or
- may find against the Appellant, with a specific statement of the facts that demonstrate fair and equitable treatment of the Appellant and the Appellant's objections.

The Level 2 Appeals Panel may not revise, approve, disapprove, or adopt a Reliability Standard, as those responsibilities remain with the ballot pool and the Board of Trustees.

The actions of the Level 2 Appeals Panel shall be publicly posted.

Following the conclusion of the appeals process, the appeals record shall be made a part of the complete record of development for proposed Reliability Standard TPL-007-1.

RECORD OF APPEAL

FOUNDATION FOR RESILIENT SOCIETIES, INC.

FIRST-STAGE APPEAL TO THE DIRECTOR OF STANDARDS

OF THE NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION (NERC)

PURSUANT TO THE NERC STANDARD PROCESSES MANUAL REV. 3,

SEEKING AMENDMENTS TO A NERC-PROPOSED RELIABILITY STANDARD

NERC STANDARD TPL-007-1,

TRANSMISSION SYSTEM PLANNED PERFORMANCE

FOR GEOMAGNETIC DISTURBANCE EVENTS

Submitted on January 4, 2015
to
Valerie Agnew, Director of Standards, NERC

Foundation for Resilient Societies
52 Technology Way
Nashua NH 03060

January 4, 2015

Ms. Valerie Agnew
Director of Standards
North American Electric Reliability Corporation
3353 Peachtree Road, N.E.
Atlanta, Georgia 30326

Dear Ms. Agnew:

The following is a First Stage Appeal of the NERC-proposed Standard TPL-0071, Phase 2, relating to "Transmission System Planned Performance for Geomagnetic Disturbance Events" adopted pursuant to FERC Order No. 779.

Amendments to the proposed standard, together with responsive comments relating to November comments in prior balloting and supporting documentation, were posted on the NERC website on December 5, 2014. The proposed standard does not adequately address the risks posed by harmonic production, VAR consumption, vibration hazards, and other omissions or inactions specified below.

In accordance with the NERC Standard Processes Manual, Revision 3, adopted by the NERC Board of Trustees on June 26, 2013, the Foundation for Resilient Societies, Inc. [hereinafter "Foundation" or "Resilient Societies"] has thirty days from the date of standard changes and publication to file an Appeal or asserted errors of commission.

Per our discussion and a telephone message you left for me in December 2014, the deadline for a timely appeal for errors of commission in standard development would be January 4, 2015. You indicated, however, that because January 4th is a Sunday, the filing of an appeal on January 5, 2015 would be deemed timely-filed. Resilient Societies is filing its First Stage Appeal to you, as NERCs Director of Standards, electronically on Sunday, January 4, 2015, thereby averting any challenge that might occur were we to file on January 5th.

We note that our Appeal asserts there are a set of *inactions or omissions* in proposed Standard TPL-007-1 (Phase 2). These are:

- Failure to include in the Benchmark Model supporting Standard TPL-007-01 risks posed by harmonic production in transformers and impacts other grid critical equipment;

- Failure to include in the Benchmark Model supporting Standard TPL-007-1 methods to estimate VAR consumption, and to estimate effects of VAR requirements, or swings in VAR consumption and their effects on voltage instability, inadequacies of regional spinning reserves, separation risks, and risks of cascading outages;
- Failure to include effects of quasi-DC current injections upon *magnetostriction* and other vibrational risks to high voltage transformers, stators, and turbines, among other equipment;
- Failure to establish standards for mandatory installation and operation of *geomagnetic induced current* (GIC) monitors at sites of high voltage transformers within the Bulk Power System;
- Failure to require of NERC-registered entities or to propose that FERC require public data release of GIC monitor data now or in the future available, including crossings of critical thresholds, or more general public release of GIC data from all GIC monitors now or in the future deployed within the U.S. Bulk Power System, thereby raising concerns that the NERC-proposed standard facilitates wholesale market manipulations and antitrust violations by market traders with preferential access to non-public GIC data or GIC data networks; and
- Failure to validate the NERC Benchmark Model for geomagnetic disturbance assessments against actual historical GIC data within the United States so that as a result the NERC GMD model might discourage and serve as an effective barrier to needed hardware protection of the North American bulk power system from severe solar geomagnetic storms;
- Failure to perform cost-benefit analyses of *averted costs* of (higher) redispatch of power; reductions in need for and costs of reactive power (VAr) production during solar storms; reductions in reduced generation and transmission system income due to off-cost sales due to regional grid congestion; reduced capacity utilization rates; reduced grid outages; and reduced losses of capital equipment; and
- Failure of essential “quality control” by the Office of Standards and the Director of Standards to assure that the essential goals and mandates of FERC Order No. 779 are met by the proposed NERC Standard TPL-007-1.
- Failure of essential “quality control” by the Office of Standards and the Director of Standards by allowing Standard Drafting Team use of a modeled GIC limit of 75 amps per phase for thermal assessment of transformers when the source for this 75 amp limit is an unapproved IEEE standard still in process.
- Failure to fully address our prior comments about the above issues submitted in NERC standard-setting.

Resilient Societies asserts, per NERC's <u>Standard Processes Manual, Revision 3</u> [hereafter "SPM_Rev3"] that the above asserted inactions or omissions to fulfill the obligations under the SMP_Rev3 are timely made, whenever filed. Because there is no time limit when seeking remediation of inactions to perform essential components of a reliability standard. Specifically, the NERC Standard Processes Manual explains, at Section 8.0 (Page 34): "Appeals shall be made in writing within 30 days of the date of the action purporting to cause the adverse effect, except appeals for inaction, which may be made at any time." (Process for Appealing an Action or Inaction).

Resilient Societies appreciates the opportunity to participate in the NERC-FERC standard-setting process. We have participated in NERC's Geomagnetic Task Force since the year 2012; we have filed comments with both NERC and FERC in advance of FERC Order No. 779 and in the Phase 1 and Phase 2 standard setting process. When FERC explained (July 2014) that their docket record did not show the locations of GIC monitors deployed as of the year 2014, we performed research and filed with FERC the locations of 102 GIC monitors that, if properly utilized and publicly reported, could significantly offset modeling defects in the NERC Benchmark model and would encourage deployment of hardware-protective equipment that is likely to generate net income for electric utilities operating within the bulk power system.

Our Summary Appeal explains why we are an aggrieved party; why the actions and inactions of NERC cause significant adverse effects upon the ability of our Resilient Societies to perform its mission, and upon the bulk power system and its electric customers; and why NERC quality controls have been inadequate in the development of standards to mitigate solar geomagnetic storms.

We include as Appendices to this Appeal (as part of the Appeal record) the following documents:

1. Group Comments submitted to NERC on Standard TRP-007-1 on November 21, 2014;
2. Separate Comments to NERC of the Foundation for Resilient Societies submitted on November 21, 2014;
3. Comments to NERC by John Kappenman in November 21, 2014 on the significant incompatibility and underreporting bias deriving from latitudinal scale factors causing the NERC model to under-report actual GIC impacts on the Maine electric grid by a factor of about 4X to 5X; and explaining why interpolation from data at different sites in scientifically valid and far more reliable than a NERC model that is widely incompatible with empirically measured geo-electric fields in the United States.
4. Report on GMD event modeling with specific analyses of the Maine grid, submitted by the EIS Council, based on its contracted analyses by John Kappenman, showing that the

unvalidated NERC Benchmark model is not compatible with empirical measurements from Chester, Maine; and why interpolation of data is scientifically valid and far more reliable than the NERC benchmark model that significantly under-estimates volts per kilometer geoelectric field for the Maine electric grid (found in Maine PUC Docket 2013-00415, Report of the EIS Council submitted to Maine PUC, October 4, 2013);

5. Central Maine Power Final Report to the Maine PUC, December 2014 in Maine Docket 2013-00415, demonstrating that the NERC benchmark model effectively exempts Maine electric utilities (and hence most likely will exempt electric utilities in all of the other 47 FERC-jurisdictional states of the U.S.) from alleged need for transformer protections; but contrasts this model with other criteria indicating benefits of installing various levels of GIC blocking devices;
6. Emprimus Final Report to the Maine PUC, in Docket 2013-00415, January 2, 2015, as Corrected January 5, 2015, which shows that the NERC model, when compared to the Chester, Maine time-series of GIC readings, may underestimate geoelectric fields and which shows that blocking devices at 12 locations in Maine and 4 locations in New Brunswick, Canada would significantly improve the stability and protection of the Maine and ISO-New England electric grids.

Respectfully submitted by:

William R. (Bill) Harris
Secretary, and

Thomas S. Popik
Chairman, for the
FOUNDATION FOR RESILIENT SOCIETIES, INC.
52 Technology Way
Nashua, N.H. 03060
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Copies transmitted electronically on January 4, 2015 and Jan 5, 2015 to:
Ms. Valerie Agnew, Director of Standards, NERC valerie.agnew@nerc.net
Mr. Mark G. Lauby, Senior Vice President &
Chief Reliability Officer, NERC mark.lauby@nerc.net
Mr. Gerry W. Cauley, President & Chief Executive Officer, NERC Gerry.cauley@nerc.net

SUMMARY OF APPEAL
SUBMITTED BY THE FOUNDATION FOR RESILIENT SOCIETIES TO THE DIRECTOR OF STANDARDS
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION
WITH RESPECT TO NERC PROPOSED STANDARD TPL-007-1 (PHASE 2)

1. FOUNDATION FOR RESILIENT SOCIETIES IS AN AGGRIEVED PARTY.

The Foundation for Resilient Societies in an independent, non-profit, 501(c)(3) research and education organization, incorporated in year 2012 in the State of New Hampshire. It is composed of Board members from New Hampshire, Arizona, California, Massachusetts, South Carolina, and Virginia. The mission of the Foundation is to perform research and education in support of greater resiliency for critical infrastructures of 21st century societies. Resilient Societies commenced its organizational efforts in year 2011, and one month before the tsunami and nuclear power plant disaster at Fukushima-Daiichi, Resilient Societies organizers submitted to the Nuclear Regulatory Commission a Draft Petition to enhance on-site backup power resources at U.S. licensed nuclear power plants. This Petition was adopted for further assessment by the Nuclear Regulatory Commission in December 2012.

Directors of the Resilient Societies have expertise in the mitigation of electromagnetic pulse (EMP), specifically high altitude EMP. One of our Directors served as Chairman from year 2001 through year 2008 of the Congressionally-designated Commission on Electromagnetic Pulse. That Commission that produced several reports, some unclassified, on the hazards of man-made electromagnetic pulse events. In April 2008 that Commission produced a detailed review of the risks to critical infrastructures, and emphasized the benefits of protecting roughly 2000 extra high voltage transformers in the United States, in part because of the dependency of all other critical infrastructures on the electric grid, and in part because of the long-lead times to replace high voltage transformers if a substantial proportion of these transformers were not protected by appropriate hardware. Another of the Resilient Societies' Directors was for many years the principal standards developer for the U.S. Department of Defense to protect critical national assets, defense assets, and operating capabilities of the U.S. government from man-made electromagnetic pulse.

In FERC Order No. 779 (May 2013), the Federal Energy Regulatory Commission determined to restrict its Order to mitigate naturally occurring electromagnetic pulses also known as geomagnetic disturbances. (GMDs). The decisions of the NERC Standards Drafting Team to develop a "benchmark model" for solar geomagnetic storms, to select a benchmark event that is substantially less severe than the Carrington event of 1859 or the New York Central Railroad Storm of May 1921, and to disregard a time series of GIC records from the State of Maine has the cumulative effect of creating a standard for hardware protection assessment that may relieve all electric utilities in all of the 48 states subject to FERC jurisdiction from any duty to install any blocking device or other transformer protection hardware.

How do the NERC Standards Drafting Team assumptions, the benchmark event selections, and the disregard of empirical data on historical GMD events in the U.S. affect Resilient Societies' interests and the ability of its Board to apply the Board's expertise in advancing protection of the North American electric grid from high altitude electromagnetic pulse risks? The answer is simple: if there is no protection of the long transmission lines and associated high voltage transformers from severe GMD events, the lack of hardware protection (whether neutral ground blockers or series capacitors) will make it impossible to also protect against the so-called E3 surges that also threaten the viability of high voltage transformers during a man-made EMP event. IF NERC promulgates and FERC adopts the benchmark model for GMD mitigation, there will be no practical way for the President, or the U.S. Congress to initiate parallel protection of the electric grid from man-made EMP events. It makes no financial sense to block E1 pulses while failing to protect against concurrent E3 pulses that occur in parallel, even if they arrive milliseconds later. Hence, our Board will of necessity fail in its designated mission to enhance the resiliency of critical infrastructures in 21st century societies. So we are aggrieved by what NERC has done with its mandate under FERC Order. No. 779.

Our Resilient Societies is further aggrieved by its dependence upon the electric grid and commercial telecommunications powered by the commercial grid among Directors in six different states to perform our research and to review our proposed filings, etc. Our activities, in short, depend upon the reliability of the electric grid, which is essential to support reliable telecommunications. This reliability is threatened by a NERC proposed standard that may create liability protection for electric utilities without enabling hardware protection of long-replacement-time grid equipment. If the electric grid is to remain unprotected from severe solar GMD events, hence also from man-made EMP events, we will be unable to fulfill with reliability our mission in the future. So far, Israel, South Korea, and India have initiated programs to protect their electric grids from man-made EMP events. All of our Board members, however, reside and work in the United States, and we are aggrieved if, however inadvertently, NERC and its Standards Drafting Team leave our nation unprotected and our Foundation unable to fulfill its purposes because of NERC's proposed Standard TPL-007-1.

2. FAILURE TO INCLUDE IN THE NERC GMD WHITEPAPERS BENCHMARKS FOR HARMONIC PRODUCTION ARISING FROM SOLAR GMD EVENTS.

See the comments of Smart Sense.Com, Inc. submitted in November 2014. We concur that understanding the extent, duration, and magnitude of harmonic productions is essential to understand thermal impacts, and reactive power impacts on grid stability, separation risks and cascading outages. See also the Emprimus Report of December 2014 to the Maine Public Utilities filed in Maine PUC Docket 2013-00415.

3. FAILURE TO PROVIDE METHODS TO ESTIMATE VAR (REACTIVE POWER) CONSUMPTION ARISING FROM SOLAR GMD EVENTS.

A March 2013 review of the Maine and ISO-New England grid under condition of solar storms (found at www.resilientsocieties.org) identified the likelihood that spinning reserve or other prompt generating reserves would be unlikely to maintain a balanced electric load in New England, absent some protective equipment. The Emprimus Report of December 2014 prepared for the Maine PUC does estimate VAR requirements under different assumptions about solar storms, the appropriate K-factor to utilize in modeling the Maine grid, etc. The failure of the NERC whitepapers to address VAR requirements could result in an underestimation of grid instability risk. Further, the absence of financial analysis in the NERC modeling effort has the effect of concealing the significant financial benefits that result from significantly reducing VAR consumption as a result of selective installation of blocking devices that reduce VAR demand.

4. FAILURE TO INCLUDE MAGNETOSTRICTION AND OTHER VIBRATIONAL RISKS TO OPERABILITY OF TRANSFORMERS, STATORS, TURBINES AND OTHER GRID EQUIPMENT.

In December 2011 to January 2012 Resilient Societies compared databases of transformer outages or fires to databases of solar geomagnetic storms in North America. This resulted in a more intense review of the concurrency of (1) a solar geomagnetic storm that occurred in North America on November 8-9, 1998, and (2) the melting and loss of the Phase A (115 kV) unit of the 345 kV transformer at Seabrook Station on November 10, 1998. Resilient Societies filed a Report of what happened at Seabrook Station in November 1998, to the NERC GMD Task Force in January 2012. Without any GIC monitoring, nor awareness of the mechanisms by which magnetostriction during GMD events can cause vibration-related equipment damage, the

Public Service of N.H. engineers at Seabrook station initially concluded that a 4 inch stainless steel bolt had randomly lo0osened, dropped into the low voltage Phase A GSU transformer winding, and caused a 12.2 day outage of Seabrook Station. Because as of January 2012, Seabrook station had not yet installed GIC monitoring equipment, that was the initial assessment of NextEra Nuclear engineering staff in January 2012. They reviewed with Mr. Harris the actual language of the November 1998 event records, which indicated the root cause of the outage was a deformed stainless steel bolt. But this was most unlikely. The 3-phase GE transformer, manufactured in 1981, and installed in 1986, had operated at full power since August 1990. Why in roughly 3000 days of operation did not the stainless steel bolt cause overheating and melting of the low voltage (24.5 kV) end of the Phase A transformer? Why did the defective stainless steel bolt shake loose, or relocate into the low voltage winding, and cause severe overheating on November 10, 1998.

The overtaking of a north-to-south GMD event of November 8, 1998 by a south-to-north GMD reversal caused a "sudden impulse " GMD event on November 9, 1998. Merely because engineers who could not observe an invisible GMD event did understand it does not mean it did not happen. While the "root cause" of the outage at Seabrook Station was a defective stainless steel bolt, the *proximate cause* of the 12.2 day transformer outage, power redispatch, and replacement of the Phase A transformer, etc. was a cannibalizing solar storm of November 8-9, 1998. The averted costs, had there been a neutral ground blocker in place, would have more than paid to install GIC blockers at all of ISO-New England's high voltage GSU transformers. The NERC Task Force has improperly omitted *magnetostriction* and other vibrational hazards from its benchmark modeling. Why?

If vibrational hazards are to be addressed, it is more likely than not that neutral ground blockers are the least-cost solution. They cost less than most series capacitors. Studies at Idaho National Laboratory in 2012-2013, and testing observed by members of the GMD Task Force, demonstrated that relatively low harmonic productions into a 138 kV transmission system caused severe vibration and associated noise. When a neutral ground blocker was activated, the vibration and nose disappeared. These experiments are reported in publications from INL and SARA in year 2013. Wishing away a hazard to transformer resiliency is not enough. The NERC GMD Task Force needs to amend its model to include vibrational risks, and report on the lowest cost solutions, such as neutral ground blockers.

Is it unusual that engineers at Seabrook Station would rather not accept that a GMD event was the cause of a multi-million dollar outage in November 1998? Not at all. In January 2012, an engineer at Seabrook Station proposed that GMD could not have been the cause of the transformer damage, because GMD would enter through the high voltage end of the transformer, but the melting was at the low voltage end of the transformer. This was an argument worth exploring. A check with John Kappenman in Duluth, Minnesota, a national expert on transformer vulnerabilities, resulted in re-examination of photos of the Salem 1 transformer loss during the Hydro-Quebec solar storm of March 13, 1989. The GICs had entered through the high voltage end of the GSU transformer, but had migrated to the low voltage windings, which had melted to destruction. So we have an expensive example of why psychological resistance to empirical evidence of transformer damage needs re-examination, whether at specific sites of transformer damage or by the Standard Drafting Team and the Director of Standards at NERC.

The Standard drafting Team needs to consider the findings of C. J. Schriejver and S. D. Mitchell, "Disturbances in the US electric grid associated with geomagnetic activity," J. Space Weather Space Clim. 3 (2013), A 19. This article highlights a combined NERC and Department of Energy database from the period 1992 through year 2010. About 4 percent of electric grid disturbances are attributed entirely or partially to severe space weather. Yet at the time, most of these events are otherwise attributed – as happened at Seabrook Station in November 1998. The odds ratio that an event among the 4 percent of outages associated with space geomagnetic weather are attributable to solar GMD events entirely or partially rather than to random outages is a ratio of 32 to 1.

The Standard Drafting Team and the Director of Standards at NERC should insist upon inclusion of vibrational hazards as a significant cause of loss or significant damage to transformers and other grid equipment. This change would increase understanding that vibrational hazards require remediation; and that the same equipment that protects against thermal stress also protects against vibrational risks. This improved modeling would be likely to accelerate voluntary commitments to deploy neutral ground blocking equipment.[1] The arbitrary exclusion

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[1] The Interim GMD Task Force Report of February 2012 did note that, due to GMD events, there could be "increased mechanical vibrations and torsional stress [within generators] due to increased negative sequence currents." (GMD Task Force Report, Feb 2012, at p. 58). See also Marius Cloutier and Mark Houghton, "Case Studies of Fiber Optic Accelerometer Used for End-winding Vibration Monitoring on Turbo-Generators," CIGRE SC A1 & EPFL Colloquium on Large electrical Machines, Lausanne, 7 Sep 2005; Mike Hoffer and Andrew Tesla, "Stator Bar Vibration Sensors and Fiber-Optic accelerometers," EPRI03 (2003); Jackson Lin, "Applying Stator End-Winding Monitoring Technology at JH Campbell Generation Plant," Conf, San Antonio, Texas, June 2002; Yuxing Wang and Ming Jin, "Finite Element Modelling of the Vibration of a Power Transformer," Proc. Acoustics, 2-4 Nov 2011; B. Garcia, et al, "Transformer tank vibration modeling as a method of detecting winding deformations, Part I," IEEE Trans. Power Del. 2006, v. 21:157-163. Overheating in bolts, such as the stainless steel bolt that dislodged at Seabrook Station in 1998, can result from GMD-induced vibrations or other vibrations. See J. Turowski, "Overheating hazard in flanged bolts of transformers," Proc. ISEF, 1985: 271-274, and Juan Carolos Olivares-Galvan, et al., "Reduction of Stray Losses in Flange-Bolt Regions of Large Power Transformer Tanks," IEEE Trans. Industrial Elec. V. 61: 44554463 (Aug. 2014). Some utilities that have upgraded their GIC monitoring capabilities already utilize sensors for "tank wall vibration" of high voltage transformers. See Richard A. Becker of Bonneville Power Administration, "GMD/GIC Activities," presented at NERC GMD Task Force meeting, July 25, 2013,

of vibrational hazards from the GMD Benchmark Model causes inappropriate dismissal of the value of blocking equipment; and allows transmission operators to avoid even assessment of GMD hazards, at generating sites and transmission systems that have experienced loss of transformers due to vibrational hazards, some the result of moderate level solar GMD events.

5. FAILURE TO ESTABLISH RELIABILITY STANDARDS FOR MANDATORY INSTALLATION AND OPERATION OF GEOMAGNETIC INDUCED CURRENT (GIC) MONITORS.

The FERC Commissioners in FERC Order No. 779 (May 2013) asked NERC to consider deployment of GIC monitors as part of the mitigation process for solar GMD events. It is a failure of quality control for the Director of Standards at NERC to fail to require consideration of this option. As the "Additional Facts" filing of Resilient Societies demonstrated in August 2014 [See FERC Order No. 779-A], there are at least 102 deployed GIC monitors in the United States, generally attached to the neutral of high voltage transformers. The locations of these GIC monitors appear to correlate to above average risks of equipment damage during or following GMD events. The costs of harnessing these GIC monitors to improve the NERC Benchmark model, and to improve the utility of operating procedures, and to aid utilities in decision-making relating to hardware protection equipment, are modest.

Estimating the total of high voltage transformers in the U.S. Bulk Power system at 2100 to 2300 systems, and using the Central Maine Power cost-estimate for purchase and installation of GIC monitoring units ($36,000 per unit),[2] the costs to instrument all high voltage transformers in the U.S. would be in the range of just $75 million to $83 million dollars. Taking into account the text of FERC Order 779 on GIC monitoring, it is a failure of quality control for the Director of Standards at NERC to avert consideration of reliability standards for GIC monitors, and the cost-benefit review of timely assessment and opportunity for pre-disaster mitigation, through use of GIC monitors. Further, commercial neutral blocking devices come equipped with GIC monitors as a standard component. Standards and benefits of GIC monitors should have been and need to be addressed.

6. FAILURE TO REQUIRE PUBLIC RELEASE OF GIC MONITOR LEVELS, OR DESIGNATED GIC WARNING THRESHOLD LEVELS, SO AS TO PRECLUDE MARKET MANIPULATION AND

"Transformer Monitoring," Slide 3 of presentation. A series of studies of vibrational hazards to transformers in the high voltage (500 kV) Chinese transmission network are addressed in: Liu, Li, and Pirjola, "Analysis of Increases of noise of 500 kV transformers," (n Chinese), High Voltage Engr. 31(4): 85-87 (2005); Liu, C.M., Liu, L.-G., and R. Pirjola, "Geomagnetically induced currents in the high voltage power grid in China," IEEE Trans. Power Delivery 24(4): 2308-2374 (2009); and Liu, Li, and Pirjola, "Observations and modeling of GIC in the Chinese large-scale high-voltage power networks," J. Space Weather Space Clim. 4 (2014), Paper A03.

[2] Central Maine Power, Final Report to the Maine PUC, December 2014, for cost estimates of GIC Monitors purchased and installed.

POTENTIAL ANTITRUST VIOLATIONS RESULTING FROM NERC RELIABILITY STANDARD-SETTING.

Presently, there are at least 102 active GIC monitoring units deployed in the U.S. electric grid. With some exceptions,[3] the 16 Reliability Coordinators do not operate GIC monitors, and their current access to GIC data is on a voluntary basis from entities that do operate GIC monitors.

Those who are allowed to participate in the EPRI-sponsored SUNBURST network have access to the entire network's GIC data. Those who are not owners or operators of GIC monitors, and those who do not have access to GIC network data are disadvantaged in the wholesale auction bidding for same day and day ahead electric auctions.

Does the NERC coordinated process for creating reliability standards inadvertently or intentionally favor certain large generator owner-operators and certain SUNBURST network participants over others in electric markets that are intended to be nondiscriminatory, just, and in the public interest? If so, this NERC Rulemaking process is a candidate for the opening of an antitrust investigation by the Antitrust Division of the U.S. Department of Justice.

Resilient Societies respectfully proposes that the NERC Director of Standards re-evaluate the consequences for fair and competitive electric markets if: generator operators need not participate in mitigation of GMD hazards, per the Phase 1 standard-setting; and generator operators and owners need not share their own GIC data with others; and if wholesale electric market participants who are not members of the SUNBURST GMD monitoring network or other electric market traders are disadvantaged by being excluded from the "GIC monitoring club" as it might be named.

In the now defunct Enron operations selling power into the CAISO market, it was a common practice to withhold electric generation, or to accelerate grid congestion; or to offer day-ahead electric power, and then be paid for withdrawing the contractual right of delivery. More recently, some participants in electric markets have made offers of power at negative prices, and then have been paid for not delivering unneeded power the following day.
At almost every meeting, NERC posts reminders about potential antitrust practices that should not be undertaken. But has NERC, perhaps unintentionally, creates a market of "haves" and "have nots" when it comes to the utilization of U.S. taxpayer-funded space warnings of potential or actual GMD events that might disrupt market activities within the bulk power system? The "haves" are able to combine the NOAA issued space weather warnings with

[3] For example, PJM Interconnection LLC operates a GIC monitor.

knowledge of GIC conditions at a wide range of power grids. The "have nots" only have access to the NOAA space weather warnings.

NERC has a duty to conduct its electric reliability standard-setting so as not to exacerbate disparities of knowledge, and disparities of trading opportunities in wholesale electric markets. Without a remedy proposed by NERC when it submits its GMD reliability standard to FERC, NERC can fairly be accused of favoring some wholesale market participants above the others, causing discriminatory, unjust, and unfair opportunities in wholesale electric markets.

Back in June 1999, the Assistant U.S. Attorney heading the Antitrust Division of the U.S. Department of Justice, Joel I. Klein, gave the Western Systems Coordinating Council (WSCC) limited and conditional approval to proceed with reliability standard setting as allowable under the antitrust laws of the United States.[4] The proposed reliability standards did not, at that time, "appear to raise significant risks to competition."

NERC 's Director of Standards, in consultation with appropriate legal staff, should consider the benefits to marketplace competition on a level playing field if GIC monitoring data is to be ordered to be shared with all market participants and with the public.[5] Otherwise, NERC risks antitrust review of what appears on its face to be an anticompetitive practice, in designing GMD operating procedures and hardware protection assessments that expand inequality of access to significant electric market factors in day ahead markets, and perhaps other markets, if GIC monitoring data is to be shared with the "haves" and withheld from the "have nots."

7. FAILURE TO VALIDATE THE NERC BENCHMARK MODEL FOR GEOMAGNETIC DISTURBANCE ASSESSMENTS AGAINST ACTUAL HISTORIC GIC DATA WITHIN THE U.S.

The NERC Standards Drafting Team cited three sets of published articles in response to our Group Concerns that the NERC benchmark model was essentially defective and unreliable because NERC made no effort to validate the findings by comparison with historic time series of data for GIC monitoring and transformer performance in the United States.

We ask the Director of Standards to mandate a comparison of how the NERC GMD Benchmark standard compares with actual historical data from the United States, on geo-electric fields and

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[4] See U.S. Department of Justice, Justice Department Approves Procedures to Establish and enforce Electric Power Reliability Standards," Jun 19, 1999, available at http://www.justice.gov/atr/public/press_releases/1999/2497.htm
[5] It is notable that the Bonneville Power administration has placed GIC monitoring data for multiple GIC monitors on its website, where anyone can view the last four days of data. We commend BPA for their transparency in this regard.

claims of diminished GIC effects – by as much as an order of magnitude – below some unsubstantiated threshold.

We objected to the use of a model of the electric grid for Finland and associated Baltic States as the basis for modeling risks and benefits of hardware protective equipment for the United States and Canada. Nonetheless, the NERC Standards Drafting Team cites as their pillar of reliability the multi-authored assessment by Pulkkinen, Bernabeu, Eichner, Beggan, and Thomson, "Generation of 100-year geomagnetically induced current scenarios," Space Weather, 10, S04003 (2012). The foundation for this model is the Finnish electric grid, where major urban centers of electric demand are in the 60˚ to 62˚ latitude range. At that latitude, there appears to be comparability between geoelectric fields in Finland and geoelectric fields in Canada.

However, as John Kappenman demonstrates, the quick fall-off of geoelectric field strength below the southern regions of Finland is not replicated when observing actual GIC readings and when interpolating geoelectric fields in the 40˚ to 45˚ latitude regions of the northern United States. See the Kappenman & Rasdasky (July 2014) and Kappenman-Birnbach (Nov. 2014) submissions to the GMD Task Force. See also the submission of the EIS Council to the State of Maine on October 4, 2013.[6]

The Kappenman analysis takes a specific GMD event form year 1998 and compares the actual GIC readings in Maine with the model derived from the Pulkkinen, et al. geo-electric field for the latitude of Chester, Maine. More recently, in December 2014, both Central Maine Power and Emprimus completed assessments of vulnerabilities and protection options for the Maine electric grid, pursuant to a state law that took effect in June 2013. These assessments are also filed, and with revisions to be filed in Maine Docket 2013-00415.

Both of the Maine study sponsors were asked to validate their models of GMD effects by using actual State of Maine historical data. It is our understanding that roughly one decade of GMD data from the early phases of EPRI's SUNBURST modeling effort were lost as a result of computer crashes without data backup.[7] Hence, it is our understanding that the Chester, Maine time series of GIC data, and the "tripping" of the Chester Static VAR compensator during just moderate solar storms, is the longest continuous time series of GIC available for any location within the United States.

[6] This paper, prepared by John Kappenman of Storm Analysis Consultants, for the EIS Council under contract, was submitted to and is an on-line retrievable document filed in Maine PUC Docket 2013-00415, with the filing date being October 4, 2013.

[7] We have been so advised, but find no acknowledgment of historic data losses posted on the SUNBURST website.

Central Maine Power, though requested by members of the Maine legislature to compare their use of the NERC GMD Benchmark model with real Maine GIC data, did not make that comparison before filing their report in December 2014.

Emprimus, also asked to compare their model of GMD hazards and criteria for installation of protective equipment, did make those comparisons. The Emprimus assessment of November 12, 2014, as updated in December 2014, determined that the GIC data for Chester, Maine may be higher than the NERC GMD model used by Central Maine Power would project.
A modeling error could have disastrous impacts on the survivability of long-replacement-time equipment needed to operate the U.S. electric grid.

The CMP utilization of the NERC Benchmark model projected just 4.53 volts per kilometer geoelectric field in Maine. Relying on the NERC model, it is likely that no utility in the State of Maine would be required to install any hardware protection equipment, including neutral ground blocking devices.

Because the Emprimus utilization of PowerWorld modeling produces results that would encourage installation of neutral ground blocking devices, the risks of grid collapse are not significantly increased even if their model under-predicts GIC intensity. This is because neutral ground blockers will keep harmonics resulting from geomagnetic induced currents out of high voltage transformers, and will protect against overheating and vibration, even if the actual GICs are higher than forecast.

In contrast, the NERC Model, adopted by Central Maine Power for their baseline assessment, will fail disastrously if the actual GICs are higher than the NERC model would predict.

We refer the NERC Director of Standards to the following assessments, all of which tend to invalidate the NERC benchmark model as a prudent basis for solar storm mitigation: the Kappenman-Radasky White Paper of July 2014; the Kappenman-Birnbach White Paper of November 2014; the EIS Council analysis of the NERC geoelectric field biases when applied to North America and not Finland and Baltic states, filed in Maine on October 4, 2013; and the two December 2014 assessments submitted to the Maine Public Utilities Commission (CMP and Emprimus), retrievable online from Maine PUC Docket 2013-00415.

Another paper cited by the NERC Standards Drafting Team is that by Ngwira, Pulkkinen, Wilder and Crowley, "Extended Study of Extreme Geoelectric Field Scenarios for Geomagnetically Induced Current Applications," Space Weather v. 11:121-131 (2013). Relying upon the DST network, with its equatorial weighting and risk of under-reporting of more northerly-centered solar storms, this study concedes it may be in error by an order of magnitude. The December 2014 Emprimus analysis of how the NERC GMD Benchmark model stacks up when applied to the Maine electric grid suggests that the NERC GMD benchmark model underreports actual GIC data, such as the mean of GICs experienced at Chester Maine.

A third reference cited by the NERC Standards Drafting Team does utilize 28 European observatories to assess historical, and one in 100 year and one in 200 year solar weather hazards. Once again, this is a model for *Western Europe* and not for *North America.* Even if this modeling effort is accurate for Europe, there is no prudent basis for its application to the geoelectric fields of the United States. Especially when other modes correlate better with the actual data.

Moreover, the meltdown of a transformer in southern New Jersey (at the Salem Unit 1 powerplant) during a modest solar storm centered in Canada, on March 13, 1989 provides a case study of why assumptions about rapidly declining geoelectric fields by latitude in the mid-Atlantic region are dangerous and imprudent, and not appropriate to fulfill the FERC mandates in Order No. 779. If the geoelectric field declines by roughly an order of magnitude, why did the Salem 1 GSU transformer windings melt in March 1989?

Hence, we request that the Director of Standards compare the modeled geoelectric currents in the NERC model to the historical data for Maine, and for historical data in the as yet publicly undisclosed SUNBURST database.

Finally, we note that the NERC Standard Drafting Team objects to the interpolation, using geomagnetic intensity from different observatories, and interpolating and estimating field strength of geomagnetic storms based on geospatial relationships is suspect.

We suspect that the NERC Standards Drafting Team objects to interpolation – widely used in many solar weather and grid assessments over decades – primarily because the NERC benchmark model fits so poorly with historically-recorded geomagnetic induced current data.

We cite, and request that the Director of Standards at NERC review a peer-reviewed paper that analyzes the value and limits of interpolation to estimate geoelectric fields at the surface of the earth. This paper is: Lisa H. Wei, Nicole Homeier, and Jennifer L. Gannon, "Surface electric fields for North America during historical geomagnetic storms," Space Weather 11: 452-462 (2013). The lead author utilized this modeling effort in conjunction with a Lloyd's of London assessment of claims for electrical equipment and other insurance losses; and Ms. Gannon is an experienced scientist at the USGS facility in Boulder, Colorado. There is a sound basis for interpolation.

To paraphrase John Kappenman, in his analysis of NERC geoelectric field bias submitted by the EIS Council to the State of Maine (October 4, 2013), studies that *interpolate* using real historical data are more reliable than models whose sponsors *refuse to compare their model to the historic time series of data for the region for which they propose reliability standards.*

We ask the NERC Director of Standards to compare the modeling projections for the United States with the time series of actual data for the United States. Otherwise, the NERC model may merely provide liability protection while leaving the U.S. electric grid entirely unprotected from severe solar geomagnetic storms. This outcome would defeat the purposes of FERC Order No. 779. The quality control required by the NERC Standard Processes Manual requires a higher standard of care.

8. FAILURE IN QUALITY CONTROL AND FAILURE TO CONSIDER TECHNICAL OBJECTIONS IN OUR COMMENTS TO A MODELED GIC LIMIT OF 75 AMPS PER PHASE FOR EXEMPTION OF TRANSFORMERS FROM THERMAL IMPACT ASSESSMENT

In our comments in NERC standard-setting, we commented:

> The most recent version of the "Screening Criterion for Transformer Thermal Impact Assessment"[8] 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 Standard Drafting Team did not appropriately respond to our comment and did not present technical evidence that a 75 amp limit is supported, other than to reference a standard-setting at IEEE that is still in process.

9. FAILURE TO PERFORM COST-BENEFIT ANALYSIS OF GRID PROTECTION OPTIONS

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[8] "Screening Criterion for Transformer Thermal Impact Assessment," NERC Standard Drafting Team (October 2014) available at http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/GMD_Thermal_screening_Oct27_clean.pdf.

FERC Order No. 779 encouraged cost-benefit analysis of grid protection measures. The NERC Standards Drafting Team, by failing to itemize the categories of cost and cost-avoidance through mitigation measures, has the effect of discouraging investments in grid protection. This runs contrary to the purpose of FERC Order No. 779, which was to protect the electric grid from severe solar weather. It was not to provide a shield from liability without providing any practical protection for operation and recovery of the electric grid during and after severe solar storms.

We ask the NERC Director of Standards to review the two recently filed Reports to the Maine PUC, the December 2014 Report by Central Maine Power, and the December 2014 revised Emprimus Report, also to the Maine PUC. Both of these reports provide options for protection of electric transmission and transformer equipment.[9] We request that the NERC Director of Standards utilize these reports to identify mitigation options, and to compare costs of alternative or complementary mitigation options.

IN CONCLUSION:

The Foundation for Resilient Societies asks the Director of Standards at NERC to review the NERC proposed standards to mitigation solar geomagnetic disturbances, to correct deficiencies that we have cited or enumerated, and to better reconcile the NERC proposed standard TPL-007-1 with the purposes and requirements of FERC Order No. 779.

Respectfully submitted by:

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[9] Resilient Societies wishes to thank Justin Michlig of Central Maine Power for identifying in his December 2014 Report some grid protective options that have not been widely discussed within the NERC GMD Task Force.

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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Endnotes:

[1] "Electromagnetic Pulse: Effects on the U.S. Power Grid," Oak Ridge National Laboratory (June 2010) available at http://web.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Executive_Summary.pdf.
[2] "Solar Storm Risk to the North American Electric Grid," Lloyd's and Atmospheric and Environmental Research (2013) available at https://www.lloyds.com/~/media/lloyds/reports/emerging%20risk%20reports/solar%20storm%20risk%20to%20the%20north%20american%20electric%20grid.pdf.
[3] "Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment," C. J. Schrijver, R. Dobbins, W. Murtagh, and S.M. Petrinec (June 2014) available at http://arxiv.org/abs/1406.7024.
[4] "Benchmark Geomagnetic Disturbance Event Description," NERC Standard Drafting Team (October 2014) available at http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Benchmark_GMD_Event_Oct28_clean.pdf.
[5] "Screening Criterion for Transformer Thermal Impact Assessment," NERC Standard Drafting Team (October 2014) available at http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/GMD_Thermal_screening_Oct27_clean.pdf.
[6] "Generating Availability Data System (GADS)," NERC (Undated) available at http://www.nerc.com/pa/RAPA/gads/Pages/default.aspx.
[7] "Transmission Availability Data System (TADS),"NERC (Undated) available at http://www.nerc.com/pa/RAPA/tads/Pages/default.aspx.
[8] "Standard Processes Manual, Version 3," NERC (June 26, 2013), page 28, available at http://www.nerc.com/comm/SC/Documents/Appendix_3A_StandardsProcessesManual.pdf.
[9] "SUPPLEMENTAL INFORMATION SUPPORTING REQUEST FOR REHEARING OF FERC ORDER NO. 797, RELIABILITY STANDARD FOR GEOMAGNETIC DISTURBANCE OPERATIONS, 147 FERC ¶ 61209, JUNE 19, 2014 AND MOTION FOR REMAND," Foundation for Resilient Societies (August 2014) available at http://www.resilientsocieties.org/images/Resilient_Societies_Additional_Facts081814.pdf.
[10] "Standard Processes Manual, Version 3," NERC (June 26, 2013), page 28, available at http://www.nerc.com/comm/SC/Documents/Appendix_3A_StandardsProcessesManual.pdf.
[11] Comment of, "Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard," J. Kappenman and W. Radasky (July 30, 2014) available at http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/WhitePaper_NERC_Model_Validation_07302014.pdf.
[12] "Comments of John Kappenman & Curtis Birnbach on Draft Standard TPL-007-1," J. Kappenman and C. Birnbach (October 10, 2014), available at http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/GMD_comments_received_10152014_final.pdf.
[13] "Response to NERC Request for Comments on TPL-007-1," Foundation for Resilient Societies (October 10, 2014) available at http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/GMD_comments_received_10152014_final.pdf.
[14] Standard Processes Manual, Version 3," NERC (June 26, 2013), page 4, available at http://www.nerc.com/comm/SC/Documents/Appendix_3A_StandardsProcessesManual.pdf, page 4.
[15] "Comment of Manitoba Hydro" Joann Ross, (October 10, 2014), http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/GMD_comments_received_10152014_final.pdf.

[16] "American National Standards Institute, Essential Requirements: Due process requirements for American National Standards," ANSI (January 2014) available at: http://publicaa.ansi.org/sites/apdl/Documents/Standards%20Activities/American%20National%20Standards/Procedures,%20Guides,%20and%20Forms/2014_ANSI_Essential_Requirements.pdf .

[17] "Standard Processes Manual, Version 3," NERC (June 26, 2013), page 20, available at http://www.nerc.com/comm/SC/Documents/Appendix_3A_StandardsProcessesManual.pdf.

[18] "TPL-007-1 — Transmission System Planned Performance for Geomagnetic Disturbance Events," NERC Standard Drafting Team (October 2014) available at http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/tpl_007_1_20141027_clean.pdf.

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, 2014.

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 al 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 assertions criticisms of the NERC Benchmark model. Moreover, if the NERC Director of Standards and Standards Department fails 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 removal of GICs from entry through high voltage transformers into the bulk transmission system. 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 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 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 rationally required.

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:

Comments of John Kappenman & Curtis Birnbach on Draft Standard TPL-007-1
Submitted to NERC on October 10, 2014

Discussion of Inadequate Reference Field Storm Peak Intensity and Geomagnetic Field Scaling Factors
As Daniel Baker and John Kappenman had noted in their previously submitted comments in May 2014, there have been a number of observations of geomagnetic storm peaks higher than those in the NERC proposed in TPL-007-1 Reference Field Geomagnetic Disturbance[1]. The purpose of this filing is to further elaborate upon the NERC Draft Standard inadequacies and to also propose a new framework for the GMD Standard.

It is the role of Design Standards above all other factors to protect Society from the consequences possible from severe geomagnetic storm events, this includes not only widespread blackout, but also widespread permanent damage to key assets such as transformers and generators which will be needed to provide for rapid post-storm recovery. It is clear that the North American power grid has experienced an unchecked increase in vulnerability to geomagnetic storms over many decades from growth of this infrastructure and inattention to the nature of this threat. In order for the standard to counter these potential threats, the standard must accurately define the extremes of storm intensity and geographic footprint of these disturbances. It is only then that the Standard would provide any measure of public assurance of grid security and resilience to these threats. It is clear from the prior comments provided by a number of commenters that the NERC TPL-007-1 Draft Standard is not adequate to define a 1 in 100 year storm scenario and is not conservative as the NERC Standards Drafting Team claims.

Figure 1 provides a graphic illustration of the NERC Standard proposed geomagnetic field intensity in nT/min, adapted from Table II-1 of α "Alpha" scaling of the geomagnetic field versus latitude across North America[2].

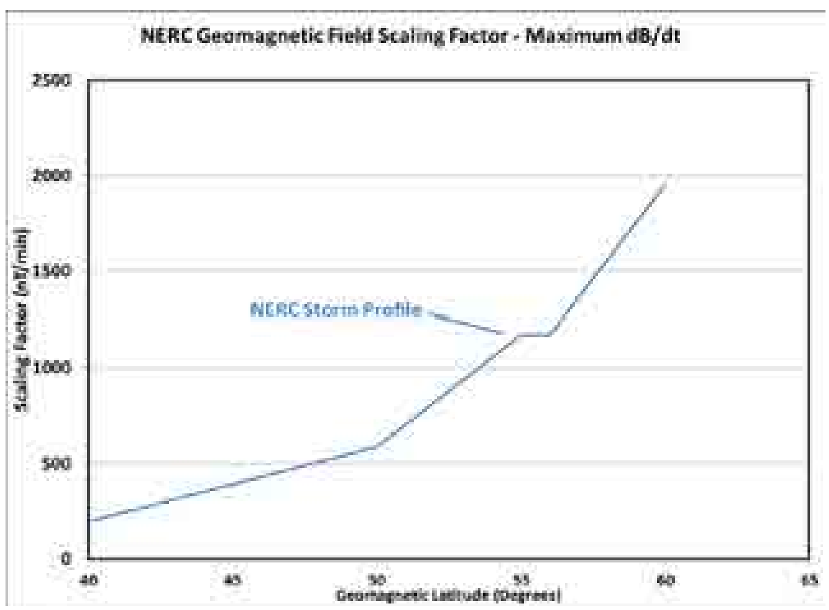

Figure 1 - NERC Proposed Profile of Geomagnetic Disturbance Intensity versus Geomagnetic Latitude

[1] Daniel Baker & John Kappenman "Comments on NERC Draft GMD Standard TPL-007-1 – Problems with NERC Reference Disturbance and Comparison with More Severe Recent Storm Event", filed with NERC for Draft Standard TPL-007-1, May 2014

[2] Page 20 of NERC Benchmark Geomagnetic Disturbance Event Description, April 21, 2014.

NERC has developed the intensity and profile described in Figure 1 from statistical studies carried out using recent data from the Image Magnetic observatories located in Finland and other Baltic locations[3]. This data base is a very small subset of observations of geomagnetic storm events, it is limited in time and does not include the largest storms of the modern digital data era and is limited in geography as it only focuses on a very small geographic territory at very high latitudes. The lowest latitude observatory in the Image array is at a geomagnetic latitude approximately equivalent to the US-Canada border, so this data set would not be able to explore the profile at geomagnetic latitudes below 55° and therefore reliably characterize the profile across the bulk of the US power grid. The NERC Reference Field excludes the possibility of a Peak disturbance intensity of greater than 1950 nT/min and further excludes that the peak could occur at geomagnetic latitudes lower than 60°. As observation data and other scientific analysis will show, both of these NERC exclusions are in error.

For the NERC Reference profile of Figure 1 to be considered a conservative or 1 in 100 year reference profile, then no recent observational data from storms should ever exceed the profile line boundaries. However as previously noted, the statistical data used by NERC excluded world observations from the large and important March 1989 storm and also from two other important storms that took place in July 1982 and August 1972, a time period that only covers the last ~40 years. In addition, data developed from analysis of older and larger storms such as the May 1921 storm have been excluded by NERC in the development of this reference profile. In just examining the additional three storms of August 4, 1972, July 13-14, 1982, and March 13-14, 1989, a number of observations of intense dB/dt can be cited which exceed the NERC profile thresholds. Figure 2 provides a summary of these observed dB/dt intensities and geomagnetic latitude locations that exceed the NERC reference profile.

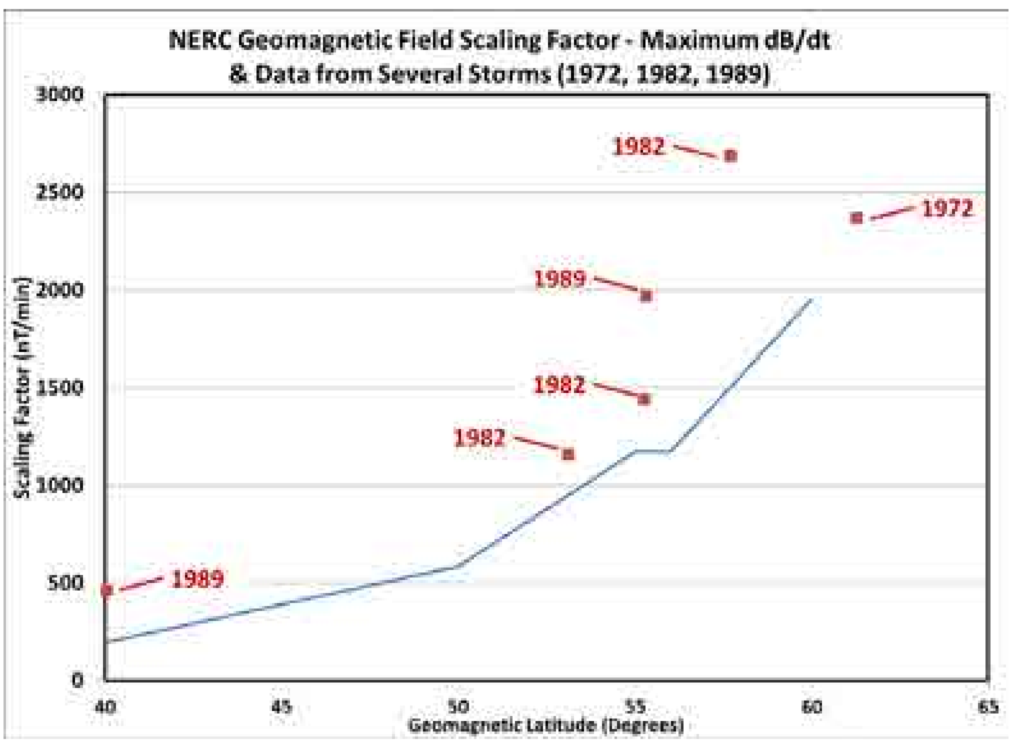

Figure 2 – NERC 100 Year Storm Reference Profile and Observations od dB/dt in 1972, 1982 and 1989 Storms that exceed the NERC Reference Profile

[3] 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.

As Figure 2 illustrates that are a number of observations that greatly exceed the NERC reference profile at all geomagnetic latitudes in just these three storms alone. The geomagnetic storm process in part is driven by ionospheric electrojet current enhancements which expand to lower latitudes for more severe storms. The NERC Reference profile precludes that reality by confining the most extreme portion of the storm environment to a 60^{o} latitude with sharp falloffs further south. This NERC profile will not agree with the reality of the most extreme storm events. The excursions above the NERC profile boundary as displayed in Figure 2 clearly points out these contradictions.

In terms of what this implies for the North American region, a series of figures have been developed to illustrate the NERC reference field levels at various latitudes and actual observations that exceed the NERC reference thresholds. Figure 3 provides a plot showing via a red line the ~55^{o} geomagnetic latitude across North America which extends approximately across the US/Canada border. Along this boundary, the NERC Reference profile sets the Peak disturbance threshold at 1170 nT/min, but when considering the three storms not included in the NERC statistics database, it is clear that peaks of ~2700 nT/min have been observed at these high latitudes over just the past ~40 years. As will be discussed later, it is also understood that extremes up to ~5000 nT/min can occur down to these latitudes. Figure 4 provides a similar map showing the boundary at 53^{o} geomagnetic latitude across the US and per the NERC Reference profile, the peak threat level would be limited to 936 nT/min. Yet at this same latitude at the Camp Douglas Station geomagnetic observatory, a peak dB/dt of ~1200 nT/min was observed during the July 1982 storm. Figure 5 provides a map showing the boundary at 40^{o} geomagnetic latitudes and the NERC Reference peak at this location of only 195 nT/min. This figure also notes that in the March 1989 storm the Bay St. Louis observatory observed a peak dB/dt of 460 nT/min, this is 235% larger than the NERC peak threshold.

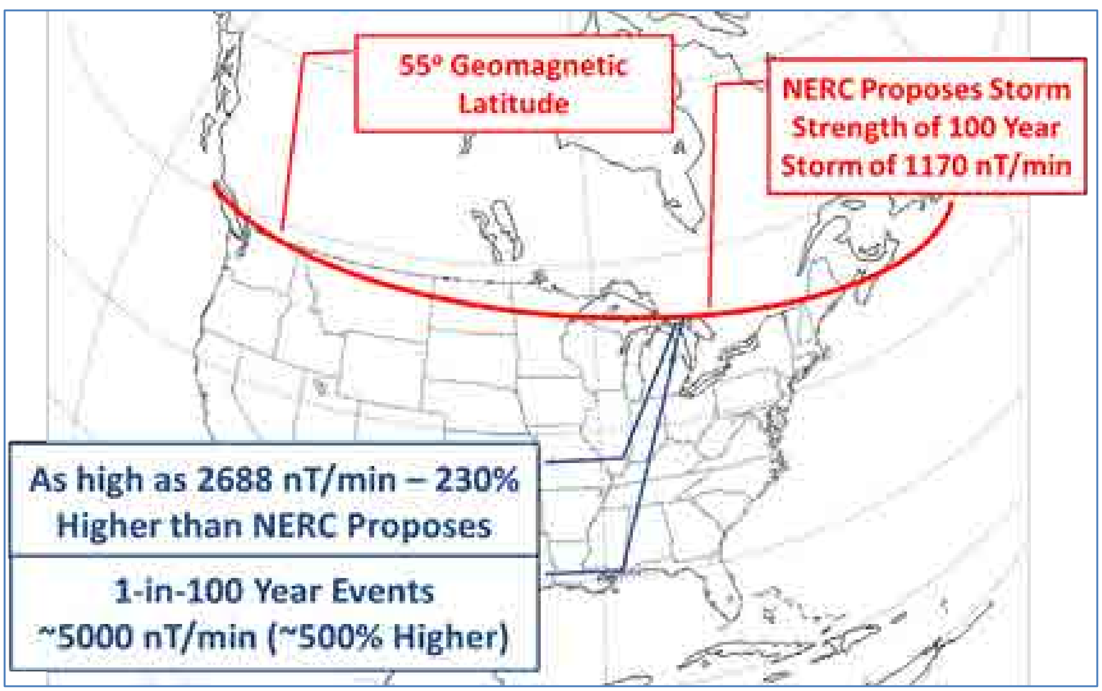

Figure 3 – Comparison of NERC Peak at 55^{o} Latitude versus Actual Observed dB/dt

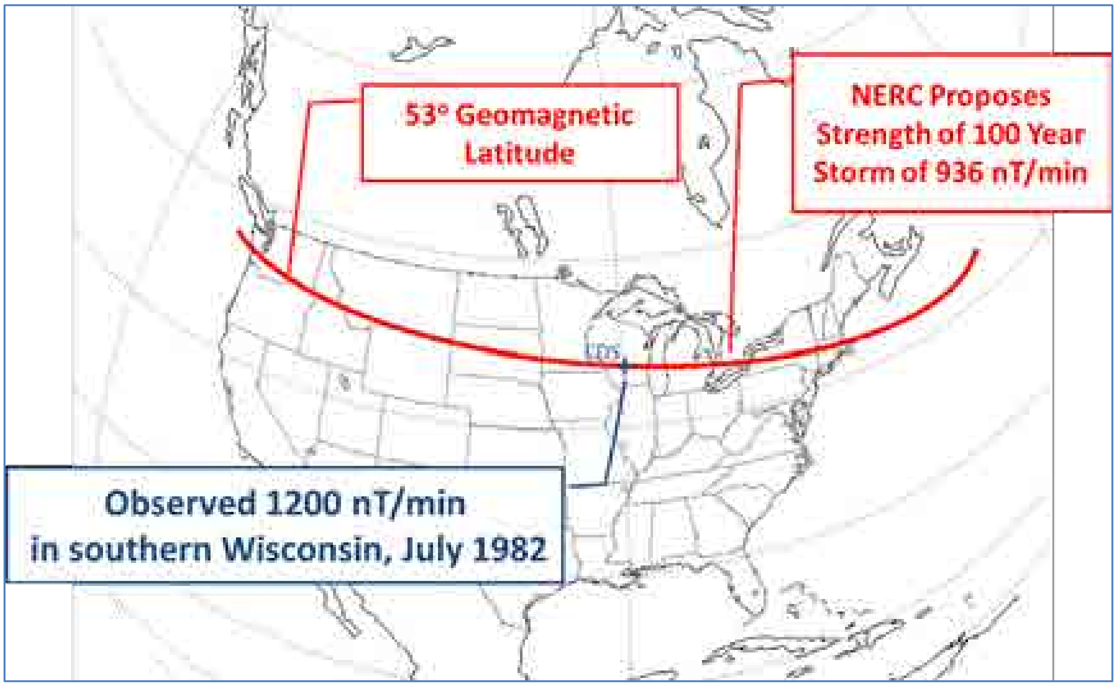

Figure 4 - Comparison of NERC Peak at 53° Latitude versus Actual Observed dB/dt

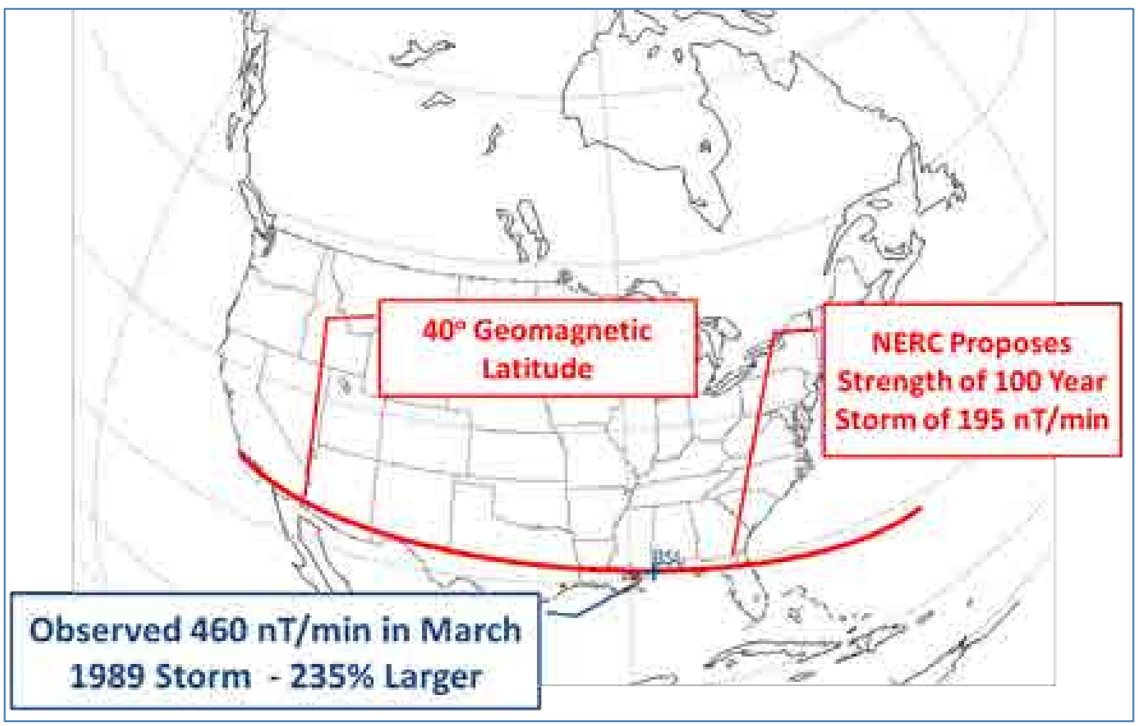

Figure 5 - Comparison of NERC Peak at 40° Latitude versus Actual Observed dB/dt

In summary, these storm observations limited to just three specific storms which happen to fall outside the NERC statistical database all show observations which exceed the NERC Reference profile at all latitudes. This illustrates that the NERC Reference profile cannot be a 1 in 100 year storm reference waveform and is not conservative. It should also be noted that even these three storm events are not representative of the worst case scenarios. In an analysis limited to European geomagnetic observatories, a science team publication concludes “there is a marked maximum in estimated extreme levels between about 53 and 62 degrees north" and that "horizontal field changes may reach 1000-4000 nT/minute, in one magnetic storm once every 100 years"[4]. One advantage of this European analysis, it did not exclude data from older storms like the March 1989 and July 1982 storms, unlike in the case of the NERC database statistical analysis. In another publication the data from the May 1921 storm is assessed with the following findings; "In extreme scenarios available data suggests that disturbance levels as high as ~5000 nT/min may have occurred during the great geomagnetic storm of May 1921"[5]. In another recent publication, the authors conclude the following in regards to the lower latitude expansion of peak disturbance intensity; "It has been established that the latitude threshold boundary is located at about 50–55 of MLAT"[6]. It should be noted that one of the co-authors of this paper is also a member of the NERC Standards drafting team. All of these assessments are in general agreement and all call into question the NERC Reference Profile. Figure 6 provides a comparison plot of these published results with respect to the NERC Draft Standard profile and illustrates the significant degree of inadequacy the NERC Reference profile provides compared to these estimates of 100 Year storm extremes.

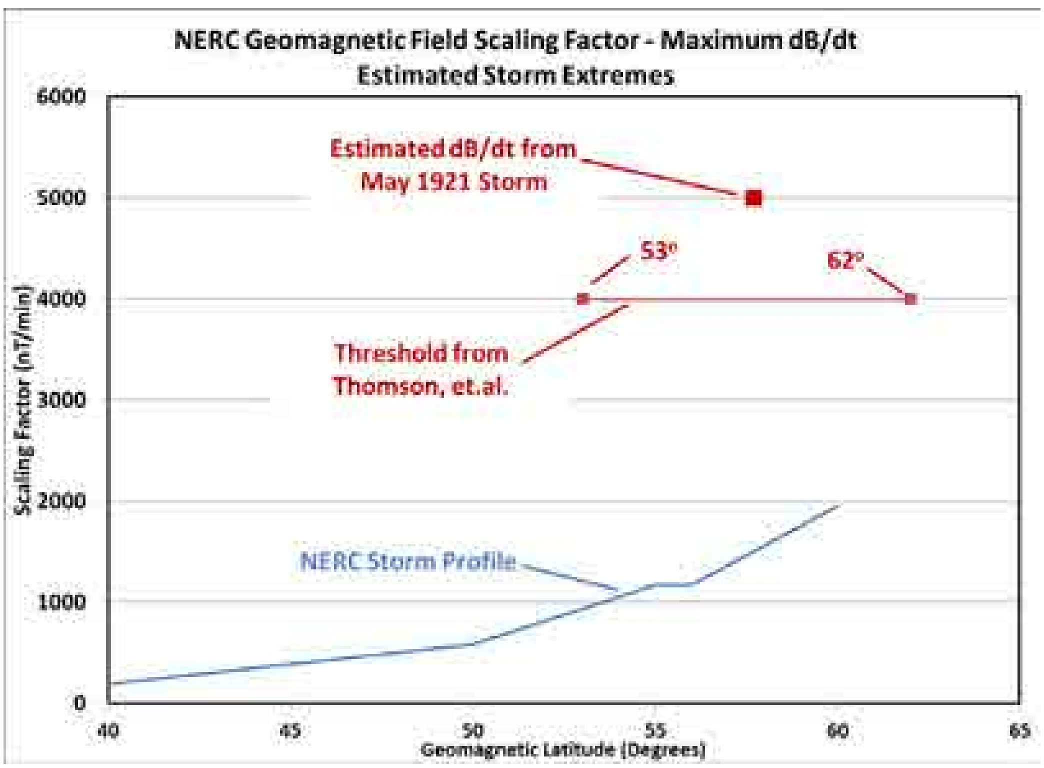

Figure 6 – Scientific Estimates of Extreme Geomagnetic Storm Thresholds compared to Propose3d NERC Draft Standard Profile

Discussion of Inadequate Geo-Electric Field Peak Intensity

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[4] Thomson, A., S. Reay, and E. Dawson. Quantifying extreme behavior in geomagnetic activity, Space Weather, 9, S10001, doi:10.1029/2011SW000696, 2011.

[5] John G. Kappenman, Great Geomagnetic Storms and Extreme Impulsive Geomagnetic Field Disturbance Events – An Analysis of Observational Evidence including the Great Storm of May 1921, Advances in Space Research, August 2005 doi:10.1016/j.asr.2005.08.055

[6] 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.

As the prior section of this discussion illustrates, the Peak Intensity of the proposed NERC geomagnetic disturbance reference field greatly understates a 100 year storm event. In prior comments submitted, it was also discovered that the geo-electric field models that NERC has proposed will also understate the peak geo-electric field[7]. In developing the Peak Geo-electric field, NERC has proposed the following formula:

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

Figure 7 – NERC Peak Geo-Electric Field Formula

As discussed in the last section of these comments the α (Alpha) factor in the above formula is understated at all latitudes the NERC 100 year storm thresholds. In addition, the White Paper illustrates that the NERC proposed β (Beta) factor will also understate the geo-electric field by as much as a factor of 5 times the actual geo-electric field. When these two factors are included and multiplied together in the same formula, this acts to compound the individual understatements of the α and β factors into a significantly larger understatement of Peak Geo-electric field.

This compounding of errors in the α and β factors can be best illustrated from a case study provided in the Kappenman/Radaksy White Paper. In this paper, Figure 27 (page 26) provides the geo-electric field recorded at Tillamook Oregon during the Oct 30, 2003 storm. Also shown is the NERC Model calculation for the same storm at this location. As this comparison illustrates, the NERC model understates the actual geo-electric field by a factor of ~5 and that the actual peak geo-electric field during this storm is nearly 1.2 V/km. Further this geo-electric field is being driven by dB/dt intensity at Victoria (about 250km north from Tillamook) that is 150 nT/min. Tillamook is also at ~50 geomagnetic latitude, so it is possible that the 100 year storm intensity could reach 5000 nT/min or certainly much higher than 150 nT/min. When using the NERC formula to calculate the peak Geo-electric field at Tillamook, the following factors would be utilized as specified in the NERC draft standard: For Tillamook Location, the α Alpha Factor = 0.3 based on Tillamook being at ~50 degrees MagLat, the β Beta Factor = 0.62 for PB1 Ground Model at Tillamook. Then using the NERC formula the derived Epeak would be:

"Tillamook Epeak" = 8 x 0.3 x 0.62 = 1.488 V/km (from NERC Epeak Formula)

In comparison to the ~1.2 V/km observed during the Oct 2003 storm, this NERC-derived Peak is nearly at the same intensity as caused by a ~150 nT/min disturbance. The scientifically sound method of deriving the Peak intensity is to utilize Faraday's Law of Induction to estimate the peak at higher dB/dt intensities. Faraday's Law of Induction is Linear (assuming the same spectral content for the disturbance field), which requires that as dB/dt increases, the resulting Geo-Electric Field also increases linearly. Therefore using the assumption of a uniform spectral content, which may be understating the threat environment, extrapolating to a 5000 nT/min peak environment would project a Peak Geo-Electric Field of ~40 V/km, a Factor of ~30 times higher than derived from the NERC Epeak Formula[8].

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[7] 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.

[8] Extrapolating to higher dB/dt using Faraday's Law of Induction requires only multiplication by the ratio of Peak dB/dt divided by observed dB/dt to calculate Peak Electric Field, in this case Ratio = (5000/150) = 33.3, Peak Electric = 1.2 V/km *33.3 = 40 V/km

A similar derivation can be performed for the GIC and geo-electric field observations at Chester Maine in the White Paper. From Figure 14 (page 17) the dB/dt in the Chester region reached a peak of ~600 nT/min and resulted in a ~2V/km peak geo-electric field during the May 4, 1998 storm. For this case study, the proposed NERC standard and the formula for the Peak Geo-Electric Field using the following factors for the Chester location, the Alpha Factor = 0.6 based on Chester being at ~55° MagLat, the Beta Factor = 0.81 for NE1 Ground Model at Chester. The NERC Formula would derive the Peak being only ~3.88 V/km.

"Chester Epeak" = 8 x 0.6 x 0.81 = 3.88 V/km (from NERC Epeak Formula)

In contrast to the NERC Epeak value, a physics-based calculation can be made for the case study of the May 4, 1998 storm at Chester. Again, Faraday's Law of Induction can be utilized to extrapolate from the observed 600 nT/min levels to a 5000 nT/min threshold. This results in a Peak Geo-Electric Field of ~16.6 V/km, a Factor of ~4.3 higher than derived from the NERC Formula[9].

Discussion of Data-Based GMD Standard to Replace NERC Draft Standard

As prior sections of this discussion has revealed, the proposed NERC Draft Standard does not accurately describe the threat environment consistent with a 1-in-100 Year Strom threshold, rather the NERC Draft Standard proposes storm thresholds that are only a 1-in-10 to 1-in-30 Year frequency of occurrence. Further, the methods proposed by NERC to estimate geo-electric field levels across the US are not validated and where independent assessment has been performed the NERC Geo-Electric Field levels are 2 to 5 times smaller than observed based on direct GIC measurements of the power grid.

Basic input assumptions on ground conductivity used in the NERC ground modeling approach have never been verified or validated. Ground models are enormously difficult to characterize, in that for the frequencies of geomagnetic field disturbances, it is necessary to estimate these profiles to depths of 400kM or deeper. Direct measurements at these depths are not possible to carry out and the conductivity of various rock strata can vary by as much as 200,000%, creating enormous input modeling uncertainties for these ground profiles. Further it has been shown that the NERC geo-electric field modeling calculations themselves appear to have inherent frequency cutoff's that produce underestimates of geo-electric fields as the disturbance increases in intensity and therefore importance. Hence the NERC Standard is built entirely upon flawed assumptions and has no validations.

A framework for a better Standard which is highly validated and accurate has been provided via the Kappenman/Radasky White Paper and the discussion provided in these comments. As noted in the White Paper, the availability of GIC data and corresponding geomagnetic field disturbance data allowed highly refined estimates to be performed for geo-electric fields and to extrapolate the Geo-Electric Field to the 100 Year storm thresholds for these regions. The primary inputs (other than GIC and corresponding geomagnetic field observations) are simply just details on the power grid circuit parameters and circuit topology. These parameters are also known to very high precision (for example transmission line resistance is known to 4 significant digits after the decimal point). Asset locations are also known with high precision and many commercially available simulation tools can readily compute the GIC for a uniform 1 V/km geo-electric field. This calculation provides an intrinsic GIC flow

[9] Extrapolating to higher dB/dt using Faraday's Law of Induction requires only multiplication by the ratio of Peak dB/dt divided by observed dB/dt to calculate Peak Electric Field, in this case Ratio = (5000/600) = 8.3, Peak Electric = 2 V/km *8.3 = 16.6 V/km

benchmark that can be used to convert any observed GIC to an estimated Geo-Electric Field that produced that GIC. Further this calculation is derived over meso-scale distances of the power grid assets. As summarized in a recent IEEE Panel discussion, this approach allows for wide area estimates of ground response than possible from conventional magneto-telluric measurements[10]. Figure 8 provides a map showing the locations of the Chester, Seabrook and Tillamook GIC observations and the approximate boundaries based upon circuit parameters of the ground region that could were validated.

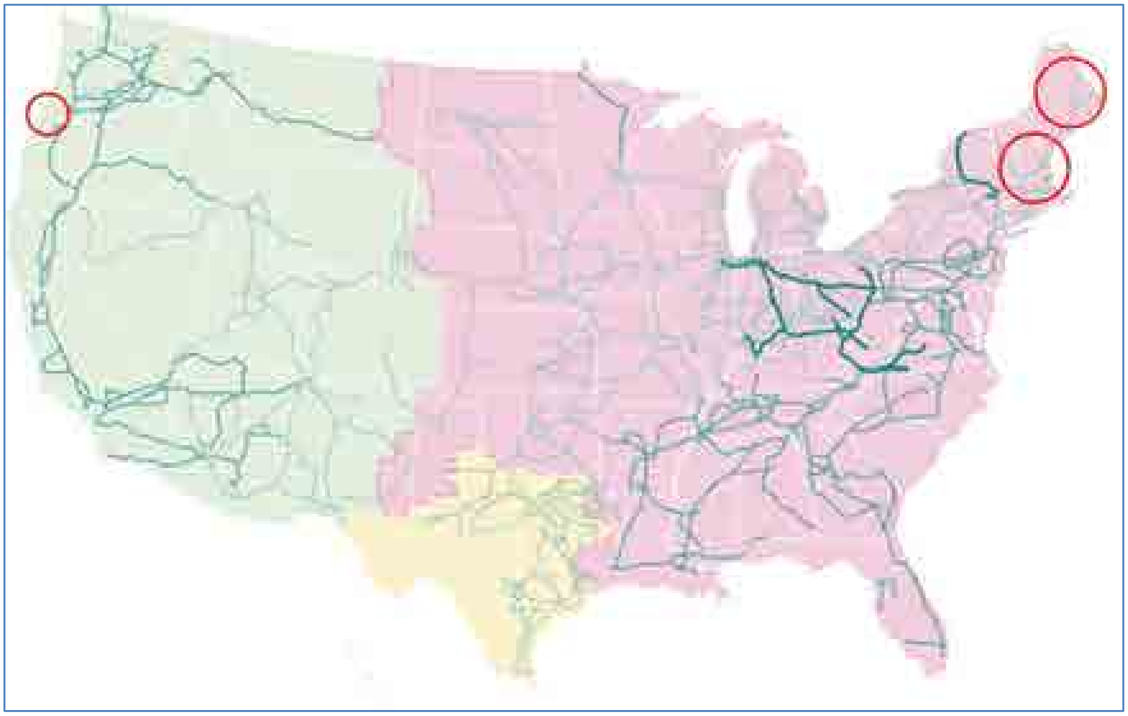

Figure 8 – Red Circles provide Region of Ground Model Validation using GIC observations from Kappenman/Radasky White Paper.

As filled in a recent FERC Docket filing[11], ~100 GIC monitoring sites have operated and are collecting data across the US. Using these analysis techniques and the full complement of GIC monitoring locations, it is possible to accurately benchmark major portions of the US as shown in the map in Figure 9. As shown in this figure, a bulk of the Eastern grid is covered and in many locations with overlapping benchmark regions, such that multiple independent observations can be used to confirm the accuracy of the regional validations. The same is also true for much of the Pacific NW. As noted in Meta-R-319 and shown below Figure 10 from that report, these two regions are the most at-risk regions of the US Grid.

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[10] Kappenman, J.G., "An Overview of Geomagnetic Storm Impacts and the Role of Monitoring and Situational Awareness", IEEE Panel Session on GIC Monitoring and Situational Awareness, IEEE PES Summer Meeting, July 30, 2014.

[11] Foundation for Resilient Societies, "SUPPLEMENTAL INFORMATION SUPPORTING REQUEST FOR REHEARING OF FERC ORDER NO. 797, RELIABILITY STANDARD FOR GEOMAGNETIC DISTURBANCE OPERATIONS, 147 FERC ¶ 61209, JUNE 19, 2014 AND MOTION FOR REMAND", Docket No. RM14-1-000, submitted to FERC on August 18, 2014.

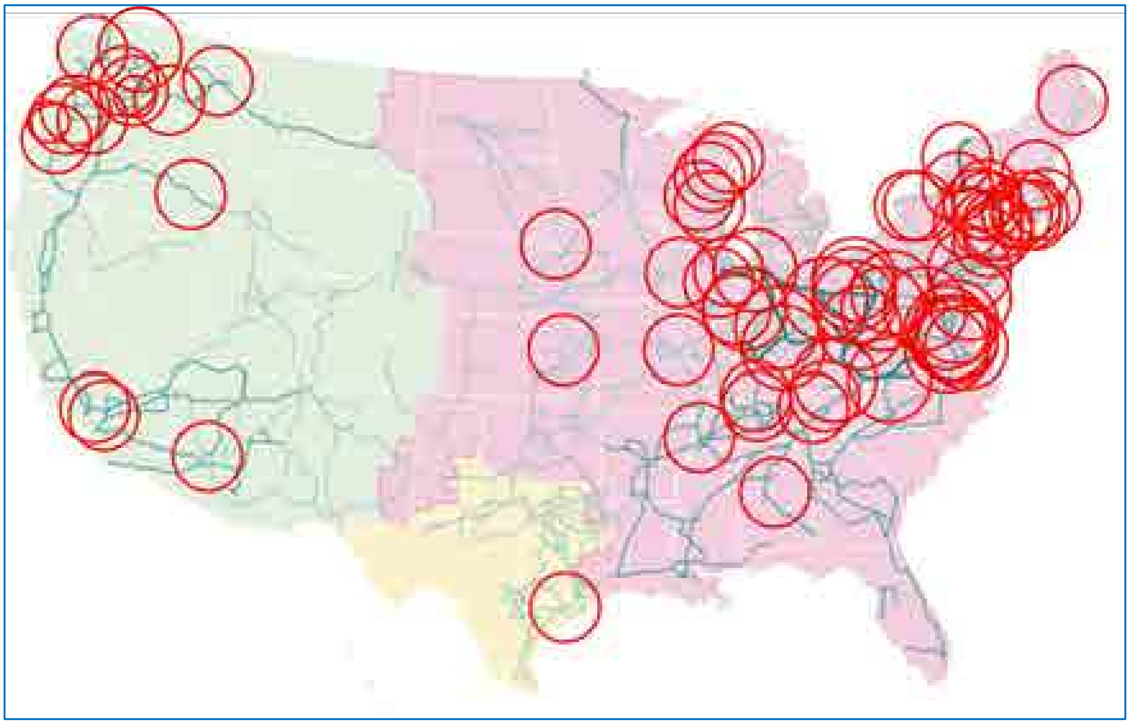


Figure 9 – GIC Observatories and US Grid-wide validation regions.

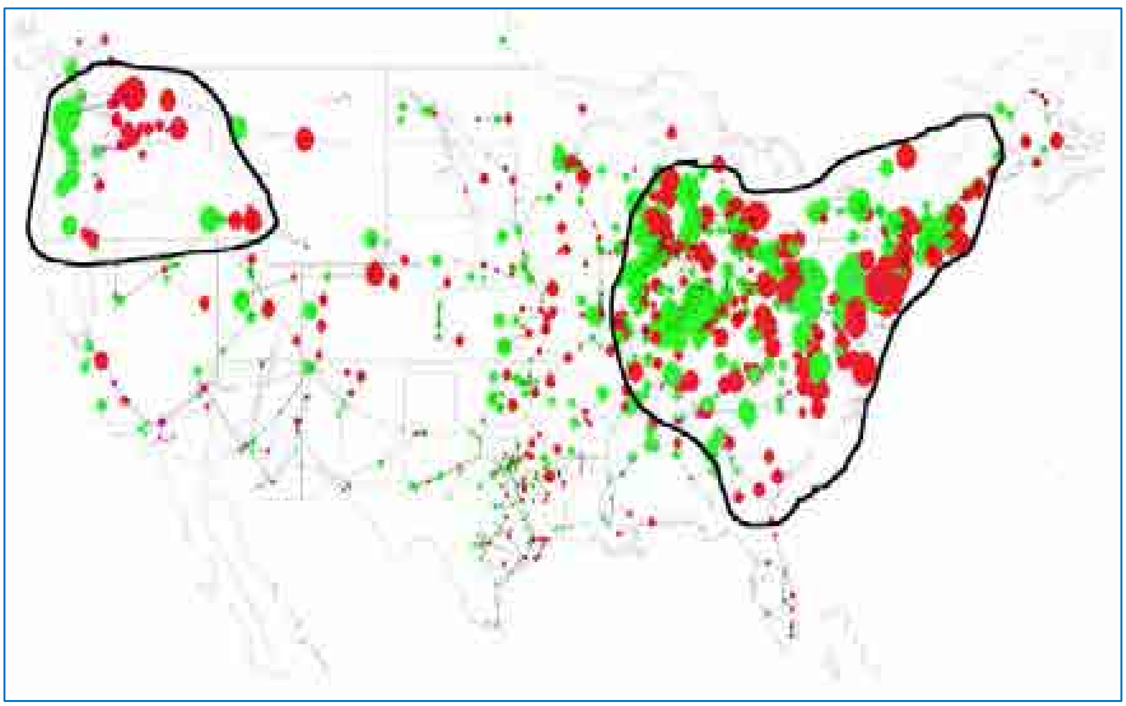


Figure 10 – Map of At-Risk Regions from Meta-R-319 Report for 50° Severe Storm Scenario

Each of these GIC measurements can define and validate the geo-electric field parameters over considerable distance. In the example of the Chester Maine case study, the validations in the case of the 345kV system can extend ~ 250kM radius. At higher kV ratings, the footprint of GIC and associated geo-electric field measurements integrates over an even larger area. As these measurements are accumulated over the US, the characterizations provide a very complete coverage with many overlapping coverage confirmations. These confirmations will also have Ohm's law degree of accuracy, whereas magnetotelluric observations can still have greater than factor of 2 uncertainty[12]. For those areas where perhaps a GIC observation is not available, this region can utilize a base intensity level that agrees with neighboring systems until measurements can be made available to fully validate the regional characteristics.

This Observational-Based Standard further establishes a more accurate framework for developing the standard using facts-based GIC observation data, and removes the dependence on simulation models which could be in error. The power system and GIC flows observed on this system will always obey the laws of physics while models may exhibit erratic behaviors and are dependent on the skill/qualifications of the modeler and the uncertainty of model inputs. Models are always inferior as they cannot incorporate all of the factors involved and can have biases which can inadvertently introduce errors. This Observational Framework methodology is also open and transparent so any and all interested parties can review and audit findings. The validations can be performed quickly and inexpensively across all of these observational regions. It also allows for simple updates once new transmission changes are made over time as well.

Respectfully Submitted by,

John Kappenman, Principal Consultant
Storm Analysis Consultants

Curtis Birnbach, President and CTO
Advanced Fusion Systems

[12] Boteler, D., "The Influence of Earth Conductivity Structure on the Electric Fields that drive GIC in Power Systems", IEEE Panel Session on GIC Monitoring and Situational Awareness, IEEE PES Summer Meeting, July 30, 2014.

Electric Infrastructure Security Council

Electric Infrastructure Security Council

Comments for Maine Public Utility Commission

Inquiry into Measures to Mitigate the Effects Of Geomagnetic Disturbances and Electromagnetic Pulse On the Transmission System in Maine

Docket Number 2013-00415

Submitted October 4, 2013

This filing is in response to the questions cited in docket number 2013-00415. Fourteen questions are posed in the NOI. Regarding the first question, EIS Council determined that it would be most beneficial for the PUC to be provided with a model analysis of geomagnetically induced currents (GIC) for the Maine 345 kV transmission system.

An Initial estimate of the components most vulnerable to GMD or EMP E3 is provided below. A more specific analysis of GMD vulnerability would need to come from a more detailed study, in coordination with the transmission owners and operators, but we hope that this brief analysis is helpful in identifying the most vulnerable components of the Maine grid.

General EMP E1 vulnerability estimates can be provided by EIS Council based on its parallel vulnerability studies (and an upcoming power grid protection plan currently being developed), but, as with GMD and EMP E3, a specific answer for EMP E1 would come from a focused study of the Maine power grid, in coordination with the transmission owners and operators.

Our brief answers to most of the other questions are supplied in the appendix at the end of this submission.

1. Identify the most vulnerable components of the T&D utility's transmission system

1. Analysis of the Maine EHV Transmission Network in Response to Maine PUC Notice Of Inquiry

Introduction and Purpose

The Maine Legislature passed and the Governor signed into law on June 6, 2013 LD-131, which directs the Maine Public Utility Commission to review geomagnetic disturbance (GMD) and electromagnetic pulse (EMP) vulnerability. This legislation was enacted partially in reaction to earlier U.S. Government-sponsored reports that included the Maine grid (as part of US-wide assessments) as being highly vulnerable to severe GMD and EMP threat scenarios. These assessments were performed of the Maine Extra High Voltage (EHV) electric grid prior to the Maine Power Reliability Program (MPRP) additions, scheduled to be completed over the next few years. These additions would significantly expand the EHV grid within the state of Maine and since these threat scenarios are in large part based upon the size of the EHV grid, hearings and other testimony provided to the State Legislators revealed that vulnerability may increase for the State of Maine with the MPRP additions.

In hearings and evidence provided by the Regional Independent System Operator (ISO), and Maine electric utility companies, it was disclosed that no prior simulations specific to these risks for the New England region or for the State of Maine had been completed. Also, as is common for all other U.S. electric utility organizations, no specific design codes exist that take these threats into consideration in the design and development of the electric grid. The ISO did provide information that they utilize an operating procedure for geomagnetic storms, but this procedure was not developed as an output of any detailed analysis of the New England grid. Rather the procedure was developed through experience from prior storm events, which were much smaller than the most severe storm threats that are now known to be plausible.

The Electric Infrastructure Security (EIS) Council recognized that the lack of detailed study of the Maine grid and MPRP additions for these threats was an important information gap. The development of appropriate public policy would be hindered without this specific analysis. As a result, the EIS has commissioned an independent expert review, performed by Storm Analysis Consultants,[1] of the Maine grid for severe GMD conditions in order to more accurately assess the State vulnerability to severe storms and by extension EMP threats to this vital infrastructure. Because of the similar physical phenomenology, many of the findings are also relevant to EMP E3 effects as well.

EIS has therefore developed and is submitting this report. The report will entail a review of prior analysis conducted for the entire US power grid. This report will then provide a more detailed new analysis of the State of Maine electric grid specific to the Pre-MPRP and Post-MPRP additions that are anticipated.

[1] John Kappenman of Storm Analysis Consultants provided expert witness testimony to the Maine Legislature's Energy, Utilities and Technology Committee during hearings held on the bill LD 131 on March 21, 2013.

2. Summary and Analysis of Severe Geomagnetic Storm Simulations in the U.S. Electric Power Grid

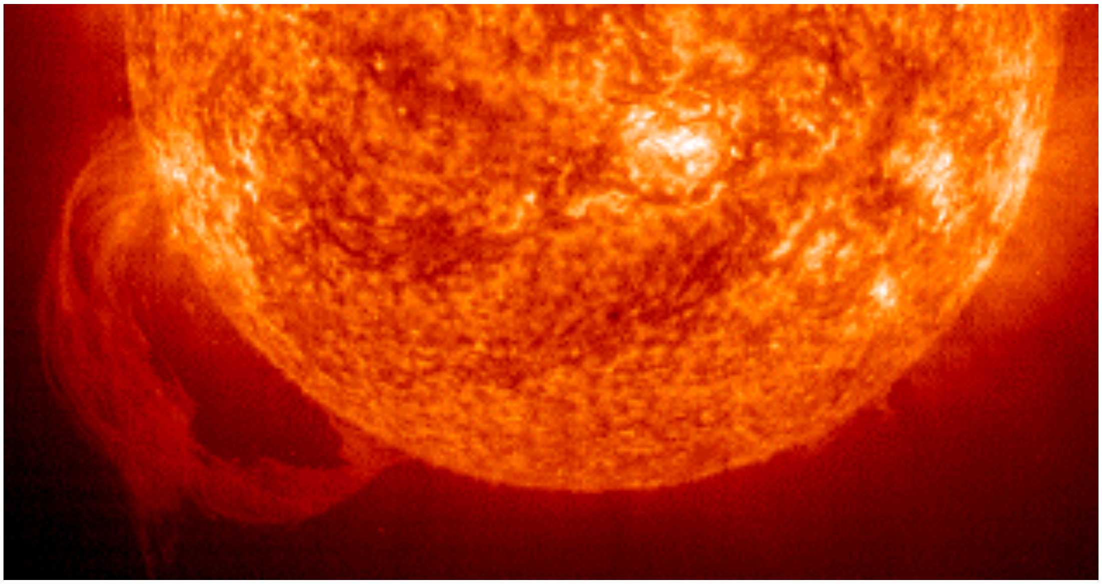


Figure 2-1- SOHO image, June 9, 2002

Prior CONUS Analysis for EMP and Severe Geomagnetic Storms

A significant amount of analysis has been performed on the U.S. electric power grid to examine for vulnerability to both EMP and severe GMD threats to this vital infrastructure. The first investigative effort was undertaken by the US Congressional Commission to Assess the Threat to the United States from Electromagnetic Pulse (the EMP Commission). The EMP Commission was chartered by Congress in 2001 to study the potential consequences on the domestic and military infrastructure from a high-altitude nuclear detonation and to issue its findings and recommendations to Congress, the Secretaries of Defense and Homeland Security, and the Director of the Federal Emergency Management Agency, and issued their final report in 2008[2]. In 2009-2010, FERC jointly with the DOE, DOD, DHS further examined these vulnerability issues and issued a series of detailed reports in late 2010[3], and the U.S. National Academy of Sciences report[4] provided additional overviews and summaries of these threats.

The purpose of this section is to provide an overview of the key vulnerability findings for the CONUS-wide analysis and then to further examine the Maine MPRP additions in further analysis that has been performed specifically for the Maine PUC Request for Comments.

Geomagnetic Storm Environment & CONUS Grid Model

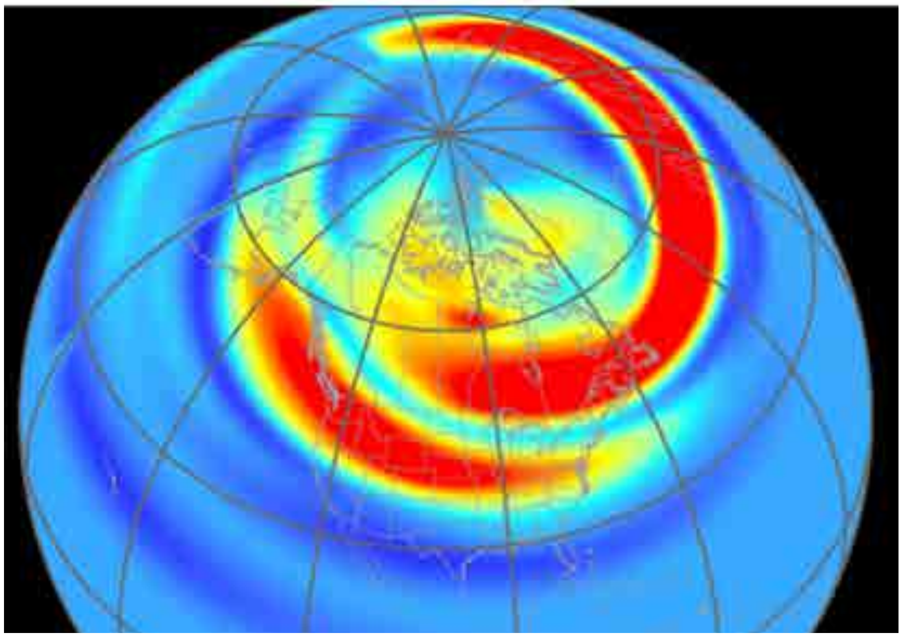
Simulation models of the CONUS region of the North American EHV Power Grid have been developed from publicly available data for the purposes of simulating the impacts of severe geomagnetic storms on

2 For the full report, please visit: http://empcommission.org/docs/A2473-EMP_Commission-7MB.pdf

3 For the full reports, please visit: http://web.ornl.gov/sci/ees/etsd/pes/ferc_emp_gic.shtml

4 For the full report, please visit: http://books.nap.edu/catalog.php?record_id=12507

these critical infrastructures. These simulation methods have been publicly reported in other recent reports to the U.S. government (Meta-R-319 – see reference 3). Additional analysis was also conducted for the electric power industry in 2011 (Storm-R-111 – provided to NERC's GMD Task Force). While the emphasis of this summary is an examination of the risks of permanent damage to EHV (Extra High Voltage) transformers due to severe GMD, the slow pulse disturbance caused by an EMP attack will produce similar overall risks to these infrastructures, so this analysis provides comparable risk



Geographic footprint of the March 13, 1989 Geomagnetic Storm – The footprint of a severe geomagnetic storm will be planetary in scope. This shows the intensity of geomagnetic field disturbances observed North America at time 22:00 GMT. New analyses of large historic storms indicate that the intensities of those storms could pose a risk that is 3 to 10 times more severe than even the large March 1989 storm, which disrupted power grids across North America. Present day electric power grids have not yet been exposed to such large storm events and recent analysis indicates large-scale multi-year outages are plausible due to damage from these storms.

assessments posed by EMP attack scenarios. In addition, the CONUS-wide analysis was performed on an EHV network for the state of Maine that was pre-MPRP additions. Therefore all results reported in this section reflect the infrastructure for Maine that existed prior to a number of MPRP additions.

As noted in prior reports, severe storm scenarios could result in geomagnetic field disturbance levels that could be significantly higher than experienced in most portions of the North American power grid during the March 13-14, 1989 Geomagnetic Storm that resulted in the province-wide blackout of Quebec. Disturbance levels that are 4 to 10 times higher have been noted in related scientific analysis. Therefore to simulate these conditions, models were run with magnetic field disturbance intensities at levels up to 4800 nT/min[5]. In addition to these severe disturbance levels, the geographic footprint of the disturbance scenarios was shifted in geomagnetic latitude to reflect varying conditions that are plausible during a severe storm event. To simulate this, each of these disturbance levels was simulated centered on three geomagnetic latitude locations, 55°, 50° and 45°. (Note- Geomagnetic Latitudes are typically as much as 11° lower than geographic latitudes across the US). Figure 2-2 provides a map showing the geographic footprint for both the 55° and 50° threat scenarios, which are of greatest importance to the State of Maine, and are more likely to occur than lower-latitude storm footprints.

[5] nT/min stands for "nano-Tesla per minute", the common unit of measure for geomagnetic field disturbances.

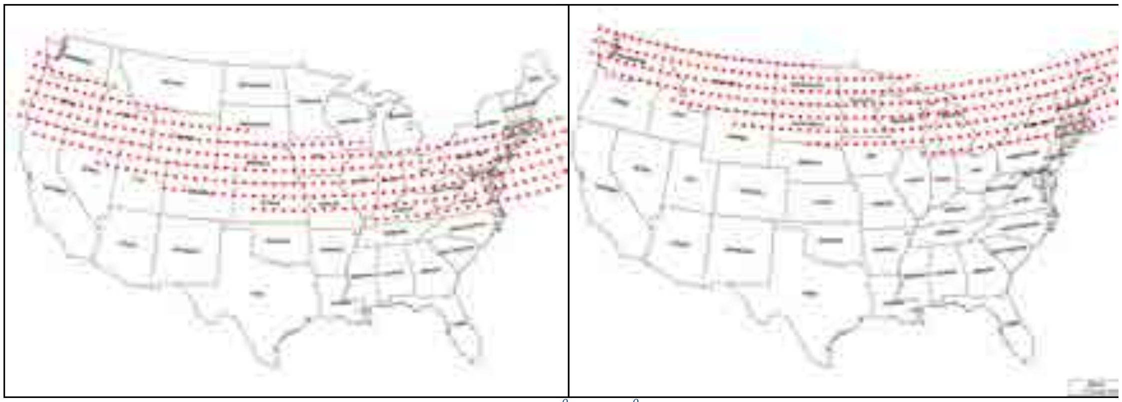


Figure 2-2- Disturbance regions for 50⁰ and 55⁰ geomagnetic latitude storms.

The US model was only limited to transformers operating at voltages of 345kV, 500kV and 765kV. Within the State of Maine, the highest transmission line voltages are limited to 345kV. While there are over 2000 transformers in each of the simulation runs, GIC flows will also occur in lower voltage lines and transformers in the bulk interconnection. This is an important caveat in that a more detailed model representation would be needed at these lower voltages to determine possible GIC flows in this portion of the network and how those flows could alter the GIC flows in the EHV portions of the network modeled in these simulations. In many cases 500kV and 345kV transformers which are auto transformers would not have detailed enough representation of the underlying voltage networks to establish certainty on GIC flows that are likely. The model is limited to the CONUS region with a few minor additions of transformers into interconnected regions of Canada, including those into Maine.

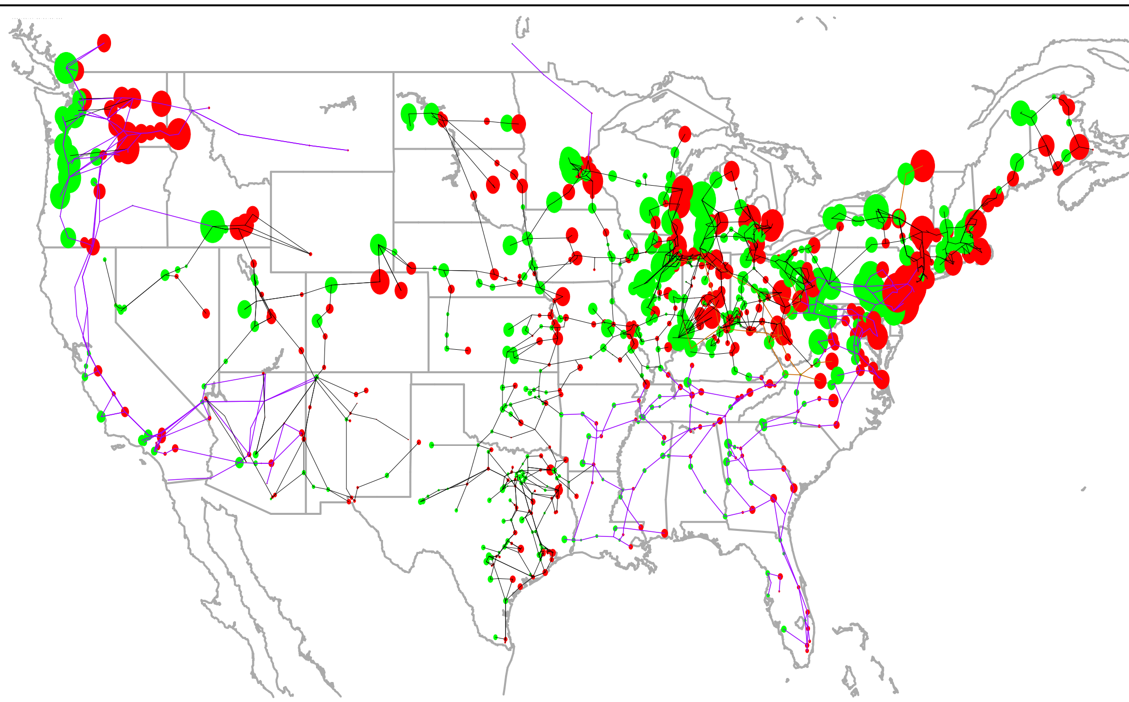


Figure 2-3. 4800 nT/min geomagnetic storm – 55 degree geomagnetic disturbance scenario. Red and Green dots indicate magnitude and polarity of GIC flow in exposed transformers

Overview of 4800 nT/min Threat Scenarios

Figures 2-3 and 2-4 provide respectively the pattern of GIC flows observed in the U.S. grid model for 4800 nT/min threat scenarios centered on 55° and 50° geomagnetic latitude locations, respectively. As these figures illustrate, as the disturbance threat location moves southward, the patterns of GIC in the U.S. grid also follow that southward progression. The higher GIC flows occur in Maine for the 55° threat scenario, which is more likely to occur.

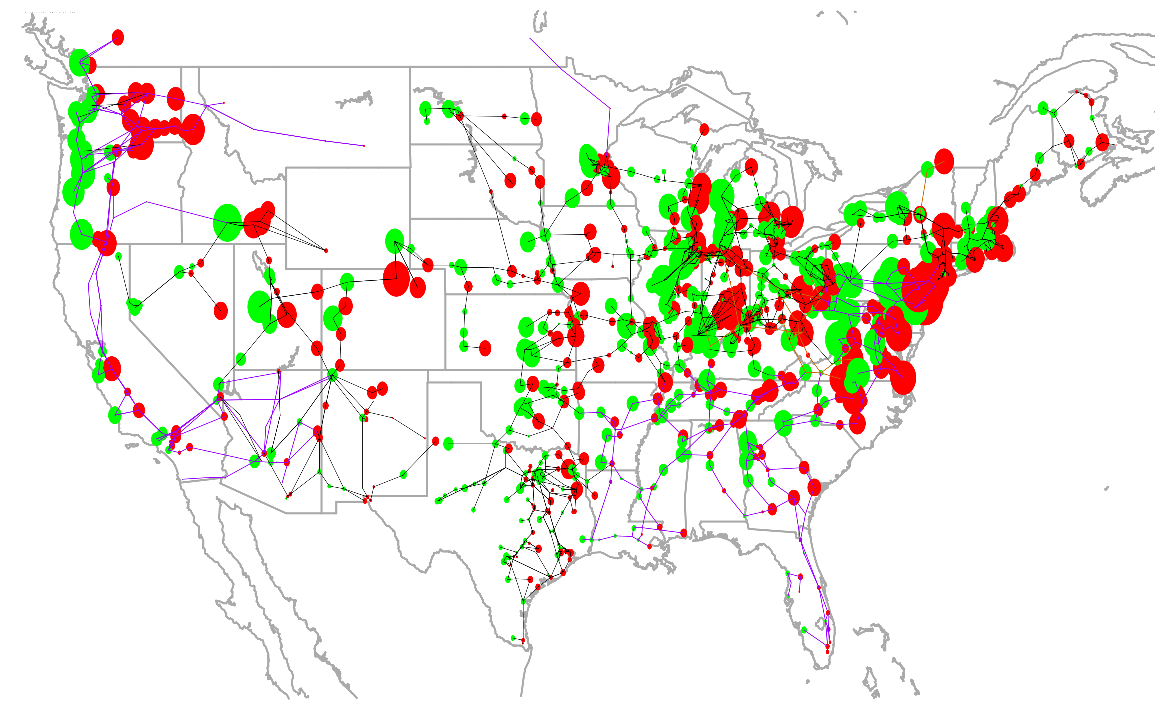


Figure 2-4. 4800 nT/min geomagnetic storm – 50 degree geomagnetic disturbance scenario. Red and Green dots indicate magnitude and polarity of GIC flow in exposed transformers

Summary of At-Risk Transformers

To simplify analysis of At-Risk transformers (due to associated lack of standards for allowable GIC exposure levels), a level of exposure of 90 Amps/phase had been used to make that distinction. As indicated by in Figure 2-5, each of these threat scenarios indicates a similar number of transformers that would meet the criteria, although the 50° Threat Scenario is slightly more severe. In order to provide more details on these high GIC flow transformers, Figure 2-5 provides a summary of the Number of At-Risk Transformers for all three of the 4800 nT/min Threat Scenarios along with the Number of At-Risk Transformers for similar Threat Scenarios only at a severity of 2400 nT/min.

Figures 2-6 and 2-7 provide geographic maps showing the locations of the At-Risk Transformers for the respective threat cases at 55° and 50° geomagnetic latitude locations. These more clearly illustrate the shift in location of At-Risk transformers as the threat environment shifts to a more southerly footprint across the CONUS region. In both cases, there are transformers identified as being At-Risk of permanent damage within Maine to the Pre-MPRP electric grid infrastructure.

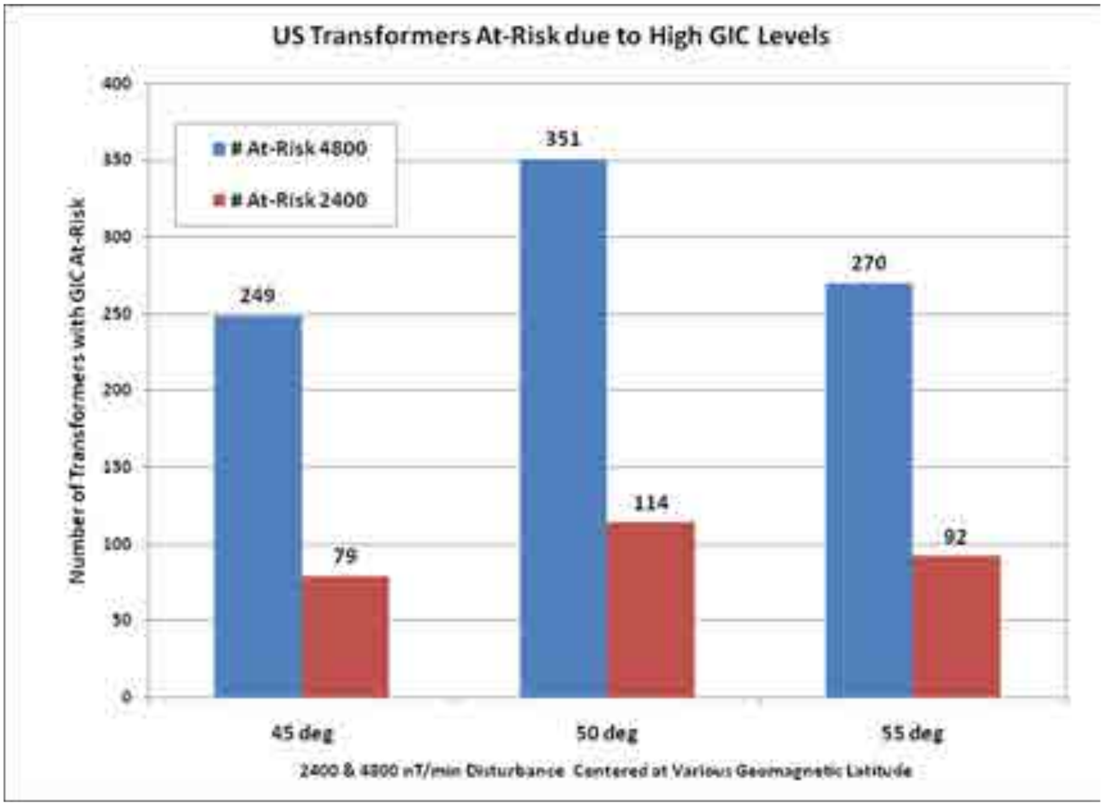


Figure 2-5- Number of At-Risk Transformers for 2400 & 4800 nT/min Threat Scenarios.

Figure 2-6- Location of At-Risk Transformers for 4800 nT/min at 55^o (GIC > 90 Amps/phase).

Figure 2-7- Location of At-Risk Transformers for 4800 nT/min at 50° (GIC > 90 Amps/phase).

Additional sections of this report will provide a more detailed analysis of the Maine grid and impacts that could occur to this grid. This will also provide an examination of the Post-MPRP 345kV transmission additions in Maine and the degree of increase in vulnerability this poses to the Maine network.

3. Development of the Maine Electric Power Grid EHV Simulation Model

Overview of MPRP Additions to Maine Simulation Model

A series of 345kV EHV transmission lines and substations are being added under the Maine Power Reliability Project (MPRP). In the prior U.S. Government reports, the Pre-MPRP 345kV transmission network for the State of Maine utilized in that study is shown in Figure 3-1.

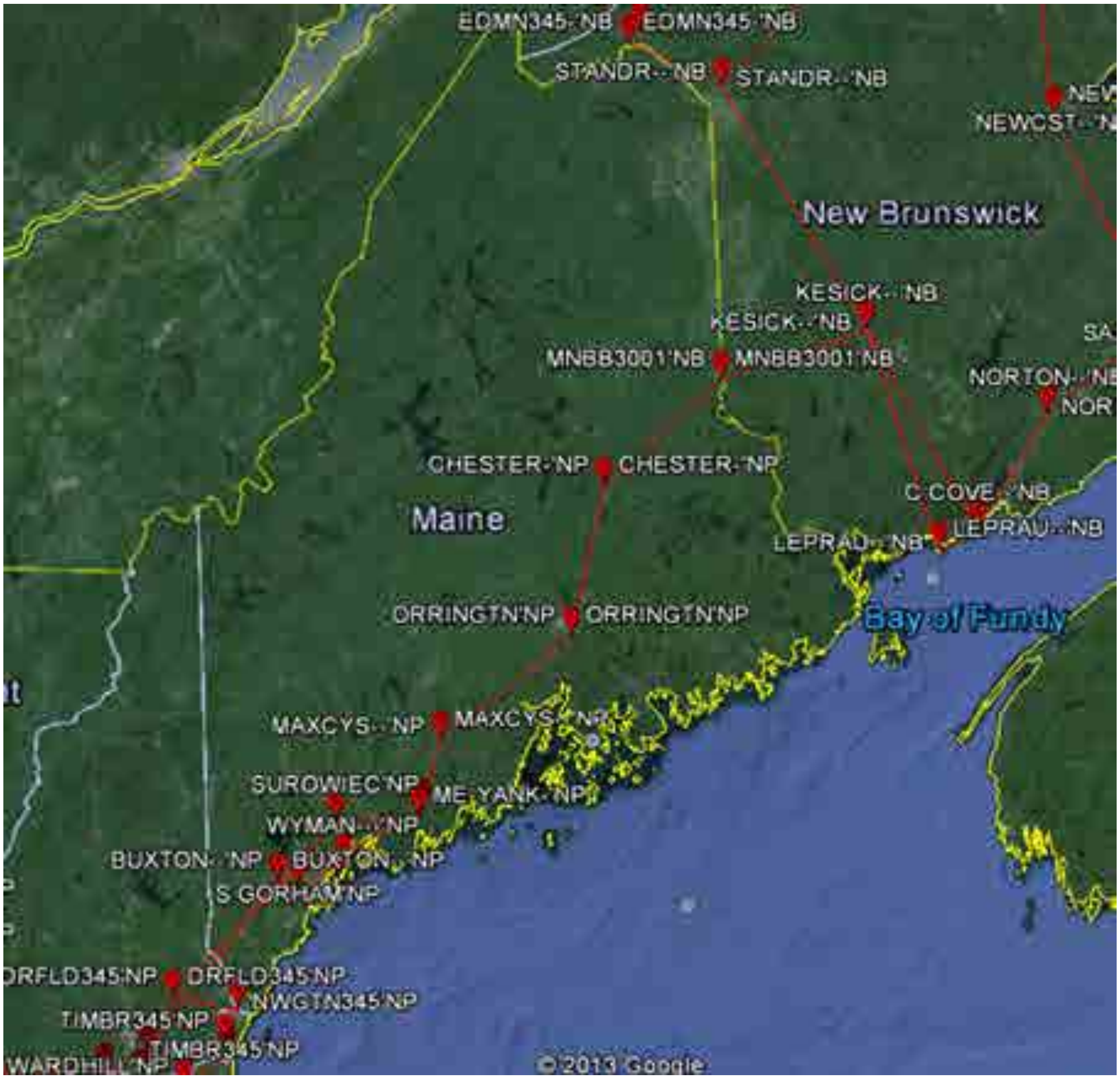


Figure 3-1 – Map of Maine Pre-MPRP 345kV transmission network simulation model

The MPRP additions that are being developed for the Maine EHV grid are highlighted in Figure 3-2. These include substantial additions to the 345kV network, which essentially convert the Maine electric grid from a topology of a single 345kV transmission line across the state, to redundant 345kV transmission lines across most of the state. While this aids the reliability against outages of a single 345kV transmission line outage and supports higher New England region imports of power from Canada, it does allow additional paths for GIC flows, which are likely to increase due to this change.

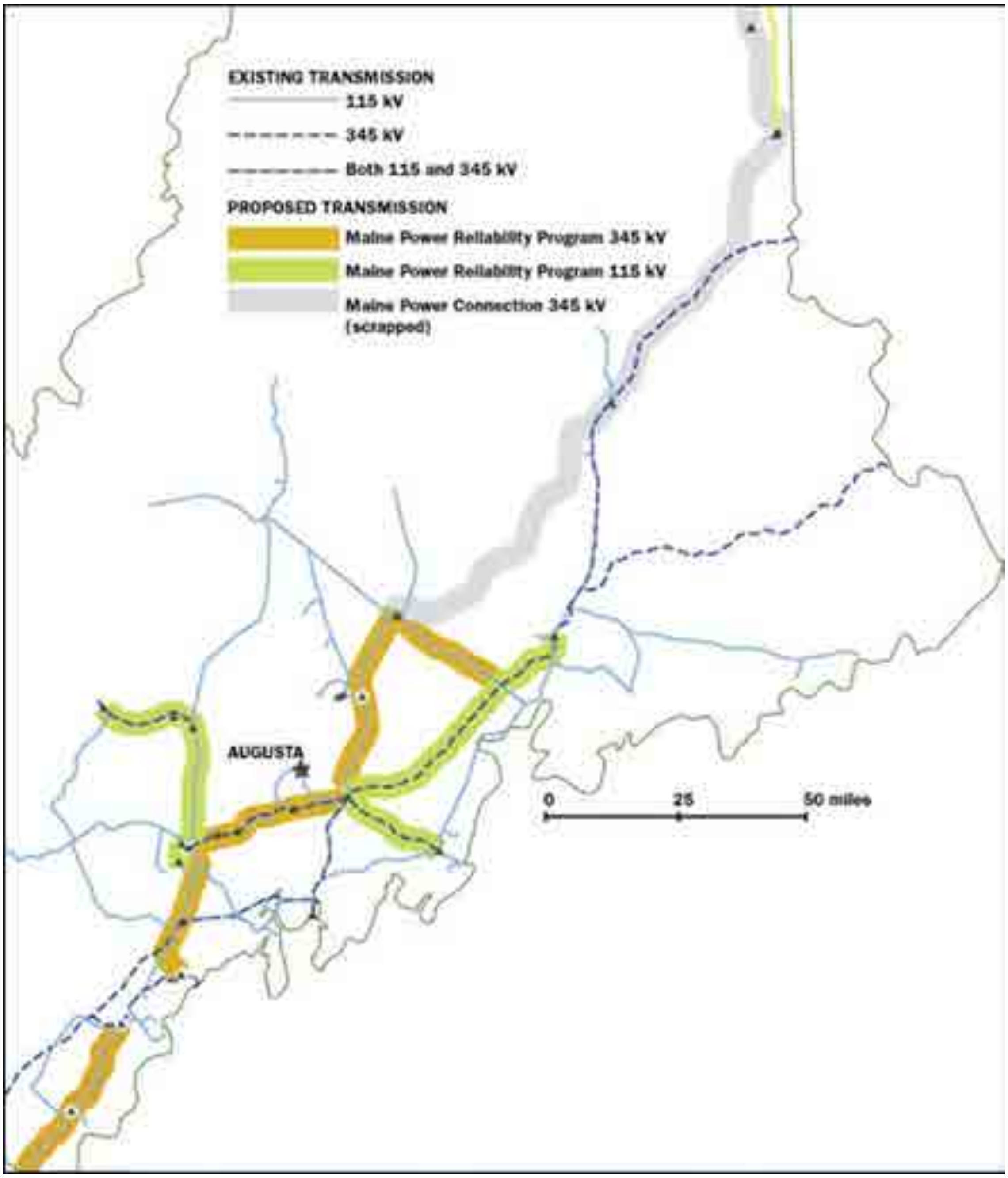


Figure 3-2 – Map of Proposed MPRP Transmission Network Additions

Figure 3-3 provides a map of the simulation model that was implemented for this Maine MPRP simulation study. In addition to the transmission line additions, details were added for transformer additions at the substations. Since the transformer and transmission line modeling details for the MPRP additions were not publicly available, the model used engineering estimates for these components based upon ratings for similar style components elsewhere in Maine and the U.S. 345 kV EHV network. While this does add some degree of uncertainty, other modeling uncertainties are also present (for example, deep Earth ground conductivity, spatial details of geomagnetic field disturbance environment) which generally entail even higher degrees of uncertainty. Therefore these inclusions, while important, are not likely to greatly influence the overall analysis results.

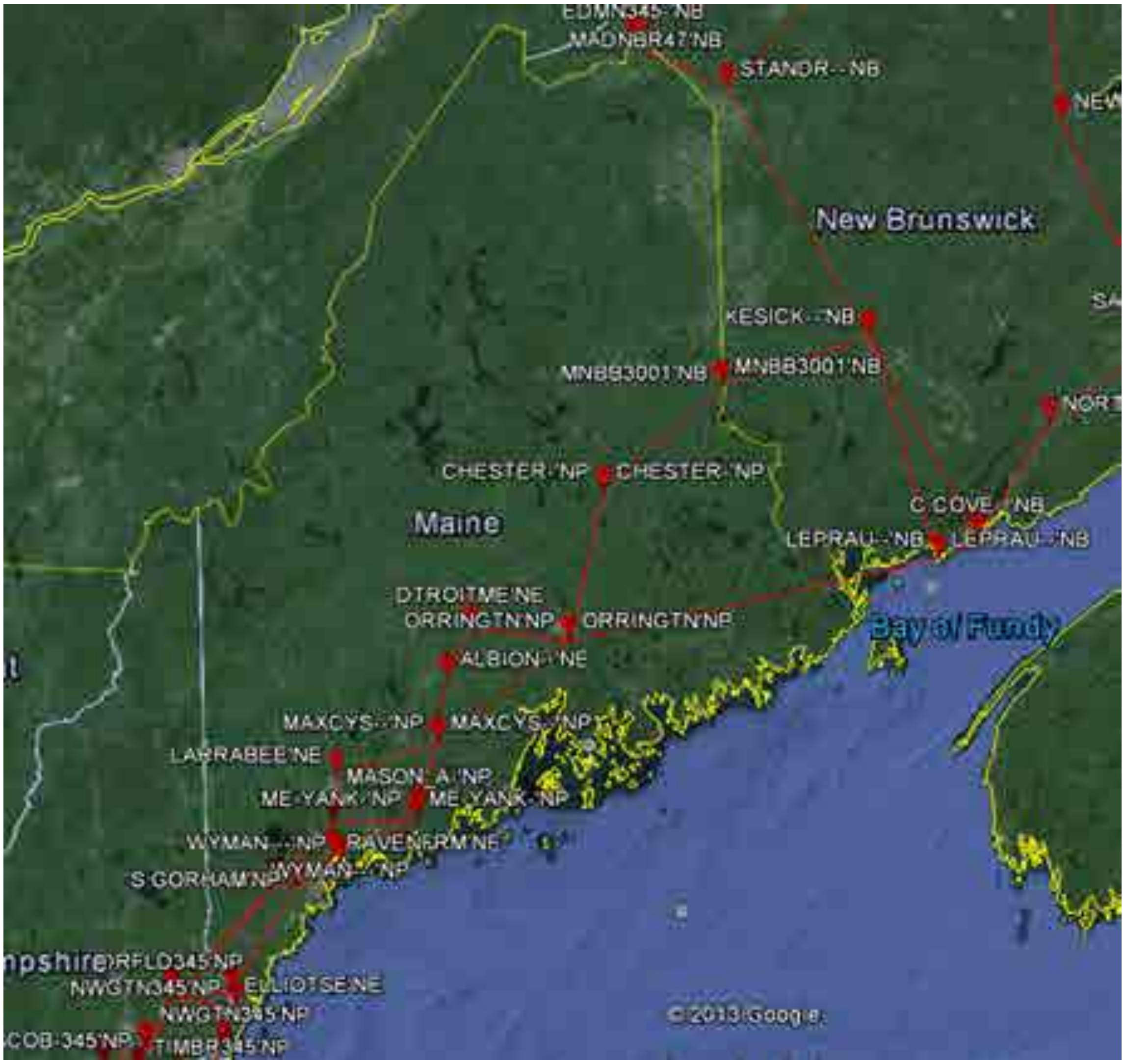


Figure 3-3 – Map of Maine Post-MPRP Transmission network simulation model

Simulation Model Validation – Maine Grid Examples

In the analysis carried out for the FERC Meta-R-319 report (see reference 3 above), extensive efforts were undertaken to verify that the simulation models for the US power grid were providing sufficiently accurate results. One of the primary approaches utilized to test these models was to perform simulations for forensic analysis purposes and comparing the results with discreet measurements that were made available.

One of the forensic simulations was actually conducted on the Maine grid and provided important verification of the ability of the model in that portion of the US grid to produce accurate estimates. Figure 3-4 provides a plot of the results of this simulation showing the Calculated versus Measured GIC at the Chester Maine 345kV transformer. This was for a storm that occurred on May 4, 1998 and was driven by the large-scale storm conditions as shown in Figure 3-5.

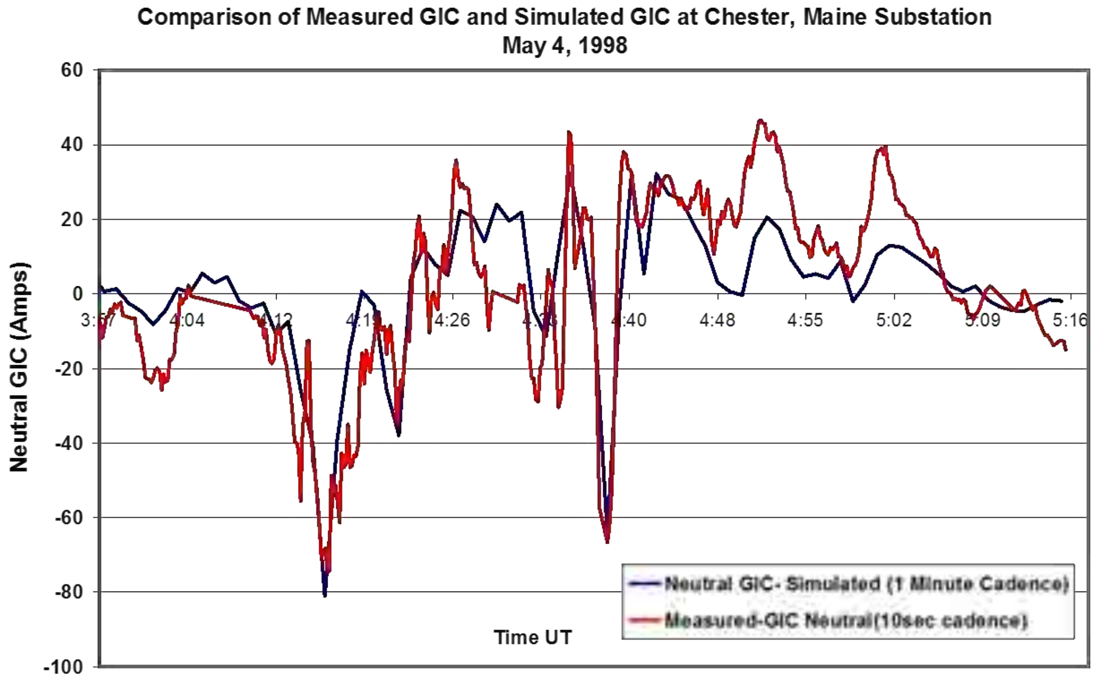


Figure 3-4 – Plot showing comparison of Simulated versus Measured GIC at Chester Maine 345kV transformer for May 4, 1998 geomagnetic storm. (Source – Meta-R-319)

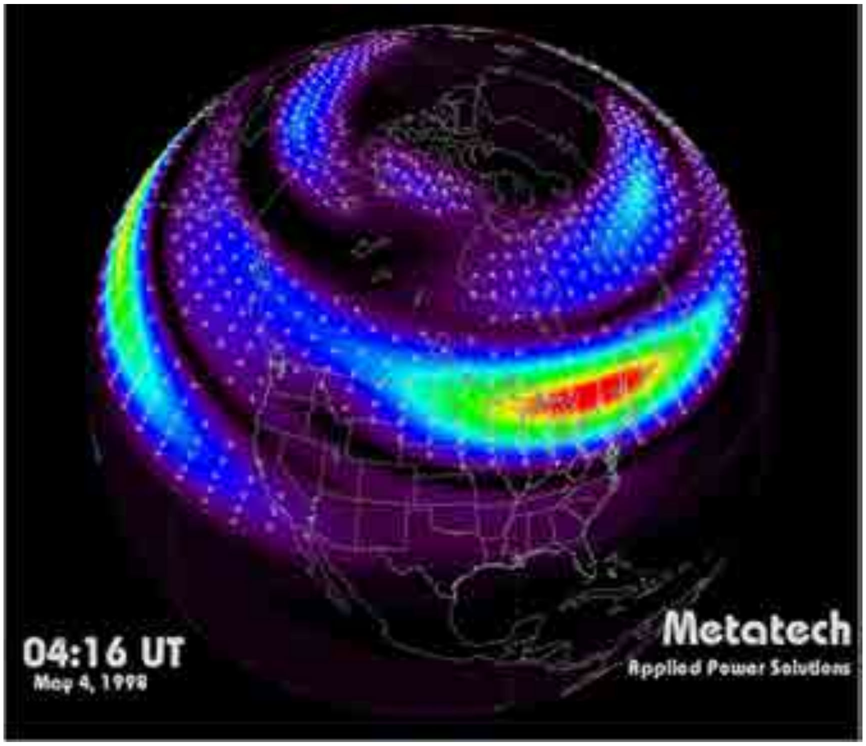


Figure 3-5 – Map of Geomagnetic Disturbance conditions at 4:16UT during May 4, 1998 storm. (Source – Meta-R-319)

The results in Figure 3-4 provide a comparison between high sample rate measured GIC (~10 second cadence) versus storm simulations that were limited to 1 minute cadence geomagnetic observatory data inputs. Due to this limitation of inputs to the model, the model would not be able to reproduce all of the small-scale high frequency variations shown in the measured data. However, the simulation does provide very good accuracy and agreement on major spikes in GIC observed, the most important portion of the simulation results that need to be validated. Figure 3-6 provides a wider view of the impact of the storm in terms of other GIC flow conditions in the Maine and New England region electric power grid, this is provided at time 4:16UT.

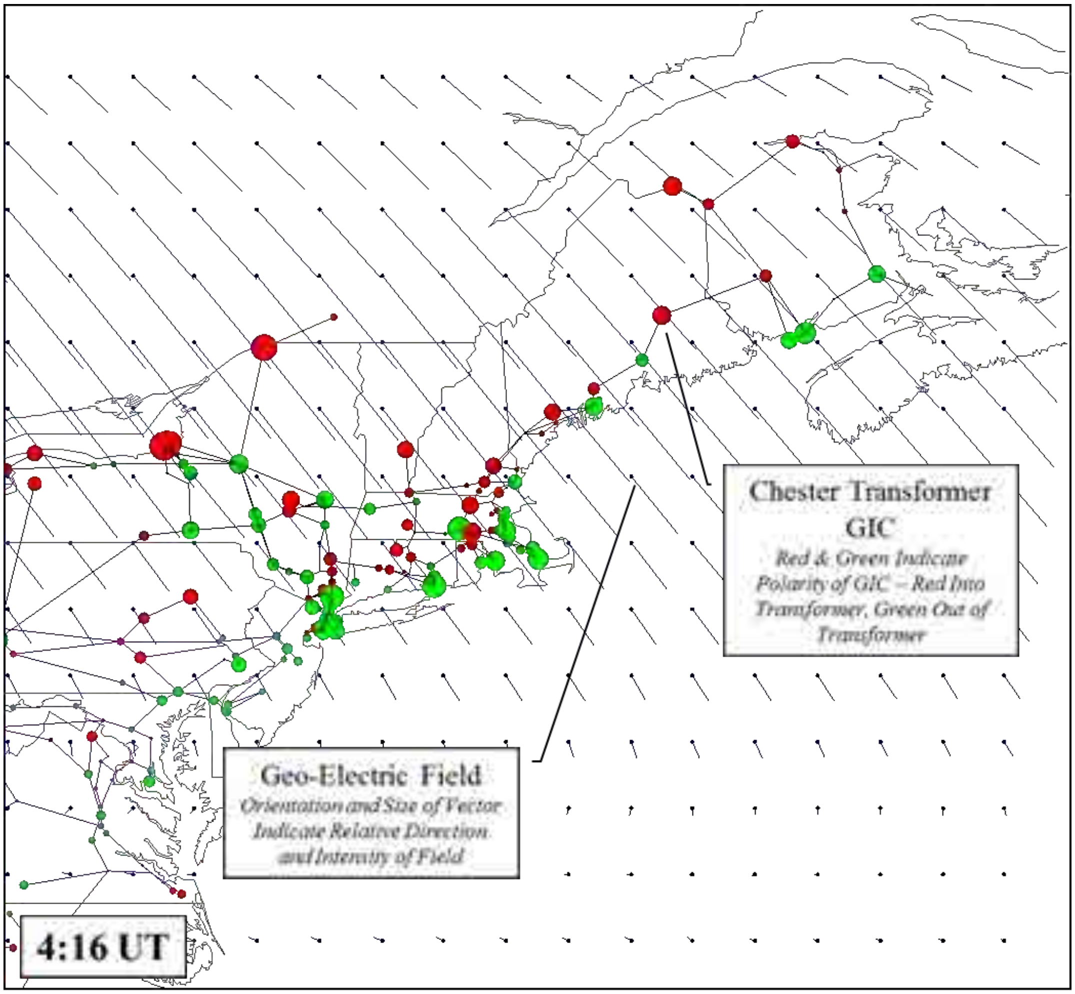


Figure 3-6 – GIC flows and disturbance conditions in Maine/New England grid at 4:16UT , May 4, 1998. (Source – Meta-R-319)

As this illustration shows, the Chester GIC flow is shown along with comparable GIC flows in a number of other locations in the regional power grid. In addition to impacts to the New England grid, extensive power system impacts were also observed to voltage regulation in upstate New York region due to storm. In this map, the intensity and polarity of GIC flows are depicted by red or green, the larger the ball the larger the GIC flow and danger it presents to the transformer and grid. Also shown are the blue vector arrows, which show the orientation and intensity of the geo-electric field that couples to the topology of the electric grid and produces the GIC flow patterns that develop in the grid.

Considerable scientific and engineering examination has been performed since the release of the Meta-R-319 report. The report and subsequent other examinations are in close agreement on a number of important parameters of severe geomagnetic storm threat conditions. For example, it is now well accepted that severe storm intensity disturbance intensity can reach levels of 5000 nT/min at latitudes of the Maine power grid. Further, the regional geological conditions of Maine and the adjacent Laurentian shield geology in New England and Canada can produce geo-electric field intensities from these severe storms reaching levels of 20 to 50 Volts/km (V/km). Observations in similar geological formations in the Baltic region during the May 1921 storm also observed geo-electric field strengths of 20 V/km, providing important observational confirmations.

Observations of GIC at the Chester Maine substation also provide important observational confirmations of severe storm levels for GIC that would be plausible for more severe storm scenarios. For example, as will be shown in section 4 of this report, a 20 V/km geo-electric field has the potential to produce as much as a ~1300 Amp neutral GIC flow at the Chester Maine transformer. Earlier this year, the Maine electric utilities provided a limited summary of peak GIC observations from their Chester transformer and the associated storm dates. Figure 3-7 provides a graphical summary of the peak GIC and peak disturbance intensities (in nT/min) observed at the Ottawa Canada geomagnetic observatory for a number of reported events. The Maine utilities did not provide accurate time stamps (just date only), so that limits some of the ability to accurately correlate disturbance intensity to GIC peaks. Also since the Ottawa observatory is approximately 560km west of Chester, there is some uncertainty to local storm intensity specifics near Chester. As shown, however, there are clear trend lines indicating the level of GIC and how it increases with storm intensity.

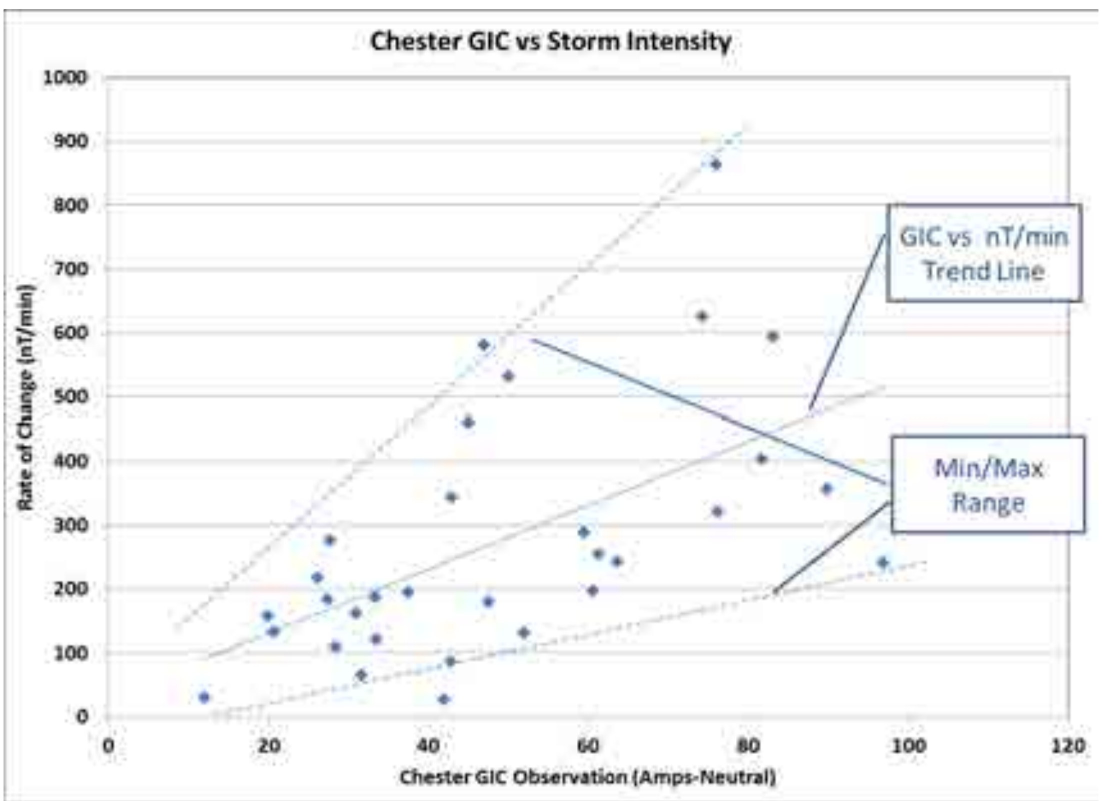


Figure 3-7 – GIC versus Storm Intensity (nT/min) from multiple observed GIC storm events at Chester Transformer.

For higher storm intensity levels, the geo-electric field and subsequent GIC flows would increase linearly (assuming similar spectral content). Because storm intensity for very severe storms can reach ~5000 nT/min, this graph can be linearly extended to project the range of GIC flows in the Chester transformer for these more extreme threat conditions. Figure 3-8 provides a plot similar to that in Figure 3-7, only with linear extensions of the GIC flow that this observational data estimates.

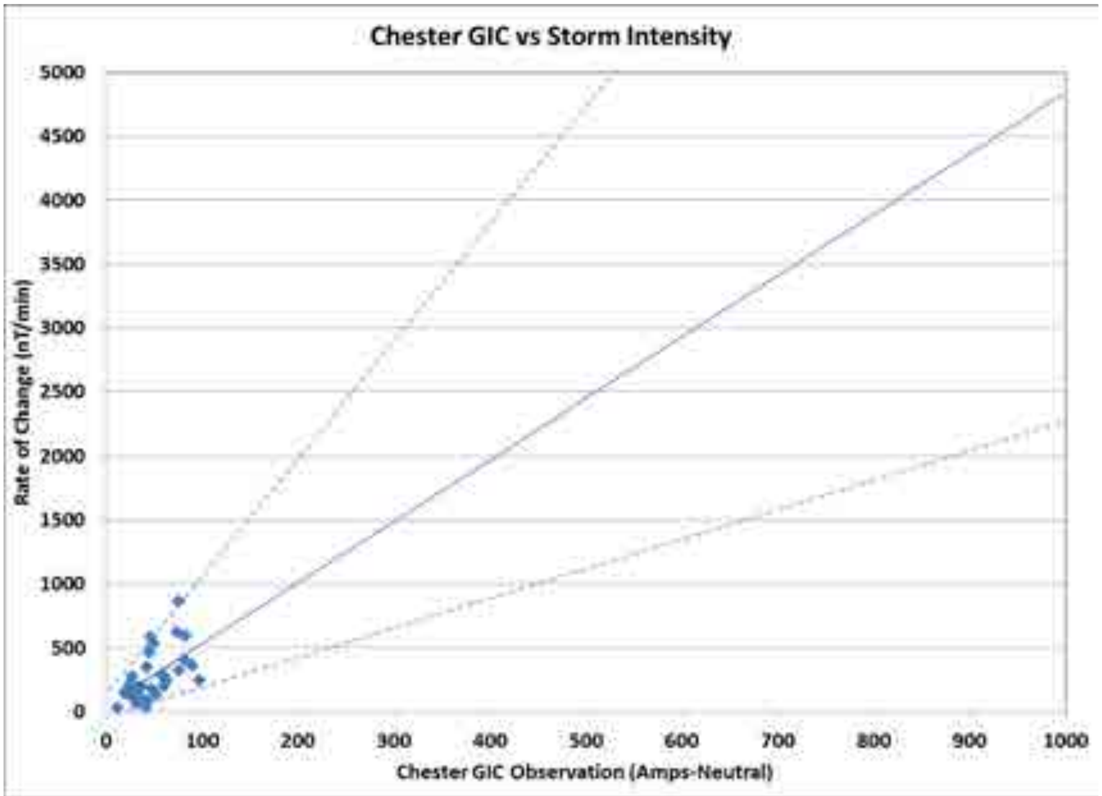


Figure 3-8 – Project4ed range of Chester GIC flow for storm intensity increasing to ~5000 nT/min.

As previously discussed, a 20 V/km geo-electric field from the simulation model of the Maine network will result in a GIC flow of ~1300 amps. The projected GIC range shown above (though somewhat wide in bounds) does project GIC flows at Chester that are in agreement with the model results. Having both model results and observational data projections that produce similar outcomes provides for additional checks and validation confirmations. Having this degree of confirmation of model results provides higher confidence in the analysis of more severe storm conditions and their potential impacts to the Maine grid, which are examined more fully in Section 4.

4. Analysis of Maine MPRP Grid Vulnerability to Severe Geomagnetic Storms/EMP

Comparison of GIC Flow Patterns for Pre and Post-MPRP Maine Grids

The intensity of the geo-electric field is important in determining GIC flows (i.e. the larger the geo-electric field, the larger the peak GIC). Prior discussion noted that geo-electric field intensity within the

State of Maine could range from 20 to 50 V/km for severe geomagnetic storms. Unclassified data[6] indicates that the geo-electric fields produced by EMP E3 could be 40 V/km, so the peak field values of the two threats are nearly the same.

While this intensity range has been described previously, the orientation of the geo-electric field must also be taken into account in determining the pattern or polarities and magnitudes of GIC at each specific transformer in the network. Therefore in order to fully examine their variation possibilities, the analysis below examines both the intensity and orientation of the geo-electric field on the Maine 345 kV transmission grid.

To examine these variations, a series of simulations are performed for peak geo-electric field intensities while varying the geo-electric field direction in 10 degree increments in a full circle of 360 degrees. The analysis was also conducted for the Pre-MPRP Maine grid additions and the Post-MPRP Grid designs, which allows for comparative evaluations to be made of the impact of those additions on the vulnerability of the Maine electric grid to GIC.

To examine these differences graphically, Figure 4-1 provides a map of the pattern of GIC flows in the Pre-MPRP grid for a northward oriented geo-electric field (0^{o} angle). Several of the stations with large GIC flows are also noted on this map. The GIC are typical for a large geo-electric field of 20 V/km.

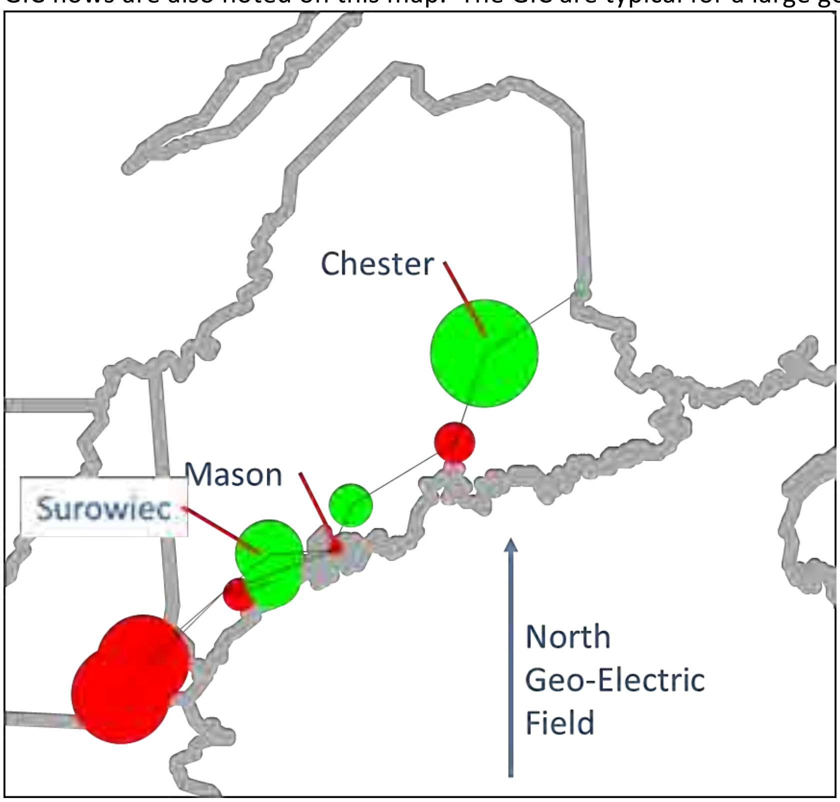


Figure 4-1 – Pattern GIC flows for northward geo-electric field of 20 V/km on Pre-MPRP Maine Grid.

At the Chester and Surowiec transformers, the green color indicates that the GIC flows are from the transformer to ground (A GIC "sink"), as GIC is entering the Maine system from sources further south in

[6] See International Electrotechnical Commission Standard 61000-2-9 (can be ordered at: http://www.iec.ch/emc/basic_emc/basic_emc_environment.htm)

the New England grid and exiting to ground at these locations. Besides points south, to a small extent Mason is a GIC "source" as well – the red indicates GIC flowing up from the ground into the system. The size of the balls also indicates that the largest GIC flow is occurring at the Chester transformer.

Figure 4-2 provides the same geo-electric field conditions applied to the Post-MPRP Maine grid. In comparing the two maps, there is little change at the Chester and Surowiec locations. At Mason, the GIC flow increases slightly and, of course, new large GIC flows now occur in the new MPRP 345 kV transformer additions north of the Mason and Surowiec stations.

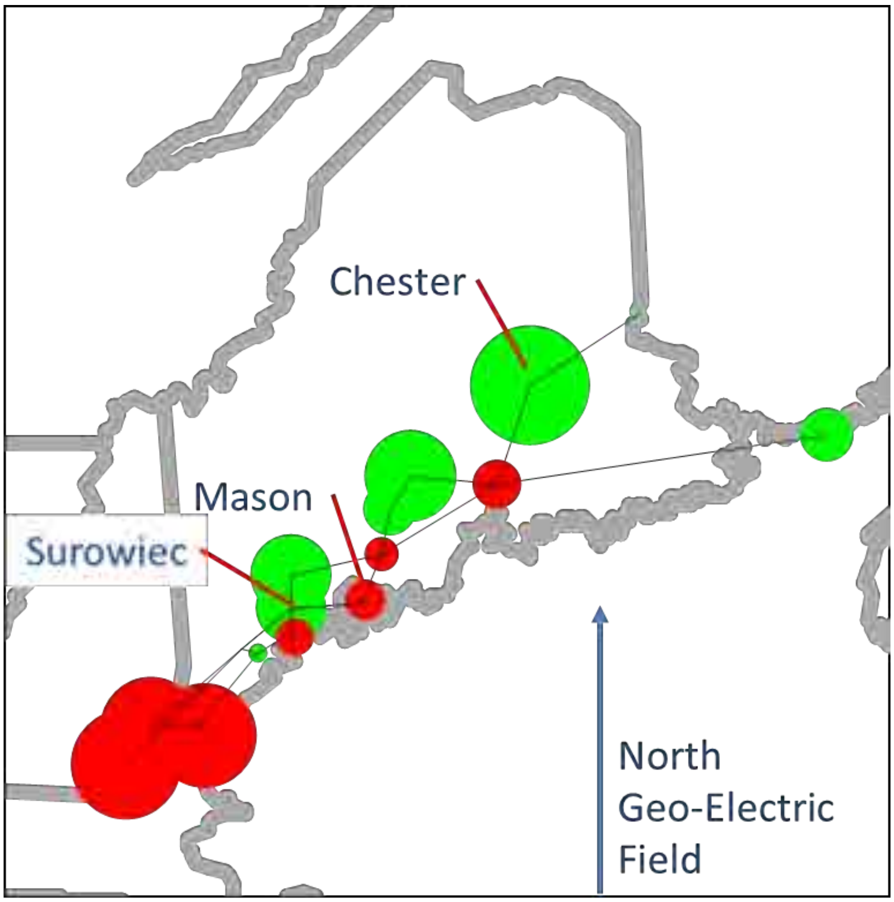


Figure 4-2 - Pattern GIC flows for northward geo-electric field of 20 V/km on Post-MPRP Maine Grid.

Figure 4-3 provides a severe storm condition of 20 V/km for a geo-electric field orientation that is directed eastward (90^{o} angle) for the Pre-MPRP Maine grid configuration. In comparison to Figure 4-1, the change in geo-electric field orientation does alter the pattern of GIC flows. In this case, the GIC flow at Mason is now larger than at Chester and Surowiec and the polarity is now the opposite direction at Surowiec. It is also evident that the GIC flow also reverses polarity and increases substantially at Orrington (the first node west of Chester). This comparison provides an important perspective on the complex pattern of GIC flows that can occur system wide during a typical geomagnetic storm as orientation during a storm is quite variable and that it can cause GIC flow distributions throughout the network and can create impacts at multiple locations when the flows shift. This comparison explains, in part, how prior storms have caused both SVC trips at Chester as well as capacitor bank trips and other upsets at Orrington and Surrowiec.

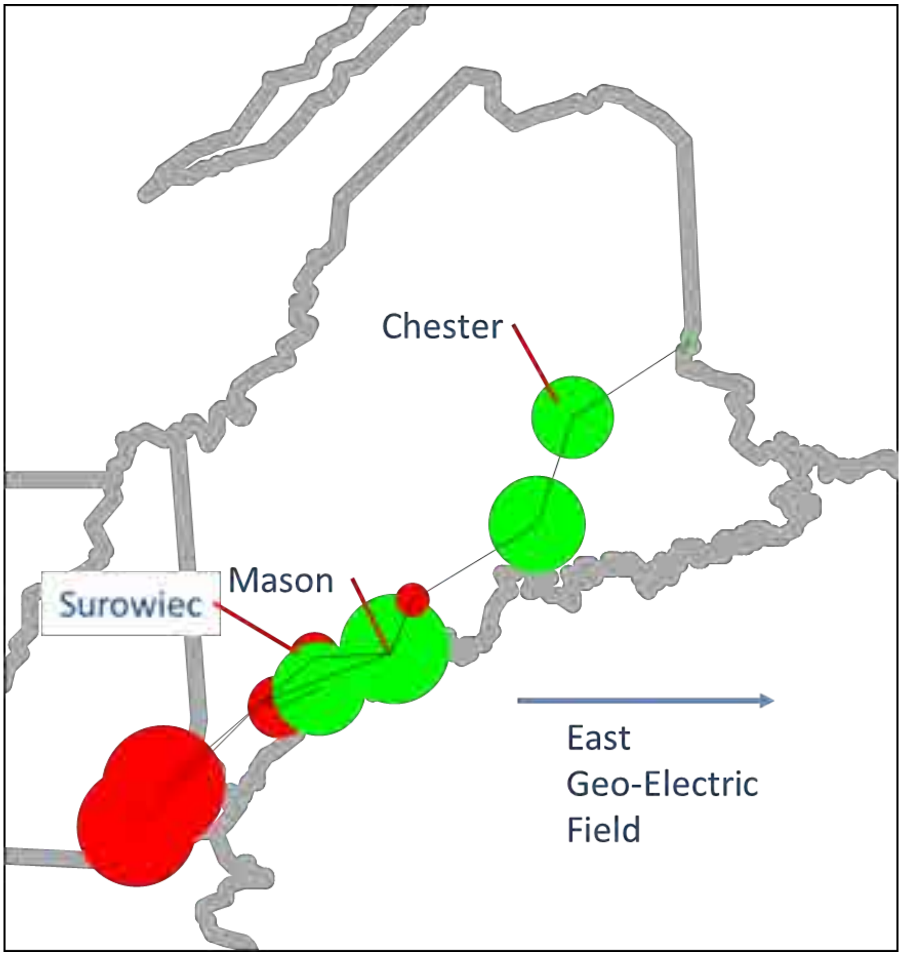


Figure 4-3 - Pattern GIC flows for eastward geo-electric field of 20 V/km on Pre-MPRP Maine Grid.

Figure 4-4 provides the map of the same eastward geo-electric field conditions for the Post-MPRP Maine grid. In comparing the pattern of flows in Figures 4-3 and 4-4, the GIC levels are not significantly changed at Chester and Mason, but it is evident that GIC participation and flows are quite large in most of the new MPRP additions north of the Mason and Surowiec locations. Hence these added GIC flows add a cumulative overall burden to the Maine network as a whole. In order to examine the change in GIC flows as a function of geo-electric field angle, Figure 4-5 provides a plot of the GIC flows at the Chester transformer both for the present grid and for the MPRP grid design for a 20 V/km geo-electric field intensity. The GIC flows shown are the GIC per phase in the transformer in Amps and reach peaks of ~450 amps at a 20^{o} orientation. As the orientation changes, the GIC flows alter and reverse polarity in the form of a sine wave. The GIC flows at Chester are not significantly altered due to the MPRP additions. Figure 4-6 provides a plot of GIC flows at Chester for a geo-electric field of 40 V/km. The only change that occurs is that the magnitude of the GIC flows double at Chester as the geo-electric field strength doubles, reaching peaks of ~900 Amps per phase for these conditions.

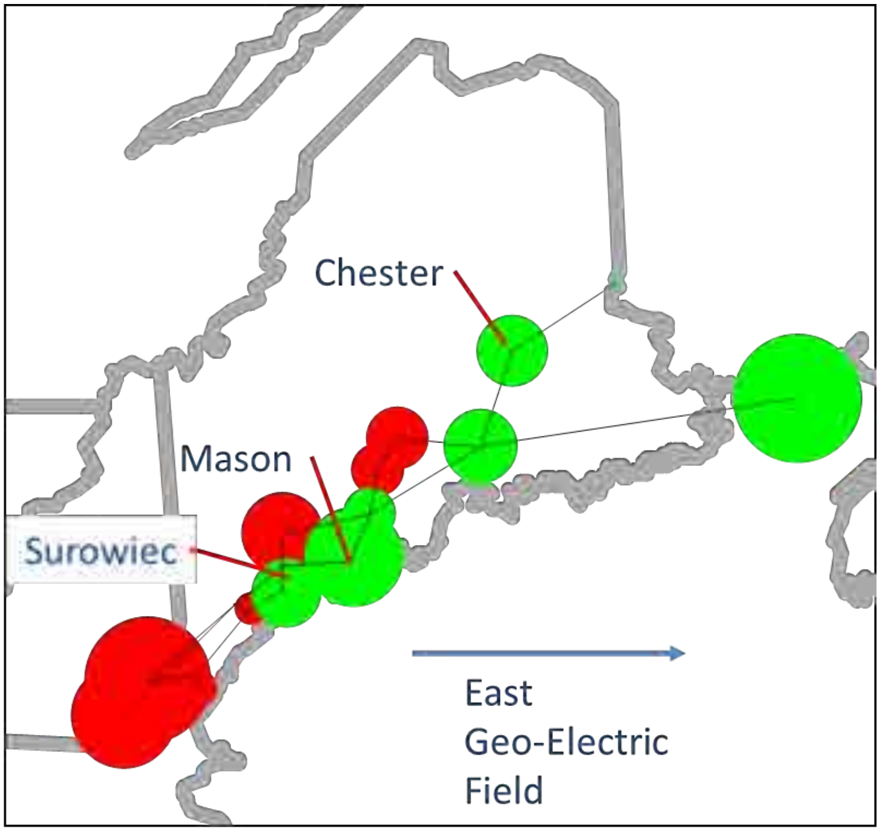


Figure 4-4 - Pattern GIC flows for eastward geo-electric field of 20 V/km on Post-MPRP Maine Grid.

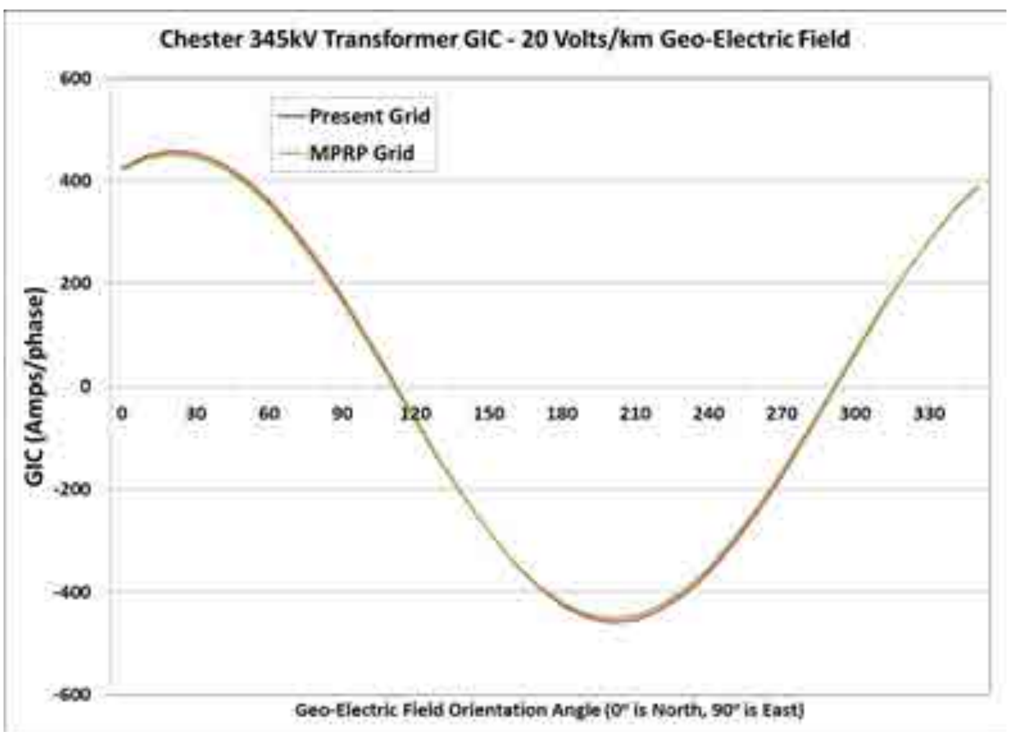


Figure 4-5 – GIC Flows at Chester for Pre and Post –MPRP grid at 20 V/km.

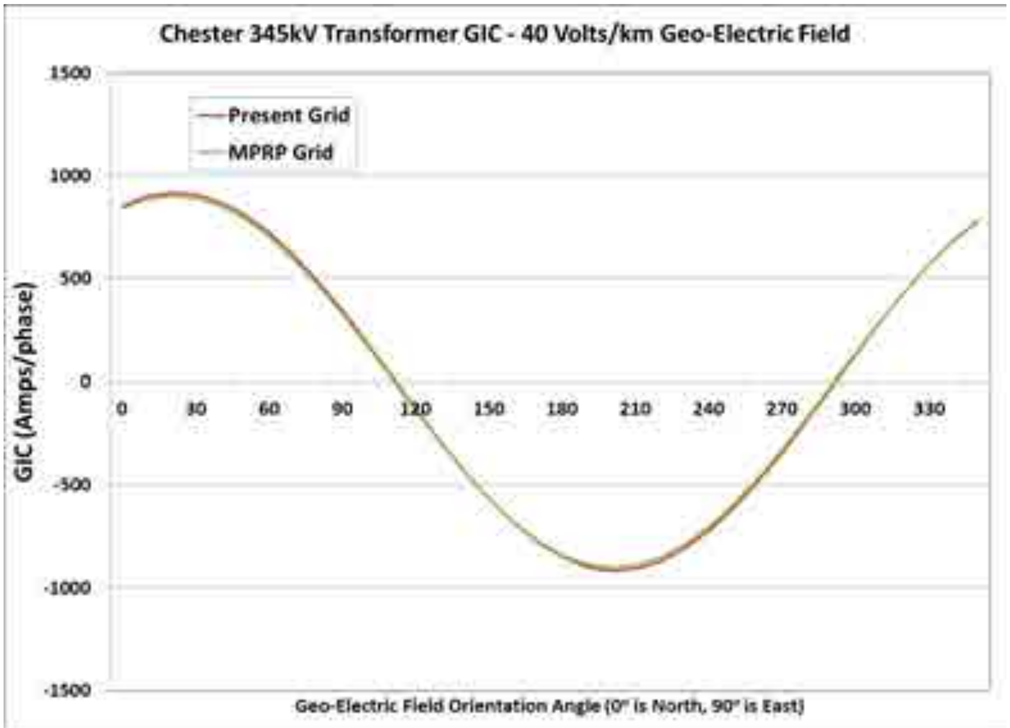


Figure 4-6 - GIC Flows at Chester for Pre and Post –MPRP grid at 40 V/km.

Figure 4-7 provides a plot of the GIC flows at the Mason transformer for a 20 V/km geo-electric field. Comparison of the Mason flows with those of Chester in Figure 4-5 indicates several important differences. First the peak GIC flows at Mason only reach ~300 Amps/phase, somewhat lower than at Chester. Further the angular orientations where the peaks occur at Mason are shifted approximately 70^{o} such that the Peak GIC flows occur at 90^{o} compared to those at Chester. Also it can be observed that the addition of the MPRP facilities also produces a slight further angular shift in GIC flows at Mason, though the peak levels remain identical.

Figure 4-8 provides a similar plot of the GIC flows at the Surowiec transformer. The characteristics of the GIC flows here also exhibit important angular orientation shifts when compared with Chester and Mason. But the peak GIC levels also show changes due to the MPRP additions. In this case the peak GIC flow Pre-MPRP reaches ~180 Amps/phase. With the addition of the MPRP, the peak GIC reduces slightly to 150 Amps, as new MPRP facilities located just to the North of this location now share some of the resulting GIC flows.

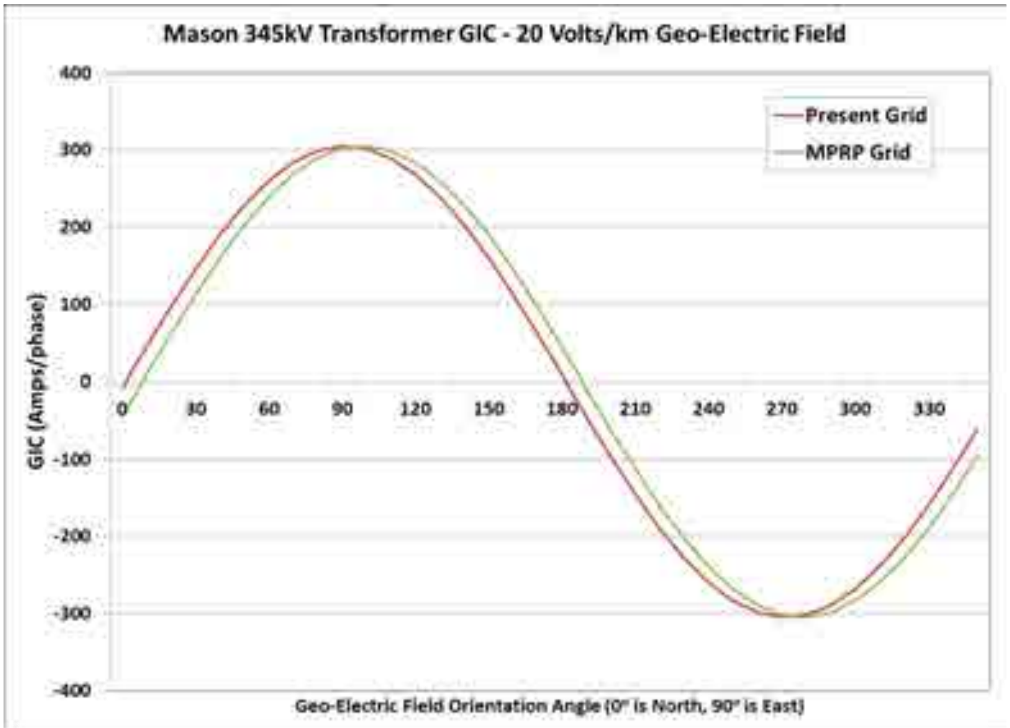


Figure 4-7 – GIC Flows at Mason for Pre and Post –MPRP grid at 20 V/km.

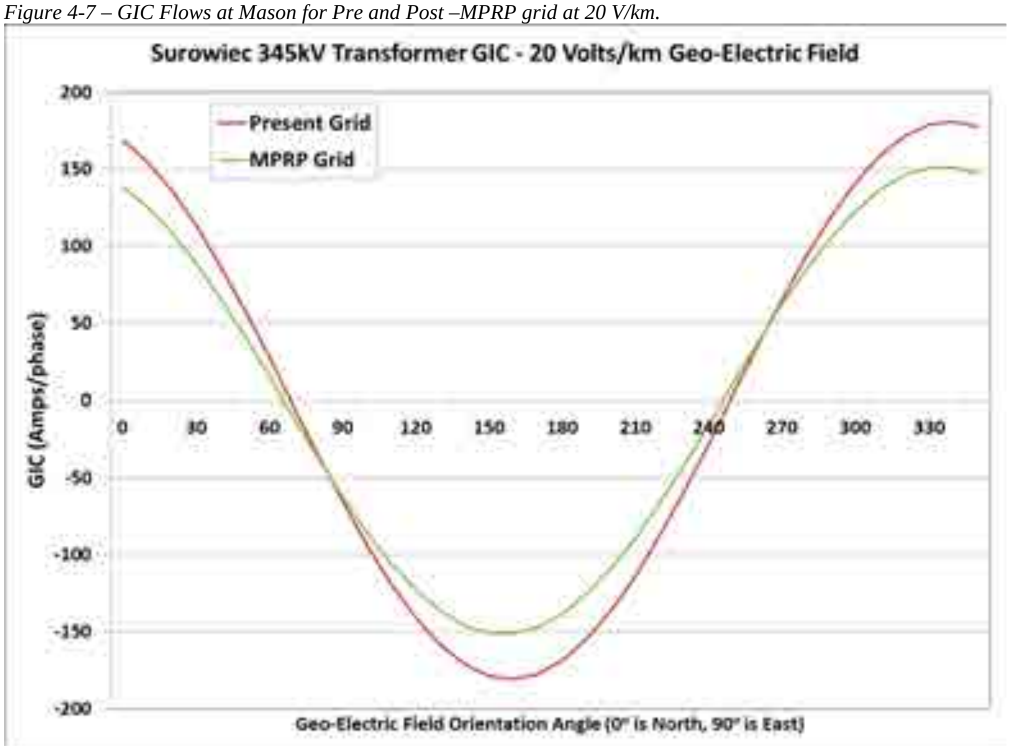


Figure 4-8 - GIC Flows at Surowiec for Pre and Post –MPRP grid at 20 V/km.

Comparison of Maine Total GIC Flows - Pre and Post MPRP

In order to simplify the analysis of how the Maine grid reacts to severe GMD or EMP environments it is necessary to develop a comprehensive screening approach that can also examine the differences in the Maine grid both Pre- and Post-MPRP. The Maine grid model presents a complex network topology, therefore no one geo-electric field orientation provides an adequate test for the coupling effects of the geo-electric field for different grid designs that were examined in prior sections of this analysis effort.

As previously discussed, in order to examine the impact of geo-electric field variations, the uniform geo-electric field was rotated a full 360°. In addition to mapping GIC flow patterns and looking at GIC flows in individual transformers, this analysis approach can be utilized to also examine total impacts on the Maine grid by performing summations of GIC flows.

Figure 4-8 provides a plot of Total GIC flow (as measured by the sum of the absolute value of GIC-Effective per phase) in all transformers across the Maine grid as a function of the orientation of the geo-electric field. In this figure the GIC sum is provided for a geo-electric field intensity of 20 V/km for both the Pre and Post-MPRP grid designs. At each angle orientation the total GIC varies for both grid designs. At a few of the orientations, the GIC flow totals are somewhat larger for the Pre-MPRP design, but at most other angles, the Post-MPRP design has larger GIC flows and at some orientations, significantly larger GIC flows will result. This summary augments and provides further details on the earlier maps of GIC flow patterns for the two grid designs. The GIC flow totals also provide a useful metric of total stress (such as voltage regulation, harmonic distortion, mis-operation and trips of key assets, etc.) to the Maine grid.

Figure 4-9 provides a similar summary of Total GIC flows in the Maine grid, only for the higher 40 V/km geo-electric field threat. As expected GIC levels in total also double due to this higher threat. These indicators clearly show that for most orientations, the stress upon the Maine grid is much larger Post-MPRP. Since the specific designs of each of the Maine transformers are unknown, (except that we know the Chester transformer is single phase units), it is difficult to assess total reactive power increases for the Maine grid. However in the case of the Chester transformer alone, the GIC levels estimated can cause increased reactive demands ranging over 500 MVARs, which exceeds the rating of the SVC at this location. At a 40 V/km level, the MVARs at Chester will be even greater. This is also true for all other Maine transformers, even though the data is not currently available from the asset owners to provide better assessments in this report. It is due to this process that grid wide voltage collapse scenarios also develop due to these cumulative impacts at multiple transformers across the grid.

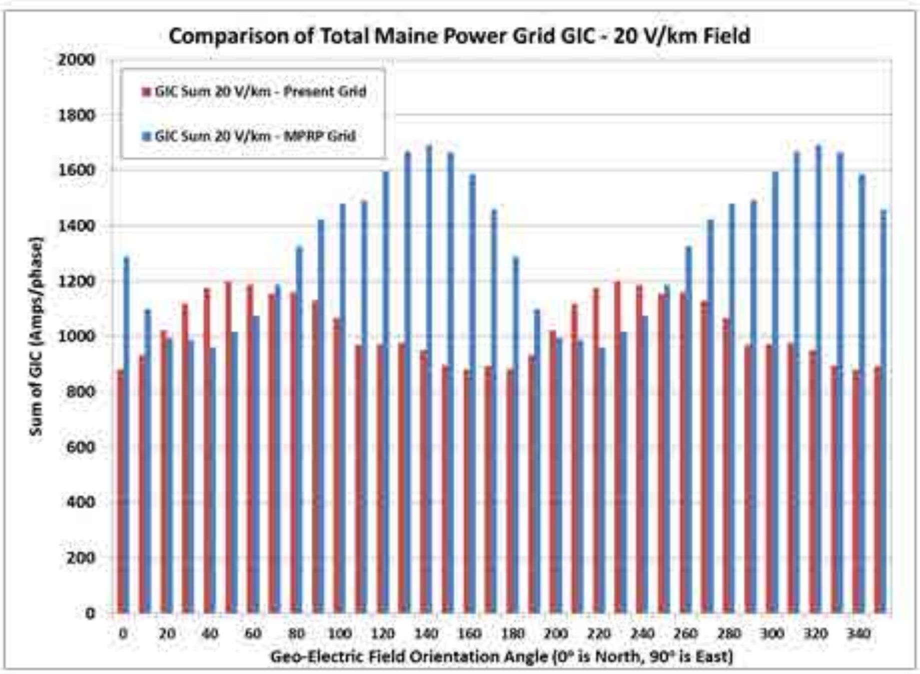


Figure 4-8 – Sum of GIC Flows in Maine Grid for both Pre and Post-MPRP at 20 V/km.

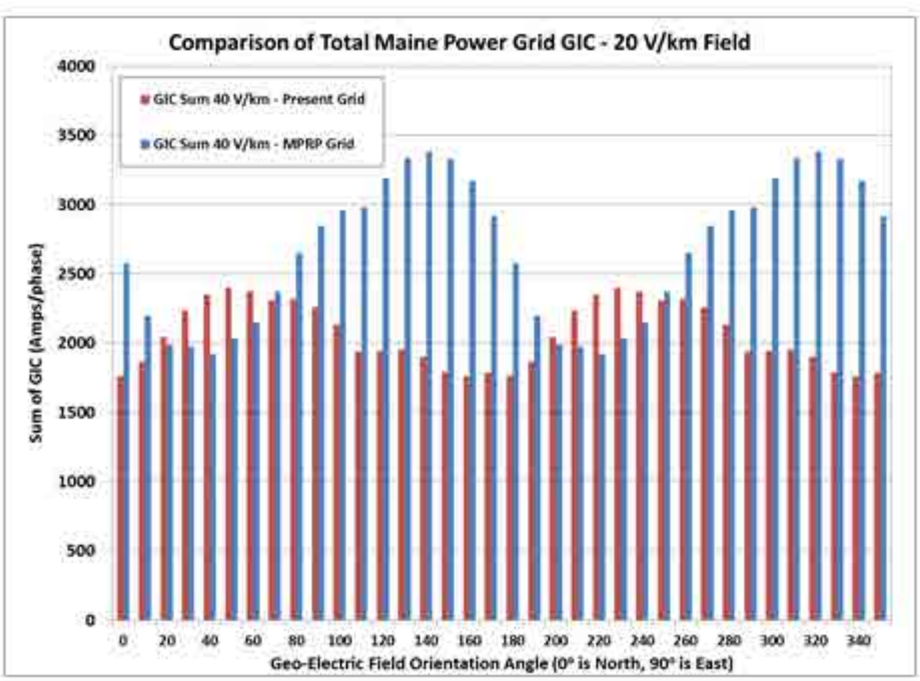


Figure 4-9 - Sum of GIC Flows in Maine Grid for both Pre and Post-MPRP at 40 V/km.

To better illustrate the impacts that the MPRP additions will have upon the Maine grid, Figure 4-10 provides a summary showing the Percentage Increase in Total GIC flow between the Pre-MPRP grid and the Post-MPRP grid. As the prior figures suggest, at some orientation angles the total GIC increases at peak slightly less than 20%. However over most of the orientation angles, the Total GIC increases reaching a peak of over an 80% increase in Total GIC at some angles. In comparison at the 0^{o} and 90^{o} angles which were previously mapped in this section, the GIC increases were ~50% and ~30% respectively.

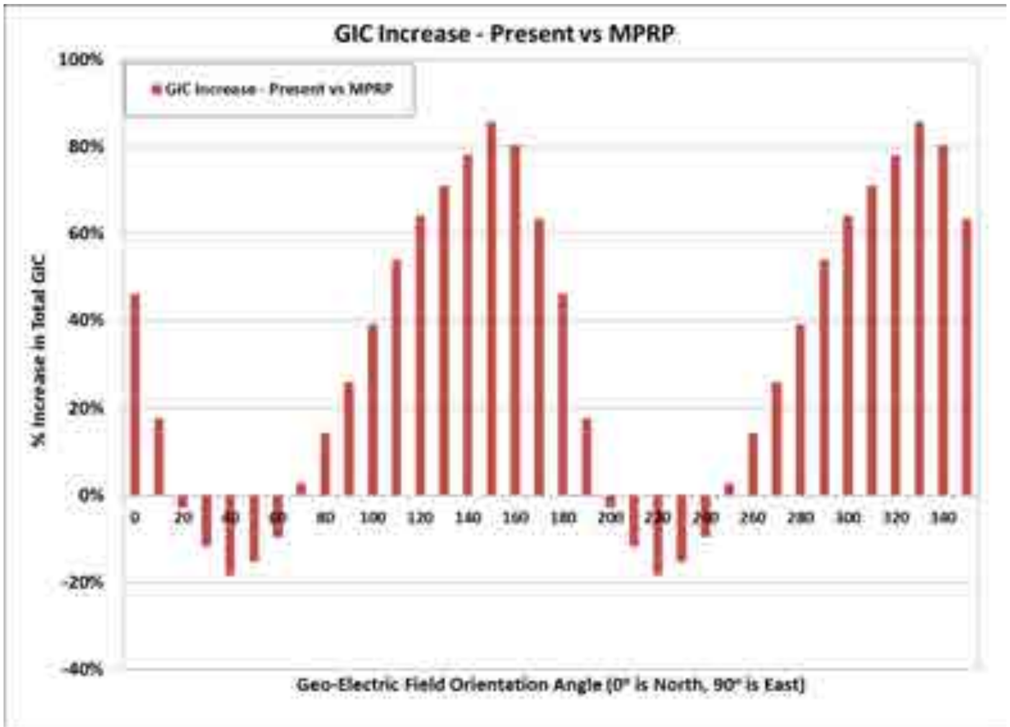


Figure 4-10 – Percentage Increase in Total GIC Flows between the Pre-MPRP and Post-MPRP Maine grid designs.

Comparison of Maine 345 kV Transformers At-Risk –Pre and Post MPRP

In Section 2 of this report, a summary was provided for the entire CONUS network of EHV transformers considered At-Risk of permanent damage due to high GIC exposures (exceeding 90 Amps/phase). For this CONUS wide summary, a total of 4 transformers in the Pre-MPRP Maine grid were considered At-Risk. This slightly more detailed evaluation of the Maine grid, considering a more complete analysis of threat levels and also comparing Pre- and Post-MPRP designs allows for re-visiting this risk assessment.

For purposes of this analysis, the 90 Amp/phase GIC At-Risk threshold for transformers will again be utilized. As has been shown for the Chester, Mason and Surowiec transformers, each of these had peak GIC flows in excess of 90 Amps/phase, depending also on the field orientation. The same is also true for many other transformers in the Maine grid. This requires an analysis of each transformer and a determination of total At-Risk Transformers for each orientation angle and at each geo-electric field intensity level for each transformer in the Maine grid.

Figure 4-11 provides a summary chart of the number of Maine 345 kV transformers that would be considered At-Risk of Permanent Damage due to high GIC exposures under a 20 V/km geo-electric field. Since the GIC flows in a transformer reverse polarity in a mirror image over a 360 degree orientation rotation, therefore it is only necessary to provide a 0^{o} to 170^{o} summary, knowing that it would also repeat for angles between 180^{o} to 360^{o}. Also this summary shows separately the number of At-Risk transformers for both the Pre- and post-MPRP additions to the Maine grid.

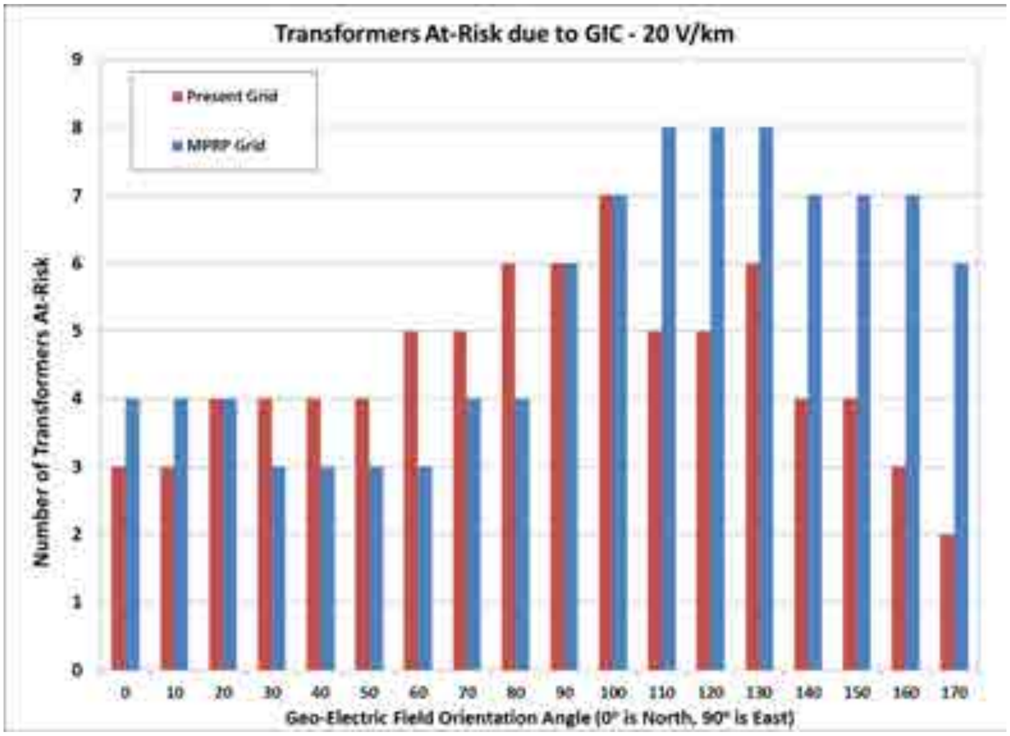


Figure 4-11 – Maine At-Risk 345kV Transformers at 20 V/km for Pre and Post-MPRP additions.

In comparison with the CONUS-wide summary of Section 2, this summary provides a more detailed evaluation of the complex risk environments. This analysis finds that more transformers are considered At-Risk than were identified in the prior CONUS study, which identified only 4 At-Risk transformers in the Pre-MPRP Maine grid. This analysis found that for the Pre-MPRP design, as many as 7 key 345 kV transformers are At-Risk. The Post-MPRP grid design generally has a higher number of transformers At-Risk for a number of geo-electric field orientations. In some cases up to 8 of the MPRP design transformers could be At-Risk. Clearly, the addition of new transformers to the Maine grid does not improve GIC resilience for the Maine network, as each of these new transformers can also have large GIC flows putting them At-Risk of failure as well. While the MPRP will surely improve reliability of the Maine grid for everyday operations, adding these transformers does not appear to increase reliability and resilience for the grid against these threats.

Figure 4-12 provides a similar summary of At-Risk transformers, except using the 40 V/km geo-electric field intensity. As expected due to the much higher GIC flows, this results in a higher number of Maine 345 kV transformers being At-Risk both for Pre- and Post-MPRP design. This increase in GIC flows pushes several other transformers in both Maine grid designs over the At-Risk threshold. Figure 4-13 and 4-14 express the At-Risk metric in terms of the percentage of 345 kV transformers in each grid design for the 20 V/km and 40 V/km threat intensity levels, respectively. As these plot summaries show, very high percentage At-Risk levels occur for both storm levels as well as for both the Pre- and Post-MPRP designs.

For some conditions, 100% of all Maine transformers would be At-Risk. It is also difficult to know without more detailed information the degree to which the extended loss of any specific transformer would impact the Maine grid or local communities within Maine. But clearly any key transformer outages in such a sparse network can be important, though that type of assessment is beyond the scope of this report.

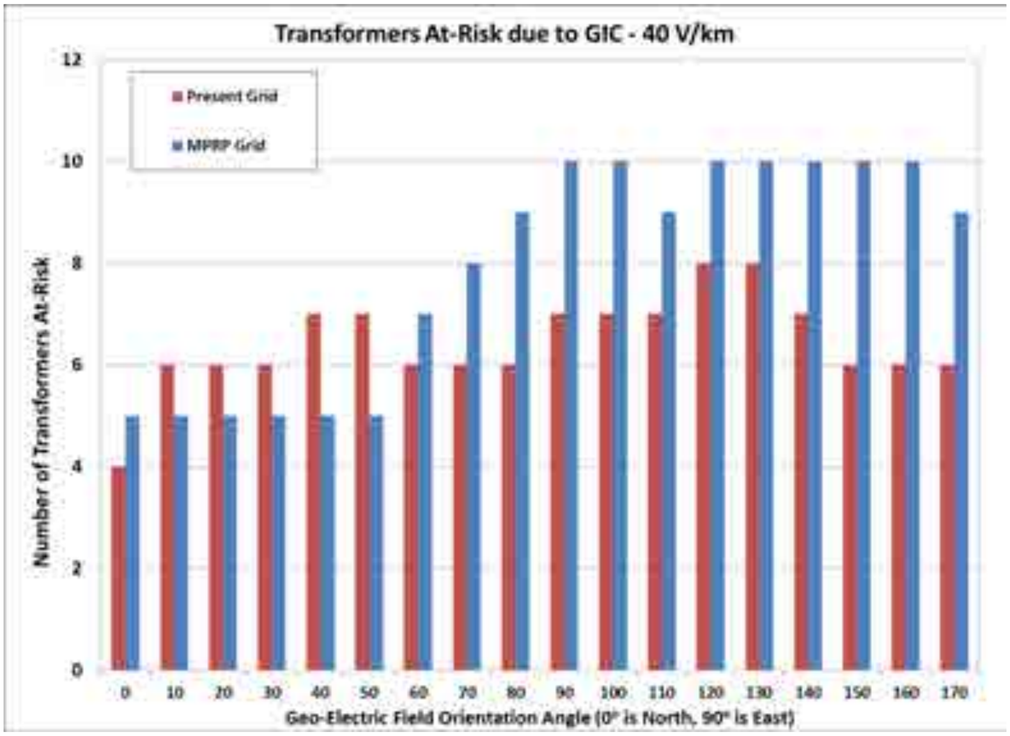


Figure 4-12 - Maine At-Risk 345kV Transformers at 40 V/km for Pre and Post-MPRP additions.

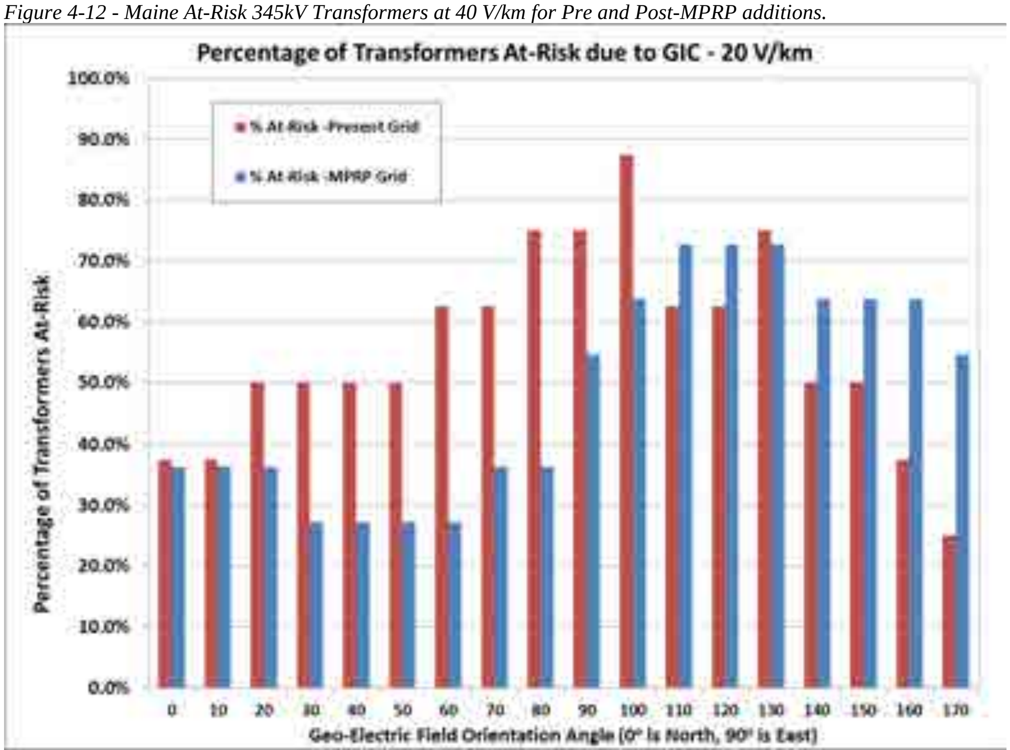


Figure 4-13 – Percentage At-Risk 345kV transformers in Maine Grid at 20 V/km.

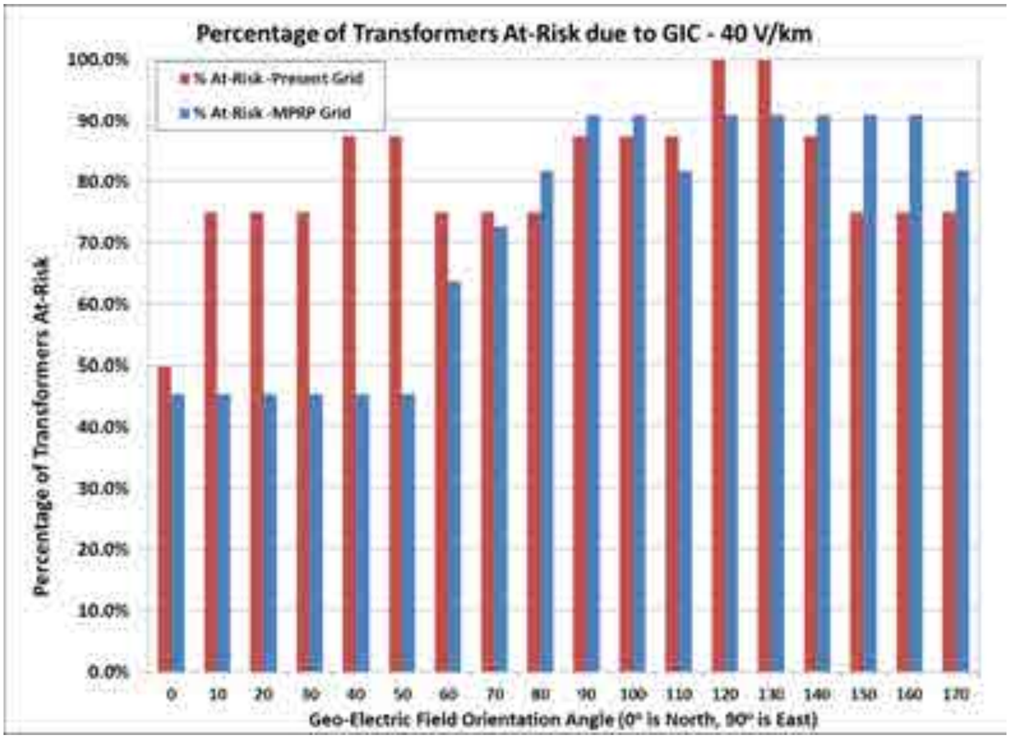


Figure 4-14 - Percentage At-Risk 345kV transformers in Maine Grid at 40 V/km.

This analysis also indicates that the new MPRP additions do not provide reliability and resilience improvements for the Maine grid for this threat, and in a number of cases, an even higher number of transformers will be At-Risk for the new MPRP grid.

5. GIC Flow Pattern and Challenges of GIC Monitoring and Situational Awareness

In Section 3 of this report, an example was provided of the observed GIC at the Chester Maine substation and the development of simulation models. This case study provides an opportunity to more fully examine the details of the storm and GIC flows elsewhere across the Maine electric grid. Figure 5-1 provides a plot (originally shown in Figure 3-4 of Section 3) with an area of the storm that is highlighted.

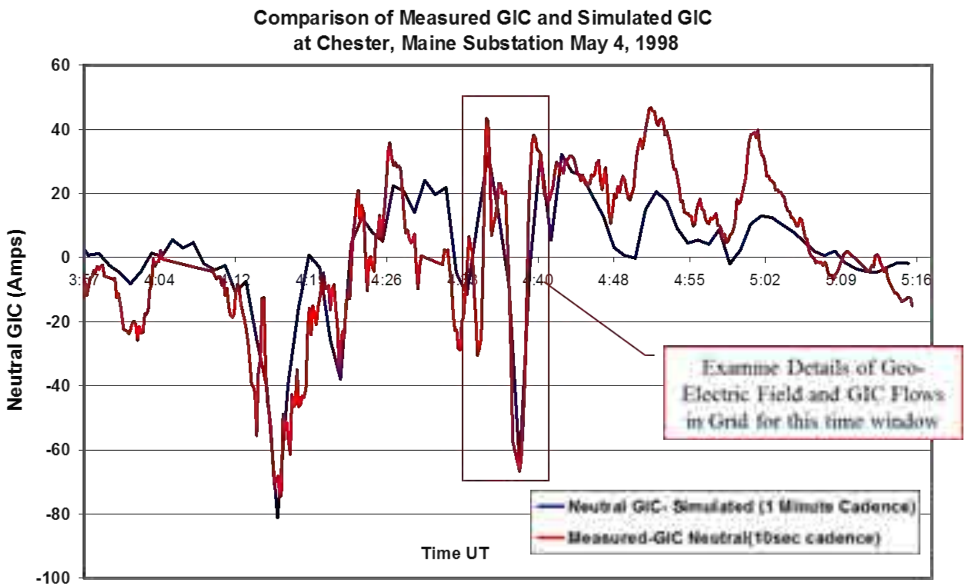


Figure 5-1 - Plot showing comparison of Simulated versus Measured GIC at Chester Maine 345kV transformer for May 4, 1998 geomagnetic storm. (Source – Meta-R-319)

In this highlighted section of the GIC measurement, there is a GIC peak and polarity reversals of GIC flow in the Chester transformer, providing a minute-by-minute snapshot of the storm conditions and pattern of GIC flows across the New England power grid. This allows a more detailed understanding of the challenges of storm monitoring and situational awareness necessary for operational procedures to be effective.

Figure 5-2 starts at time step 4:35UT and then in Figures 5-3 to 5-7 the storm is examined to time 4:40UT. As each minute is displayed over this brief interval of the storm, both the intensity and orientation of the geo-electric field exhibit large and rapid changes. Over the course of five minutes there is nearly a 360 rotation of the geo-electric field angle. This also results in changes in the size and polarity of GIC flows at many locations across the Maine and New England grid (the dots changing from Red to Green or vice versa, indicates changes in direction of GIC flows at each transformer).

In the last two minutes, times 4:39UT and 4:40UT, (Figures 5-6 and 5-7) it is noted that the GIC at Chester reaches its peak at 4:39 and then decreases to zero at 4:40UT. However when looking at the GIC’s at other locations and the intensity and orientation of the geo-electric field, it is evident that the storm conditions at both times are quit intense. This is a case where the Chester GIC monitor is providing system operators with a false sensing of a storm lull, when the opposite is the actual case. This “blind spot” can hinder effective situational awareness of storm activity for system operators.

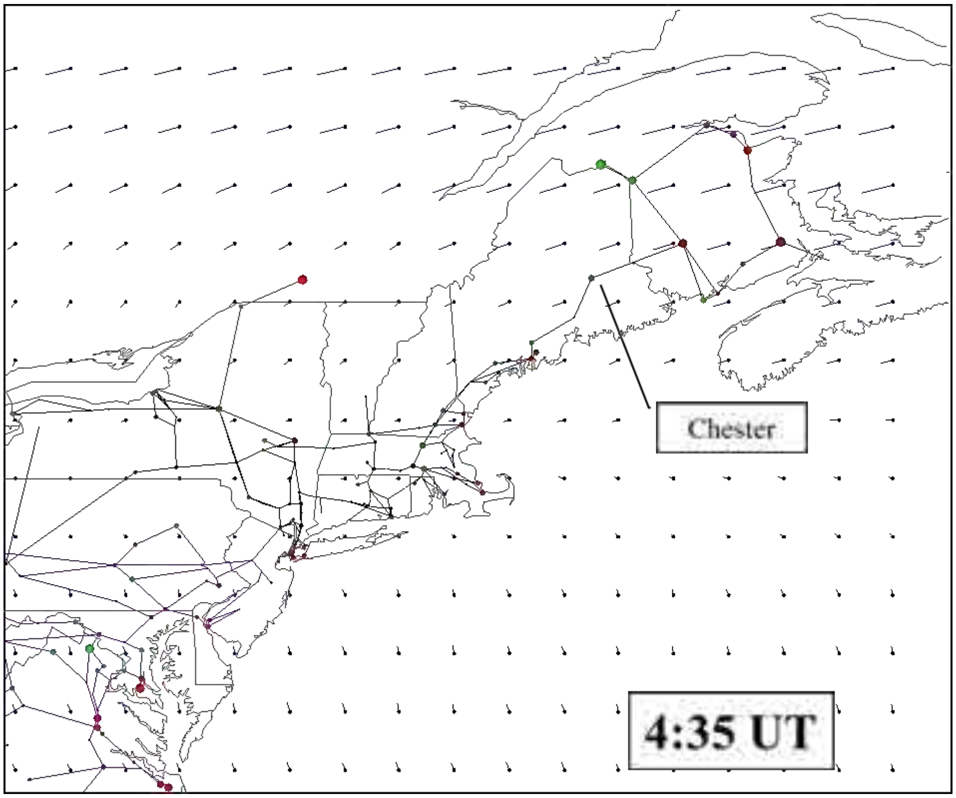


Figure 5-2 – GIC Flows in New England for May 4, 1998 Storm 4:35UT

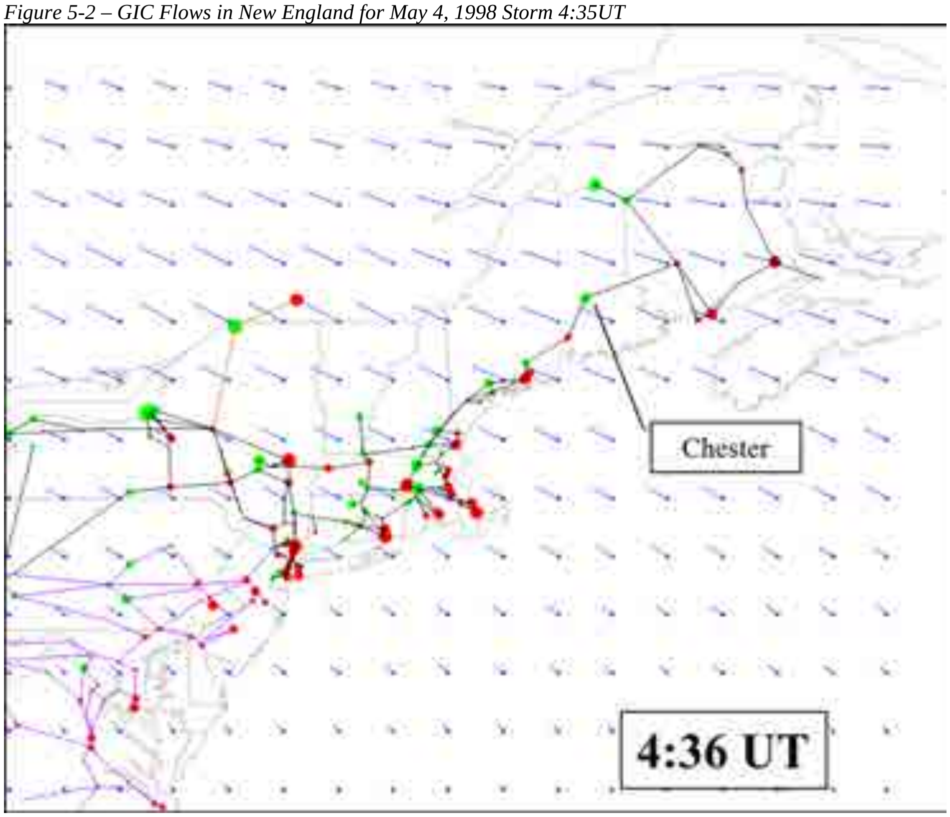


Figure 5-3 – GIC Flows in New England for May 4, 1998 Storm 4:36UT

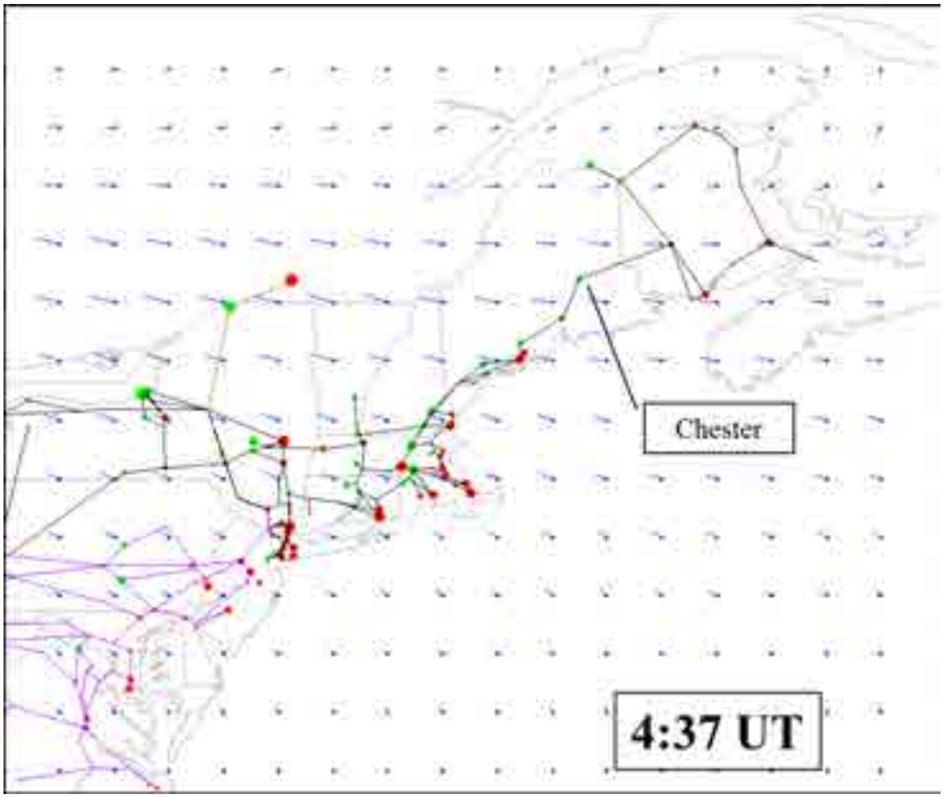


Figure 5-4 – GIC Flows in New England for May 4, 1998 Storm 4:37UT

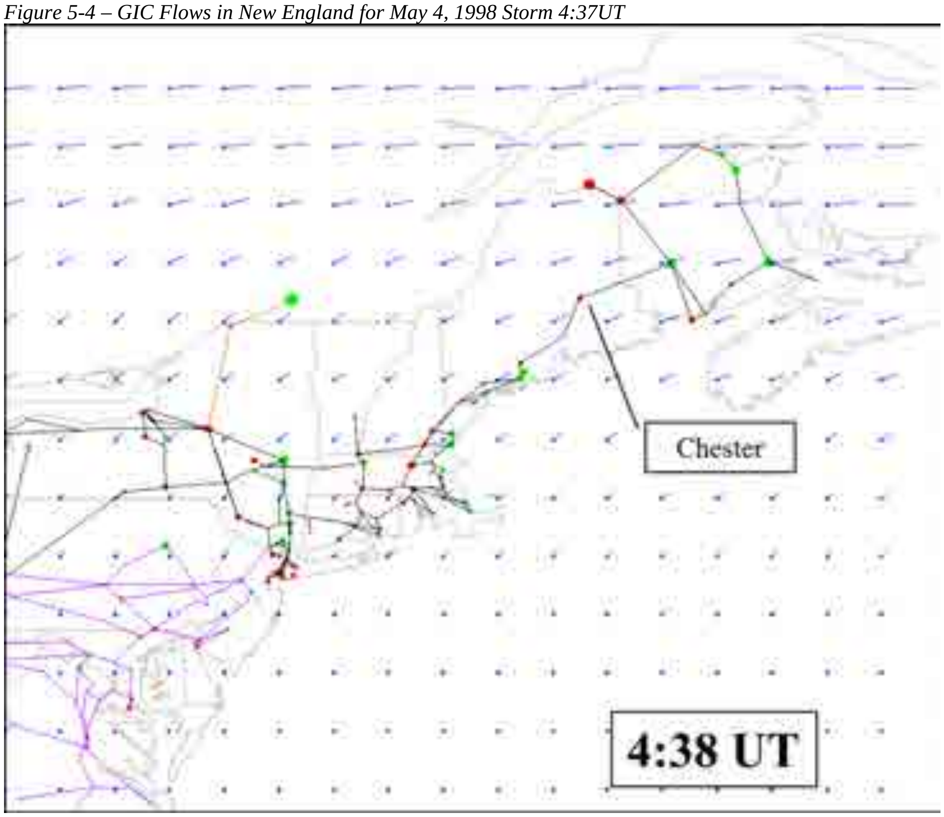


Figure 5-5 – GIC Flows in New England for May 4, 1998 Storm 4:38UT

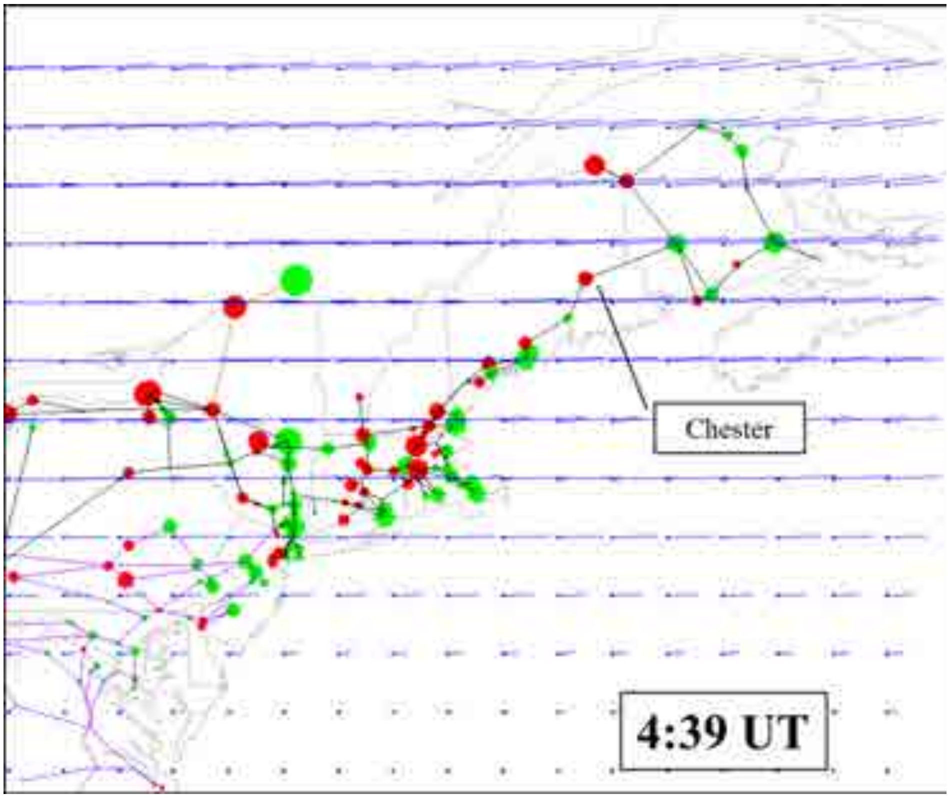


Figure 5-6 – GIC Flows in New England for May 4, 1998 Storm 4:39UT

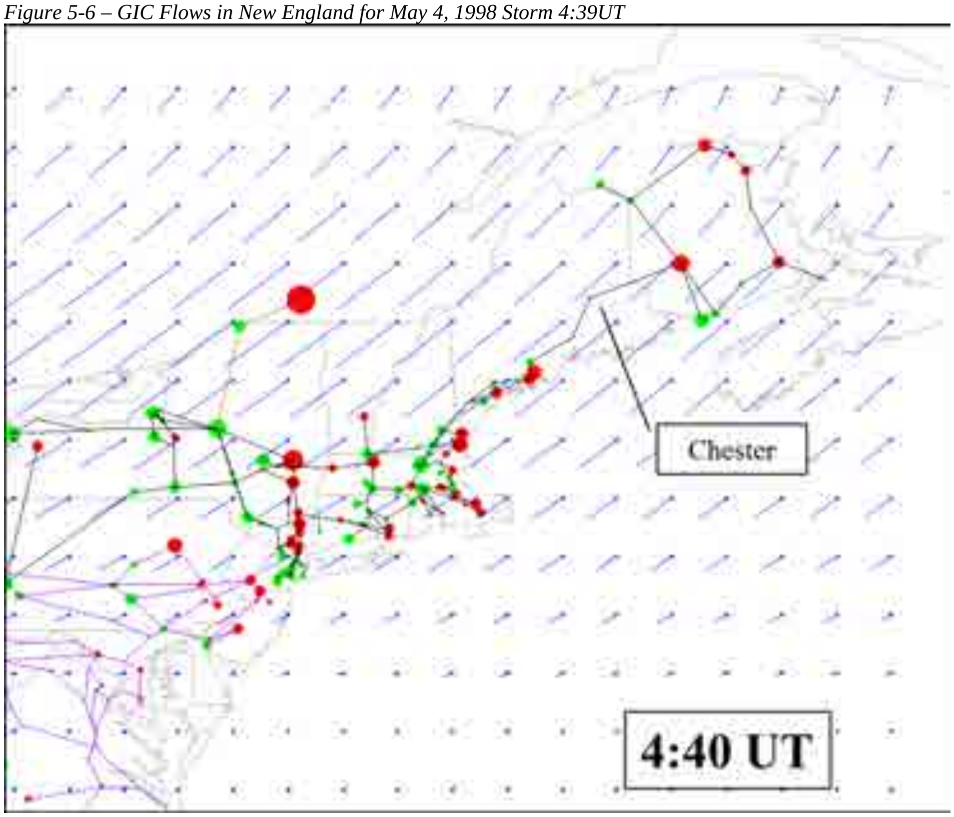


Figure 5-7 – GIC Flows in New England for May 4, 1998 Storm 4:40UT

The New England ISO and Maine utility companies noted that they always enacted operating procedures to protect the electric grid during geomagnetic storms, but that for many years had only the one GIC monitor at Chester as a primary input for real-time assessments. This storm illustrates why such a strategy can result in misleading situational awareness information. Obviously if the system operators had a more complete picture of the storm as depicted in Figures 5-2 through 5-7, they would have known more fully the details of the storm and would not be misled by a null reading at Chester at any time during the storm.

As noted in Section 4 and Figure 4-5, the Chester transformer at certain orientation angles of the geo-electric field will have zero GIC flows, even for the strongest geo-electric field conditions. This is true for any transformer in the network. This behavior does pose problems for state estimation based upon single GIC monitoring site locations, as has been the case in Maine and NE-ISO. Depending on the angle of orientation alone, the observer could be blinded even for a severe geo-electric field pulse if it happens to be at the wrong orientation from the observation point of view in the exposed network. Figure 5-8 provides an example of the Chester GIC flow at both 20 and 40 V/km intensity versus geo-electric field orientation and notes the polarity reversals that will produce observation blind spots.

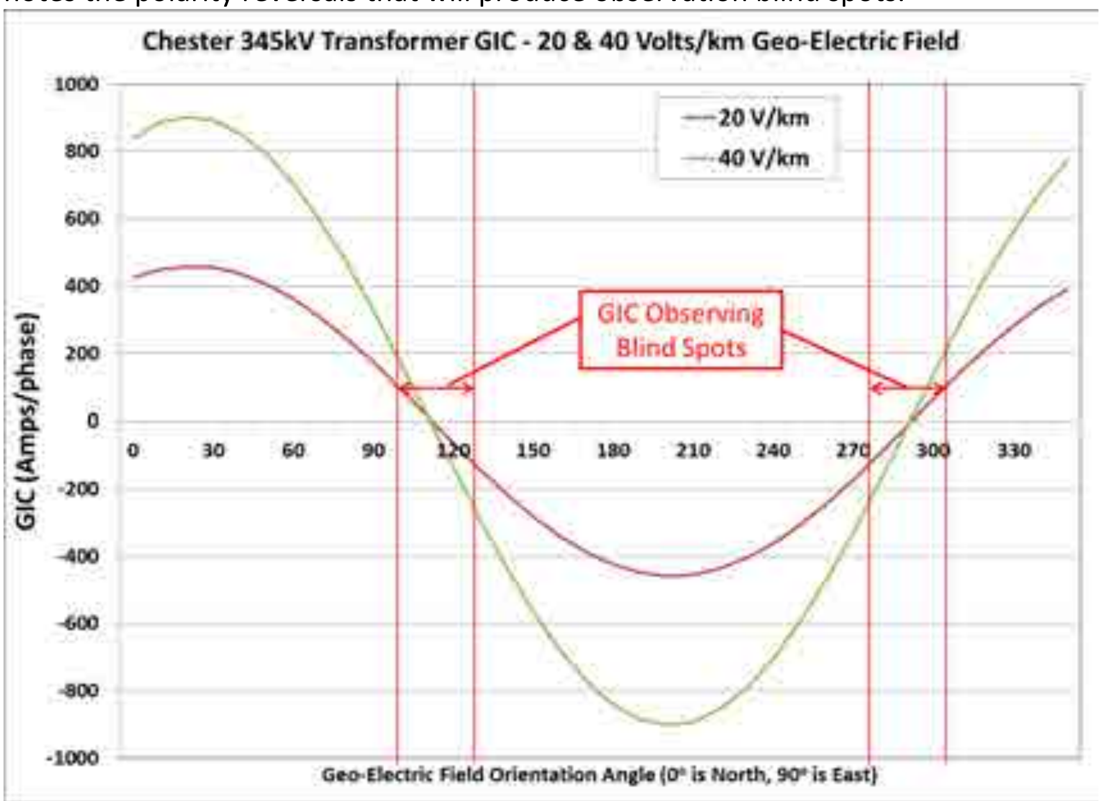


Figure 5-8 – Chester GIC at 20 and 40 V/km and observational blind spots.

Adding differing monitoring locations can add diversity in observing perspectives that help to minimize the blind spots caused by depending upon a solitary observation point. Figure 5-9 provides an example where the Mason and Surrowiec GIC flows at 20 V/km are plotted, along with Chester. The Mason and Surrowiec locations have differing phase relationships than Chester. This provides a larger grouping of observation points and the diversity of these observation points also cover additional phase angles in the geo-electric field orientations across the network. Therefore a monitoring approach using multiple monitoring points would provide much better situational awareness information on the storm conditions as there are transformers that will observe GIC levels at all orientation angles.

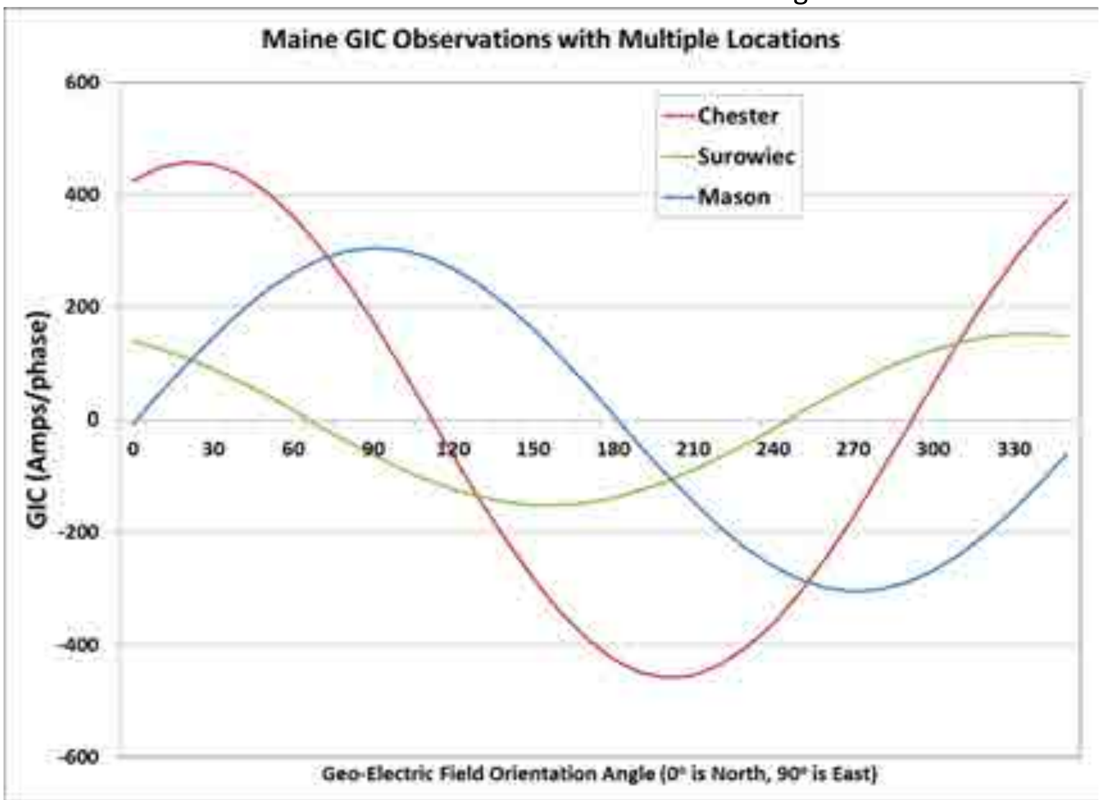


Figure 5-9 – Diverse Monitoring Points now provide assurance of improved situational awareness as one or more sites will observe GIC for all geo-electric field orientations

Measuring the GIC flows in an autotransformer is even more difficult, in that the usual observation point is the transformer neutral to ground connection. This observation point only provides information on the sum of GIC flows in the common windings of the transformer and does not provide meaningful or revealing information on the GIC flows that may be occurring in the autotransformer series windings. In certain locations, the pattern of GIC flows can vary substantially in each of these windings producing considerable uncertainty as to the total stress that is being imposed upon the autotransformer. So even with multiple monitoring points the ability to fully assess conditions remains challenging. Storm intensity information can be developed via regional observations of geomagnetic field disturbances and if a detailed model of the power grid is developed, as evidenced in this short report, a very high quality real-time situational awareness information system can be provided. A more detailed and accurate model can be developed by including more monitoring capability, coupled with information on the transformer parameters (type and age, DC resistance) and ground conductivities, which can be provided by the asset owners and operators.

Even with these advances, there remain legitimate concerns about what operating procedures can accomplish as far as assuring grid reliability and assurance that no blackout or widespread transformer damage occurs during future severe GMD or EMP events. Intense conditions can develop in a matter of a few minutes and even the best situational awareness tools will be largely after-the-fact displays and not likely to guide real-time assessments of rapidly deteriorating conditions on the grid or allow useful lead time for meaningful human actions to review and enact interventions to favorably alter the outcome. Realistic warning times for severe GMD are 30-60 minutes (provided by NOAAs ACE satellite) and EMP events would afford virtually no warning time at all. To counter such rapid onsets of disaster requires engineering the disaster scenario conditions out of the system design in the first place.

As shown in this analysis, the Maine electric power grid has extraordinarily high risks to these threats, and the addition of the MPRP facilities increases these risks further. The lack of a design code for GMD or EMP threats has unfortunately allowed these risks to the grid and to the public to go unnoticed by the owners and operators or regulatory oversight authorities.

Appendix – Brief Responses to Selected NOI Questions

III. INQUIRY

Maine investor- owned electric Transmission and Distribution (T&D) Utilities (Central Maine Power Company, Bangor Hydro-Electric Company and Maine Public Service Company) are directed to respond to the following:

1. Identify the most vulnerable components of the T&D utility's transmission system;

Addressed in Sections 1 – 5 above.

2. Provide information about the T & D utility's present practices or mitigation measures to protect the transmission system from GMD or EMP;

As was briefly mentioned above, the Maine T&D utilities do have in place an operational procedure for GMD, but not EMP. At present, there are no known hardware-based GMD or EMP hardening mitigations.

3. Discuss the extent to which present practices or mitigation measures can handle GMD or EMP events;

Operational procedures may be of some value for low-level GMD events, but for 100-year class GMD or EMP, the risk of voltage collapse or transformer damage is significant, and it is unlikely that operational procedures alone could prevent them. Currently available procedures will not mitigate the E1 pulse from an EMP event.

4. Identify additional potential mitigation measures that could be implemented to decrease the negative impacts of GMD or EMP;

To our knowledge, no study or report has ever been performed by either the ISO or Maine electric utilities to estimate the efficacy of their operational procedures for GMD. As noted in question 3, operational procedures can offer some protection. Beyond that, several mitigation options are available.

First, the use of 3-phase, 3-limb, core-form transformers improves GMD resilience, as this type of transformer is more resistant to adverse effects from GIC than other transformer configurations. Fingrid Oyj, the Finnish TSO, uses almost exclusively this type of transformer, (along with other methods to be discussed below), and as a result their grid is highly resilient to negative GIC impacts.

Second, DC current damping or blocking reduces or eliminates GIC flows in the system. Resistive devices can be placed in the neutral grounding path (a technique used by Transpower in New Zealand; Fingrid Oyj uses grouding reactors which also offer DC resistance). Capacitive devices can also be placed in the neutral grounding path (such a device - EMPRIMUS SolidGround - was tested last year by the Defense Threat Reduction Agency at Idaho National Labs, and will be field tested by American Transmission Company in Wisconsin). Series capacitors can also be placed on the transmission lines (a technique used extensively in power systems throughout the world for increased transmission efficiency, with the ancillary benefit of blocking DC currents through transmission lines).

Holding a sufficient number of spare transformers on site in order to more quickly replace damaged transformers is another option, as is de-rating transformers to ensure higher magnetic and thermal margins. De-rating may not be sufficient, however, for severe GMD or EMP scenarios.

For E1: specific, selected portions of the system that will be critical for operations and black start (SCADA systems, key communication nodes) can be identified and hardened or shielded. This could be supplemented by building a plan that provides for (a) adequate, planned, stored/shielded spares inventories, and (b) appropriate post-EMP fault finding procedures and training.

5. Estimate the costs of those potential mitigation measures to decrease the negative impacts of GMD or EMP (please include low-cost, mid-cost and high-cost measures);

HIGH COST – Series Capacitors – Ballpark estimate is that it adds about 10% to the cost of a transmission line.
HIGH COST – Large numbers of spare transformers (if new)
LOW COST – Save and spare older transformers that are to be replaced
LOW COST – Neutral blocking for transformers (EMPRIMUS device cost is estimated at $250K, and can be used on one, two, or three transformers – less than 5% of the cost of a transformer)
LOW COST – SCADA and Communications sparing and shielding.

6. What are the positive and negative effects of adopting a policy to incorporate mitigation measures into the future construction of transmission lines and the positive and negative effects of retrofitting existing transmission lines to incorporate mitigation measures?

The positive effect is assured transformer and power grid control system protection. There is no real downside if incorporated into new construction. For retrofitting, the only downside is the requirement that a transformer and/or transmission lines are taken out of service during the retrofit. A proper engineering study is required for series capacitors to avoid sub-synchronous resonance, and will not be suitable for all lines. For neutral blockers, the EMPRIMUS device was found to have no impacts on system performance. Grounding resistors do impact transformer performance to some degree. Proper engineering analysis is of course required with the installation of any new device into the system.

7. What are any potential effects of the State adopting a policy under 6 above on the regional transmission system?

Primary effect would be to prevent blackouts and equipment damage during the next severe solar storm and any potential EMP event.

8. What would be a reasonable time frame for the adoption of any additional mitigation measures?

Overall schedule would be (a) Developing a detailed plan (six months), (b) implementing E1, E3/GMD protection measures in a pilot location (six months) and (c) Overall grid protection measures installed (1.5 years).
Installation during construction of new lines would add virtually no time. Retrofitting requires scheduled outgages to complete.

9. Provide any recommendations regarding the allocation of costs to mitigate the effects of geomagnetic disturbances or electromagnetic pulse on the State's transmission system and identify which costs, if any, should be the responsibility of shareholders or ratepayers;

The cost is low, usually within a utility or transmission company's logistics and maintenance budget. All costs are recommended to be passed on to ratepayers (this will amount to less that $1 per year to ratepayers, if costs are distributed over the lifetime of a transformer, for example).

10. Discuss the relationship of any possible mitigation measures that might be undertaken by the State of Maine to measures that might result from the FERC rule. Specifically, is it possible that if Maine implements mitigation requirements in advance of NERC and FERC that such requirements might result in additional costs that might not have been necessary if mitigation requirements were not imposed on Maine T&D utilities?

The FERC rule (when it is finalized) will require that the Maine utilities have an operational procedure for GMD in place (phase 1) and to assess the vulnerability and investigate physical hardening (phase 2). There will be no conflict with Maine's use of operational procedure and/or physical hardening. If Maine adopts a robust standard (100-year solar storm, 20-50 Volts/kilometer geo-electric field as used in the analysis above) then there will be virtually no chance of falling short of the possible FERC/NERC requirement.

12. Provide information regarding any other state’s adoption of mitigation measures related to GMD and EMP, including citations to the relevant statutes and rules;

Hardware mitigation measures have been taken / are being taken in several countries (UK, Norway, Sweden, Finland, and New Zealand). None exist at present in the U.S., Maine is the first.

14. Provide, to the extent information is available, information on the extent or frequency of GMD or EMP events in Maine and the extent of any damage to the transmission system caused by those events.

Maine experiences low-level (NOAA G1 – G2 events) several times per year. The impact from these low level events is within the ability of the system to handle. The highest level events (NOAA G5 events) happen roughly once per century. The last two were in 1859 and 1921.

2014 Maine GMD/EMP Impacts Assessment

A Report Developed for the Maine Public Utilities Commission

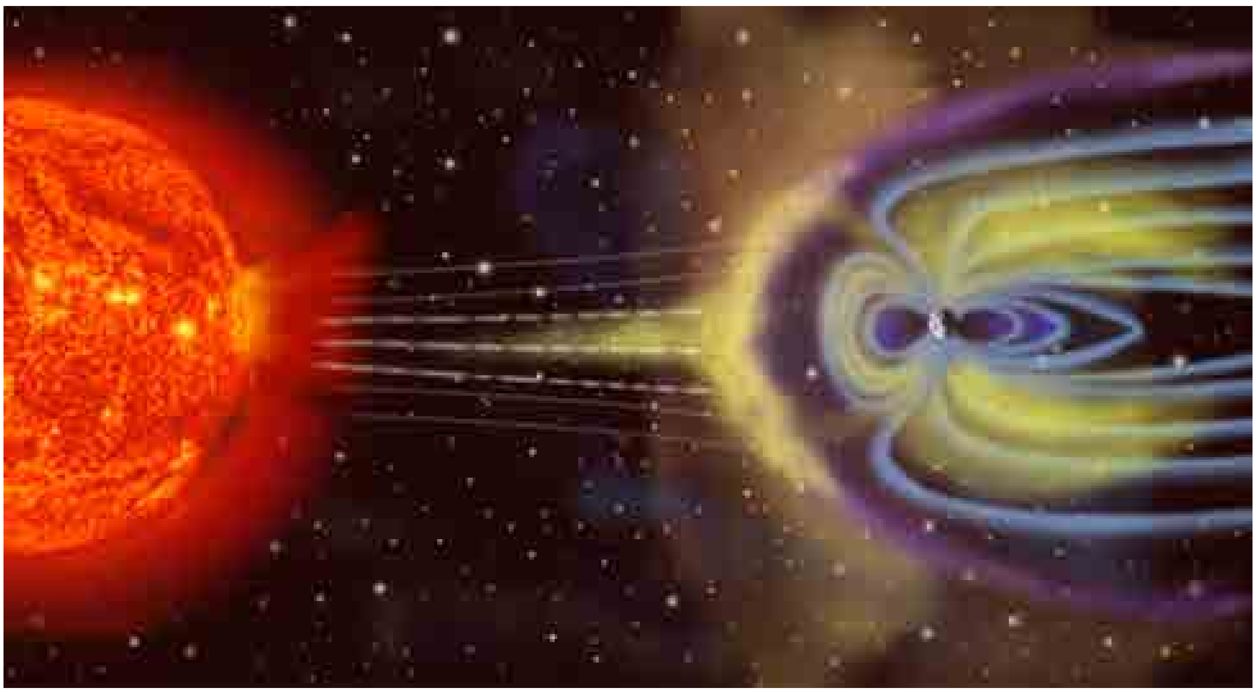


Image source: http://upload.wikimedia.org/wikipedia/commons/f/f3/Magnetosphere_rendition.jpg

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Definitions

Electromagnetic Pulse (EMP): A short pulse of electrical energy. The pulse can be created due to the switching of electrical devices or nuclear explosions. Generally, in this document, the pulse being discussed is designed to couple with other electrical infrastructure to interfere with it or cause damage.

High Altitude Nuclear Electromagnetic Pulse (HEMP): An electromagnetic pulse emanating from the explosion of a nuclear bomb at high altitude.

Coronal Mass Ejection (CME): A large mass of charged partials that are ejected from the sun. Generally they can reach the earth in 14 to 96 hours after leaving the sun.

Geomagnetic Latitude: Latitude in reference to the geomagnetic poles of the earth. This is similar to geographic latitude, but is adjusted to the position of the magnetic poles.

Geoelectric Field: As particles from a Coronal Mass Ejection interact with the earth's magnetic field, they create an electric field across the earth's surface. The resulting electric field is across a geographic area and is termed a Geoelectric Field.

Geomagnetic Induced Current (GIS): Quasi direct current flows driven by the geoelectric field across the resistance of the transmission system and earth's crust. These currents travel through the transmission lines and return to the earth through grounded transformer windings. This current can cause negative impacts to power system operations.

Geomagnetic Disturbance (GMD): Also known as a Geomagnetic Storm; represents the event and effects of charged particles bombarding the earth's magnetic field.

Harmonics: The North American electric system is operated at a fundamental frequency of 60 Hz. Non-linear loads and devices within the power system can cause multiples of the fundamental frequency to be present which are called harmonics. For example the second harmonic of 60 Hz is 120 Hz, third is 180 Hz… Etc. The presence of harmonics distorts the fundamental frequency waveform and may cause detrimental impacts to electric equipment.

Capacitor: Equipment installed on the power system for voltage control. They are designed to manage reactive power and increase voltage when energized. Capacitors may be permanently energized "fixed" or controlled with a breaker "switched" to turn on and off.

Relay: From the Institute of Electrical and Electronic Engineers (IEEE), a relay is "an electric device that is designed to respond to input conditions in a prescribed manner and, after specified conditions are met, to cause contact operation or similar abrupt change in associated electric circuits. Generally in the document relays being discussed are protective relays. Protective relays are sensory devices designed to monitor power system values with the goal to detect abnormal and intolerable conditions that may be present. Over time relay technology has advanced starting with electromechanical relays, solid state relays and most recently microprocessor based relays.

Active Power: This component represents the permanent irreversible consumption of power. Active Power is measured in the units of watts (i.e., W, kW, and MW). For example, watts are the usage of power to produce light and heat in an incandescent light bulb.

Reactive Power: Power provided and maintained for the explicit purpose of ensuring continuous, steady voltage on transmission networks. Reactive power is energy, measured in the units of volt-amps reactive (i.e., var, kvar, Mvar), which must be produced for maintenance of the power system and is not produced for end-use work. Electric motors, generators, power lines, and power electronics are all components which deliver or require reactive power.

Executive Summary

In 2014 the Maine Public Utilities Commission (PUC) requested Central Maine Power Co. (CMP), together with members of an ad hoc working group, to analyze the effects of Geomagnetic Disturbances (GMD) and Electromagnetic Pulses (EMP) on the Maine transmission system in greater detail than previous efforts reported. The effects of geomagnetic storms have been realized on the transmission system with recorded device tripping and a cascading failure of the Hydro Quebec power system[1]. EMP events have documented effects to circuitry and may damage circuitry that has an effect on power system components.

GMD and EMP, which can be broken into three categories, may affect the transmission system in several ways. The first way the transmission system may be impacted is through EMP categories E1 and E2. EMP categories E1 and E2 are fast rising energy waveforms that can couple with circuitry within communications and protection equipment and cause damage. Two delivery methods for EMP E1 and E2 are a High Altitude Nuclear Electromagnetic Pulse (HEMP) and Intentional Electromagnetic Interference (IEMI). The second group of relevant phenomena comprises the EMP category E3 and GMD. These are initiated by Coronal Mass Ejections (CME) or HEMP. CMEs are bursts of charged particles associated with a solar flare that leave the sun and bombard the atmosphere of earth and in turn create geoelectric fields. Geoelectric fields associated with GMD and EMP E3 events will cause the formation of quasi Direct Current (DC) in the Alternating Current (AC) electrical system, sometimes referred to as a Geomagnetic Induced Current (GIC). The transmission system in Maine and throughout the continent is designed to operate with three-phase AC power and the electrical infrastructure is not designed to accommodate a large DC presence. The GIC has the potential to cause disruptions to power system operations. Therefore, the EMP and GMD phenomena could have adverse impacts on the transmission system including transformer heating, reduced voltage operation and harmonics[2].

The 2014 assessment efforts within Maine described in this report were intended to present new information on the effects of EMP - E1 or E2 events and assess the impacts of GMD/EMP-E3 on the Maine transmission system. For GMD and EMP-E3, the report provides a range of costs for mitigating the effects of a range in storm intensities. This report also presents a GMD assessment of the Maine transmission system. This assessment also compares work conducted by EMPRIMUS/PowerWorld. The assessments covered a range in geoelectric field intensities measuring the electrical potential difference between two points. Geoelectric field intensities are rated in units of Volts per Kilometer (V/km). Field intensities ranged from 4.53 V/km (the 8 V/km North American Electric Reliability Corporation (NERC) benchmark event at a 60° Geomagnetic Latitude, adjusted for a northern Maine 56.95° Geomagnetic

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[1] The 1989 event affecting Hydro Quebec's electric infrastructure cause a widespread outage affecting nearly six million HQ customers for approximately nine hours. Additionally damage was reported across North America, including damage to a 500 kV transformer at a nuclear facilitate in New Jersey.

[2] Harmonics are the presence of waveforms, outside the nominal 60 Hz waveform, within the power system. The components are referred to as integer multiples of the fundamental 60 Hz frequency (2^{nd}, 3^{rd}, 4^{th}…). Some causes of harmonics are non-linear loads, power electronic device switching, and magnetic saturation. When harmonic levels are high enough in the power system they may cause adverse impacts such as motor heating, misoperation of relay devices or interference with communication circuits.

Latitude[3]), through 29 V/km (study team assumed 1 in 500 year storm). The storm intensities were analyzed with commercially available power flow modeling software packages which include GIC simulation modules. The assessments calculate and describe the performance of the power system over this range, i.e. from 4.53 V/km to 29 V/km.

The Maine Transmission system was found to perform well in storms below 14 V/km and may require mitigation in storms exceeding this level. Above 14 V/km, applying GIC reduction devices (neutral resistors or blocking devices) could be necessary to avoid equipment damage or allow transmission system performance to be maintained. In addition, general improvements including additional GIC monitoring, replacement of Electromechanical Relays and modifying switched capacitor installations to improve recovery timing, would aid in system resiliency. These inclusions are described further in the Mitigation Measures and Conclusion of this report. The costs to ensure that the Maine transmission system is capable of performing through a GMD event range from $0-$42.8M for storms less than 14 V/km and between $2.8M and $46.4M for storms exceeding 14 V/km. Costs for the improvements shown in Table 1 include GIC monitoring, replacement of sensitive relays, GIC monitors and improvements to capacitor switching recovery time. The improvements listed are not an "all-or-none" option. Each installation would improve the power system's resiliency to GMD impacts.

Geoelectic Field / Resiliency Installation	4.53 V/km	14 V/km	20 V/km	23.5 V/km	29 V/km
	NERC 1 in 100 year Benchmark	Study team assumed 1 in 50 year event	Study team assumed 1 in 100 year event	Study team assumed 1 in 200 year event	Study team assumed 1 in 500 year event and EMP-E3 level
Transformer GIC blocking	$0	$2.8M	$2.8M	$3.2M	$3.6M
GMD monitoring	$576k for 16 locations				
Replacement of all susceptible capacitor relays	$1M for 4 Capacitors				
Replacement of all susceptible relays 100+kV	$20.25M for 81 Local Zones of Protection				
IPO breaker installation to improve capacitor recovery	$21M for 9 locations				

Table 1: Summary of GMD Resiliency Installations and Cost

Research of GMD effects first appeared in Institute of Electrical and Electronics Engineers (IEEE) research papers dated from the 1960s on communications and power systems, with more reported research in the early 1990s through present. As a result of this research, NERC has proposed Reliability Standard

[3] NERC Common Questions and Responses 6/12/2014: The 1-in-100 year storm reference peak geoelectric field was 20 V/km in the 2012 NERC GMD Report. With spatial averaging, the same data produces a conservative 1-in-100 year peak geoelectric field of 8 V/km for the reference geomagnetic latitude and earth model.

TPL-007-1[4]. Electric transmission companies have recently begun to incorporate the study of GMD events on the transmission system. Commercial tools to study the effects of GMD on power systems have become available within the last few years and transmission companies are beginning to be trained on them and implement their use.

While this report documents effects to the Maine transmission system and highlights potential costs to improve resiliency, it has not been coordinated with adjacent transmission owners. CMP relies on the Independent System Operator of New England (ISO-NE) planning process to coordinate facilities across transmission owners and to provide cost sharing opportunities. Constructing a more GMD resilient transmission system in Maine for extreme conditions will help system performance during GMD events locally, but because of the nature of the interconnected transmission system, GMD effects throughout the Eastern interconnection and Northeastern transmission system may still impact Maine unless coordination and mitigation is performed beyond the borders of Maine. Proposed federal standards have an approximate five-year implementation time frame to assess GMD impacts and issue recommendations to bolster the system after NERC Reliability Standard TPL-007-1 is approved by the Federal Energy Regulatory Commission (FERC). This allows for utilities and regional transmission organizations to coordinate efforts, study the transmission system and implement corrective actions to the transmission system.

Estimates provided in this report are an indicative cost for implementing projects. Further estimation at a specific location would be needed to develop more accurate installation costs for each component. Central Maine Power and EMPRIMUS are providing these preliminary numbers to indicate the order of magnitude of conceptual costs, but at this point cannot confirm their estimate accuracy.

[4] NERC Reliability Standard TPL-007-1

History

In 2013, the Legislature passed a resolve[5] requiring the Maine Public Utilities Commission to "examine the vulnerabilities of the State's transmission infrastructure to the potential negative impacts of a geomagnetic disturbance or electromagnetic pulse capable of disabling, disrupting or destroying a transmission and distribution system and identify potential mitigation measures." The PUC submitted its report[6] to the Legislature on January 20th, 2014. Since data did not yet exist to identify Maine specific transmission system risks and mitigation measures, the Commission report gathered information on general types of effected equipment and costs to alleviate GMD impacts.

Since the report supplied to the Maine Legislature was delivered, EMPRIMUS and CMP have acquired GMD analysis software. This software has been used to calculate GMD effects on the Maine transmission system. The remainder of this report documents results from the CMP effort, compares the results of the CMP assessment with the work done by EMPRIMUS (filed to docket 2013-00415 as a separate report), and summarizes a range of GMD impacts and mitigation measures.

Scope

This assessment focuses on new information relating to the Maine transmission system in studying GMD and EMP effects. The area under review is the State of Maine, excluding the former Maine Public Service territory in northern Maine. The excluded system is interconnected with only the New Brunswick transmission system and has minimal impact on the operation of the power system in the rest of the state.

Due to the acquisition of GMD modeling software by CMP and efforts made by EMPRIMUS/PowerWorld, targeted study results are available studying the impacts GMD and EMP – E3 in Maine. The response of the transmission system studied and presented in detail are the steady state reactions to the presence of geoelectric fields. These reactions include system voltage changes due to transformer reactive power consumption and transformer heating concerns. The highest geoelectric field studied (i.e. - 29 V/km) was postulated by the study group to represent the effects of an EMP – E3 event. In addition to GMD effects, the study group provides new information on EMP E1 and E2 if new information exists. Beyond documenting the range of effects that GMD and EMP can have on the Maine transmission system, the costs associated with mitigation are developed for the range of geoelectric fields.

[5] LD 131, *'Resolve, Directing the Public Utilities Commission To Examine measures To Mitigate the Effects of Geomagnetic Disturbances and Electromagnetic Pulse on the State's Transmission System'*, Resolves 2013, ch. 45, 2013 Session – 126th Maine Legislature

[6] *Report to the Legislature Pursuant to Resolves 2013, Chapter 45, Regarding Geomagnetic Disturbances (GMD) and Electromagnetic Pulse (EMP)*, Maine Public Utilities Commission, January 20, 2014

FERC/NERC Developments

On May 15, 2013, FERC directed NERC to submit proposed Reliability Standards addressing the impact of GMD on the reliable operation of the Bulk – Power System (BPS). See Order No. 779, *Reliability Standards for Geomagnetic Disturbances,* 143 FERC ¶ 61,147 (2013) rehearing denied, 144 FERC ¶ 61,113 (2013) (Order No. 779). Order No. 779 directs NERC, in stage one, to submit, within six months of the effective date of the Final Rule, one or more Reliability Standards that would require owners and operators of the BPS to develop and implement operational procedures to mitigate the effects of GMDs. In stage two, NERC is required to submit by January, 2015 one or more Reliability Standards that require owners and operators of the BPS to conduct initial and on-going assessments of the potential impact of benchmark GMD events on BPS equipment and the BPS as a whole.

On November 7, 2013, the NERC Board of Trustees approved standard EOP-010-1, Geomagnetic Disturbance Operations the purpose of which is "to mitigate the effects of geomagnetic disturbance (GMD) events by implementing Operating Plans, Processes and procedures." EOP-010-1(3). NERC filed this Report on GMD and EMP January 20, 2014 and proposed standard at FERC on November 14, 2013 in Docket RM14-0100, available at the following link:
http://elibrary.ferc.gov/idmws/file_list.asp?accession_num=20131114-5150

The proposed standard applies to Reliability Coordinators and Transmission Operators. It requires each Reliability Coordinator to develop, maintain and implement a GMD Operating Plan that coordinates GMD Operating Procedures within its Reliability Coordinator Area. The plan must include a description of activities designed to mitigate the effects of GMD events on the reliable operation of the interconnected transmission system within the Reliability Coordinator Area and a process for the Reliability Coordinator to review the GMD Operating Procedures of Transmission Operators in the Reliability Coordinator Area. Further, each Reliability Coordinator is required to disseminate forecasted and current space weather information as specified in the GMP Operating Plan. The proposed standard also requires each Transmission Operator to develop, maintain and implement Operating Procedures to mitigate the effects of GMD events on the reliable operation of its respective system. Included in these required operating procedures are; (1) steps or tasks to receive space weather information, (2) System Operator Actions to be initiated based on predetermined conditions and (3) the conditions for terminating the Operating Procedure or Operating Process. The proposed standard also has provisions for reviewing and monitoring GMD operating plans and procedures.

On January 16, 2014, FERC issued a Notice of Proposed Rulemaking (NOPR), proposing to approve EOP-010-1. In Order No. 797, the Commission adopted the NOPR proposal to approve Reliability Standard EOP-010-1. On October 16, 2014, FERC issued Order No. 779-A, Order Denying Rehearing.

The NERC Standard Drafting Team is currently developing the TPL-007-1 Reliability Standard. TPL-007-1 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 FERC Order 779. The drafting team established the methodology for a benchmark GMD event for the purpose of identifying the level of severity of GMD events that applicable registered entities must assess for potential impacts on the Bulk-Power System. If the assessments identify potential impacts from benchmark GMD events, TPL-007-1 will require the registered entity to develop and implement a plan to mitigate the risk of instability, uncontrolled separation, or cascading as a result of a benchmark GMD event. The development of this plan cannot be limited to considering operational procedures or enhanced training alone, but must, subject to the potential impacts of the benchmark GMD events identified in the assessments, contain strategies for mitigating the potential impact of GMDs based on factors such as the age, condition, technical specifications, system configuration, or location of specific equipment. TPL-007-1 is currently received approval in the balloting stage. It will soon be sent to the NERC Board of Trustees for adoption and then routed to FERC who will approve and create Notice of Proposed Rulemaking (NOPR). Once the NOPR is filed in the Federal Registry the standard will become effective after its implementation time has passed.

EMP E1 and E2

An EMP is a high-intensity burst of electromagnetic energy than can occur naturally as a result of a solar storm or a product of an intentional attack aimed at crippling critical infrastructure. Electromagnetic Pulses can be into three categories. The first two categories of EMP, E1 and E2, have the capability to disable and damage electronic circuits. These circuits are used in the operation of power systems both in communication and the protection of components. Examples of transmission system components that could be disabled or damaged include the transmission Control Room, Supervisory Control and Data Acquisition (SCADA) communications, protection systems and relays.

During the proceeding[7] leading up to the PUC's January 20, 2014 Report, the Foundation of Resilient Societies provided a cost estimate of approximately $25 million to protect Maine's electric utility control rooms against E1 level EMP events and estimated the costs to protect the Maine Emergency Operations Center for E1 and E2 hazards to be about $1 million. While the study group continued efforts to quantify the number and location of other devices on the Maine transmission system used for operating and protecting the power system, no assessment was made to project how EMP could harm these devices through modeling or testing. As this is a new area of study for the electric utilities, simulation software and other analytic tools are not readily available in the marketplace. A more refined estimate would require a direct assessment of how these components would respond to an EMP event. Some commenters in this proceeding have submitted their assessments of the risks and mitigation costs relating to EMP E1 and E2. The submissions are included in the proceeding and indexed in the PUC's delivery to the legislature.

Central Maine Power is committed to ensuring the construction and operation of a reliable power system and will continue work internally and with external teams on GMD and EMP. This work will utilize a team including Telecommunications, System Operators, System Protection, System Planning and other available experts. This work will continue to comply with NERC standards and demonstrate due diligence to the design of the power system. In recognition of the need to study the impacts of EMP the section *Future Work on GMD and EMP* includes this recommendation.

[7] *Maine Public Utilities Commission, Notice of Inquiry Into Measures to Mitigate the Effects of GMD and EMP on the Transmission System in Maine,* Docket No. 2013-00415 (August 21, 2013).

GMD and EMP – E3 Vulnerable Components

Electromagnetic and Solid State Relays Without Harmonic Filtering

Relays are devices installed on the transmission system to sense voltage, current, frequency and other attributes. Many relays are configured to monitor a specific line, transformer or other equipment for abnormal conditions. Relays measure operating conditions and send a signal to a breaker (or other device) based on present conditions. This forms a local zone of protection around that equipment. Advances in technology have improved relay technology from Electromechanical to solid state, and current technologies use microprocessors. This signal is intended to remove faulted equipment from service, initiate the insertion or removal of reactive facilities, or trigger other actions. Electromechanical relays are susceptible to misoperation in the presence of harmonics such as those created during a GMD event[8]. Newer microprocessor based relays have the capability to filter the harmonic content of input signals and avoid inadvertent operations. Misoperation events where reactive devices have been tripped due to GMD events have occurred on the Maine transmission system.

Calculation of the exact effects due to harmonics on electromechanical relays is not possible on a wide scale, because testing is based on experimental values for a fundamental 60 Hz operation[9]. Since there is no test that would indicate which particular relays should be replaced to enhance resilience to GMD and EMP-E3, a general program to upgrade relays within the Maine transmission system may provide a good opportunity to improve such resiliency. In addition to the resiliency for harmonic blocking, newer microprocessor relays have many capabilities not available with older units. For example, new relays have the ability to store data about system events and provide more information to system operators.

A relay replacement program would likely be organized into two phases. The first phase would target reactive devices with a susceptibility to trip, and the second phase would target remaining relays. There are approximately 4 capacitors within the phase one group and 81 zones of protection in the phase two group. Phase one would cost approximately $1M dollars to implement and phase two would cost up to $20.25M.

Switched Capacitors

Switching capacitors may experience a problem during GMD events. They may be switched out-of-service and would be unable to provide voltage support if a subsequent peak in GMD activity were to occur within five minutes. Power system studies assume a constant DC offset for calculating the effects of GMD on the transmission system. In comparison to a 60 Hz sinusoidal wave, the GMD event appears as a DC offset to the fundamental operating point. It is necessary to calculate the magnitude of Effective GIC and VAr consumption within transformers to determine voltage reductions to the transmission system that would result from such a DC injection. Power flow models capture the steady state

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[8] North American Electric Reliability Corporation, *2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System*

[9] S. Zocholl and G. Benmouyal. "HOW MICROPROCESSOR RELAYS RESPOND TO HARMONICS, SATURATION, AND OTHER WAVE DISTORTIONS." *Schweitzer Engineering Laboratories, Inc.,* 1998

response of the transmission system at any given instant. Generally this is performed at the highest intensity (largest DC offset) portion of a GMD event.

GMD events have peaks and valleys in their intensities. It is possible to have capacitors switch on due to an increase in storm intensity and then turn off as the intensity decreases. This becomes a concern with GMD events due to the nature of capacitors installed on high voltage systems. When capacitors are disconnected from the power system once their support isn't needed, they carry a residual charge that is drained over time. If they were to be put back in-service to support voltage prior to being drained, transient voltage problems can occur[10]. To address this concern a drainage resistor is integrated into the standard capacitor bank which will draw the charge to zero over a five minute period.

During the operation of a power system without the presence of GMD, the five minute recovery period of a capacitor is acceptable. The appearance of a GMD event on the system could create the need for recovery in less than five minutes. Figure 1 is a GMD event field plotted against a timeline. It shows that the event creates a varying field which can change in intensity quickly. To improve resiliency in the Maine transmission system, Independent Pole Operating (IPO) breakers for capacitor switching could be installed to eliminate recovery time. Currently there are 14 capacitors without this capability positioned along the 345 kV transmission paths through Maine. These capacitors would be most influential to the 345 kV operating voltage, and thus are prime candidates for IPO breakers.

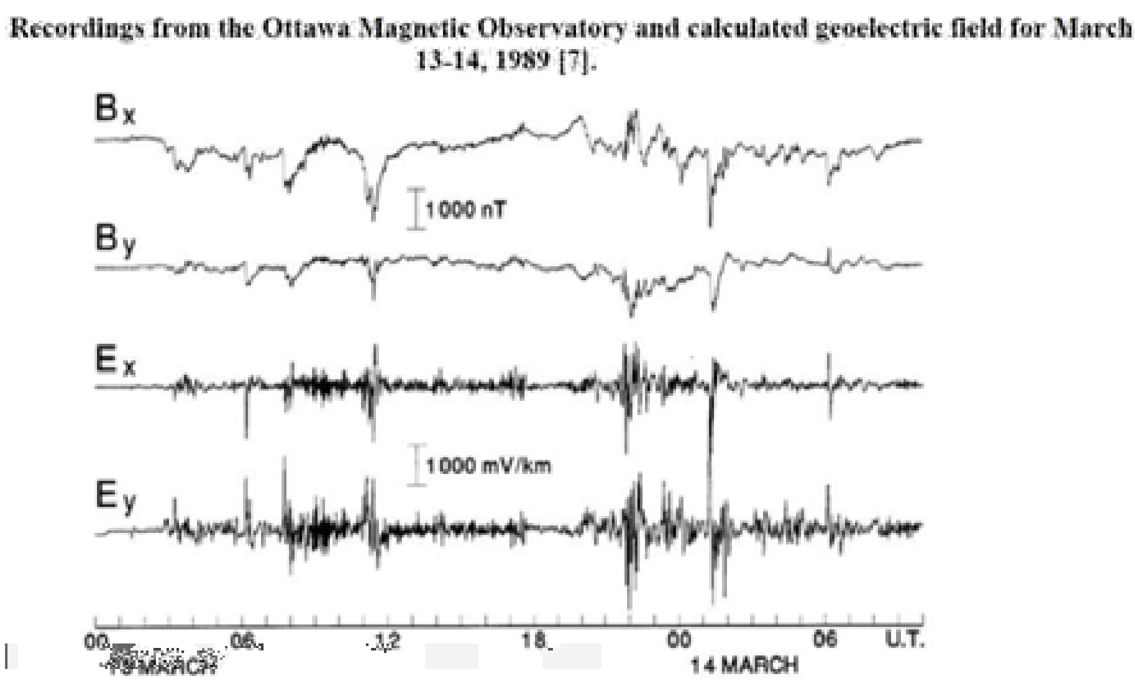

Figure 1: Geoelectric and Geomagnetic field intensity over time[11]

[10] A Greenwood. "Electrical Transients in Power Systems 2nd edition". NY: John Wiley & Sons, 1991, pp. 104-113
[11] "Application Guide Computing Geomagnetically-Induced Current in the Bulk-Power System." Internet: http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GIC%20Application%20Guide%202013_approved.pdf, December 2013

Replacement of the existing switching devices for capacitor banks with IPO breakers is another program that could be initiated to improve the resiliency of the Maine transmission system. Each installation will vary in its cost due to specific substation sites and constraints. CMP estimates an average cost of approximately $1.5 million per installation comprising the cost for replacement of a non-IPO switching device with an IPO breaker, relaying, relocation of the capacitor bank due to the increase in size of the breaker, disconnect switches and installation. The installations for all capacitors along the 345 kV corridors are estimated to cost $21 million. The installation of all 14 capacitor improvements is not an "all or none" expense; it would be possible to conduct a study to determine which capacitors were most critical. Further replacements and capacitor reclosing scheme changes throughout the transmission system could be explored, but this estimate targets the most impactful capacitors.

Geomagnetic Disturbance Monitoring Systems

Monitoring geomagnetic events is also an important element of GMD and EMP-E3 preparedness. Currently there is one monitoring station within the State of Maine. Data from this station has been used for calculating GMD effects, but one data point has limited functionality. Additionally there are approximately six GIC neutral current monitoring stations within the ISO-NE control area with additional planned. Throughout the United States there has been an increase in installing GMD monitoring equipment. Gathering more data points will allow for validation of Ground Induced Current modeling techniques, Transformer GIC effects, VAr consumption and resistivity modeling.

The installation of these monitoring devices would be an inexpensive way to gain knowledge of GMD on the Maine transmission system. It is estimated that each installation would cost of $36k. Installations would be placed at locations that contain a grounded transformer winding connection. Installation locations would be beneficial along 345 kV corridors in Maine and remote 115 kV generating stations. The 345 kV corridor locations with autotransformers and Generator Step Up Transformers (GSUs) provide ground paths, and the lines create a long path between Canada and the remainder of New England that would show the effects of geoelectric fields. Remote 115 kV generation stations would be ideal locations due to the possibility of GMD coupling with 115 kV transmission corridors connecting them to the 345 kV transmission path.

Covering these locations would require up to 16 installations (9 - 345 kV locations with Autos, 1 - 345 kV GSU, and up to 6 locations on the 115 kV system). These locations for installation include Maine Transmission company equipment and Independent Power Producers (IPP) equipment. Along the 345 kV corridors and extents of the 115 kV system, installations could be reduced to only the transformers showing the most response to GMD events. Installing at all 16 locations would cost $576k.

Maine GMD & EMP – E3 Study Results

Geomagnetic Disturbances and E3 Electrical Magnetic Pulses have effects on the transmission system. They appear as a quasi DC flow within the transmission system. Effects on the transmission system occur due to the grounded transmission transformer paths for DC current. As DC current flows through transformer windings, the transformer begins to experience heating and consume reactive power due to the electrical steel becoming oversaturated within the transformer. The DC flux offsets the AC waveform into a nonlinear region of magnetic operation. This can drive voltage deviations on the transmission system and harmonics. Figure 2 is a diagram of the DC effects on a grounded power transformer. In simple terms, the DC flows created by the GMD at high levels may overload a transformer. This would degrade its ability to operate effectively, and if severe enough, cause physical damage.

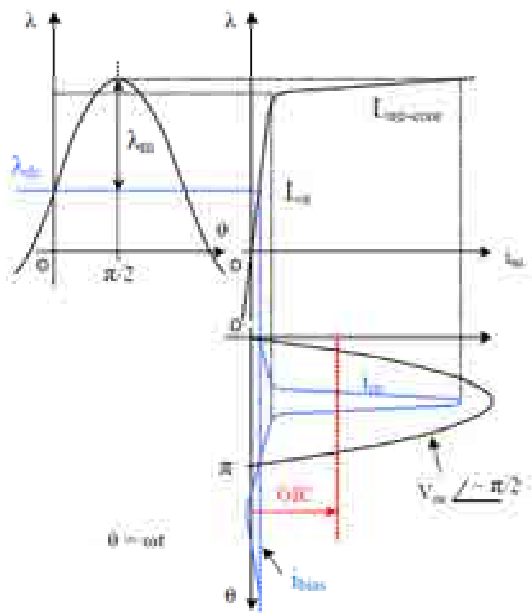

Figure 2: DC offset to Transformer sinusoidal operation (Source: NERC State2 GMD webinar)

GMD events can have a range of magnitudes and directions within a large area over several days. A short term (over minutes) GMD event will generally occur with a geoelectric field predominantly in a single orientation with some variation in the field direction. GMD storms impacting the earth are dynamic events, so when a short term (on the order of minutes) geoelectric field aligns with the direction of the longest transmission lines, the GIC current will be the greatest. The GIC current generated in transmission lines that are perpendicular to the long lines will have much lower GIC currents. Therefore, it would be unlikely that all transformers could see their maximum GIC currents at the exact same time. Over several days as multiple Coronal Mass Ejection (CME) waves impinge the earth, the geoelectric fields can be expected to vary greatly in both magnitude and direction such that other transmission lines and transformers could experience their maximum GIC currents at different times over these several days while the GMD storm is present. Therefore, for short term impacts not all transformers will likely see their maximum GIC currents at the same time. But over several days, it is possible that a larger number of transformers will witness their maximum GIC currents at some point within the event.

The Magnitude of the GIC flow through each transformer in the transmission system depends on multiple factors including the transformer construction type, winding configurations including how they are grounded, substation ground grid resistance, transformer winding resistance, angle of geoelectric field, magnitude of the geoelectric field and how the transmission lines are geographically oriented that connect to the substation. Two variable factors are the geoelectric field angle and its magnitude. Non-variable factors at each substation will determine a specific angle that drives the most GIC flow on a transformer. A GMD event will generally occur with a geoelectric field predominantly in a single orientation. To determine heating of an individual transformer the specific field orientation angle driving the most GIC flow on a transformer should be analyzed, bearing in mind that at any given geoelectric field angle, it is impossible to have the highest GIC flow on all transformers. When analyzing other effects, including transmission system voltage, the most globally impactful angle of geoelectric field should be used.

CMP Study

The study performed by CMP was performed on the Maine transmission system to view its performance under GMD events. The study was performed in five stages:

1) Develop the study area and models
2) Calculation of a conservative NERC benchmark geoelectric field intensity in Maine
3) Establish a geoelectric field orientation
4) Test for transformer response over the range of GMD events
5) Test for transmission system voltage response over the range of GMD events

Study Area, Model, Tools and Assumptions

The CMP assessment of the transmission system used the NERC Geomagnetic Planning Guide[12]. Per the Planning Guide, the study focused on the 230+ kV transmission system for Maine in the DC portion of the model. Within Maine this includes all 345 kV lines, substations and transformers with a at least one winding of 345 kV. A 2023 power flow model was developed by ISO-NE and underlying local transmission added. Transfers from New Brunswick to Maine were about 1,100 MW. The scope of the DC model extended two substations into the New Brunswick system and two substations into New Hampshire. The AC portion of the power flow model included all facilities from the 345 kV to local distribution transformers as provided in the eastern interconnect model.

Siemens' Power System Simulator (PSS®E Version 33.5) was the primary software used to study the effects of GMD on the transmission system. The program has a GIC module which develops a DC model,

[12]"Geomagnetic Disturbance Planning Guide." Internet: http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GMD%20Planning%20Guide_approved.pdf, December 2013

calculates the GIC induced currents and reactive power consumption of transformers. The results from the DC module are then incorporated into the AC transmission system model and the power system performance is analyzed. The DC portion of the assessment was limited to transmission lines and transformers with at least one winding over 230 kV within the study area.

Because data collection and modeling are still relatively new in this field, this study necessarily relies on a number of assumptions, including the following:

1) Transformer DC resistance values were based on PSS®E calculated for establishing the worst field intensity orientation. Values were revised with test report information when establishing the effective GIC for each transformer. Transformer DC resistance values for each simulation were very close resulting in less than a 0.17% change in calculated voltage at 29 V/km.
2) Values for transformer Mvar consumption were left as PSS/E default as shown in Figure 3. These values are established by previous calculations for typical transformer construction[13].

Figure 3: PSS®E Default Mvar loss factors

3) The solution technique when other values are not specified used was Full Newton-Rhapson, all automatic reactive components adjustments allowed, Load Tap Changers (LTC) enabled, phase shifting transformers enabled, and DC tap adjustments.
4) Previous modeling used three two-winding transformers to construct a three winding transformer in PSS/E. In this study, CMP used single three and two winding transformer modeling representations. This was to ensure proper calculations with the GIC module because previous modeling techniques could have resulted in double counting reactive consumption of transformers in the AC power flow calculations.

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[13] X. Dong, Y. Liu, J.G. Kappenman, "Comparative Analysis of Exciting Current Harmonics and Reactive Power Consumption from GIC Saturated Transformers," *Proc. IEEE 2001 Winter Meeting*, Columbus, OH, Jan. 2001, pp. 318-322.

Calculation of the NERC GMD Benchmark Geoelectric Field Magnitude

The NERC Benchmark, under the proposed TPL-007-1 event geoelectric field strength is 8 V/km at 60° magnetic north latitude. Equation 1 is the scaling function for the NERC benchmark event. It can be applied to the 8 V/km field intensity from the NERC standard to develop a geoelectric field amplitude at any magnetic latitude. The peak field is derived by scaling the 8 V/km benchmark by its geomagnetic location (α) and soil resistivity (β) scaling factors.

$$\mathrm{E}_{peak} = 8 \times \alpha \times \beta \; (V/km)$$

Equation 1: Geoelectric Benchmark Field Equation

To project a conservative value using this formula on testing geoelectric field, the most northerly point in the State of Maine was tested. Table 2 below shows both the Geographic and Geomagnetic location used. The α geomagnetic location scaling factor is described by Equation 2. In addition the values for soil resistivity are given as β = .81 within the NERC standard.

2015 Geomagnetic conversion	Latitude	Longitude
Geographic	47.467N	69.217W
Geomagnetic	56.95N	4.24E

Table 2: Geomagnetic location vs. Geographic Location for Northernmost point in Maine

$$\alpha = .001e^{0.115*L} = .6987$$

Equation 2: Geomagnetic location scaling factor.

This methodology yields a geoelectric field intensity of 4.53 V/km[14] for Maine in a NERC benchmark 8 V/km event. The location for which the values were based is the most conservative reference point that could be used to model the transmission system within Maine; as the result, the calculation provides the highest possible field intensity using the NERC Benchmark field scaling equation. There are no portions of the transmission system in Maine which are directly tied to the remainder of the Eastern Interconnect as far north as the point selected. This NERC benchmark event represents the lowest of the event intensities the study evaluated in assessing the risk to the Maine transmission system.

[14] The NERC Geoelectric Benchmark Field Equation was not applied to any of the other intensity levels evaluated in this study.

Establishment of the field orientation

Geoelectric fields will cause GIC flows within the transmission system based on the magnitude of the event and orientation in which they occur. For example, a field occurring which lines up north-south (0 degrees) will affect the transmission system differently than a field occurring east-west (90 degrees). Generally, as a field lines up with the geo-orientation of a transmission line it will cause the most GIC flow along that transmission line. Because lines are networked in different geophysical orientations, the magnitude by which the GIC affects the transmission system varies as the field orientation changes.

For this study, the orientation for GIC testing was established by rotating the geoelectric field in 1 degree increments at 15 V/km. The results of the DC GIC model were introduced to the AC power flow model to review voltages on the 345 kV system. The field orientation in the direction of lowest voltage (i.e., highest impact) was used as the field orientations in the remainder of system tests. Additional analysis could be explored to check for potential greater effects at other field angles specific to individual devices.

The study produced two graphs for each set of assumptions. The first graph in the series has degrees represented on the x – axis and voltage on the y – axis. The second is a representation of voltage magnitude as it rotates around the center point. Both graphs present the same information, but provide a different visual representation. Voltages for the Entire Study Area and the State of Maine are presented on two different curves for each graph.

Four iterations with varying assumptions were tested for the resulting GMD/EMP-3 impacts to system voltage, to account for the dynamic nature of system operations. Voltage controlling devices will automatically respond to system changes to maintain adequate voltage levels. While reviewing the results, it is important to notice the scale associated with each graph. Python computer programming code for performing this analysis in PSS/E is included in Appendix A: Code for performing Geoelectric Field calculations. The variations tested are:

1) All system reactive devices responding with normal operation
2) Shunt capacitors locked, dynamic devices enabled
3) Shunt capacitors locked, Chester offline with step-up transformer in-service
4) Shunt capacitors locked, Chester offline with step-up transformer offline

All system reactive devices responding with normal operation

With all reactive devices available and switching as designed, the voltage profile of the area studied and the Maine transmission system are very well controlled. There is only an approximate 1% change in voltage throughout the full 360 degree rotation of the geoelectric field for the NERC benchmark event. Within the State of Maine (red) it can be seen that switched reactive devices are turning on and off which looks like a disjointed line Figure 4 and circle in Figure 5.

The substations reporting the lowest voltages in the Entire Study Area are Larrabee Road at the ~340° - 20° and 160° - 200° regions and substations in New Brunswick for the dips. Within the State of Maine Larrabee Road is the lowest voltage substation throughout the plot. The low voltage acceptable limit is .95 V PU during operation of the power system, so all substations are performing very well for voltage. The notch is near 120 degrees is due to the switching of Mason capacitor banks and resulting voltage at Larrabee Road. Larrabee Road's capacitor banks are not automatically switched, but are available for operator control to improve voltage. The voltage is steady across all orientations of the geoelectric field.

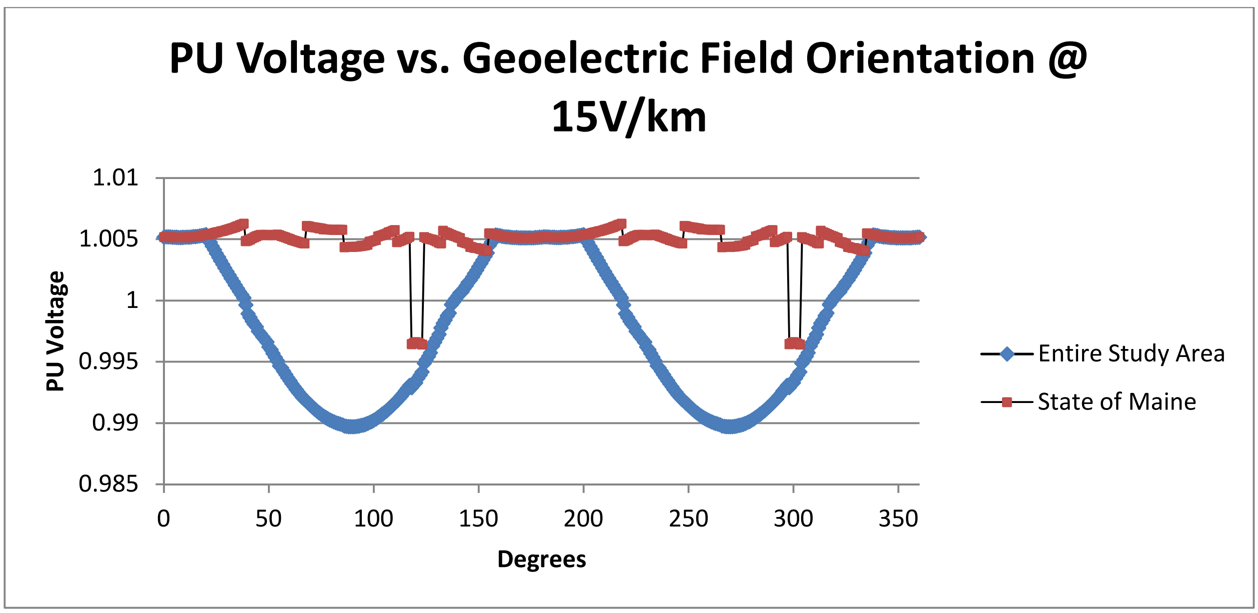


Figure 4: Transmission voltage response to geoelectric field rotation linear representation

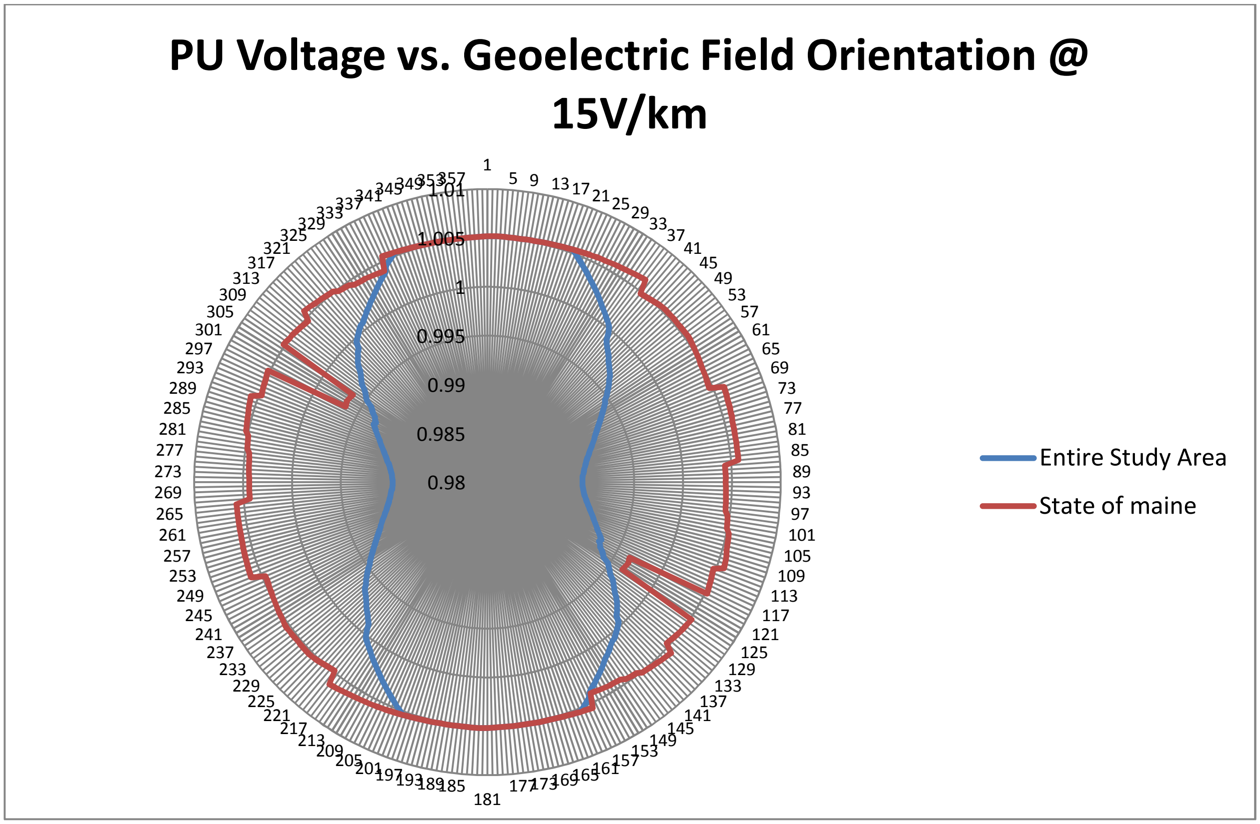


Figure 5: Transmission voltage response to geoelectric field rotation polar representation

Shunt capacitors and LTCs locked, dynamic devices enabled

During this variation, all capacitors and Load Tap Changers (LTCs) were locked in the model and continuously variable devices were allowed to adjust. A capacitor being "locked" in the power flow model means that it is not allowed to switch. LTCs being locked means that they are left in the same tap position as before the field is applied. The reactive device state (on/off or energized/out-of-service) was left in its original status of the pre GIC power flow case after applying transformer reactive consumption. This leads to the smooth transition of voltages throughout the 360 degree analysis as generators and SVCs are continuously adjusting.

There are noticeable troughs around the 80° to 90° and 260° to 270° field orientation. This is seen in Figure 6 and Figure 7 for both the Entire Study Area view and the State of Maine.

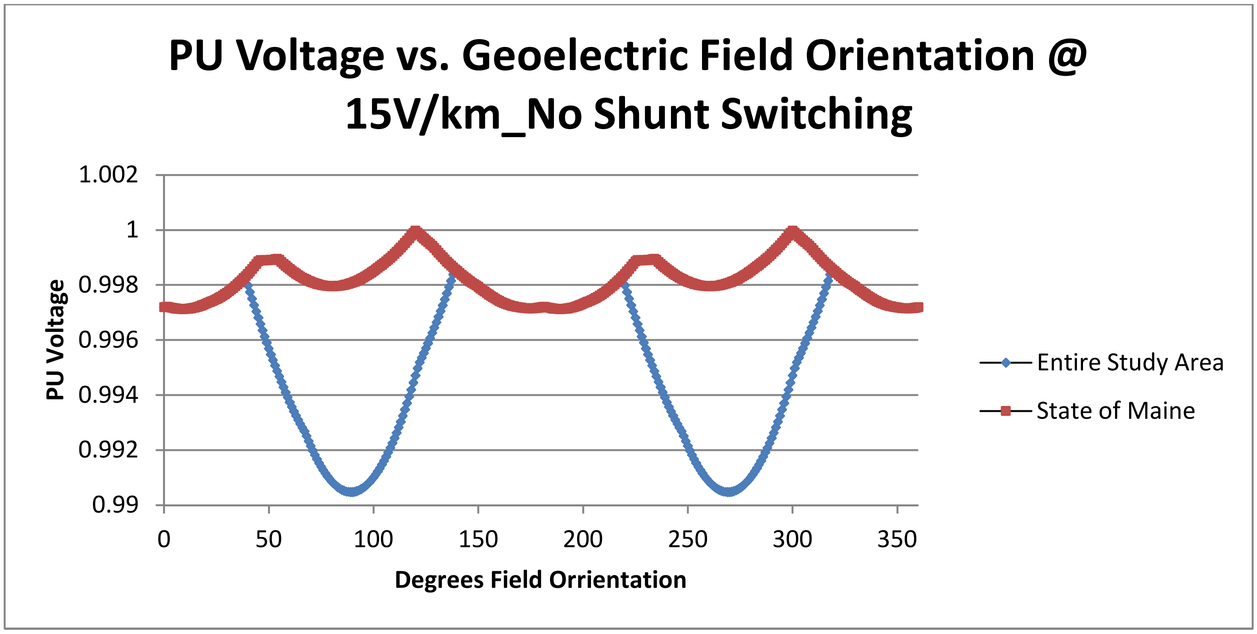


Figure 6: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching linear representation

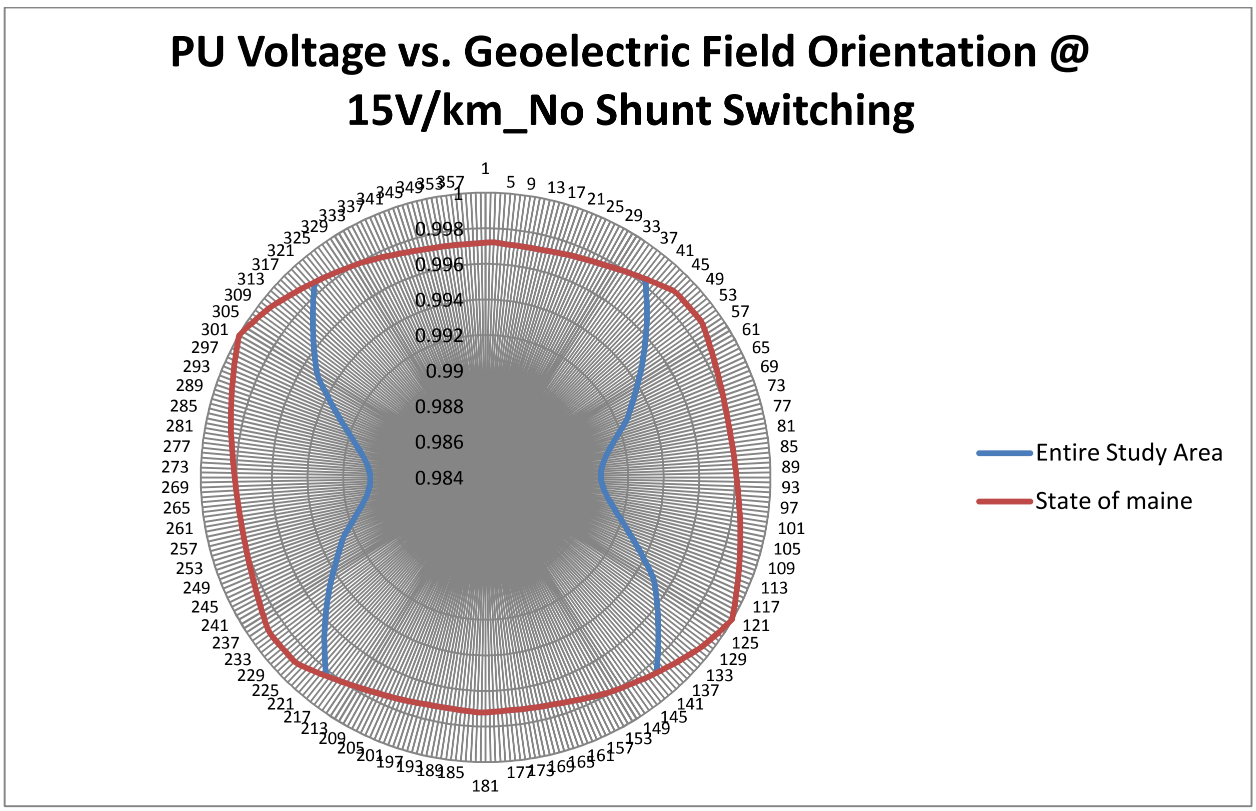


Figure 7: Transmission voltage response to geoelectric field rotation without reactive device or LTC switching polar representation

Shunt capacitors and LTCs locked, Chester Offline with step-up transformer in-service

This scenario is not likely, but analyzed to view the effect of all transformers in-service without the influence of the Chester SVC. Similar to the previous section, all capacitors and LTCs are locked. If the Chester SVC were to be removed from service due to a fault or incidental trip during a GMD/EMP-3 event, the 345/18 kV step-up transformer would also be de-energized. The interrupting breaker is located at 345 kV on the system side of the step up transformer. If the Chester step-up transformer were left in-service and the Chester SVC nonfunctional, the worst field orientation is around approximately 150° as seen in Figure 8 and Figure 9. Minimum voltages for both the study area and State of Maine are seen at the Chester 345 kV substation.

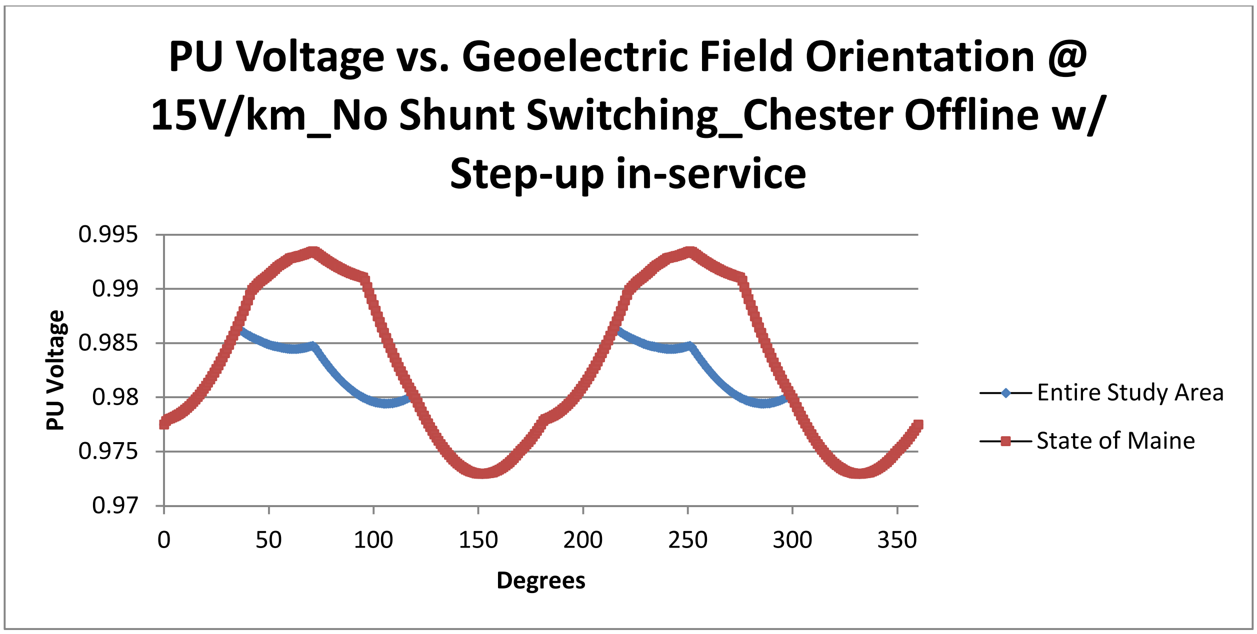


Figure 8: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching and Chester offline (step-up energized) linear representation

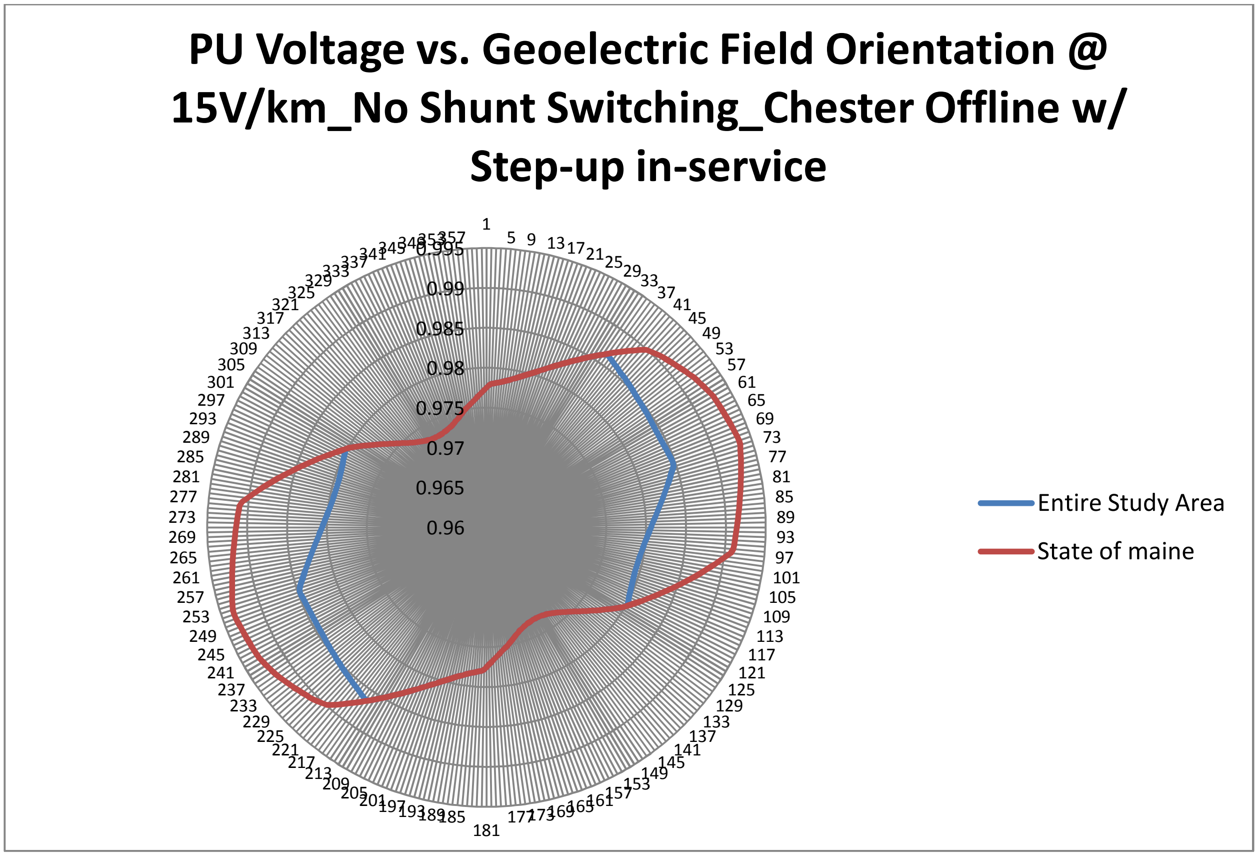


Figure 9: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching and Chester offline (step-up energized) polar representation

Shunt capacitors and LTCs locked, Chester Offline with Step-up Transformer offline

To test the transmission response after a trip of the Chester SVC, this final voltage profile was constructed. This simulation occurs with capacitors and LTCs locked and the Chester SVC station offline. The worst voltage is seen again in the 80° to 90° field orientation. For the State of Maine, the duration of the curve is represented by Larrabee Road. The Entire Study Area dips as areas in New Brunswick are experiencing reduced voltage.

It is worth comparing the rotation of the geoelectric field with the Chester step-up transformer out of service and the higher performing voltage on the transmission system. If the Chester SVC were to experience problems the protection system is designed to remove the step-up transformer from the transmission system. The effects from its VAr consumption would not be realized by transmission system. This variation highlights how assumptions can impact the magnitude of voltage and orientation of worst geoelectric field. There are improvements in voltage when the Chester step-up transformer from service vs. the previous section's simulation. Figure 10 and Figure 11 show the results of this variation.

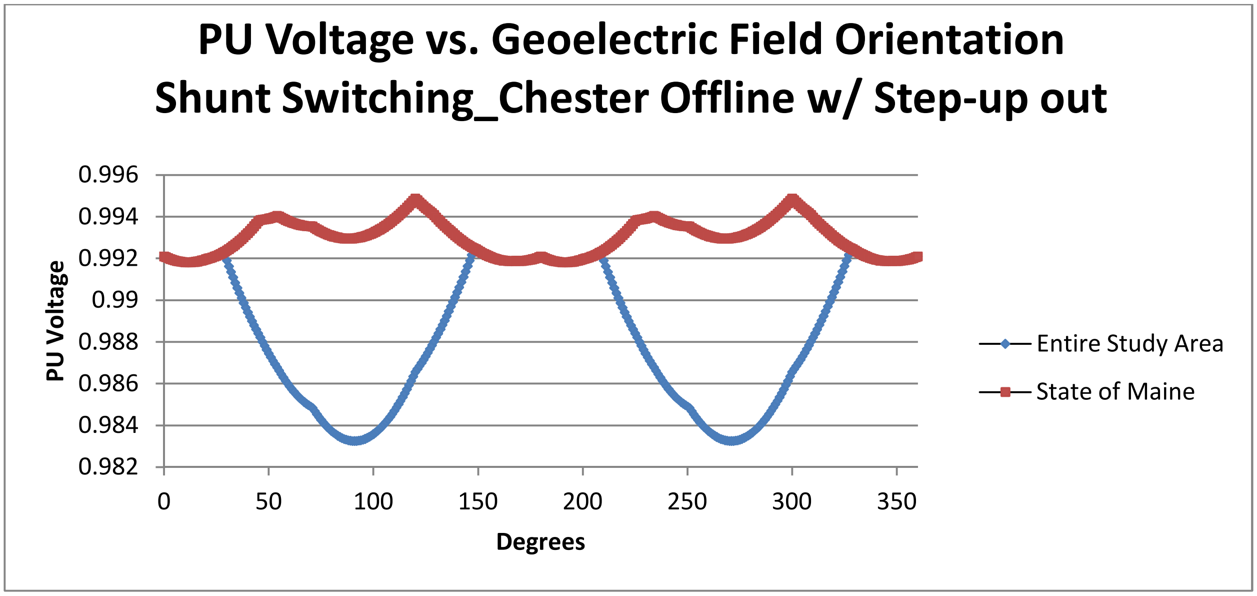


Figure 10: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching and Chester offline (step-up de-energized) linear representation

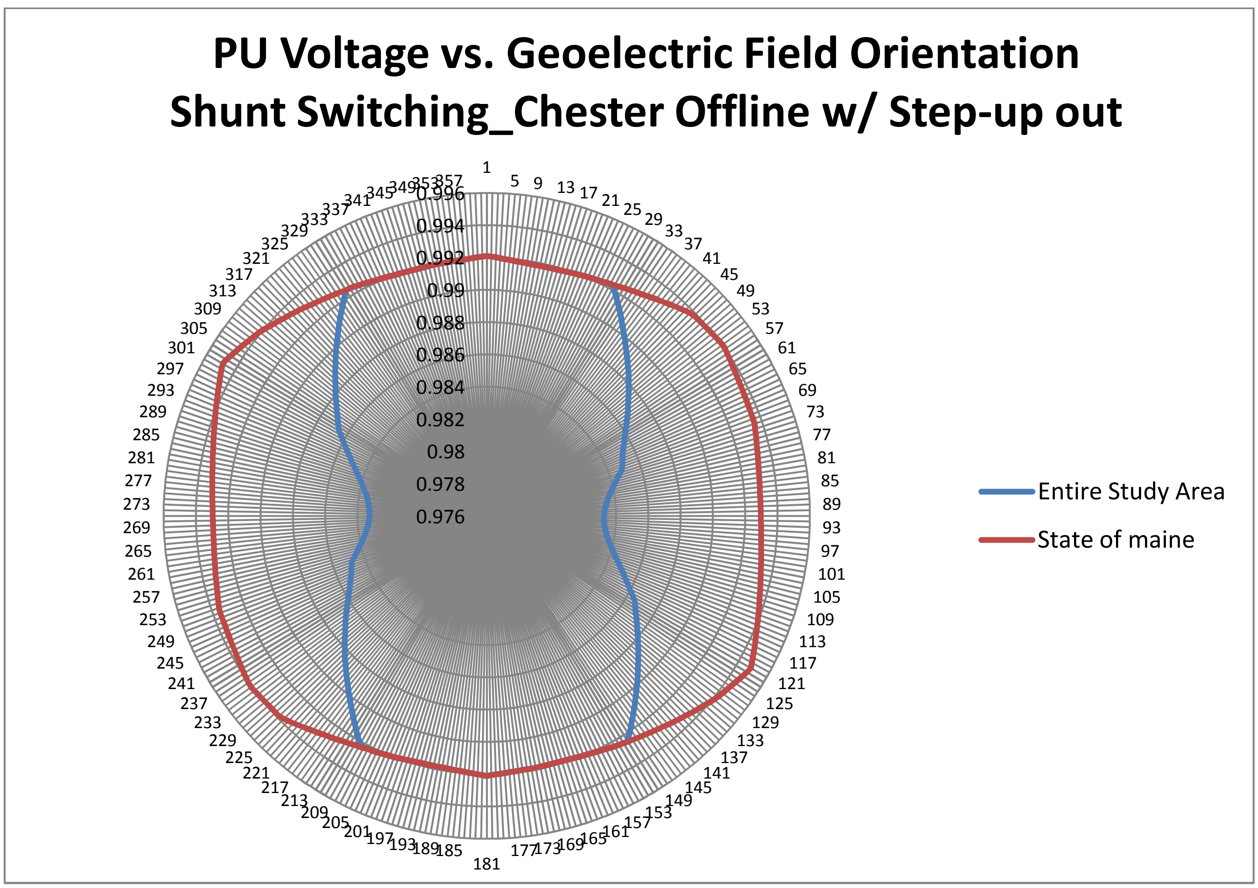


Figure 11: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching and Chester offline (step-up de-energized) polar representation

Resulting Field Orientation

Though each transformer and substation will respond uniquely to each field orientation, a single orientation is picked for additional testing of voltage response, GIC Effective A/phase, transformer reactive consumption and reactive margin. After reviewing the results from the four variations tested for field orientation CMP selected an 88° geoelectric field for further testing. Because testing with all voltage control devices enabled masked the effects of voltage response on the system and leaving the Chester SVC step-up transformer in-service is not a manner in which the power system would be operated, those scenarios were not relied upon in determining geoelectric field orientation. Both testing of locking capacitive shunts and LTCs and the same with removal of the Chester SVC show the lowest voltage response at the chosen field orientation of 88°.

Transformer Effective GIC A/Phase

One component to studying GMD events within a power system is studying the response of power transformers. Current is induced into the transformer neutral in the presence of a geoelectric field during a GMD event. This current is calculated as an Effective GIC value in Amps per Phase (A/phase). The presence of effective GIC through the neutral winding of transformers has the potential to produce excessive heating in transformers to the point of failure. The NERC standards drafting committee has issued guidance on screening transformer heating and recommends further analysis for transformer heating when the “Effective GIC” values are above 75 A/phase. For the purpose of this analysis it is assumed that transformers will have excessive heating and need mitigation above the NERC screening threshold.

Table 3 shows the results of effective GIC in 345 kV connected transformers during the assessment. These results are then plotted in Figure 12. Each transformer was tested on its most impacted angle of GMD storm and recorded in the table. There are no transformers within the State of Maine that are exceeding the 75 A/phase threshold during the NERC benchmark event (4.53 V/km). Once fields exceed 14 V/km, seven transformers exceed the threshold for screening. The number increases to 8 transformers above the Effective GIC threshold by 29 V/km. Maine transformers near 75 Effective GIC A/phase are highlighted in yellow as they are close to the screening threshold and will likely result in heating within specifications for GMD events while lightly loaded. Transformers clearly exceeding the screening threshold are highlighted in Red. These transformers may still pass thermal screening tests, but is assumed to be mitigated in this report. Graphs and transformer totals are reported on the transmission transformers within the State of Maine connected at 345 kV and above.

Effective GIC A/phase for Maine transformers		Degree Amp Max	4.53 V/km NERC 1 in 100 year Benchmark	14 V/km Study team assumed 1 in 50 year event	20 V/km Study team assumed 1 in 100 year event	23.5 V/km Study team assumed 1 in 200 year event	29 V/km Study team assumed 1 in 500 year event
2 winding delta - wye	Chester SVC 18/345 kV	162	76	235	336	395	487
	Yarmouth GSU 22/345 kV #4	144	49	152	217	255	315
	Keene Road GSU 115/345 kV	160	32	98	140	165	204
2 winding Auto Xfmrs	Orrington 345/115 kV #1	64	4	14	20	23	29
	Orrington 345/115 kV #2	64	4	12	17	20	25
	South Gorham 345/115 kV #1[15]	60	1	3	5	6	7
	South Gorham 345/115 kV #2	60	12	36	51	60	74
	Mason 345/115 kV #1	111	6	20	28	33	41
	Maguire Road 345/115 #1	30	27	83	120	139	172
	Keene Road 345/115 kV #1	160	6	18	26	31	38
3 winding Auto xfmrs	Coopers Mill 345/115 kV #3	30	35	109	155	182	225
	Surowiec 345/115 kV #1	38	17	52	75	88	108
	Albion Road 345/115 #1	30	60	186	266	313	386
	Larrabe Rd 345/115 #1	135	48	149	213	250	308

Table 3: Effective GIC in transformers for variations in geoelectric field

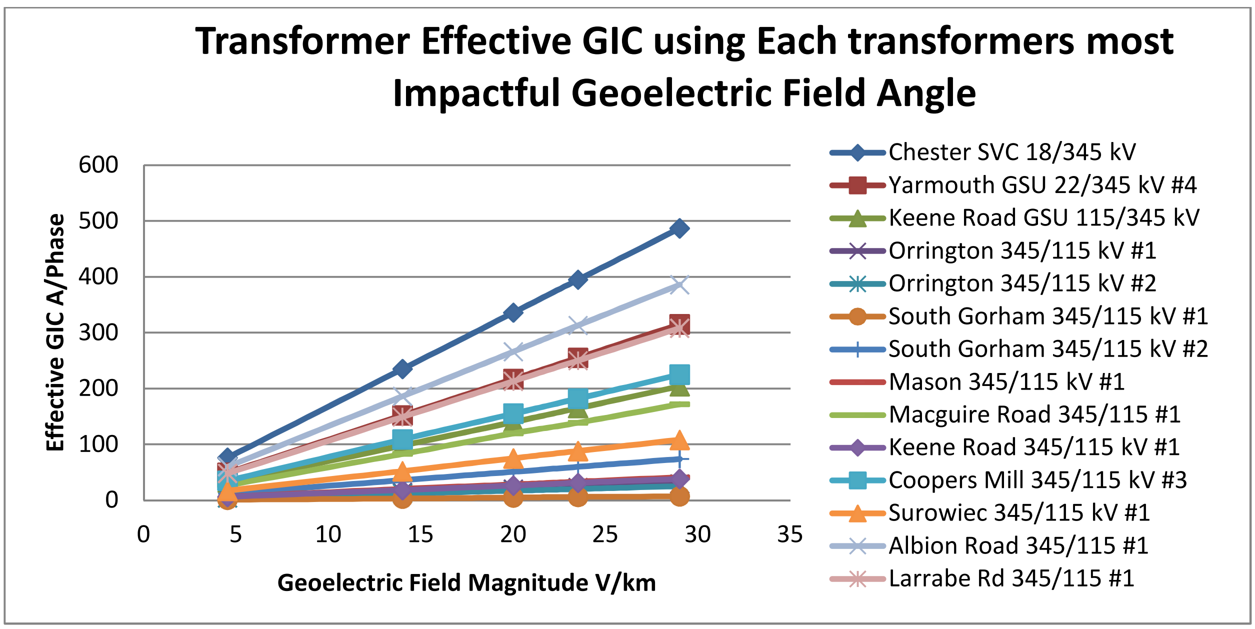


Figure 12: Effective GIC in transformers vs. geoelectric field

[15] The performance difference between the South Gorham 345/115 kV transformers was suspect in simulation. Further investigation into the cause in future study work will be worthwhile.

Figure 13 below shows how the transformers perform in the presence of a single geoelectric field orientation. This is the field orientation established as the most impactful to transmission system voltage. As the field is increased, transformers experience more Geomagnetic Induced Current. The levels of GIC realized at this orientation may not be the maximum of any specific transformer, but is the worst among the group of transformers.

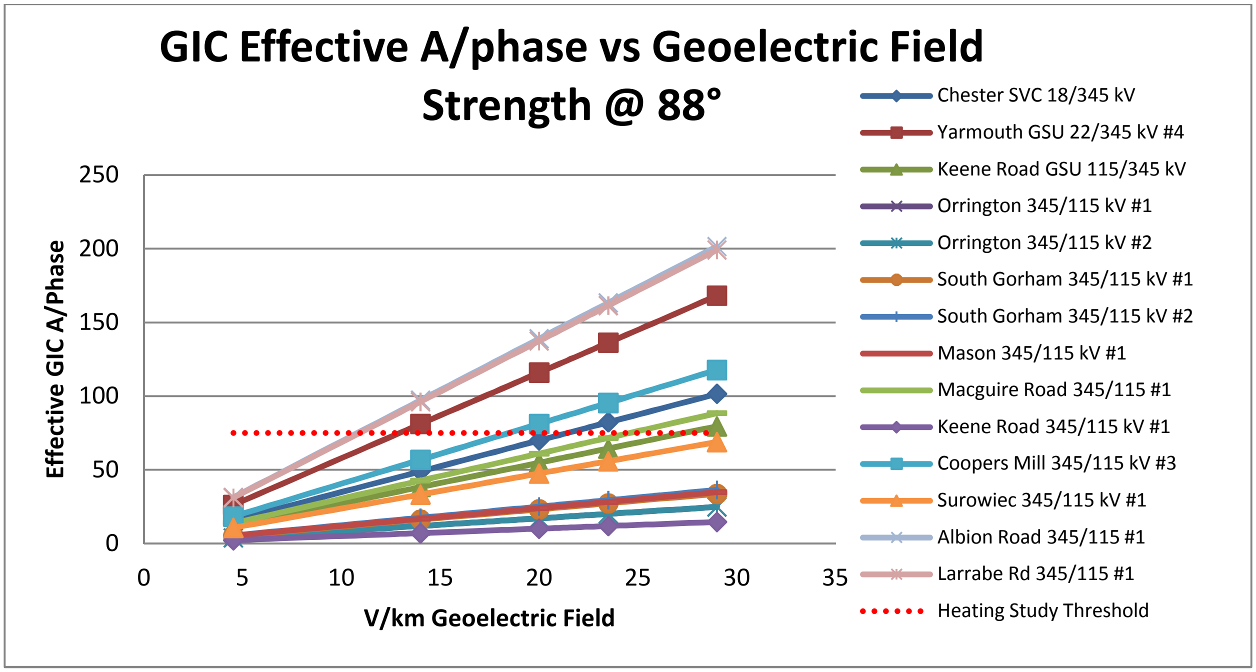


Figure 13: Effective GIC in transformers Vs. geoelectric field

Transformer Mvar consumption and Transmission system voltage response to GMD events

During a GMD event transformers get offset from their normal magnetic operating region and begin to saturate. As this saturation becomes more prominent, the transformer starts to consume more Mvar. This phenomenon is equivalent to adding reactors or more load to the transmission system thereby reducing voltage. Figure 14: Transformer Mvar consumption vs. geoelectric field, shows the Mvar consumption due to saturation of the transformers. As the geoelectric field increases the transformers consume more Mvar. The increase in VAr consumption is fairly linear.

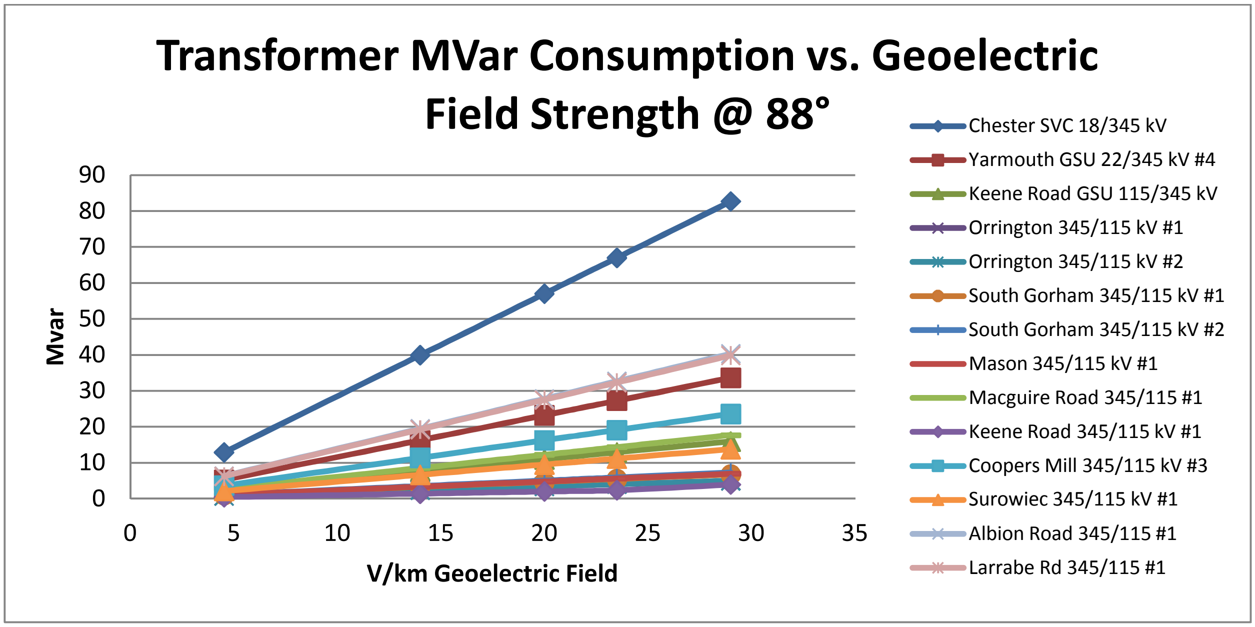


Figure 14: Transformer Mvar consumption vs. geoelectric field

Many devices are installed on the transmission system to regulate voltage. Generators are the largest source of reactive power on the transmission system. They are a dynamic source of reactive power and are continuously adjustable based on the magnitude of the excitation field applied. Other dynamically adjusting reactive devices include Flexible Alternating Current Transmission Systems (FACTS) which include Static VAr Compensators and other power electronic devices along with synchronous condensers. Static reactive devices include capacitors and transmission lines.

Voltages will begin to degrade if other reactive power producing elements are not available and equipment can overload. The effect capacitors and the Chester SVC is evident in Figure 15: Maine transmission voltage vs. geoelectric field at 88°, as there is a constant voltage through the bandwidth of studied geoelectric fields. It can be seen that there is an initial trend for lower voltage levels followed by a rise from 20 V/km to 23.5 V/km. This is due to additional reactive support being provided from devices switching within the power system. After the initial rise, voltages trail downward driven by the increase in reactive consumption within the transformers. Voltages on the Maine 345 kV transmission system stay stout throughout all modeled field intensities. Further losses of reactive devices should be studied for system voltage support per TPL-007-1.

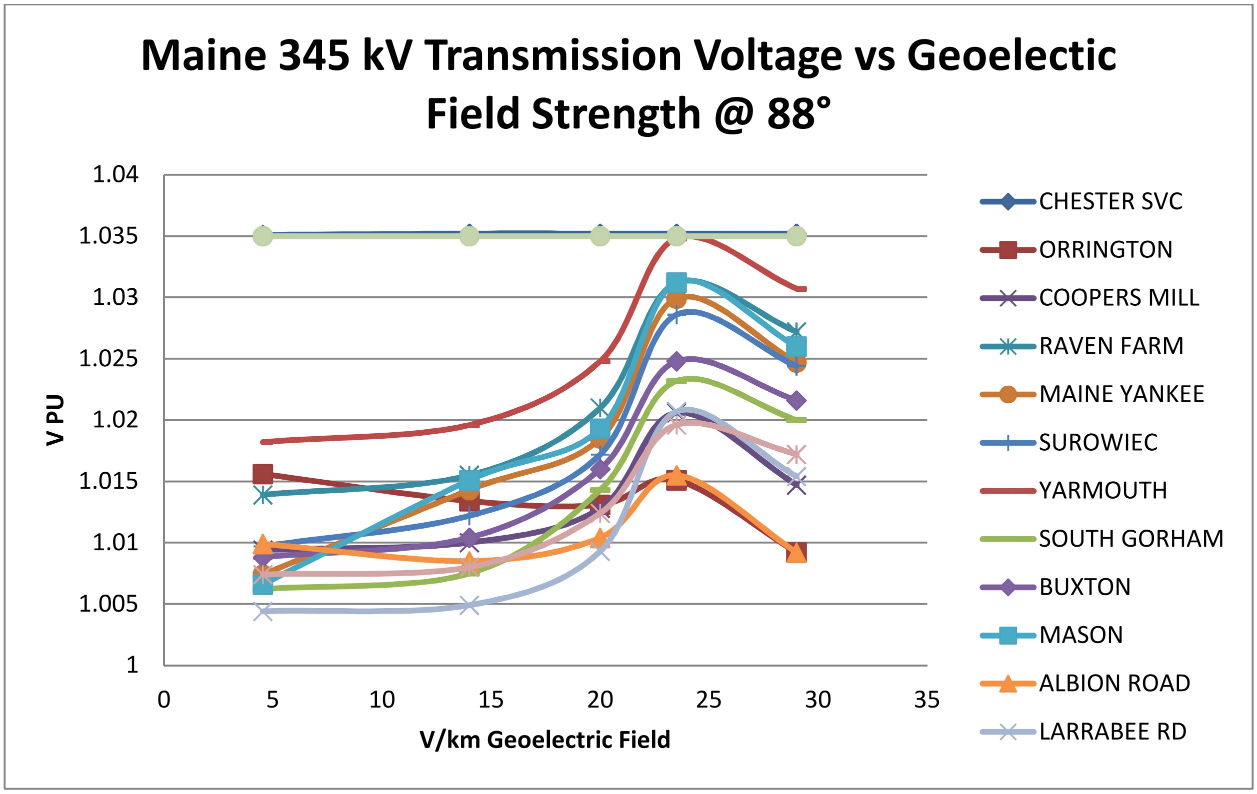


Figure 15: Maine transmission voltage vs. geoelectric field at 88°

Switched shunt and Generator reactive reserves were observed within the power flow simulations. . Figure 16 plots the total installed switchable shunt capacity and the energized Capacitor Reactive Reserves as the field strength is varied. The increase in voltage from 20 V/km to 23.5 V/km from Figure 15 is directly tied to the increase in reactive devices online in Figure 16. Capacitors are either automatically or manually switched to increase voltage on the transmission system. Within the State of Maine, capacitors are energized as voltages fall below 1 PU to regulate a system voltage slightly over that magnitude.

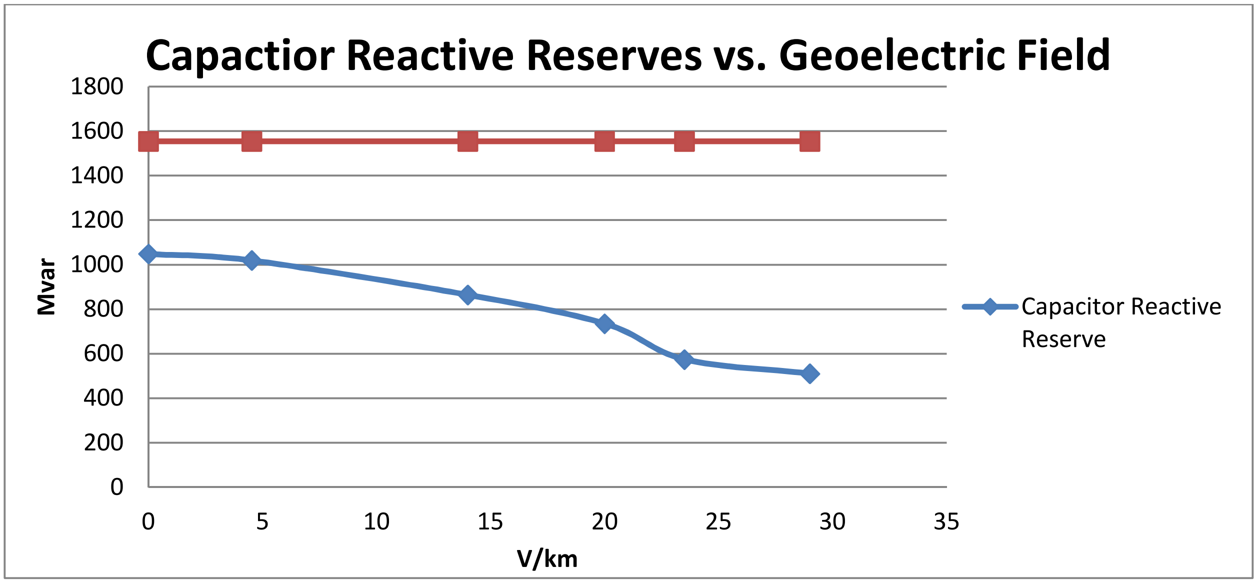


Figure 16: Installed Reactive Capacity and Reactive Output vs. geoelectric field Magnitude at 88°

Generation reactive reserves were also monitored for their reactive output during simulation. The reactive capability of a generator varies with its power output and is generally not available when the generator is not online. As generators decrease output of active power (MW), their ability to produce or adsorb reactive power (Mvar) increases. This power flow study utilized generator maximum reactive output capabilities at full active power output to be conservative. Generator reactive margins with ISO-NE and New Brunswick are reported in Figure 17 and will likely be greater than shown. There are approximately 20 GVAr of reactive capability within the same area when all offline generators (not producing power) are considered. Only generators online (producing power) in the power flow model were added together to form the curves.

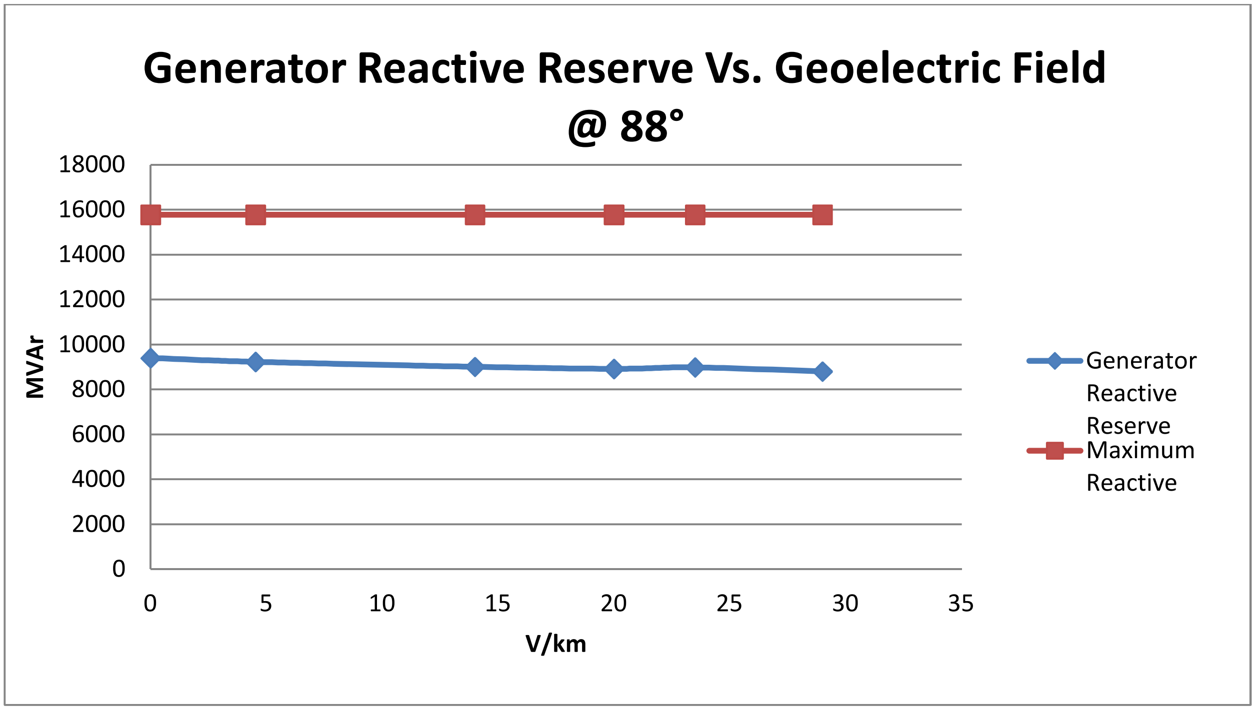


Figure 17: Generator Reactive Reserve

To show the magnitude of reactive reserves Figure 18 represents the total generator and capacitor margins. From the transmission system operating without the presence of a GMD to the 29 V/km event, 1,134 Mvar are utilized to maintain voltage. There is a large margin of reactive capability to manage for the loss of reactive power producing resources.

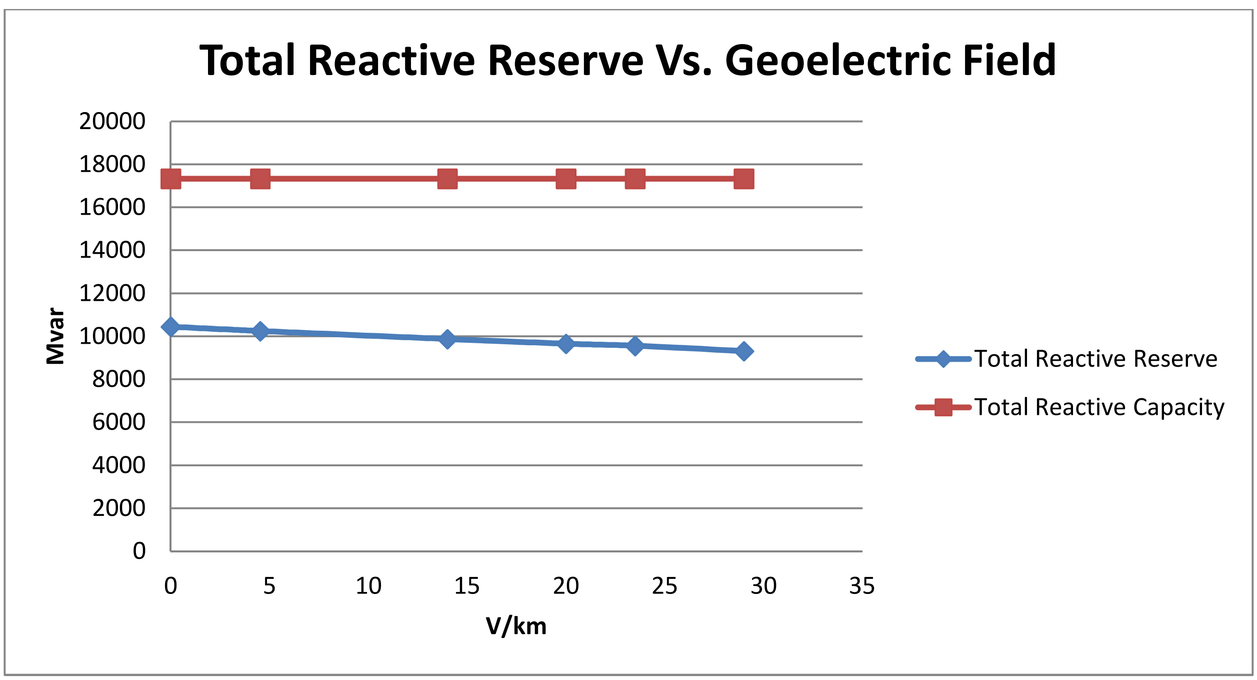


Figure 18: Total Reactive Reserve

EMPRIMUS study

EMPRIMUS used PowerWorld as a consultant to calculate the effects of GMD on the transmission system within the State of Maine. The consultant PowerWorld used the program PowerWorld to conduct its study work. The program is similar to PSS/E which was used by CMP. They both contain a GIC calculation and AC power flow simulator.

The CMP and EMPRIMUS studies show similar performance to power system response during perturbations, but the EMPRIMUS study indicates lower voltages on the transmission system at the tested geoelectric field strengths. This is significant because low voltage has the potential to negatively affect power quality and harm consumer devices. If voltage drops low enough and is not corrected it can lead to power outages. Therefore, the level at which protection is needed depends upon the view one takes on the modeling. Specific comparisons are made during the next section of this report. The topics of harmonics and probability of geoelectric field strength are also reviewed in the EMPRIMUS report.

Compare and contrast EMPRIMUS and CMP Study

Using currently available power system modeling tools, transformer heating and voltage stability with the loss of capacitor bank functionality show the highest levels of risk to the power system performance in the State of Maine. Generally the study work performed by PowerWorld and Central Maine Power show similar results. Within each study, many assumptions were made to develop the data used in calculations. Future studies will have these inputs replaced over time increasing the accuracy of the results. These accuracies will come as benchmarking to recorded data and testing becomes more prevalent.

The CMP and EMPRIMUS model showed similar results for GIC flow. There was, however, a difference in reporting between the two studies. CMP reported the Effective GIC A/phase [16] while PowerWorld reported GIC common winding A/phase. With the same reported values, GIC flows were trending quite close in value. Both studies showed that transformers could see excessive heating due to GIC flows when fields are at 14 V/km and above. In addition, the EMPRIMUS report the potential an additional risk which is damage to generator rotors by GIC induced harmonics in the Generator Step Up (GSU) transformers. This is a factor to consider in the selection of possible GIC blocking integration to protect Maines' generating resources from GMD events.

The treatment of switching for voltage controlled equipment provided the largest difference between the CMP and PowerWorld studies. Within the PowerWorld study, all switched capacitors, Static VAr Compensators (SVCs) and Load Tap Changers were locked into the state after the GMD event was applied as they were in before the GMD event. The CMP study allowed capacitors, SVCs and LTCs to adjust as voltage changes occurred on the system. Allowing capacitors to change status models the flexibility of the system as it was designed to operate. Not allowing capacitors to change status illustrates how the loss of reactive supply (either driven by a fault or second GMD event during its recovery period) may affect the transmission system. Disabling the functionality of the Chester SVC without removing the step up transformer will produce lower voltages on the transmission system than would be expected during normal operation. Whereas both studies assume an angle which represented

[16] K. Patil, "Modeling and Evaluation of Geomagnetic Storms in the Electric Power System", C4-306, CIGRE, 2014

the worst voltage performance on the Maine transmission system; the assumptions of no reactive device changes yielded a ~135° geoelectric field orientation while the CMP study utilized 88°. Generally, the results of the PowerWorld study has lower voltages during GMD simulation.

The final difference between the CMP and PowerWorld study was a change in transformer modeling techniques. There are multiple representations that can be utilized in three winding transformer representation. The models used along with the manner in which transformers will react to GIC are different. Some of the three winding transformers on the CMP system were represented as three 2-winding transformers in the EMPRIMUS study. These were revised to a single three winding or two winding transformer in the CMP study. Siemens PSS/E support was contacted and the model change does not have an effect on total GIC calculations, but will sway the effective GIC calculation along with the Mvar losses for transformers. This could result in lower voltages on the transmission system than using a 3 2-winding transformer representation of a three winding transformer. In addition to what transformer models were utilized, the K-factors chosen in the EMPRIMUS report is twice that of those utilized in the CMP assessment. The values used by CMP are chosen to correlate to the design of the transformers installed. EMPRIMUS utilized K-factors which are assumed for an unknown transformer type of .6 for all transformers. This is can be recognized as conservative, increasing the impact of GIC and lowering the resulting voltage calculations.

Mitigation Measures

General mitigation measures

GMD Monitoring

One way to prepare for GMD events is to know more about how they manifest on the transmission system. Currently there is only one GMD monitoring station in the State of Maine. Additional GIC monitoring is being incorporated throughout the United States. To establish a greater presence within the State of Maine of monitoring GMD 16 transformers could be monitored for a cost of $576k.

This estimate is based on a $36k per installation and the locations described under the GMD and EMP E3 Vulnerable components section. Specific components of the cost estimate are listed in Table 4. The dollars estimated were based on 2014 escalation. The design, installation and commissioning time per installation is estimated at two months. This results in an approximate 32 month implementation time for all 16 sites.

Item	Type	Qty or Hrs	Work Required Description	Total (USD*)
1	Labor	40	Per (2) CMP substation personnel onsite to install GMD device and 24x24x12 stainless steel cabinet.	$5,600
2	Material	1	(1) Eclipse GMD device in a steel 24x24x12 stainless steel cabinet.	$13,000
3	Material	1	Materials required to install Eclipse GMD device. i.e. SIS wire, crimp connectors, and etc.	$1,400
4	Labor	80	(1) P&C engineer to design, implement, and test the changes required for Eclipse GMD system.	$16,000
			Total	**$36,000**

Table 4: Cost Estimate Breakdown for GMD Monitoring

Replacement of Electromechanical and Solid State Relays

The replacement of harmonic sensitive relays with Microprocessor based relays that can filter harmonics would improve GMD resiliency. The replacements could occur in two phases described in the GMD EMP E3 Vulnerable Components section. Replacing the susceptible relays controlling capacitor banks installed above 100 kV is expected to cost $1M. If the replacements were continued in a second phase to replace all susceptible relays at 100kV+, it would cost up to an additional $20.25M.

This estimate was developed through Central Maine Power's historical cost in replacing relays considering the scope of CMP and Maine Electric Power Company (MEPCO) facilities. As part of standard construction practices within CMP, the replacement of Electromechanical and Solid State relays is targeted when equipment that the relay is monitoring gets upgraded or replaced. The replacement of a zone of protection with microprocessor based relays has cost approximately $250k escalated to 2014 dollars. There are four capacitors utilizing GMD susceptible relays and an additional 81 zones of protection included in this estimate.

Based on historical timelines for relay replacements, the first phase replacing capacitor controlling relays is likely to take two years from the project initiation. The second phase of relay replacements would take approximately four to five years from project initiation. Project initiation is considered to be the time where funds have been budgeted and the design work begins on the project. The total installation time of this estimate is designed to capture engineering, construction and commissioning of the project. The consideration of Emera Maine, municipal utilities and generator facilities would increase costs and possibly timelines presented in this section.

Capacitor Bank Recovery Time Improvement

Improving capacitor recovery time would improve the performance of voltage on the transmission system during a large GMD event. If peaks in the storm intensity occur close in time, the capacitors may be unavailable to aid during a subsequent peak due to capacitor recovery timing. To improve resiliency, IPO breakers can be installed to switch breakers. This will allow capacitors to be available for subsequent peaks. As described in within the vulnerable components, the cost to implement this mitigation would be $1.5M per installation and up to $21M to bolster the performance of the 14 impactful capacitors.

Replacing the switching devices controlling capacitors has the most variability in scope of work. Depending on the existing infrastructure spacing, real estate, and other factors each installation will have a higher level of customization to each site. It would be expected to take up to two years from project initiation to install this enhancement for a single capacitor. If all capacitors were targeted, with efficiencies in ordering materials and construction, it could take up to 10 years to complete.

Maine tailored system resiliency improvements

Transformer Neutral Resistor or GIC Blocking

Deficiency in voltage was not a factor in determining whether to install transformer blocking devices. Voltages were found to be adequately performing throughout the GMD assessment range in the CMP study while possible concerns arose in the EMPRIMUS study. Concerns within the EMPRIMUS study are seen due to the assumption that voltage control devices other than generators are not available to regulate system voltage. Improving general mitigation measures such as relay replacements and improving capacitor bank recovery timing would likely remove the voltage concerns shown.

Transformer GIC blocking devices would, however, address the concern relating to excessive transformer heating. Both studies realized additional flow within transformers due to GIC. Below is Table 5 which displays the number of transformers from the CMP study which would require reductions/blocking GIC current utilizing the NERC 75 A/phase threshold. The threshold was established for further investigation into transformer heating by the NERC standard drafting committee. Costs are assumed at $400k for integration of a GIC blocking device based on estimates within the EMPRIMUS study.

Event	4.53 V/km	14 V/km	20 V/km	23.5 V/km	29 V/km
	NERC 1 in 100 year Benchmark	Study team assumed 1 in 50 year event	Study team assumed 1 in 100 year event	Study team assumed 1 in 200 year event	Study team assumed 1 in 500 year event and EMP-E3 level
# of transformers above 75 A/Phase	0	7	7	8	9
Cost	$0	$2.8M	$2.8M	$3.2M	$3.6M

Table 5: Transformer GIC mitigation for studied geoelectric fields

Transmission Cost allocation

A power system is typically designed to efficiently move power disregarding city, state, company or other boundaries. When investing in an approved transmission project needed for regional reliability, the benefits extend beyond the immediate area and help the transmission system as a whole. Cost allocation is a method of pooling funds that are utilized on transmission system improvements to lessen the burden towards one company at any given time and to allocate cost throughout the region among all that receive a benefit. In New England all approved transmission project costs for Pool Transmission Facilities (PTF) are pooled and participating companies pay a portion of the total cost.

Cost allocation is a process under the authority of the ISO New England Inc., as set forth in ISO-NE's FERC-approved Open Access Transmission Tariff (OATT). The sharing of costs is limited to transmission facilities. Emera Maine and Central Maine Power Company are part of the ISO-NE Regional Transmission Organization (RTO).

It is possible that if Maine implements mitigation requirements in advance of NERC and FERC that such requirements might result in additional costs that might not have been necessary if mitigation requirements were not imposed. The upgrades must first be determined to be needed to meet reliability requirements to qualify for regional cost allocation. Once determined to be needed, the project components are reviewed for localized costs. Should Maine's transmission owners seek region-wide cost allocation for compliance with a local or state law/regulation that is not a reliability criteria (i.e. NERC, NPCC, or ISO-NE criteria requirement), the project will most likely not qualify for regional cost allocation. If the state or local laws or regulations are also NERC, NPCC or ISO-NE criteria, then the project may qualify for cost allocation subject to review for localized costs. In that case, the ISO will then determine, with the advice of NEPOOL's Reliability Committee (RC), whether the costs resulting from the requirements of any local or state regulatory and/or legislative requirements will be identified as localized or regionalized costs. For additional information, see *Planning Procedure 4 (specifically Attachment A),* which provides guidance as to what projects or portions of a project the ISO and RC should consider local or regional.

Conclusion

Large scale power flow studies of GIC impacts to power transmission systems are relatively new to the industry. The first such GIC modeling programs integrated into standard power flow software became available approximately two years ago. Tools, knowledge, and the understanding of effects related to GMD within the power system continue to improve. The two studies conducted on the Maine transmission system show that GMD events can cause concern above a 14 V/km geoelectric field strength. Using current study techniques, transformer heating and voltage with the loss of capacitor bank functionality show the highest level of risk to power system performance in the State of Maine.

To improve the voltage performance on the transmission system, improvements could be made to relays and switching devices. The cost to upgrade relay technology and replace existing switching devices with IPO breakers would cost up to ~$42.8M. These upgrades would improve resiliency to GMD events, but do not have a calculable geoelectric field level at which they may be effective.

Targeted transformer blocking can be implemented to transformers depending on the strength of geoelectric field being mitigated. These costs range between $0 for a 4.53 V/km field to $3.6 million at a 29 V/km field. Below is a summary table of possible mitigation measures. The general mitigation costs would improve system performance at any GMD level, but there is no available calculation to determine the field strength at which, or if, they become necessary. Completing all improvements discussed in this assessment would cost approximately $46.4M.

GMD Event Geoelectric Field	4.53 V/km	14 V/km	20 V/km	23.5 V/km	29 V/km
	NERC 1 in 100 year Benchmark	Study team assumed 1 in 50 year event	Study team assumed 1 in 100 year event	Study team assumed 1 in 200 year event	Study team assumed 1 in 500 year event and EMP-E3 level
Transformer GIC blocking Cost	$0	$2.8M	$2.8M	$3.2M	$3.6M
Cost Ranking	low-cost		mid-cost		high-cost

Table 6: Cost of Calculable Maine GMD Resiliency Improvements

GMD Resiliency Improvement	Cost	Cost Ranking
GMD monitoring	$576k for 16 locations	low-cost
Replacement of all susceptible capacitor relays	$1M for 4 Capacitors	
Replacement of all susceptible relays 100+kV	$20.25M for 81 Zones of Protection	mid-cost
IPO breaker installation to improve capacitor recovery	$21M for 9 locations	high-cost

Table 7: Cost of General GMD Resiliency Improvements

Future Work on GMD and EMP

The work within this report's body does not include calculations of all known effects of GMD and EMP. For EMP - E1 and E2 analysis no simulations were performed to demonstrate the effects of HEMP or IEMI on the protection systems and communications of the Transmission System. As this topic develops, substations, control centers and other power system components should be tested for their vulnerabilities.

Harmonics were not studied to identify areas within the power system where they may become a concern. A description of possible effects is included in EMPRIMUS study. Harmonic studies are very complex and usually focused on a small subsection of a transmission system. As the industry develops its understanding of GMD effects, it is recommended to review the issue on the Maine transmission system.

Appendix A: Code for performing Geoelectric Field calculations

```
## In the code below, “folderlocation” should be replaced with the specified path
##for the powerflow case and “powerflowcase” with the case name
minvolt=1.5
minvolt2=1.5
allvolt = [0]
allangle = [0]
allBuses = [0]
allvolt2 = [0]
allangle2 = [0]
allBuses2 = [0]

psspy.bsys(2,0,[0.0,0.0],0,[],17,[100001,100002,100004,100005,100007,100050,100051,100052,100086,100087,100088,100089,100090,100091,100092,100095,100098],0,[],0,[])
for y in range(0,361):
	print y
	psspy.case(r"""“folderlocation”\C1T1D1_R6_FNSL_Updated_orr2wind.sav""")
	psspy.bsys(1,0,[0.0,0.0],0,[],25,[100001,100002,100004,100005,100007,100050,100051,100052,100086,100087,100088,100089,100090,100091,100092,100095,100098,103001,103710,103712,104054,104063,190230,190231,190237],0,[],0,[])
	psspy.gic(1,0,[0,0,1,1],[ 15.0, y,_f,_f,_f],[-1,0,1,0,1,0,1],r"""“folderlocation”
\pti_gicdata_345kV_orr2wind.gic""",str(‘“folderlocation”\ ' + str(y) +'_1.raw'),str(‘“folderlocation”\
'+str(y)+'_2.raw'),str(‘“folderlocation” \ ' +str(y)+'_3.raw'))
	psspy.rdch(0,str(“folderlocation”\ '+str(y)+'_1.raw'))
	psspy.fnsl([1,0,1,1,1,0,0,0])

#Check for lowest votlage in study area
	ierr, busarray = psspy.abusint(1, 1, 'NUMBER')
	ierr, rarray = psspy.abusreal(1, 1, 'PU')
	temp = min(rarray)
	t = min(temp)
	allBuses.append(busarray[0][temp.index(t)])
	allangle.append(y)
	allvolt.append(t)
	print allvolt

#Check for lowest votlage in Maine
	ierr, busarray2 = psspy.abusint(2, 1, 'NUMBER')
	ierr, rarray2 = psspy.abusreal(2, 1, 'PU')
	temp2 = min(rarray2)
	t2 = min(temp2)
	allBuses2.append(busarray2[0][temp2.index(t2)])
	allangle2.append(y)
	allvolt2.append(t2)
	print allvolt2



	if t < minvolt2:
		minvolt2 = t2
		angle2 = y
	if t < minvolt:
		minvolt = t
		angle = y
```

Appendix B: Buses included in reactive reserve calc

Bus Number	Bus Name	Bus Number	Bus Name
100109	BELFAST 115.00	100317	LARRABEE_C 115.00
100134	ELM STREET 115.00	100318	CHESTER SVC 18.000
100222	KIMBALL RD_C115.00	100338	SUROWIEC_R 13.800
100232	LARABEE RD_R13.800	100340	SUROWIEC_C1 115.00
100242	COOPERS ML_R13.800	100341	SUROWIEC_C2 115.00
100249	ALBION RD_R 13.800	100342	SUROWIEC_C3 115.00
100303	CROWLEYS_C 115.00	100513	PLEASANTHILL34.500
100304	RILEY_C 115.00	101380	SPRING ST 34.500
100305	SANFORD_C 115.00	102026	BELFAST 34.500
100306	MAGUIRE RD_C115.00	102238	ELM STREET 34.500
100308	RUMFORD IP_C115.00	103056	ORRINGTON_R 13.800
100310	HEYWOOD RD_C115.00	103057	ORRINGTON_C1115.00
100311	S.GORHAM_C1 115.00	103058	ORRINGTON_C2115.00
100312	S.GORHAM_C2 115.00	103059	ORRINGTON_C3115.00
100313	COOPER ML_C1115.00	103084	KEENE ROAD_C115.00
100314	COOPER ML_C2115.00	103720	3RIVERSN13_C115.00
100315	MASON_C1 115.00	902510	Q272_TAP 115.00
100316	MASON_C2 115.00		

Report:

Effects of GMD & EMP on the State of Maine Power Grid

January 2, 2015
Corrected January 5, 2015

Prepared by:

Emprimus

In Partnership With:

Central Maine Power
Emera Maine

TABLE OF CONTENTS

Introduction

Before we even begin, Emprimus would like to thank all the partners to this process including the PUC, Central Maine, and Emera Maine. This has been an honest effort by everyone to get the most accurate analysis with the data that is available. The modeling and data used is cutting edge and everyone is working with key concepts and issues not studied or even identified before to this detail in the power industry. There has not been time to resolve all data/modeling issues, but there is reference and discussion concerning the largest outstanding difference in modeling which is the PowerWorld use of worse case K-Factors, and the PSSE modeling with use of non-worse case K-Factors.

The State of Maine passed legislation on June 11, 2013 requiring the Public Utilities Commission to "**examine measures to mitigate the effects of geomagnetic disturbances and electromagnetic pulse on the state's transmission system**". In addition, two years prior to the Maine legislation, the National Association of Regulatory Utility Commissioners (NARUC) Board passed a resolution stating "**NARUC member States recognize and consider …design features rendering infrastructure less susceptible to the threat of damage from sever space weather and EMP" , and supporting "protection of utility infrastructure against electromagnetic effects."**

What drives this concern for the power grid? There is agreement in the space weather scientific community that a severe solar storm capable of collapsing the power grid will happen with a 100% certainty. And these experts are predicting a 12 percent chance in the next 10 years and a 50 percent chance in the next 50 years (a very high set of probabilities to most certainly affect us, our children and grandchildren for sure). In a similar analogy, we feel it would be better to focus on what measures it would take to make transmission towers and lines more resilient against ice and wind storms rather than to calculate the probability that a severe ice storm will hit Maine or a particular part of Maine.

In addition to studying grid collapse and damage from severe solar storms and EMP, a recent study led by Zurich Insurance revealed that harmonics on the power lines, caused by ordinary low-level solar storms, are causing significant damage to customer equipment, and generating billions of dollars in annual insurance claims in the US. By prorating these findings to Maine the losses could equal $40M or more per year. So the problem now is not just a 1 in 10 or 1 in 50 year problem, it is also an every year problem.

Currently, Emprimus, PowerWorld and Central Maine Power are working to resolve recently discovered data issues relating to worse case VAR loss consumption (K Factors). PowerWorld modeling uses "worse case" K-Factors which are twice the value of some of the K-Factors used in the PSSE modeling by CMP which will primarily affect the portion of the studies showing voltage/grid collapse. There is not time at present for CMP to re-run and to test the differences in results with new K-Factors. To date, no "safety factor" has been put into all of the analysis considering public health and safety and national security are affected, and so Emprimus urges the use of the larger K-Factors. There is a safety factor of 2 used in the design of many buildings, for example.

Most high voltage transformers that have been evaluated in these studies show vulnerability or are the cause for mitigation because of multiple factors including voltage/grid collapse for severe solar storms and EMP, to prevent damage to Maine customers and utility equipment from harmonics caused by the every year occurring low level solar storms, and thermal heating. Nearly every transformer identified for neutral blocking has at least 2 independent analyses requiring blocking and some have 5 independent analyses to support blocking.

The Maine PUC has raised interesting and legitimate preliminary questions which are answered in a new section added after the Executive Summary. We urge a long view that takes into account not only the damage to Maine customers due to harmonics generated by low level solar storms occurring every year, but the absolutely devastating effect on the State caused by a solar super storm (with a 100 per cent chance of occurring sooner or later) on the entire US including the entire State of Maine.

This report by Emprimus LLC is to be considered along with a parallel report by Central Maine Power. Both reports include partnering efforts on securing data and other information by other organizations as well including Emera Maine. The results of the initial studies performed to answer the questions raised in Maine's 2013 legislation (and NARUC's supporting resolutions) are included in these two reports.

Emprimus LLC is a research and development organization that is focused on the development of mitigation equipment to protect our electrical and computing infrastructure against Geomagnetic Disturbances (GMD), Electromagnetic Pulse (EMP) and Intentional Electromagnetic Interference (IEMI). Emprimus has partnering efforts with:

1. Utilities to model the effects of Geomagnetic Disturbances on the power grid,
2. Utilities to design mitigation strategies and protective equipment,
3. Space scientists and physicists to establish credible GMD, IEMI and EMP threat levels,
4. Data centers and control centers for protection against IEMI, EMP, and GMD vulnerabilities
5. Equipment suppliers to design and fabricate protective GMD,EMP, and IEMI mitigation equipment
6. PowerWorld LLC to perform power system modeling studies,
7. Idaho National Labs, KEMA, Environ and other companies for testing protective equipment.

Protective equipment that has been prototyped, tested, and modeled is then licensed to reputable suppliers for direct sale to utilities, data centers and other companies.

Emprimus has partnered with Central Maine Power, and Emera, to study the effects of GMD and EMP on the Maine power grid. The studies included a vulnerability threshold analysis, neutral GIC current harmonic thresholds, power transfer and initial contingency sensitivity, the results of putting neutral blocking systems on certain high voltage transformers, and an initial cost benefit analysis.

Executive Summary

The Maine grid and the high voltage transformers in particular were evaluated for solar storm (GMD) vulnerability for both severe infrequent events and common every year low level solar storms, EMP level geo-electric fields using multiple criteria including grid voltage collapse and harmonic damage and disruption to customers and utility equipment. Two grid models, PowerWorld and PSSE, were independently run and results are all tabulated together in one table to show each transformer's vulnerability on five separate factors. Each transformer with suggested neutral blocking is identified by at least one factor. Most transformers for which neutral blocking is recommended has been identified by at least two factors and some are identified by five factors. At the present time the model PowerWorld has been run with the "worse-case" transformer K Factors per the recent paper by T. Overbye, while the PSSE modeling did not use "worse case" K Factors. The higher the K Factor, the larger VAR loss/consumption is modeled which will have a significant effect on voltage/grid collapse. The PowerWorld recommended K Factors are about twice as large as that used in the PSSE modeling. Emprimus believes that for a risk involving public health and safety including national security, the proper modeling should use "a worse case" third party recommendation. It is like designing a bridge or building for worse case loading, not average loading, or designing with a safety factor.

The Emprimus / PowerWorld modeling of the Maine power grid was validated by comparing the GIC current predictions with available GIC data collected at the Chester, Maine substation. **This validation shows that the modeled maximum GIC currents at Chester for the highest geo-electric coupling field angles are about a factor of three lower than the maximum Chester data when plotted against the recorded magnetic rate of change data.** This validation shows that the Emprimus/ PowerWorld modeling can be used for conservatively predicting, to within a factor of three, the GIC currents that can be expected for future severe GMD events.

Further research is recommended to better reconcile the higher actual geomagnetic induced currents recorded at Chester, Maine, and the recurrent "tripping" of the Chester Static VAR compensator with the current Emprimus-PowerWorld modeling effort. If the modeling of projected solar storms produces systematically *lower* volts per kilometer per phase of high voltage transformers, the risks of grid collapse in the State of Maine may be under-estimated. Hence, improvements in modeling are needed to better reconcile actual historical data and the models used to make decisions on hardware protection of critical grid equipment.

The Maine grid has significant vulnerability to severe GMD storms under peak transfer conditions even without system contingencies (grid voltage collapses) at or less than 1 in 50 year event and has significant vulnerability to EMP geo-electric fields which are even higher than severe GMD storms. Initial modeling showed numerous transformers with GIC levels of 150 amps of neutral current which can cause generator and customer equipment damage. The analysis also showed a number of neutral currents in excess of 50 amps which will likely lead to harmonic related damage to customer equipment.
The grid can be easily protected with high voltage neutral blocking at just 12 substations (18 transformers) for GMD events and studies show EMP levels of protection can be achieved with neutral blocking applied to about 30 transformers in Maine and surrounding areas (i.e. about 12 outside of Maine). To achieve full EMP E3 protection some transformers in neighboring systems

will also require neutral GIC blocking systems four of which resided in New Brunswick as seen in the table. The higher level of blocking will also give much added levels of protection to customers, transformers and generators from GMD/ EMP induced harmonics.

A recent publication by a group from Zurich, Lockheed Martin and NOAA [13] suggests about a $2B per year loss in the United States which can be attributed to harmonics caused by low level solar storms. This would then represent customer damage on the order of $20 - 40 M per year for Maine customers

New NERC and existing utility operational standards require power transfers to be reduced by 10 percent during a significant GMD event. Modeling shows that these operational standards are of little value to maintain grid stability, and do almost nothing to reduce the effects of harmonics that are introduced into the grid by all level solar storms. Modeling the effects of GMD showed that transfers will need to be reduced dramatically (i.e. by 80 percent or more) to have a meaningful effect if operating procedures rather than neutral blocking are to be relied upon. This preliminary study has not attempted to offer revised operating procedures for Central Maine, and Emera Maine. However, if neutral blocking is used, most of the GMD operating procedures become moot and unnecessary with regard to GMD and EMP E3 threats. If new Independent Pole Operation (IPO) is installed in the grid, it will enhance somewhat the ability to keep the grid operational for lower level solar storms but not severe solar storms nor EMP. IPOs will do little to reduce the harmonic issues.

The following table summarizes the results of the analysis for each critical transformer in the Maine grid. All of the transformers recommended for neutral blocking have a minimum of one factor supporting the recommendation, but most transformers have at least two independent factors supporting blocking, and some have five reasons to support blocking. Note that seventeen (17) transformers satisfy at least two criteria for applying neutral blocking systems. Four of the five generated columns come directly from CMP data and modeling which are not dependent upon changing K Factors. The higher K-Factors primarily affect the vulnerability for voltage collapse illustrated in the first column.

Comparison of Five Criteria for Selecting Transformers for Neutral Blocking Protection

	PowerWorld Model /worst case K-Factors	CMP/ PSSE Model and non-worse case K - Factors	PSSE Model	PSSE Model	PSSE Model
Maine Transformers	**GMD Voltage Collapse [1,2]**	**GMD Transformer Damage [1,3]**	**GMD Harmonic IEEE Std [1,4]**	**EMP E3 Harmonic IEEE Std [1,4]**	**GMD Generator Heating [1,5]**
2 winding delta - wye					
Chester SVC 18/345 kV	1	1	1	1	1
Yarmouth GSU 22/345 kV #4	4	1	4	4	4
Keene Road GSU 115/345 kV		1	1	1	1
Newington TR1			1	1	
Bucksport (3 GSUs)	1				
2 winding Auto Xfmrs					
Orrington 345/115 kV #1	1			1	
Orrington 345/115 kV #2	1			1	
South Gorham 345/115 kV #1	1			1	
South Gorham 345/115 kV #2	1			1	
Mason 345/115 kV #1	1			1	
Maguire Road 345/115 #1	1	1	1	1	
Keene Road 345/115 kV #1	1			1	1
Keene Road 345/115 kV #2	1				1
3 winding Auto xfmrs					
Coopers Mill 345/115 kV #3	1	1	1	1	

Surowiec 345/115 kV #1	1	1	1	1	
Albion Road 345/115 #1	1	1	1	1	
Larrabee Rd 345/115 #1	1	1	1	1	
Total Neutral Blocking Sys	**18**	**8**	**12**	**18**	**8**
New Brunswick Transformers					
2 winding delta - wye					
COLESON COVE 19/345 kV GSU 1		1	1		1
COLESON COVE 19/345 kV GSU 2		1	1		1
COLESON COVE 19/345 kV GSU 3		1	1		1
Pt Lepreau GSU 26/345 kV		1	1		1
Total Neutral Blocking Sys	**0**	**4**	**4**	**0**	**4**

1. Note: All Criteria for a one in 100 Year GMD Storm (20 V/km)
2. Results from Emprimus/ PowerWorld Analysis for Line Voltage < 95%
3. Results from CMP PSSE Analysis for GIC > 75 Amps per phase
4. Results from Emprimus/ CMP PSSE Analysis for GIC > 32 Amps per phase
5. Results from Emprimus/ CMP PSSE Analysis for GIC > 50 Amps per phase

<u>GMD events</u>

The power system analysis conducted on the Geomagnetic Disturbance (GMD) effects on the Maine Bulk Electric System (BES) shows that voltage collapse occurs at Electric Field (E-field) levels of 16 V/km (summer peak load) to 21 V/km (shoulder load). In addition the analysis shows the voltage collapse point is extremely sensitive to the amount of power imported from New Brunswick. For the maximum of 1,000 MW allowed cross the border the analysis shows the voltage collapse point at 14V/km (summer peak load) and 15.5 V/km (shoulder load). These E-field strengths can be present from GMD events that statistically can occur once every 50 years. These fields should be contrasted with the much higher 40V/km geo-electric fields present during an EMP event.

The analysis also studied the application of the SolidGround neutral blocking systems on transformers in Maine. The analysis applied the SolidGround neutral blocking systems at substations with the highest Geo-Electric Induced Currents (GIC). The results show a significant improvement of the resiliency of the Maine Bulk Electric System (BES) when neutral blocking was applied to twelve substations (eighteen transformers). The voltage collapse E-fields with neutral blocking systems applied at ten substations were improved to 16 V/km (summer peak load) and 32 V/km (shoulder load).

<u>EMP events</u>

Solid Ground is designed with EMP mitigation in mind, and it is a vital component for providing mitigation for the Maine BES against this electromagnetic threat. PowerWorld modeling shows that Maine can achieve significant protection from the EMP E3 (i.e. geo-electric field of 40 V/km) component by protecting the transformers with Solid Ground neutral blocking systems. However, for full protection the neighboring power systems will need some protection as well. In addition, EMP mitigation requires protection of sensitive electronics from the EMP E1 pulse. Solid Ground's electronics are shielded, but other substation and SCADA equipment will need to be shielded and protected as well. PowerWorld modeling to date shows that employing a number of Solid Ground systems for GMD mitigation in the Maine BES will approach the desired levels for full EMP E3 protection.

Response to Maine PUC Staff Comments and Questions on Emprimus Report

1. Referencing page 3, please clarify the reference to "transfers". Is this a reference to the 1,000 MW North to South transfers from NB to ME or are there other transfers that will need to be reduced dramatically to lower the effects of GMD event in ME?

   Answer -This is the primary transfer being considered. However with the new transmission going into service, and the growth of the load, these transfers could also occur in other or increased amounts.

2Referencing the cost of re-dispatched generation seen in the PJM market, ISO-NE has stated that it has never had to re-dispatch generation as a result of a GMD event. Given that, why should savings on re-dispatch costs be considered in a cost-benefit analysis?

Answer – There is clear documentation that NextEra Seabrook generation plant has reduced generating power as a result of a weak solar storm warning. This occurred on July 14- 16, 2012 when power generated at the plant was reduced from 85% to 63% for a duration of 40 hours because of a long elevated GIC event [23]. This reduced power operation action was taken as the result of a NOAA Solar Storm warning. The NOAA alert was for a K-index 6 storm (from a scale of K -1 to K- 9. GIC current peak recordings of one burst at 40 Amps DC and three peaks recorded at 30 Amps DC. It should be noted that Seabrook at the time was de-rated to the 85% power level due to an unrelated issue with the main generator. The above information was presented in a paper titled "Next Era Nuclear GMD Mitigation", by Kenneth R. Fleischer, P.E. of NextEra Energy [23]. Some of this information can also be found in the US Government records at http://www.nrc.gov/reading-rm/doc-collections/event-status/reactor-status/2012/20120716ps.html#r1. This report states "REDUCED POWER DUE TO SOLAR MAGNETIC ACTIVITY CAUSING HIGH CIRCULATING CURRENT IN UNIT 1 TRANSFORMER - POWER LIMITED TO 85% BASED ON GENERATOR STATOR COOLING DELTA T LIMIT - SWITCHYARD MAINTENANCE ON-GOING UNTIL APPROX. 7/17/12". And additionally, a Reuters News article "NextEra cuts N.H. Seabrook output due to solar activity", by Scott DiSavino, July 16, 2012.

What is more important is that the new NERC GMD Operational standards require such actions from the utilities in most states. In addition, ISO NE operating procedures have provisions for this and also make provisions for Transmission Congestion Costs which create non-economic dispatch costs for a whole variety of conditions, including GMD. The ISO NE Transmission Congestion costs for 2012 was $40 Million. If just 5 per cent of this was due to GMD, or will be due to new GMD NERC operating procedures, this would cost Maine customers $2M/year.

In addition to non-economic dispatch costs, a recent publication strongly suggest high customer losses due to harmonics of low level solar storms [13]. The latest Zurich/Lockheed Martin/NOAA study suggests about a $2B per year loss for the 48 states. This would then represent customer damage on the order of $20 - 40 M per year to Maine customers. These damages are most likely caused by the GIC generated harmonics which violate the IEEE 519 Power Quality standard.

3 The estimate used on page 4-5 for the cost of the uneconomic dispatch assumes 1,000 MW for a 24 hour period. A) Are the 1,000 MW referenced intended for ME load? Is the 24- hour period representative of the GIC occurrence?

Answer: The 1989 Solar storm lasted approximately 30 hours. The 1859 Carrington event lasted 12 days or about 288 hours. Large generators are unable to be turned completely on and off on short notice. The large boilers supporting the turbines usually take a minimum of 24 hours to turn off and about the same duration to back up to full generation when starting up. Nuclear plants can take even longer. Since it is unknown how long solar storms will usually last, it would be risky to attempt to change generation in a non-economic dispatch situation before the peak geo-electric fields have passed. If the New Brunswick to ME transfers would be greatly reduced (whether or not serving Maine customers directly), it could lead to grid collapse in Maine.

1. On page 5, please attribute where the revenue losses are occurring.

Answer: If a customer has equipment that is susceptible to harmonic damage, such as motors, condensers, air conditioning, computer data centers, etc, then not only will the customer suffer equipment damage, but also loss of revenue due to their main equipment being disabled for an extended period of time. Large motors, condensers, computer UPS systems, etc take some time to be replaced. An estimate was used to reflect those businesses whose electric use was approximately 10 per cent of their operating expenses/revenue (appropriate for businesses with large motors, pumps, condensers, UPS systems, etc). If these businesses lose power, then the revenue loss is approximately 10 times the electric use cost.

5. On page 6, please include any information on the frequency actionable solar storms hit ME, if known.

Answer – A summary can be found in the NERC Reliability Guideline: GMD Disturbances, March 21, 2005. This guideline states that "On average there are 200 days over the 11-year solar cycle with strong-severe 86 geomagnetic storms, and approximately 4 days of extreme conditions." So on average over 18 days of strong to severe GMD storms per year which hit the Earth. Such storms are typically many thousands of times larger than the Earth. For example the CMEs ejected from the sun in July of 2012 were about 150 million miles wide after traveling 93 million miles – published by Dr. Daniel Baker et al of the University of Colorado and NOAA, 2013 [24]. In this case the width of the CMEs were over 18,000 times the diameter of the Earth (7,918 miles). Note, the Solar CMEs of July 2012 did not hit the Earth as they were ejected out the back side of the sun. Therefore when these extremely wide multiple CMEs, ejected over several days, we can expect that all regions of the Earth are vulnerable. For example the Halloween solar storm of 2003 resulted in Geomagnetic Disturbances in North America as well as in Europe. The actionable solar event for Maine should be the roughly 20 minute warning alert from NOAA that a solar event of K 6 or above will hit the Earth. Therefore the frequency as stated above is 18 days of actionable solar storm events per year (or 200 days over an 11 year solar cycle).

Additionally, A recent publication shows that there is significant customer equipment damage (insurance claims of over $2B per year) caused by harmonics are attributed GMD events every year [13].

Finally, a solar super storm is estimated by four experts to hit the US, and the State of Maine, with a frequency of about 12 per cent in 10 years and 50 per cent in 50 years (see figure 1 and table 1 in the report and the four referenced publications). Such a solar super storm would hit all of the US and likely a major portion of North America and Europe.

6. Regarding page 7 Table 1, is the assumption that the Carrington Storm type event will hit Earth, or is the assumption more specific in relation to location? Has Emprimus attempted to determine the probability that a Carrington type event will hit the Maine or New England area?

Answer – A Carrington storm will be much larger than the Earth as was described in the answer to Question #5 above so it will impact not only New England and Maine but all of the US, Canada and Mexico. The Carrington event included observations of Northern Lights in Cuba, bright auroras in Colorado such that miners got up in the middle of the night to fix breakfast. Such a storm will easily cover all of Maine, New England and the entire United States. So the probability of a Carrington event hitting Maine and New England is the one in 50 years as described in the table which was taken from the four publications cited.

An EMP event could also cover a large area including all of New England. In fact, many experts believe the eastern US is a likely first target for EMP including targets such as New York, Washington DC, Baltimore, and Atlanta. The every year lower level solar storm causing harmonic damage to customers hits Maine every year. Everyone, including NERC, believes the Northern States are the most susceptible states.

Cost Benefit Analysis

The total cost of mitigation must be compared with the benefit received for each level of mitigation. The assumed installed cost per blocking unit used for this study is $400,000. This cost excludes engineering, controls and training in the use of the device. The cost of training and use of controls will be higher for the first blocking unit installed and relatively small for the additional units.

The true cost of the blocking devices should be reduced by the averted cost/penalty incurred by utilities (and their customers) otherwise employing re-dispatching / non-economic dispatch of energy when NOAA issues a GMD actionable warning of K-7 or higher. These re-dispatch actions occur on the average once per 2 month period based on NOAA and PJM geomagnetic disturbance (GMD) data [1]. Many utilities, including much of the East Coast, attempt to operate through GMD events by re-dispatching energy from the least-cost available generators (base load at a cost of about $40/MWHR) to gas turbines (operating on the spot market at a cost of in excess of $100/MWHR). The preparatory strategy is to have as many generators operating as possible to respond to large grid VAR swings which occur when the transformers go into ½ cycle saturation during GMD events. The cost of this uneconomic dispatch per 1000 MW per 24 hour period is $60 x 1000 x 24 = $1,440,000. We discovered that power transfers need to be reduced by 80% or more to be effective. A power transfer change of 1000 MW or more maybe required. Power transfers are currently limited to 1,000 MW so transfers should be reduced to 200 MW (i.e. a 800 MW reduction). However, if the transfer limit goes up to 1,300 MW when the new transmission facilities are in place, transfers alone would need to be reduced by 1,000 MW. On top of that, base load generation reduction of 1000-2000 MW could easily occur for some utilities. If a total of just 1,000 MW were re-dispatched, it could easily result in an increased energy cost of $1,440,000 (which could happen about once per 2 months) for a total yearly cost of $8,640,000.

The averted annual costs of redispatch and reduced transmission throughput could fund the total purchase and installation costs of up to 21.6 blocking units per year. This is probably the most realistic level of re-dispatch for CMP due to the need to reduce imports/exports during solar storms without hardware protection of transformers. If 2,000 MW were re-dispatched (for the larger ISO NE system), the cost to all regional utilities and its customers would be $2,880,000 per two month period or equivalent to 43 blocking units per year of operations. Thus, a large portion, if not all of the cost, of the blocking units could be paid for by the utility installing blocking and not having to re-dispatch energy at much higher rates.

If one assumed no benefit whatsoever from eliminating re-dispatch of generation the total assumed cost to install blocking for 15 transformers to achieve minimum GMD grid protection for the state of Maine would be about $6,000,000. The preliminary, but uncompleted studies show further significant grid improvement (nearly to the EMP E3 level) and for harmonics by installing 30 total blocking units for a cost of about $12,000,000. For true High Altitude EMP protection, additional shielding costs will be incurred to protect controls from E1. However, most of Maine's large, long lead time transformers will be protected and most of Maine's customers will be protected against grid harmonics (as well as preventing grid collapse).

The offsetting benefits to protecting the Maine grid include:

1. Loss of revenue for blackouts in Maine is about 2000 MW x $120/MWHR times 24 hours = $5,760,000 per day. Some energy costs in New England are much higher. If an extended outage for a severe storm occurred the estimate of lost revenue balloons to $40.6 M per week or over $161 M per month.
2. Permanent damage to transformers. Loss of just several high voltage transformers could be $10-15M including engineering, transportation and installation. Loss of 10 could be $50M plus installation and the lead time could be 1-2 years or more.
3. Permanent damage to generators from harmonics. The damage to each generator could be $10-50M or more. Thus, just the loss of two could be $20-100M, depending upon size of the generator.
4. Loss of revenue to customers. The customers, for long term outages, would likely suffer many multiples of the energy loss shown in number 1. If one assumed an average of energy being 10% of the cost of a company's budget (some would be higher and some would be lower), the loss of revenue to Maine customers would be $57,600,000 per day of blackout. Many customer employees would likely suffer layoffs, with additional indirect losses for the entire Maine economy.
5. Loss due to equipment damage to customers. Customers who lose their equipment to harmonics damage would also suffer an extended loss of revenue. The total of these costs, if damage occurred to just 10 percent of Maine customers, could easily exceed another $100M. Many customer employees would be likely laid off as well.
6. Public health, safety and security. The additional cost and difficulty for first responders, to maintain order, public safety, medical aid, securing necessary supplies, alternative housing and food, water and fuel, etc for extended outages is believed to be substantial and could result in personal injury and death (especially for the sick, disabled and elderly).

Probability of Solar Super Storm Occurrence

New independent findings by several scientists now show that a Carrington type severe solar storm could well be a one in fifty (50) year event rather than the previously understood one in one hundred (100) year event. These new findings are described in the materials presented below.

Actionable solar storms hit North America on average about every other month [1]. The probability of a Solar Super Storm hitting the Earth again has been examined by several independent authors and four papers [2-5] have been published in scientific journals within the last two years. The Solar Super Storm is defined as a Carrington Storm (nominally 4,800 nT/min) that was experienced in 1859 and again in 1921. The four papers which address this issue were published by P. Riley (2012), R. Thorberg (2012), J.J. Love (2012), and R. Kataoka (2013). These authors all employ the so called Poisson process which results in a cumulative probability P(t) that is given by the exponential distribution

$$P(t) = 1 - \exp(-\lambda t)$$

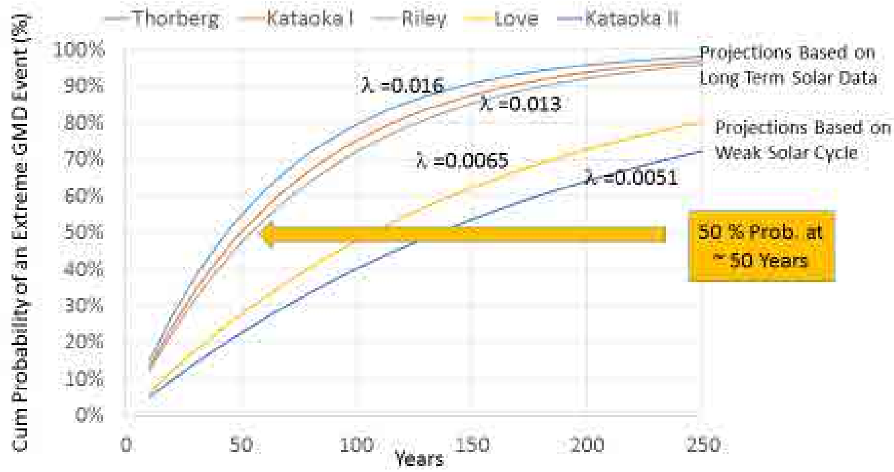
where t is time in years and λ is a single parameter that is selected to fit to the recorded data. These authors also used different sources of long term recorded solar storm data as the basis for their findings. For example; P. Riley used 45 years of magnetic data and 10 years of CME speed data from NASA recorded sources, R. Katakoa examined 89 years of recorded magnetic data from the Kataoka Observatory in Japan, J. J. Love used 10 years of USA recorded magnetic data and R. Thorberg employed 60 years of magnetic data records from Northern Europe. The basis for using the Poisson process can be found in several papers and in a book by S.M. Ross [6]. The results presented by these papers show the cumulative probabilities of a Carrington event hitting the Earth in future years. For comparison the results presented in these papers are shown in the first column of table I below.

Table I - Probability a Carrington Storm (4,800 nT/min) will hit within 10, 20, 30 & 40 Years (data fit to Poisson Distribution)

Published Predictions	Predicted Probability (%) Within 10 Yrs	Probability (%) Within 20 Yrs (Poisson Dist.)	Probability (%) Within 30 Yrs (Poisson Dist.)	Probability (%) Within 40 Yrs (Poisson Dist.)
P. Riley [1]	12	22.6	31.9	40.1
R. Katakoa [2]	13	24.3	34.2	42.7
R. Thorberg [3] *	14.7	27.2	37.9	47.1
J. F. Love [4] Weak Solar Cycles	6.3	12.2	17.7	22.9
R. Katakoa [2] Weak Solar Cycles	5	9.8	14.3	18.6

Note that the Thorberg provided a probability for a super solar storm within a 3 year period of 4.7% which has been extended in Table I to a probability within 10 years of 14.7% assuming a Poisson process. This Table also shows the cumulative probability for 20 years, 30 years and 40 years again using the Poisson process for the results presented for each of these four authors. These same cumulative probabilities are shown graphically in Figure 1 below.

Figure 1 - Cum Probability of an Extreme (Carrington) GMD Hitting the Earth versus Future Years



These graphical results show a remarkable agreement for the results of three of the predicted probabilities for an extreme Carrington GMD event hitting the Earth. These plots suggest that there is a 50% probability that a solar super storm (Carrington event) will hit the Earth within 50 years. Hence, the so called one in one hundred year Carrington event could well be a one in 50 year event. It should be noted that R. Kataoka treated two cases; namely, probabilities based on long term solar storm data and based on a weak solar cycle. The weak solar storm cycle cumulative probability is shown in the lower Kataoka II curve while the long term probability curve is shown in the upper Kataoka I plot. The prediction by J. J. Love is believed to also treat the case of a weak solar cycle.

Geo-Electric Field Strengths and Harmonic Standards

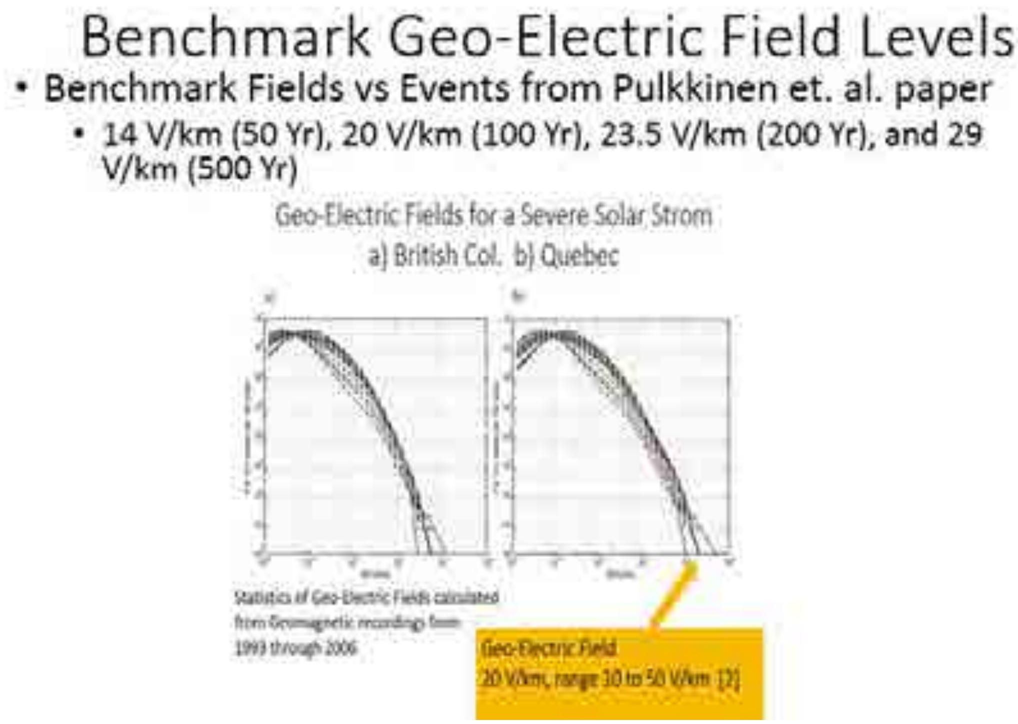
Geo-Electric Field Strengths

All standards protecting the public health and welfare must be peer reviewed and must protect against the most severe credible threat or conditions. Bridges are built for maximum stress, not average load. Hurricane, wind, aviation and seismic standards follow similar requirements. Typically a safety factor of two (2) or higher for these type of standards are required when designing structures and equipment to withstand these type of events. When such standards are not followed, sooner or later drastic results will follow (i.e. Hurricane Sandy and Katrina). For GMD and EMP risks, the highest credible electric fields need to be modeled (as opposed to average fields), and resulting harmonics and customer damage should be reviewed for all field levels (low and high).

Initial studies were performed with a range of values higher and lower around the vetted standard of 20 v/km for a solar super-storm (14, 20, 23.5, and 29 v/km corresponding to 50, 100, 200 and 500 year solar storm projections). The 20 v/km standard is supported by:

1. A. Pulkinnen et al peer reviewed paper published in 2012 and Kappenman reviewed work which closely correlates to these numbers. This paper established a range of 10-50 v/km with an average of 20 v/km.
   The Geo-Electric Benchmark Fields were established at the initiation of the vulnerability analysis of the Maine Bulk Power System related to Geomagnetic Disturbances (GMDs). The field values were derived from the peer reviewed, vetted and published data in 2012 of Pulkkinen et al [7]. The published data was taken over 13 years (January 1993 to December 2006). Two soil types were considered, an electrically conductive soil like that in British Columbia and a less conductive soil like that found in the providence of Quebec. Earlier published work has shown that the soil type in Maine is very similar to that of the Quebec province [8]. Therefore the benchmark soil conductivity of Maine was assumed to be the same as that of the Quebec province. The data used by Pulkkinen et al to generate the statistics was 10 second data similar to that used by others such as R. S. Weigel et al [9] and J. Kappenman [10]. The results show the geo-electric field intensity of a severe Carrington one in one hundred year, solar storm impacting the Earth is 20 V/km with an error range of 10 V/km to 50 V/km, shown in Figure 1.

Figure 1. Geo-Electric Fields for Quebec from Pulkkinen et. al. Space Weather paper



Analyzing the same data set results in mean value severe storm field intensity levels for a 50 year, 200 year and 250 year storms as 14 V/km, 23.5 V/km and 29 V/km respectively. These are all mean values, i.e. no error ranges applied, derived from the available vetted data presented in the Pulkkinen et al published paper [7].
The earlier (2010) published results by Kappenman [8] are in reasonable agreement with the more recent Pulkkinen et al findings [7]. This comparison is shown in Table I below.

Table I. A Comparison of Geo-Electric Fields for a One Hundred Year Solar Storm

100 Year Geo-Electric Field Magnitudes for 4,800 nT/min Storm

Area in NA	Southern States (AL, GA, NC, SC, TN)	British Col.	WI, MI, VT, NH, ME, Ont., Quebec	Lower NY, NJ, Eastern PA
100 Year Geo-E. Field J. Kappenman	4.8 V/km	4.4 V/km	15.2 V/km	31.2 V/km

Area in NA		British Col.	Quebec	
100 Year Geo-E. Field A. Pulkkinen et.al.,		5 V/km (3 to 15 V/km)	20 V/km (10 to 50 V/km)	

Estimates from J. Kappenman are from MetTech Report # 319, 2010 scaled up to 4,800 nT/min.
Estimates from A. Pulkkinen et.al. are from Space Weather publication in 2012

For the soil types of the northern US states, Ontario and the province of Quebec Kappenman's data for a one hundred year storm (4,800 nT/min) is 15.2 V/km. Whereas the Pulkkinen et al paper (2012) show a value of 20 V/km with an error range of 10 to 50 V/km. For the purposes of the Maine vulnerability analysis the mean field levels for the various severe storms were derived from the Pulkkinen findings.

2. The EMP field to be protected against is a minimum of 40 V/km which is higher than the projected 29 V/km for a 500 year solar event. It should be noted that the mitigation recommended achieves protection to 30 V/km which is approaching the EMP threat levels. Further analysis was not completed at this time but more mitigation would be necessary to protect an EMP level of 40 V/km.

3. The latest, as yet unapproved NERC Benchmark model, contains a 200 km by 200 km area with a geo-electric field 20 V/km "hot spot" which moves around significantly during a 12 day solar super-storm like the Carrington event [11]. Such a hot spot could easily cover the State of Maine and is another data point supporting the 20 V/km hot spot. Once again, the worst credible threat must be used for public health and safety.

4. A recently paper [12] published in 2014 states the following: "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." The paper reports geo-electric field observations as high as 0.67 V/km for a solar storm in China at a geomagnetic latitude of less than 13

degrees which occurred in 29 – 30 May 2005. This storm was a moderate to weak storm (K7) with magnetic recordings which did not exceed 30 nT/min (or 0.2 nT/sec). However, using the proposed NERC GMD Standard TPL – 007 formula for this low geomagnetic latitude (13 degrees) results in a geo-electric field of only 0.03 V/km for a one in one hundred year storm. Therefore, recorded and published geo-electric field data for a weak storm (May 2005) exceeds the proposed NERC one hundred year storm standard field by more than a factor of twenty (20). This is a clear demonstration that the proposed latitude dependence used in the proposed NERC GMD standard is flawed as it differs by orders of magnitude with recorded data in China, in the U.S., and elsewhere.

Harmonic Impacts

Many transformers can be driven into saturation at low GIC (i.e. DC) current levels. This saturation in turn results in the generation of harmonics that can propagate throughout a network. It is well known that these harmonics can have a wide variety of impacts to the bulk electrical system (BES) and customer equipment. The following materials describe some recent findings related to GMD harmonic issues.

A. GMD Induced Harmonics Cause Power Quality Issues

Recent Insurance Study Shows Losses Related to Solar Storm Events

A recent insurance study by C. J. Schrijver, R. Dobbins, W. Murtaugh, and S.M. Petrinec in the Space Weather Journal, 2014 shows a statistical relationship between billions of dollars of equipment and business interruptions losses in the USA that related to elevated geomagnetic activity [13]. This statistical study used insurance claims over an eleven year period (2000 to 2010). The estimated losses that correlate to GMD activity are conservatively on the order of $2 to $3 billion annually.

The likely candidate cause of these losses is the GMD generated harmonics levels, caused by the half cycle saturation of transformers due to geomagnetically-induced currents (GICs).

B. IEEE Harmonic Standard and Potential for GMD Component Damage

The IEEE Standard for harmonic power quality are available in the IEEE 519 – 2014 document. This standard is aimed at preventing heating and potential damage to generators and customer equipment and associated customer power outages. A table from this document is shown below in figure 3.

Figure 3. – IEEE 519 standard for Voltage Distortion Limits

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq$ 69 kV	3.0	5.0
69 kV < $V \leq$ 161 kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

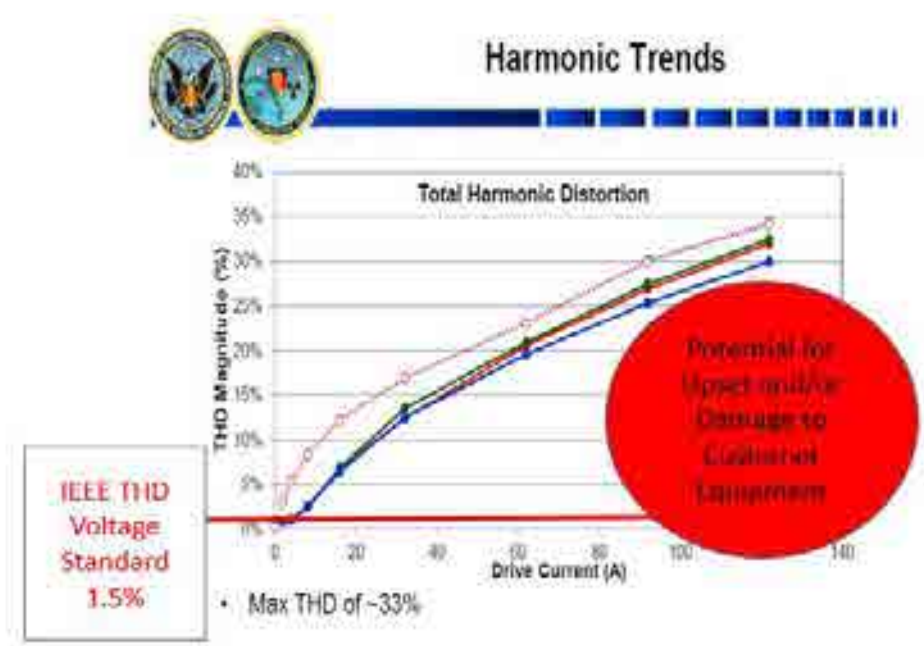
The voltage total harmonic distortion (THD) limit for high voltage buses (V> 161 kV) for longer than three (3) seconds is 1.5%. And the Voltage THD limit for medium voltage buses (69 kV to 161 kV) longer than three (3) seconds is 2.5%.

In a paper published by Rezaei-Zare and L. Marti it was shown that the standards underestimate the GMD induced effective negative sequence current which contributes to generator rotor heating [14]. The paper concludes that “the simulation results reveal that the generator capability limit can be exceeded at moderate GIC levels, e.g. 50 A/phase, and rotor damage is likely during a severe GMD event.”

C. Power Quality Issues Seen in Idaho National Labs Testing

In September of 2012 the Department of Homeland Security (DHS) conducted a series of tests on a live power grid at the Idaho National Laboratories in Idaho Falls, Idaho [20]. The initial set of tests injected DC currents (simulated GIC currents) into two power transformers to determine potential power quality issues related to GMD events [15]. An example of on such test is shown in figure 4.

Figure 4 – THD Harmonic Distortion versus injected DC current.

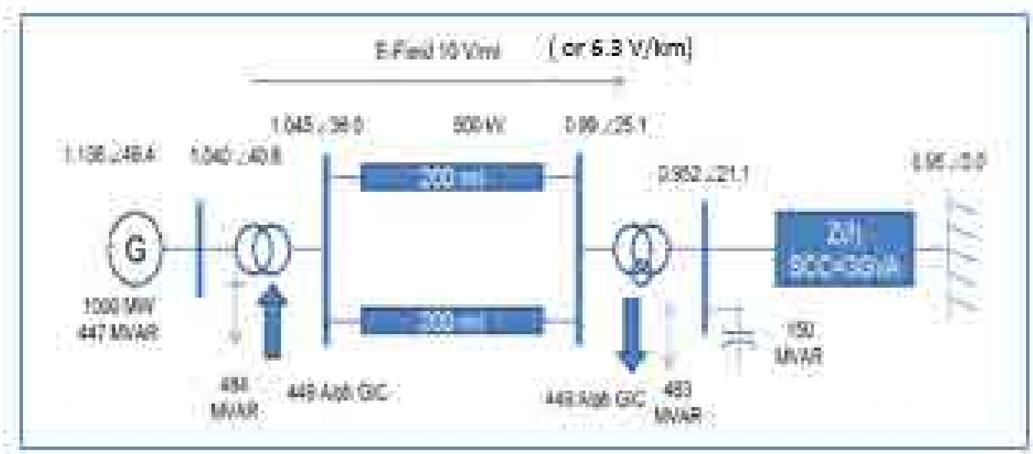


It was observed that at 6 Amps or less the IEEE 519 standard for voltage total harmonic distortion was exceeded. And at 120 Amps of DC injected current the harmonics were above 30 %. Such harmonics are therefore a concern and a potential issue that can result in power equipment and customer equipment damage.

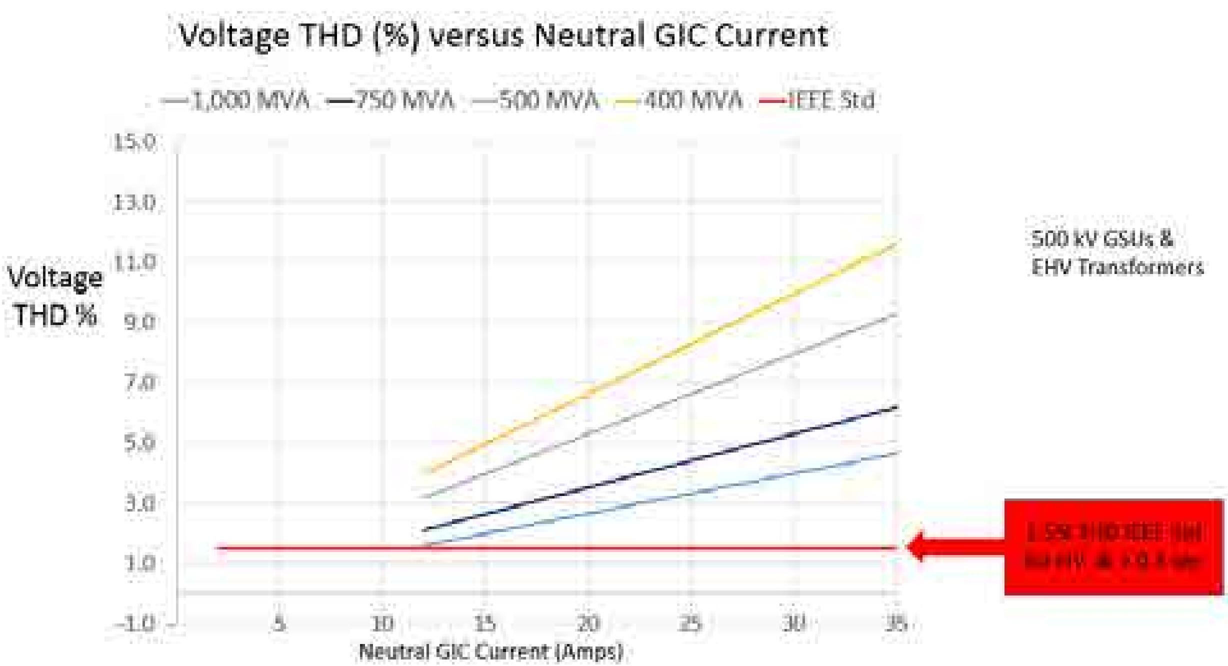
D. GMD Induced Harmonics in Power Grids

A paper published by Dong et al in 2001 analyzes GMD induced current harmonics for four transformer types [16]. A recent paper by R. Walling examines both current and voltage harmonics for single phase transformers [17]. The current harmonic

results present by Dong et al for single phase transformers are in close agreement with the Walling results.
The Walling report then goes on to examine GMD induced voltage harmonics in a hypothetical 500 kV network with single phase GSU and EHV transformers (400 to 1,000 MVA). This hypothetical network is shown in figure 5.
Figure 5 – Power Network Analyzed for GMD Harmonics by R. Walling



The results indicate that the IEEE 519 standard for voltage harmonic distortion (1.5%) will be exceeded at Neutral GIC current levels of less than ~ 8 Amps. Converting Walling's results from pu units to THD % and Amps the results shown in figure 6 can be derived again for high voltage single phase transformers.
Figure 6 – Voltage THD (%) versus Neutral GIC Current



The results show that the IEEE 519 Standard for Voltage THD will be exceeded at Neutral GIC currents well below 12 Amps for a Single Phase transformer.

It is also shown by Dong et al that Single Phase transformers produce that highest harmonics among the five types of transformers analyzed. This analysis then indicates the following transformers will exceed the IEEE 519 standard at the following Neutral GIC currents:

Table 2 GIC Currents at which the IEEE 519 Voltage THD Std is Exceeded

Type	Neutral GIC (Amps)	GIC per phase (Amps)
Single Phase	12	4
3 Phase – Shell	192	64
3 Phase – 3 Legged Core	96	32
3 Phase – 5 Legged Core	24	8

Since these current levels have been observed during many moderate solar storms around the world, it appears clear that the annual equipment and business losses found in the statistical study by C. J. Schrijver et al [13] are indeed caused by power quality or harmonic issues caused by induced geomagnetic currents (GICs).

E. Neutral Blocking Selection Criteria Based on meeting IEEE Harmonic Standard

To insure that a network will meet the IEEE 519 Standard for Voltage Total Harmonic Distortion (THD) (i.e. $< 1.5\%$) we can apply the above current for each type of transformer in a GIC modeled network, see Table 2 above. That is using power flow modeling such as PSSE, Power World or other, the GIC present in each transformer versus geo-electric field strength can be calculated. Such results for the Maine power grid are shown in Table 3 below. The data is taken from the recent CMP modeling analysis of the Maine and surrounding power grid using the PSSE software program.

The transformers for which their GIC current will result in the IEEE Harmonic Standard to be exceeded is shown in red. This selection is based on the fact that most of the transformers in the network are the 3- Phase – 3 Legged Core type. From the GIC criteria in Table 2 the GIC current for this type transformer is 32 Amps per phase.

It is easily observed that the IEEE Harmonic standard will be violated for many sites for a one in 50 Year GMD Storm. It is also observed that the Generator Step-Up (GSU) transformers and the Three Winding Auto-Transformers will all exceed this Harmonic standard for a one in 50 Year GMD storm.

And finally, it is seen that the Generator Step-Up (GSU) transformers in New Brunswick exceed the Harmonic Standard at very low geo-electric field levels. Hence, because the GIC currents are generally the largest in the Generator Step-Up (GSU) transformers and since a first priority should be to protect its own power sources, the first priority given to selecting transformers for neutral blocking protection should be the GSUs.

In addition to the GMD geo-electric fields the EMP E3 field of 40 V/km is shown in the last column of the this table. It shows that all but one transformer will exceed the IEEE Harmonic criteria for this field level. The only transformer in the Maine system is Keene Rd.

Table 3 – GIC Currents in Transformers versus GMD/EMP Field Strength (V/km)

IEEE Total Harmonic Distortion (THD) Criteria

(Transformer GIC < 32 Amps/phase to Achieve THD < 1.5%)

Maine Transformers **Effective GIC A/phase of transformers**	**NERC Std** 4.53 V/km GIC Amps	**50 Yr** 14 V/km GIC Amps	**100 Yr** 20 V/km GIC Amps	**200 Yr** 23.5 V/km GIC Amps	**250 Yr** 29 V/km GIC Amps	**EMP E3 Level** > 40 V/km GIC Amps
2 winding delta - wye						
Chester SVC 18/345 kV	15.87	49.05	70.07	82.34	101.6	140
Yarmouth GSU 22/345 kV #4	26.2	81.19	115.98	136.28	168.17	232
Keene Road GSU 115/345 kV	12.42	38.38	54.83	64.43	79.51	110
Newington TR1	51.93	160.49	229.28	269.4	332.45	459
2 winding Auto Xfmrs						
Orrington 345/115 kV #1	3.89	12.02	17.17	20.18	24.9	34
Orrington 345/115 kV #2	3.89	12.02	17.17	20.18	24.9	34
South Gorham 345/115 kV #1	5.27	16.27	23.24	27.32	33.71	46
South Gorham 345/115 kV #2	5.69	17.59	25.13	29.53	36.44	50
Mason 345/115 kV #1	5.45	16.84	24.06	28.27	34.88	48
Maguire Road 345/115 #1	13.82	42.71	61.01	71.69	88.46	122
Keene Road 345/115 kV #1	2.3	7.1	10.15	11.93	14.72	20
3 winding Auto xfmrs						
Coopers Mill 345/115 kV #3	18.39	56.83	81.19	95.4	117.73	162
Surowiec 345/115 kV #1	10.77	33.29	47.56	55.88	68.96	95
Albion Road 345/115 #1	31.47	97.26	138.95	163.27	201.48	278
Larrabee Rd 345/115 #1	31.11	96.16	137.37	161.41	199.19	275
New Brunswick Transformers						
2 winding delta - wye						
COLESON COVE 19/345 kV GSU 1	39	120.53	172.18	202.32	249.67	344
COLESON COVE 19/345 kV GSU 2	39	120.53	172.18	202.32	249.67	344
COLESON COVE 19/345 kV GSU 3	38.45	118.84	169.78	199.49	246.18	340
Pt Lepreau GSU 26/345 kV	105.81	327.02	167.17	548.92	677.39	334

Based on this Harmonic criteria and protection from a one in 100 year GMD storm the results show that Maine will require nine (9) neutral blocking systems to protect the grid and customers

from the harmonics generated by these transformers. Additionally, it is recommended that neutral blocking system be installed on four (4) New Brunswick GSU transformers.
Using this same Harmonic criteria and an EMP event (40 V/km) the results show Maine will require fourteen (14) neutral blocking systems and New Brunswick will again require four (4).

F. Neutral Blocking Selection Criteria Based Protection of Generator Rotor Heating
Another selection criteria for neutral blocking protection is based on the GIC currents that can result in generator rotor heating caused by near-by harmonic generation. A paper by Rezaei-Zare and L. Marti [14] shows that a severe GMD storm can result in generator rotor damage. The paper suggests that GIC currents of 50 Amps per phase in a single phase GSU transformer can result in such heating and damage. If we apply this GIC criteria to the calculated currents shown in the previous table (#3), we obtain the results shown in table 4 below.
In this table the red shading shows the GSU transformer GIC currents that exceed both the 50 Amp per phase (light red) and the 100 Amp per phase (darker red) currents. Note there are only two GSU transformers in Maine for which this generator damage criteria is exceeded for a one in 50 year GMD storm. The other four generator transformers are in New Brunswick and all exceed a 100 Amp per phase current for the one in 50 year GMD storm. Again when selecting transformers for neutral blocking protection the generators and generator step-up (GSU) transformers should gain top priority. It we have generation after either a GMD or EMP event we can recover. But with generation rotor heating and potential damage, recover will be a much larger challenge.
Finally, the EMP E3 field of 40 V/km is included in the last column of the table.

It should also be noted that harmful harmonics can be generated at the non-GSU transformers as well. The non-GSU transformers that will generate harmonics are shown for both the 50 Amp per phase (light yellow) and 100 Amps per phase (dark yellow). In this case however in order for the harmonics to cause generator rotor damage they will typically need to be close to the generator site. The largest magnitude harmonics will typically be the 2nd and 3rd components. These will propagate with less loss than the higher components (> 3rd) due to the frequency dependence of the transmission line inductance. At present the calculation of the propagation of these harmonics in typical power grid networks has not been demonstrated.

Generator Rotor Heating Criteria

(Transformer GIC < 50 & 100 Amps/ phase to Avoid Rotor Heating)

Maine Transformers	**NERC Std** 4.53 V/km	**50 Yr** 14 V/km	**100 Yr** 20 V/km	**200 Yr** 23.5 V/km	**250 Yr** 29 V/km	**EMP Level** 40 V/km
Effective GIC A/phase of transformers14	GIC Amps	GIC Amps	GIC Amps	GIC Amps	GIC Amps	GIC Amps
2 winding delta - wye						
Chester SVC 18/345 kV	15.87	49.05	70.07	82.34	101.6	140.1
Yarmouth GSU 22/345 kV #4	26.2	81.19	115.98	136.28	168.17	232.0
Keene Road GSU 115/345 kV	12.42	38.38	54.83	64.43	79.51	109.7
Newington TR1	51.93	160.49	229.28	269.4	332.45	458.6
2 winding Auto Xfmrs						
Orrington 345/115 kV #1	3.89	12.02	17.17	20.18	24.9	34.3
Orrington 345/115 kV #2	3.89	12.02	17.17	20.18	24.9	34.3
South Gorham 345/115 kV #1	5.27	16.27	23.24	27.32	33.71	46.5
South Gorham 345/115 kV #2	5.69	17.59	25.13	29.53	36.44	50.3
Mason 345/115 kV #1	5.45	16.84	24.06	28.27	34.88	48.1
Maguire Road 345/115 #1	13.82	42.71	61.01	71.69	88.46	122.0
Keene Road 345/115 kV #1	2.3	7.1	10.15	11.93	14.72	20.3
3 winding Auto xfmrs						
Coopers Mill 345/115 kV #3	18.39	56.83	81.19	95.4	117.73	162.4
Surowiec 345/115 kV #1	10.77	33.29	47.56	55.88	68.96	95.1
Albion Road 345/115 #1	31.47	97.26	138.95	163.27	201.48	277.9
Larrabee Rd 345/115 #1	31.11	96.16	137.37	161.41	199.19	274.7
New Brunswick Transformers						
2 winding delta - wye						
COLESON COVE 19/345 kV GSU 1	39	120.53	172.18	202.32	249.67	344.4
COLESON COVE 19/345 kV GSU 2	39	120.53	172.18	202.32	249.67	344.4
COLESON COVE 19/345 kV GSU 3	38.45	118.84	169.78	199.49	246.18	339.6
Pt Lepreau GSU 26/345 kV	105.81	327.02	167.17	548.92	677.39	934.3

G. NERC GMD Standard for GMD Induced Harmonics

The proposed NERC GMD standard does not adequately cover the potential for damage to customer equipment nor damage to utility power components, such as generators, Static VAR Compensators (SVCs) and capacitor banks, by even moderate GIC currents that produce harmonics in half-cycle saturated transformers. While the potential for harmonic damage is briefly referred to, the proposed standard gives no guidance for harmonic levels that could cause damage. And the standard gives no guidance on how to analyze a network for this issue.

Power System Analysis

<u>Principles</u>

Geo-magnetic Disturbance (GMD) effects on the Bulk Electric System (BES) and associated equipment have been observed and documented for the last few decades. GMD events produce an E-field across the Earth surface that results in quasi-DC currents to flow between grounding points of the BES, primarily grounded-wye connections of power transformers. These Geo-Magnetic Induced Currents (GIC) cause power transformers to over-saturate, which results in additional Mvar losses and harmonic currents from these power transformers. These additional Mvar losses coupled with the existing Mvar usage from transportation of energy and usage by customer equipment, can result in voltage collapse if there is an insufficient supply of Mvars from on-line generators and shunt capacitors. The study determines the voltage collapse points. The principles of a power system analysis for a GMD event couple the determination of the transformer Mvar losses and a variety of system conditions, such as:

1. High customer demand (summer peak),
2. Sensitivity of high energy transfer (Mvars are consumed in energy transportation).
3. Effect of contingent loss of Mvar resources, i.e. generator and/or shunt capacitors)

<u>Modeling</u>

Emprimus, PowerWorld, Central Maine Power (CMP), and Emera Maine initiated a study of the Geomagnetic Disturbance (GMD) effect on the Bulk Electric System (BES) and mitigation strategies. PowerWorld developed software [18] utilized the 2015 power system model for the Summer Peak conditions from FERC 715 filing for ERAG/MMWG and updated the 2014 Shoulder Load model with the 2015 new facilities. PowerWorld built a DC model of the Maine Bulk Electric System (BES), based geo-coordinates of the transmission and generation facilities, transformer connections and default DC resistances. Emprimus and CMP verified the transformer connection types. CMP has initiated a project to acquire actual DC resistance of the transformer windings and ground connection. The studies presented here used reasonable agreed upon default values for the windings and ground connections. When actual resistance values become available they will be substituted into the model to determine if there are any changes in the results.

It should be noted that the modeling results are dependent on the grounding resistance values assumed for the transformers or substations. It is understood that if the assumed ground resistance of a substation is increased the resulting GIC current will be reduced accordingly. A recent published paper by U. Bui, et al addresses this modeling sensitivity issue [19]. An example given in this paper shows that for an assumed 20 bus representative network exposed to a 1 V/km geo-electric field that by increasing the grounding resistance at one generation site from 0.15 ohms to 0.5 ohms, the GIC GSU transformer neutral current was reduced from 213

Amps to 98 Amps. It was also noted that in this study case the GSU transformers were highly susceptible to GIC currents. That is if the geo-electric field reached the published one-in-one hundred year level of 20 V/km, the neutral GIC currents for the above example would be 4,260 Amps and 1,960 Amps respectively for the assumed grounding resistances of 0.15 and 0.5 ohms.

Reactive Operation

Even though the GMD event produces a quasi-DC, the event is cyclic over time. The TPL-007 reference storm has a cyclic pattern over 32 hours. There will be several periods of peak E-field and several period of virtually zero E-field (i.e. geo-electric field). With the uncertainty of rise time in the E-field and the subsequent collapsing of the voltage, reactive switching (Capacitors and Reactors) and Load Tap Changer (LTC) movement in the power flow studies to determine the voltage collapse point was not allowed. The rational is static capacitors have an inherent delay and a designed deliberate delay in their insertion, thus they may not be fast enough to arrest voltage collapse. Reactive switching and LTC movement was allowed in the base case just prior to the application of the E-field.

Once the GMD field was applied, power flow studies allowed generators to perform voltage control. The rationale is that generators are dynamic reactive source with virtually no delay.

As a later sensitivity study, capacitors were allowed to switch to correct the transmission voltage as the E-field was applied. The study then removed the E-field to determine the degree of overvoltage until the capacitors are remove automatically due to high voltage. The results of this sensitivity study is discussed later in this report.

Chester Operation and Contingency

The information provided to Emprimus by CMP to set up the initial Emprimus / PowerWorld studies was that Chester SVC controls were set for fault recovery, i.e. fast voltage change and that voltage changes due to MVAR losses from GMD events would probably not be fast enough to activate the Chester SVC controls. Also, CMP indicated that loss of the Chester SVC is considered their worst voltage contingency.

In the initial Emprimus / PowerWorld studies, Chester was not allowed to control voltage based on CMP's state control mode which did influence the voltage collapse results. Because the Chester SVC was not controlling voltage, loss of the Chester SVC had minimal impact.

CMP later brought to the attention of Emprimus that the information about the control of the Chester SVC was incorrect. The Chester SVC is on voltage control mode and would control voltage under a GMD event.

However, it was also observed that the Chester SVC had a significantly high MVAR flow in order to maintain the transmission voltage. With the high MVAR flow, the loss of the Chester SVC becomes the most significant and credible voltage contingency on the Maine transmission system. Essentially all of the voltage graphs in this report represent the transmission voltage under conditions of loss or inoperability of the Chester SVC.

History has demonstrated the loss of Chester SVC as credible and very likely. Chester SVC has tripped on harmonics from GMD events that are apparently significantly lower than the geo-electric field levels studied in this report. Because Chester step-up transformer is comprised of singe phase transformers and without neutral blocking, the Chester step-up transformer will be largest harmonic source in the state of Maine and one of the highest in the New England area. The harmonics generated by the Chester step-up transformer for most GMD events will exceed the threshold of the IEEE-519 standard and will represent an equipment risk to many customers.

Power System Studies

Overview of GIC and Power Flow Network Modeling

GIC modeling of networks has been introduced in recent years as a module addition to standard power flow modeling programs. It is now available from several suppliers; namely, PowerWorld TM, PSSE, GE, Mitsubishi etc. The GIC calculations are straight forward as GIC is essential a DC current hence the same network that is used in the power flow calculation is used for the GIC calculations. Since the power flow calculations are well established, it follows that the GIC currents calculations will likewise be reliable. Also included in the these programs is the reactive power which results from the half- wave saturation of transformers caused by the quasi-DC GIC currents. This reactive power then is integrated into the power flow analysis so that the interaction of GIC with power flow can be realized. A key portion of these calculations requires knowledge of the saturation parameters of each transformer.

Validation of PowerWorld GIC Modeling of Maine Power Grid

To validate the PowerWorld and PSSE modeling of the Maine power grid we compared the GIC neural modeling results against recorded Maine GIC neutral current data taken at the Chester substation [12]. This GIC current data was correlated to the rate of change of magnetic field magnitude (dB/dt) from data recorded in Ottawa, Canada some 500 km distance from the Chester site. To be clear, the magnetic data does not include the magnetic field direction which obviously results in the spread of data points shown in the graph (see figure below). However, the maximum range of GIC currents represents the data points for which the geo-electric fields were aligned with the primary NE to SW direction of the Maine power lines which is the field angle which produces the largest coupling and hence the largest GIC current flows. The spread in the data points are then a result of geo-electric fields at various angles that do not produce maximium coupling for GIC currents.

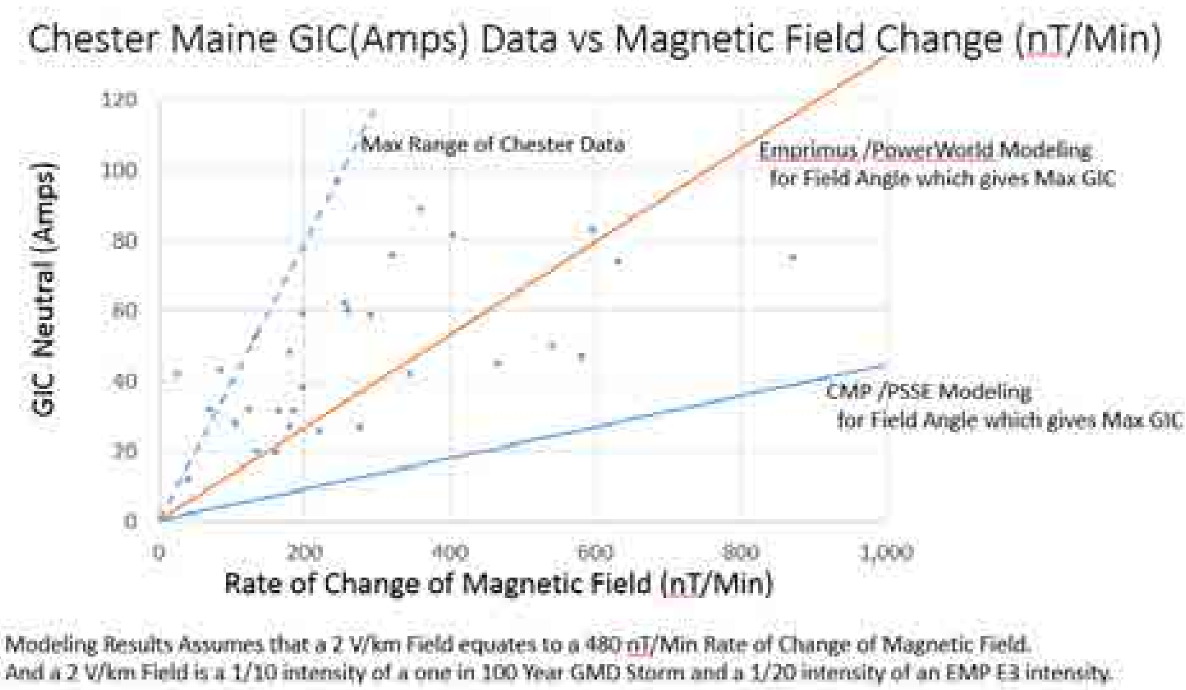
Also shown in the graph below are the Emprimus /PowerWorld and CMP / PSSE modeling results for the GIC currents at the Chester substation. It should be noted that numerous input parameters to these two modeling efforts were different and no attempt was made to make an accurate comparison of the two software models. An accurate comparison of this type to check of these software and several other programs was performed and good agreement in GIC current modeling was reported and published by R. Horton et al [26]. Therefore, the differences in the GIC results of these two modeling efforts can be attributed to the various differences of the input configurations and parameters that were assumed. In general we found that the average GIC current results for the PowerWorld modeling were more than a factor of two (2) larger than those of the PSSE modeling. At the Chester site, the PowerWorld modeled for Effective GIC current at a field angle for maximum coupling was more than a factor of four (4.3) larger than the PSSE GIC Effective current at a field angle for maximum coupling. These results are shown in the figure below as a function of the rate of change of magnetic field (dB/ dt [nT/min]. To enable the comparison of these two models to the actual data available from the Chester substation we assumed a relationship between the geo-electric fields, E [V/km], used in the modeling programs, and the rate of change of magnetic field, dB/dt [nT/min] which is typical for the soil conditions of the New England area. This assumed relationship is the following: a 4,800 nT/min magnetic field rate of change will result in a geo-electric field of 20 V/km. Both of these values have been described in the published papers as being typical for a one in 100 year storm [7, 8]. We have shown previously that the frequency of such a solar storm is more likely to be a one in 50 year event. This relationship is Faraday's law is a linear relationship over the entire range of GMD events of interest. This relationship does depend on the soil type as has been described in several publications [7, 8]. And as shown by A. Pullkinen et al and J. Kappenman the soil type for the New England area results in higher geo-electric fields than that of British Columbia [7, 8]. Finally, it should be noted that a recent published paper from Europe reports that a near Carrington rate of change of magnetic field was observed October 29th of 2003 in Rorvik, Norway with a magnitude of 77 nT/second or 4,620 nT/min [27]. It should be noted that this magnitude was within 4% of what is often considered to be a one in one hundred year or Carrington storm. And large GIC currents were observed. The paper sited shows that the sum GIC currents in all the nodes of the Statnett 2012 Grid was 7,000 Amps. The paper does not give the individual node currents but it can be assumed that several were in the many hundreds of Amps. Apparently no extremely individual GIC currents were recorded possibly a result of the geo-electric field angles not aligning with the major long transmission lines in the system.

Further support for the relationship between magnetic field rate of change and geo-electric field is found in the publication by Minna Myllys et al in Table 5 [27]. The average of the five magnetic field values is 26.1 nT/sec (or 1,566 nT/min). And the average of the geo-electric fields is 6.76 V/km. By linearly extending this relationship to 4,800 nT/min gives a geo-electric field of about 21 V/km which is in good agreement with that in the publications of others [7, 8]. It should be recalled that this relationship depends on the type of earth structure and this relationship above is then valid for Norway and surrounding Scandinavian countries. So it may also be valid for the similar rocky mountainous regions of Maine and New England.

This above relationship, between the magnetic field rate of change and the geo-electric field, was then used to convert the geo-electric field parameter to the rate of change of magnetic field so that the modeled GIC currents, for both modeling results, could be compared to the Chester GIC data as shown in the graph below. The results show that the Emprimus/ PowerWorld modeling, which is for the maximum coupling field angle, when compared to the maximum range line for the Chester GIC data is about a factor of three (3) lower than that of this maximum line. And this PowerWorld modeling is about a factor of 1.5 lower than the median of all the GIC current data points. This might indicate that the transmission line resistances and grounding resistances used in the PowerWorld modeling may be higher than that of the actual resistances in the lines and grounding connections. But to our knowledge this is the first attempt made to correlate GIC modeling against recorded GIC data. And considering the accuracy of both the recorded and correlated data as well as the various assumed modeling input parameters, we believe that this result represents a good validation of the Emprimus/ PowerWorld modeling results. And the validation suggests that the modeling may in fact be resulting in GIC currents that are lower than can be expected by future GMD and EMP events.

The modeling results by CMP/ PSSE, shown by the line in the graph, are about a factor of about nine (9.4) lower than the maximum actual Chester GIC data recorded over more than two decades. As pointed out earlier, the same rate of change of magnetic field relationship to geo-electric field was used to enable comparison to the Chester data. And as stated earlier the basic PSSE program should not be an issue as it was earlier verified against several other programs [26]. Therefore, the lower GIC currents must be attributed to the various assumptions about the Maine network configuration and the assumed specific network input parameters. More specifically, the transmission line resistances and grounding resistances used in the PSSE modeling may be higher than that of the actual resistances in the lines and grounding connections.

If the lines in the graph were extended to show a one in one hundred year storm (4,800 nT/min), more recently assessed as more likely a one in fifty year storm, the maximum line for Chester data results in a GIC neutral current of about 1,900 Amps. Whereas the median of the Chester data points results in a projected GIC current of about 880 Amps. The Emprimus/ PowerWorld modeling if extended to a one in one hundred year storm predicts a GIC neutral current of 625 Amps. Here again this prediction is lower than the extended Chester data by about a factor of three. And the CMP/ PSSE model if extended to a one in one hundred year storm predicts a GIC neutral current of 210 Amps or a factor of about nine lower than the extended projection from the actual recorded Chester data during far less severe solar storms.



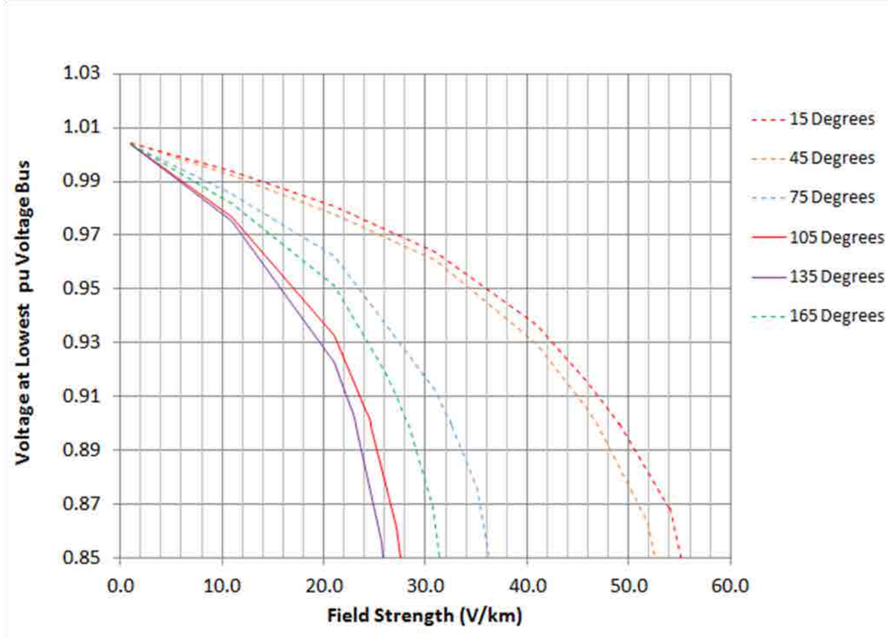
Selection of K-Factor Transformer Saturation Parameter

It has been shown that to a very good approximation the reactive power Q is a linear function of the GIC current in the transformer. This linear relationship is called the k-factor which is simply Q divided by the GIC current. The selection of k-factors in the use of initial network analysis typically relies on published values to determine initial worst case conditions. Such K-factors for initial screening purposes were published by T. J. Overbye et.al. in 2012. The work recommends that a K-factor of 1.7 for single phase (normalized to 500 kV) transformers. And a K-factor of 0.8 (normalized to 500kV) for all others. Therefore since the Maine system is all at 345 kV and lower, the recommend K-factors should be 1.17 for single phase generator step-ups and 0.55 for all others. This recommendation was based on published values by X. Dong et.al. [16], J. Kappenman [21], and R. Walling [22]. In a recent discussion with J. Kappenman he stated that all these K-factors are just a starting point for worst case analysis which should be used for initial assessments. He stated that he would not argue with the K-factors suggested in the T. Overbye et.al. paper [12].

It is also noted that to accurately calculate the reactive power the effective GIC current in auto-transformers and not the neutral GIC current should be used. The effective current reflects the actual current in the primary and secondary windings and is the current that is used when calculating transformer heating due to GIC.

PowerWorld initially conducted studies to determine the worst orientation of a GMD geo-electric field (E-field) that produces the most GIC to flow. The results showed that this case is a NE to SW E-field (135 degrees measured counter clockwise from North) which is consistent with the NE to SW direction of the Maine 345 kV network direction.

Graph #1 – Voltage at Lowest Bus versus GMD E- Field for various Field directions



PowerWorld also provided power flow studies for increasing E-field strengths with corresponding increased transformer reactive (Mvar) losses from over-saturation until the voltage collapsed, i.e. when the model failed to converge. PowerWorld provided graphic representation of the voltage collapse in order to identify the 95% and 90% BES voltage collapse points. These value represent the accepted transmission planning voltage criteria for normal and emergency (contingent) conditions. PowerWorld then conducted an additional study that included increased imports across the New Brunswick border to the maximum level allowed by ISO New England (ISO NE) i.e. 1,000 MW.

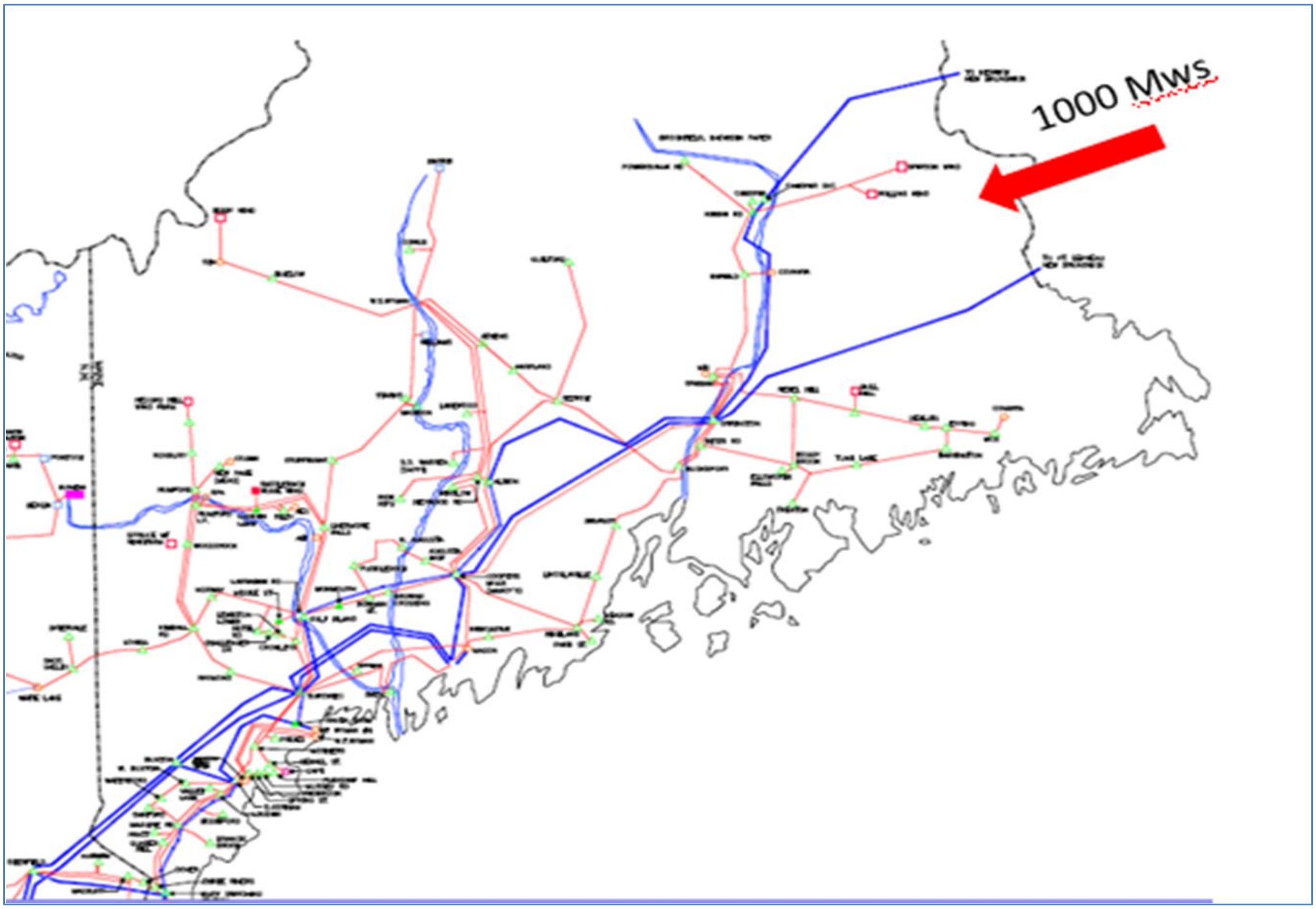


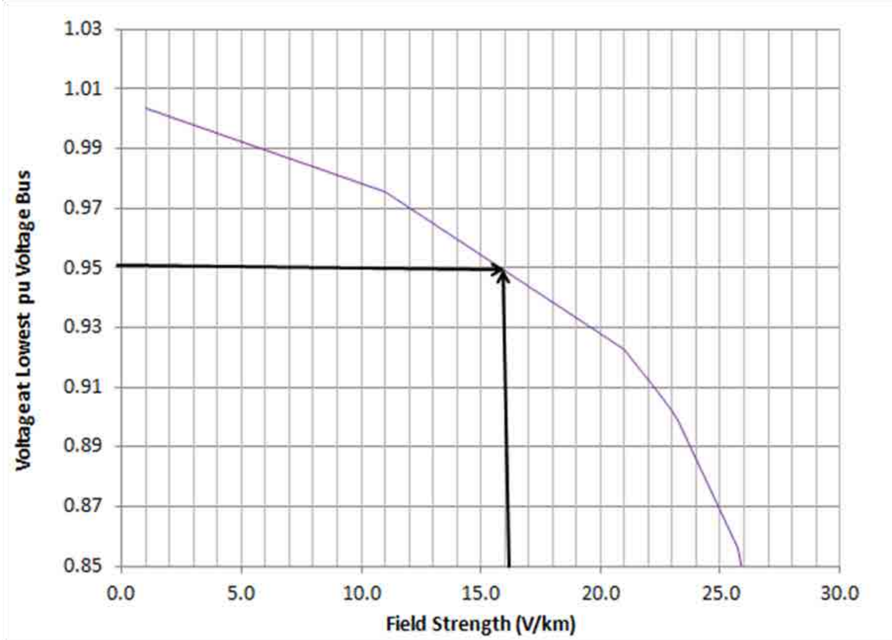
Figure 2 – Maine Bulk Electric Power System Map

PowerWorld conducted a similar analysis on the 2015 Shoulder Load case. This load level is more likely than the peak load condition and also represents a higher probably of peak transfers from the economic exchange of energy in the ISO NE market.

<u>Summer Peak Cases</u>

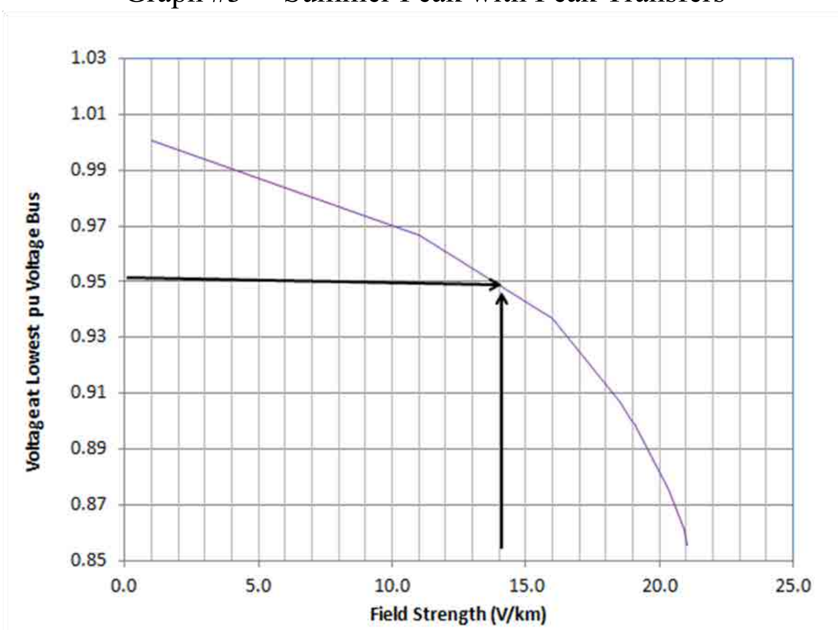
The Summer Peak case with normal firm transfer study results are shown in Graph #2. The voltage collapse is determined from the lowest voltage in the BES that drops below a given voltage level. For this case shown in graph #2 the 95% voltage point occurs at an E-field of 16 V/km for the NE to SW field direction (135 degrees). For reference the one in one hundred year storm for soil conditions similar to that in Maine is 20 V/km with an error range of 10 to 50 V/km as published by A. Pulkkinen et.al. in 2012.

Graph #2 – Voltage Collapse versus E-Field for the Summer peak case



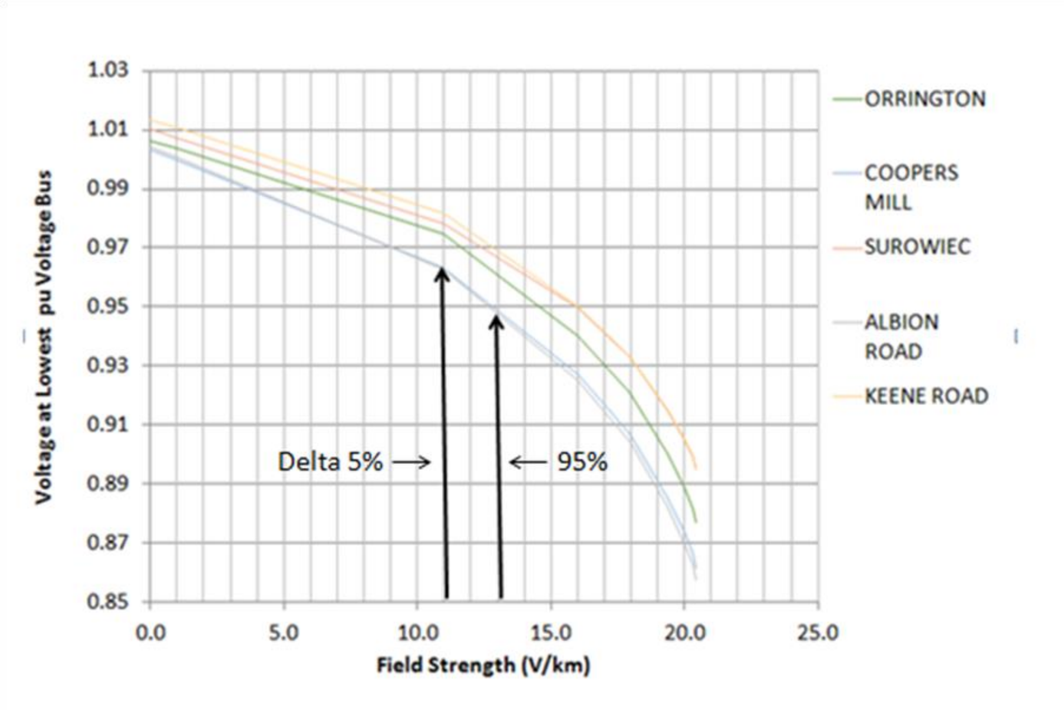
The Summer Peak case with peak transfers study results are shown in Graph #3. The 95% voltage point occurs at an E-field of 14 (placeholder) V/km.

Graph #3 – Summer Peak with Peak Transfers



Graphs 2 and 3 represents the voltage at the lowest point of the BES (115kv and above). CMP expressed the primary system voltage control strategy is to maintain the voltage on the 345kv network within planning and operating criteria. Graph #4 represents the voltage for summer peak load and transfers at 5 CMP-selected buses.

Graph #4 – Summer Peak with Peak Transfers (Selected 345kv buses)



By using the 345kv system as the voltage criteria, 95% voltage is reached with an even lower field strength 13V/km vs 14V/km. It should also be noted that some systems use a delta 5% change in voltage on their highest voltage facilities as a means to avoid voltage collapse. If CMP would use such a criteria, a 5% drop in 345kv system voltage occurs with an E-field of 11V/km.

Based on the E-field that results in 95% BES voltage, the transformer neutral GIC values were calculated as shown in Table #1.

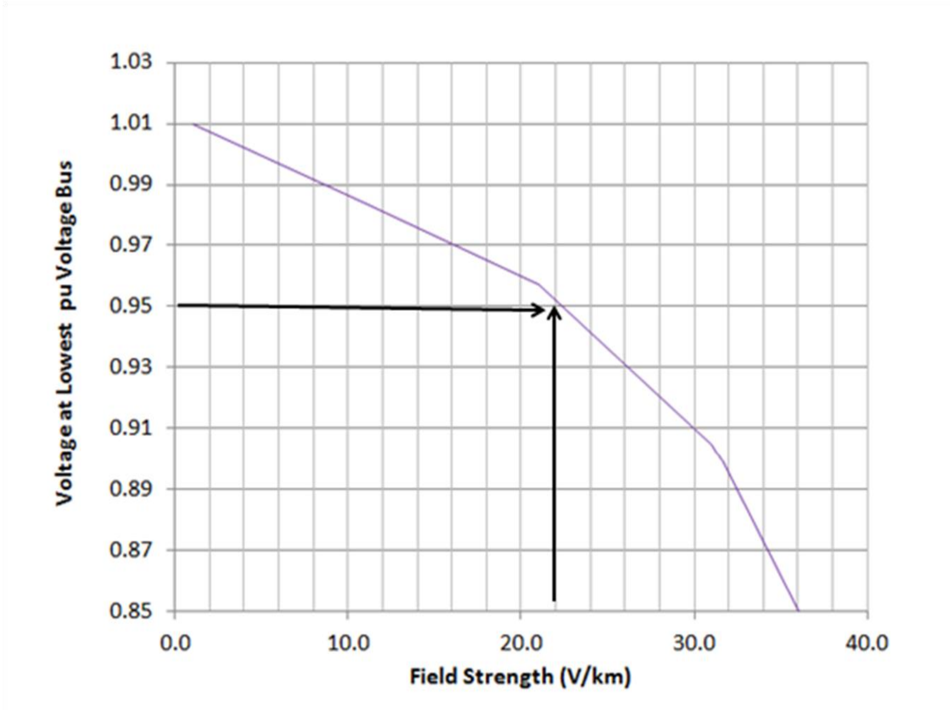
Table #1 – GIC currents for Summer Peak conditions with Normal and Peak Transfers

Transformer Description	Neutral GIC (Amps) for Summer Peak Normal Transfers	Neutral GIC (Amps) for Summer Peak Peak Transfers
Larrabee Rd 345/115/13.8 #1	765	669
Mason Steam 345/115 #1	622	545
Yarmouth 345/22 #1	563	493
Chester 345/18 #1	500	438
Albion Rd. 345/115/13.8 #1	454	397
Surowiec 345/115/13.8 #1	397	348
Coopers Mills Road 345/115/13.8 #1	262	230
S. Gorham 345/115 #1	232	203
Keene Rd. 345/115 #1	196	171
Orrington 345/115/13.8 #1	177	155

Shoulder Load Level Cases

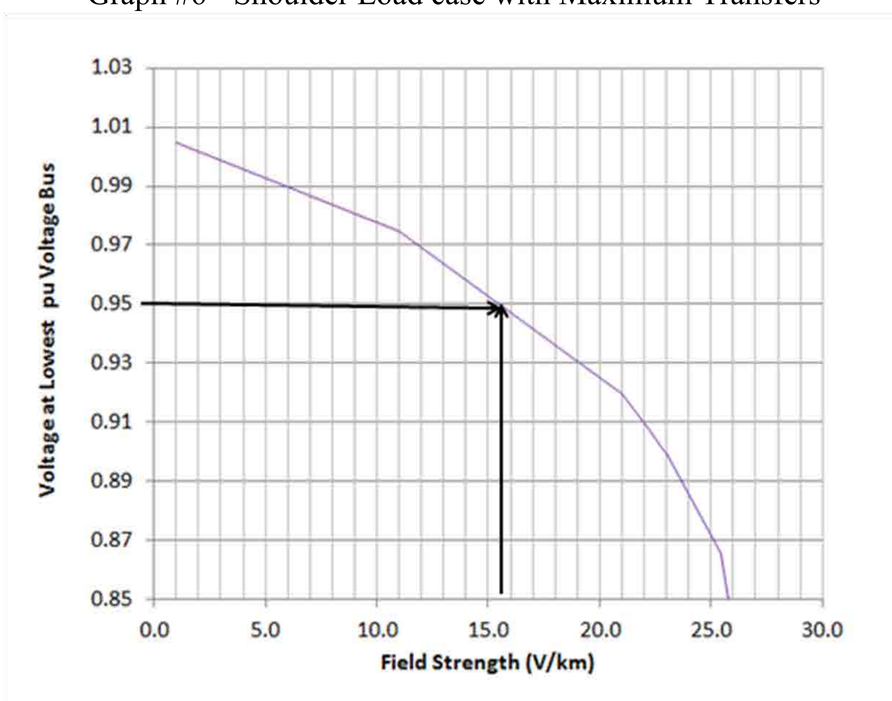
The Shoulder Load case with normal firm transfers study results are shown in Graph #5. The 95% voltage point occurs at an E-field of 21 V/km for the NE to SW field direction.

Graph #5 – Shoulder Load case with Firm Transfers



The Shoulder Load case with maximum transfer study results are shown in Graph #5. The 95% voltage point occurs at an E-field of 15.5V/km.

Graph #6 - Shoulder Load case with Maximum Transfers



Shoulder Load case requires a higher E-field to reach voltage collapse, because the lower customer demand. This lower customer demand results lower system Mvar losses, which in turn reduces the Mvar loading on on-line generators. This reduces Mvar output allows greater Mvar support during the GMD event. However, it should be noted that the system at the shoulder loads is more sensitive to increased transfers. Increased transfers under summer peak loads required a 2 V/km less E-field, whereas increased transfer during shoulder loads required a 5.5 V/km less E-field.

Overvoltage Study

As a sensitivity study, capacitors were allowed to switch with the application of the E-field. The objectives of this study were to:

1. Determine if there was sufficient capacitive reactance to correct the voltage for a 20 V/km (100 year storm) E-field
2. Determine the magnitude of overvoltage if the E-field was to suddenly disappear.

The table below is a summary of the voltages at key 345kv substations. Studies were performed at summer peak loads with normal transfers from New Brunswick (NB) and at 1,000 MWatts (peak). It can be observed that there are enough capacitors to bring the voltage from emergency levels to within the normal range. The rise for switching capacitors post-GMD field will be 3 to 10%, depending on the NB imports. However, an additional rise of 5 to 7% will occur when the GMD is removed and before capacitors trip on overvoltage.

		Normal Based Transfers pu Volts			1,000 MW Transfers from NB pu Volts		
Sub Name	Nom kV	Step 1	Step 2	Step 3	Step 1	Step 2	Step 3
Orrington	345	0.9549	1.0020	1.0498	0.9067	0.9864	1.0408
Coopers Mills Road	345	0.9323	0.9750	1.0376	0.8883	0.9546	1.0249
Keene Rd.	345	0.9635	1.0350	1.0929	0.9298	1.0350	1.0991
Surowiec	345	0.9543	0.9869	1.0347	0.9159	0.9728	1.0288
Albion Rd.	345	0.9321	0.9733	1.0381	0.8860	0.9520	1.0244

The highlighted voltages shown in red above are unacceptable to customers.

There are two important takeaways from this data:

1. Once a capacitor trips on overvoltage, there is a five (5) minute delay to allow trapped charge to drain before re-energization, thus making the capacitor not available for a rapid re-application of the E-field.
2. Depending on the timing of the application of the capacitors and the subsequent removal of the E-field, distribution voltage regulation may have attempt to correct the initial low voltage and still be in that position when the overvoltage condition occurs. This may result in the customer equipment damage from seeing full brunt of the voltage change between Step 1 and Step 3, which can be from 9 to 17 percent.

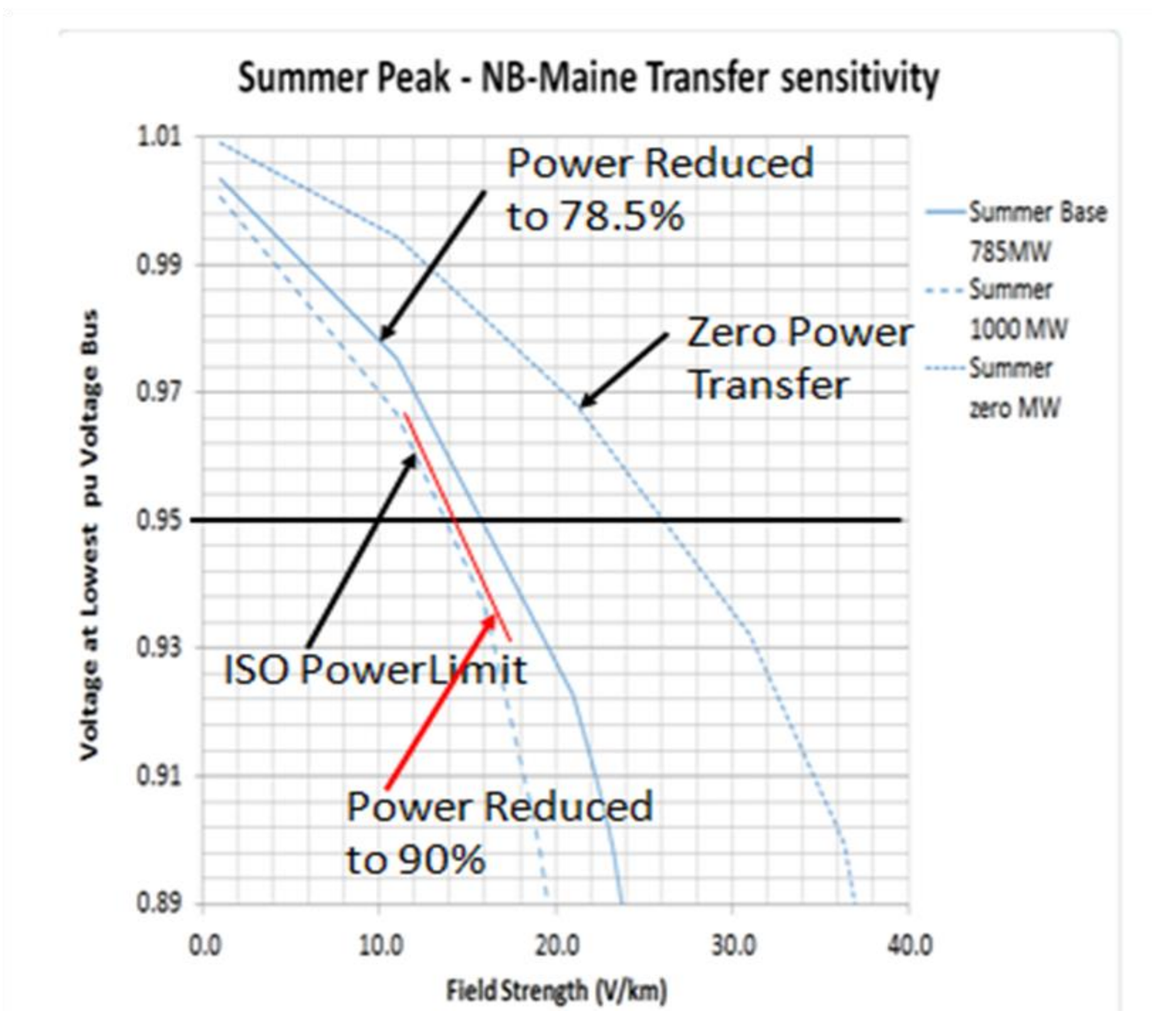
Contingent Operations

The modeling of a power grid which includes the effects of GMD or EMP E3 should include the operation of the network under contingency operations. Various contingencies operations can produce significantly different and important modeling results. CMP has indicated that the Chester SVC has been identified as one of the most severe voltage contingencies. As of the date of this report, the modeling and analysis of this contingency operation has not been studied.

Mitigation

Operating Procedures

ISO NE has developed GMD Operating Procedures that call for reduction of key transmission lines to 90% or less of their rating. The following graph shows the voltage collapse sensitivity to flow on the New Brunswick interface.



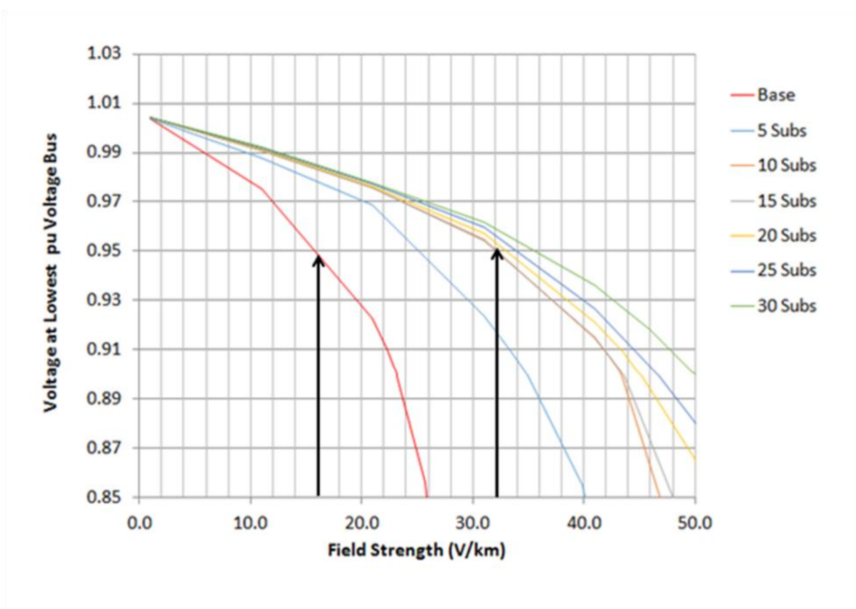
The conclusion from this graph is that an adjustment reducing the flow from 100 to 90% on the New Brunswick interface has little impact on the voltage collapse point. To have a significant impact the ISO NE must request more than a reduction to 50% of the flow on the interface. Since the operating procedures instruct ISO NE to make adjustments to bring the flow to 90% or less, it is presumed that any interface already at 90% or less will have no further adjustments, this make the operating procedure useless in mitigating voltage collapse risk and does nothing to reduce GIC generated harmonics.

Neutral Blocking Selection for Voltage Collapse

PowerWorld conducted voltage collapse analysis with several different applications of the SolidGround blocking systems inserted in the transformer neutrals. PowerWorld ran the analysis by blocking the neutral of transformers in 5 substations with the highest GIC currents. PowerWorld then re-ran the analysis to recalculate GICs in the remaining transformers and determine the voltage collapse point. PowerWorld then determined the next highest 5 substation to have SolidGround blocking devices installed. PowerWorld repeated this process until 30 substations in Maine had neutral blocking applied.

Graph #8 shows the voltage collapse improvement as SolidGround systems were inserted into the modeling for the Maine network. Blocking GICs at 10 substations improves the resiliency of the BES to a GMD event from 16 V/km to a 32 V/km E-field that results in a 95% system voltage.

Graph #8 – Voltage Collapse Improvement as Neutral Blocking is Inserted



The table below shows the location and number of transformers selected for blocking. The table also shows the average GIC of all 115kv and above transformers before the blocking was applied to the substations. (TBD - data for GIC after previous blocking run).

	Neutral GIC based on # of blockers				Neutral GIC based on # of blockers				Neutral GIC based on # of blockers		
First 5 Substations	0	5	10	Second 5 substations	0	5	10	Third 5 substations	0	5	10
Yarmouth 345/18 GSU	563	0	0	Coopers Mills (1 auto)	262	387	0	Westbrook (3 GSUs)	32	38	79
Yarmouth 115/14.4 GSU	82	0	0	Orrington #1 auto	177	171	0		32	38	78
Yarmouth 115/13.8 GSU	35	0	0	Orrington #2 auto	97	93	0		32	38	78
Yarmouth 115/13.8 GSU	35	0	0	S. Gorham #1 auto	232	273	0	Bucksport (3 GSUs)	37	54	139
Mason Steam (1 auto)	622	0	0	S. Gorham #2 auto	109	128	0		8	14	35
Chester (1 GSU)	500	0	0	Surowiec (1 auto)	397	457	0		2	5	12
Albion Rd (1 auto)	454	0	0	Keene rd (1 auto)	196	398	0	Maine Independence (3 GSUs)	16	15	58
Larrabee Rd (1 auto)	765	0	0	Keene rd (1 auto)	57	134	0		16	15	57
									16	15	57
								Jay Hydro (3 GSUs)	32	45	56
									32	45	56
									32	45	56
								McGuire Rd (1 auto)	154	179	279
Voltage Collapse before	16	V/km		Voltage Collapse before	25			Voltage Collapse before	30		
Voltage Collapse after	25	V/km		Voltage Collapse after	30			Voltage Collapse after	30.5		
Ave GIC 223 amps				Ave GIC 134 amps				Ave GIC 94 amps			

It can be concluded from these results that neutral blocking at the initial ten (10) sites has the predominant amount of benefit from the voltage collapse perspective. Blocking at the initial 10 sites changes the voltage collapse point from 16 V/km to 30 V/km. Whereas the third set of 5 sites only improve the voltage collapse point by 0.5 V/km. This third set of 5 sites has 2 transformers with relatively high GIC (Bucksport and McGuire road). These transformers are recommended to have neutral blocking to reduce excessive Mvar losses and harmonics. The initial ten sites with the additional two transformers bring the total recommended transformers for neutral blocking to eighteen (18), which will also significantly reduce the GIC generated harmonics.

Comparisons of Four Selection Criteria

Several criteria for selecting transformers for neutral blocking systems were developed during the course of this study. The first is based on a potential for transformer damage due to heating from hot spots when GIC results in half-wave saturation. The criteria were established from the NERC GMD Task Force recommendation of GIC > 75 Amp per phase [11]. This specific criterion was used in the main body of the full CMP report for a one in 100 year storm (20 V/km) using the CMP/PSSE GIC modeling data and is shown in the first column of the table below. The total transformers selected for neutral blocking protection is eight (8) in Maine and four (4) in New Brunswick.

The second selection criteria is for Voltage Collapse as described in the previous section of this report. This criteria is based on the voltage collapse of a power grid when the reactive power demand exceeds the available generation or compensation resources. The generally accepted criterion is when the lowest line voltage drops below the 95% of the nominal operating line voltage. This criterion was used with the modeled GIC current data for the Maine power grid for a one in 100 Year GMD storm (20 V/km) using the Emprimus /PowerWorld modeling results. The total transformers selected by this criterion for neutral blocking protection is eighteen (18) in Maine. Note the Emprimus modeling approach blocks all transformers at selected sub-station as

it was determined that if only one transformer was blocked the GIC current would just move to the other transformers at the location. This results in four (4) transformers selected at Yarmouth as opposed to one (1) selected in the CMP / PSSE selections.
Also note that the PowerWorld modeling results did not report the GIC data for the New Brunswick generation sites although the full network over the north east region is included in the network that was analyzed. It is understood that the GIC currents at the New Brunswick sites will have similar values to that found in the CMP / PSSE results. And it is assumed that these GIC currents would again result in the selection of four (4) neutral blocking systems for the nearby generation sites in New Brunswick.

One of the major differences between the CMP / PSSE and Emprimus / PowerWorld modeling inputs is the difference in the transformer saturation parameters or the so-called K – factor. CMP chose a K of 0.2 (for 345 kV) for three (3) phase, three (3) core transformers as typical for most of the transformers in the Maine network. Whereas, Emprimus /PowerWorld selected a worst-case K of 0.4 (for 345 kV) for all the transformers in the network. This difference in the K-factor is largely responsible for the Emprimus / PowerWorld study showing voltage collapse at moderate – strong GMD disturbances. It is the Emprimus opinion that a worst-case analysis at this time is appropriate so that all potential mechanisms for or power blackout are identified. Additionally, the recommendations from the analysis should include a safety factor or several safety factors when the consequences of a severe solar storm could be a prolonged blackout which risks national security and the potential loss of life of millions. Therefore we recommend both worst case analysis along with design safety factors when selecting the mitigation solutions.

Table on Comparison of Five Selection for Transformer Neutral Blocking Protection

	PowerWorld Model /worst case K-Factors	**CMP/ PSSE Model and non- worst case K - Factors**	**PSSE Model**	**PSSE Model**	**PSSE Model**
Maine Transformers	**GMD Voltage Collapse [1,2]**	**GMD Transformer Damage [1,3]**	**GMD Harmonic IEEE Std [1,4]**	**EMP E3 Harmonic IEEE Std [1,4]**	**GMD Generator Heating [1,5]**
2 winding delta - wye					
Chester SVC 18/345 kV	1	1	1	1	1
Yarmouth GSU 22/345 kV #4	4	1	4	4	4
Keene Road GSU 115/345 kV		1	1	1	1
Newington TR1			1	1	

Bucksport (3 GSUs)	1				
2 winding Auto Xfmrs					
Orrington 345/115 kV #1	1			1	
Orrington 345/115 kV #2	1			1	
South Gorham 345/115 kV #1	1			1	
South Gorham 345/115 kV #2	1			1	
Mason 345/115 kV #1	1			1	
Maguire Road 345/115 #1	1	1	1	1	
Keene Road 345/115 kV #1	1			1	1
Keene Road 345/115 kV #2	1				1
3 winding Auto xfmrs					
Coopers Mill 345/115 kV #3	1	1	1	1	
Surowiec 345/115 kV #1	1	1	1	1	
Albion Road 345/115 #1	1	1	1	1	
Larrabee Rd 345/115 #1	1	1	1	1	
Total Neutral Blocking Sys	**18**	**8**	**12**	**18**	**8**

New Brunswick Transformers

2 winding delta - wye					
COLESON COVE 19/345 kV GSU 1		1	1		1
COLESON COVE 19/345 kV GSU 2		1	1		1
COLESON COVE 19/345 kV GSU 3		1	1		1
Pt Lepreau GSU 26/345 kV		1	1		1
Total Neutral Blocking Sys	**0**	**4**	**4**	**0**	**4**

1. Note: All Criteria for a one in 100 Year GMD Storm (20 V/km) except EMP E3 (40 V/km)
2. Results from Emprimus/ PowerWorld Analysis for Line Voltage < 95%
3. Results from CMP PSSE Analysis for GIC > 75 Amps per phase
4. Results from Emprimus/ CMP PSSE Analysis for GIC > 32 Amps per phase
5. Results from Emprimus/ CMP PSSE Analysis for GIC > 50 Amps per phase

The third selection criteria is for Harmonics that exceed the IEEE 519 Standard for power quality (i.e. Harmonics). This standard states that voltage total harmonic distortion (THD) must not exceed 1.5% for more than 3 seconds for power transformers of line voltage greater than 161 kV. Transformer voltage THD as a function of GIC current was published in a paper by R. Walling for single phase transformers [17]. The results, when converted from pu units to Amps, show that a 1,000 MVA transformer will exceed the THD standard at a GIC current above 12 Amps of neutral current or 4 Amps per phase. To convert this finding to other transformer types we used the published results of Dong et al that shows the relative generation of harmonics of four transformer types which is shown in the table below. Combining this relationship with the R. Walling results above the current at which each transformer type will exceed the IEEE voltage THD standard can be derived. These results are also shown in this table. This criteria was applied against the CMP/PSSE GIC data for a one in 100 year GMD storm (20 V/km) and the selected transformers for protection are shown in the third column below. In this case twelve (12) were selected in Maine and four (4) selected for New Brunswick.

These results suggest that moderate solar storms are resulting in harmonic levels that are routinely violating the interconnection agreements between utilities. Furthermore, these harmonics are resulting in reduced power quality to customers.

Transformer Type	Multiplier for GIC Current to Exceed IEEE 519 Std *	Neutral GIC (Amps)	GIC / Ph (Amps)
Three Phase Shell	16	192	64
Three Phase , Three Legged Core	8	96	32
Three Phase , Five Legged Core	2	24	8
Single Phase	1	12	4

* Multiplier from Dong et. al., Comparative Analysis of Exciting Current Harmonics and Reactive Power Consumption from GIC Saturated Transformers, IEEE 2001, [17].

The fourth selection criteria is for potential generator rotor damage caused by harmonics. The selection of this criteria is based on the published paper by Rezaei-Zare and L. Marti, which shows that there is potential for rotor damage when GIC currents exceed 50 Amps per phase [14]. This criteria was applied against the CMP/PSSE GIC data for a one in 100 year GMD storm (20 V/km) and the selected transformers for protection are shown in the fourth of the table. In this case eleven (11) transformers were selected in Maine and four (4) selected for New Brunswick.

The results of this comparison for different selection criteria show that that number of transformers selected for protection ranges from eight (8) to eighteen (18) for the Maine grid and a consistent four (4) for the New Brunswick generator step-up transformers. To avoid damage to power equipment (voltage collapse not considered) the selection shows a range from eight (8) to twelve (12) transformers should be protected.

EMP Mitigation

To mitigate the Maine BES against the effects of an EMP event requires protection of induced EMP E3 quasi DC currents in the network as well as shielding electronics against the short duration EMP E1 pulse. Generally, the EMP E3 threat levels (~ 50 V/km) are typically somewhat higher than a one in one hundred year GMD storm level. Therefore to achieve EMP E3 protection will usually require a larger number of neutral blocking systems in the network and nearby neighboring networks.

In addition to EMP E3 protection, all electronics in the BES will require shielding to attenuate and protect against the high intensity, short duration EMP E1 electro-magnetic (EM) pulse. The frequency of such pulses are typically in the microwave range of 10 MHz to 20 GHz. Protection of BES substation control electronics such as SCADA systems and other electronic controls will require highly shielded and filtered electronic cabinets. Such protective cabinets are available and have already been applied to the protection of some critical military and intelligent electronic computing equipment.

Conclusions / Recommendations

The PowerWorld studies shows that the Maine BES will be subjected to voltage collapse for E-fields from GMD events that are significantly less than the one and 100 year storm. The studies further indicate the application of SolidGround blocking systems in as little as 12 substations (18 transformers) can provide improve the resiliency of the Maine BES by a factor of two (16 V/km to 32 V/km).

Concurrently, the installation of neutral ground blocking devices protects the long-replacement-time high voltage transformers. So even in the event of a low probability severe solar storm, and the temporary collapse of the Maine electric grid, key 345 kV (high voltage) transformers will have been protected and will be available for a faster restart of the Maine electric grid.

The following recommendations are concluded from the studies and analysis:

1. Neutral blocking should be pursued in the 18 transformers with the highest GIC.

2. Install EMP/IEMI detectors at key substations.

3.Install EMP/IEMI protective cabinets at key substations.

4.(A) Monitor the costs and benefits deriving from protection of the Maine electric system from harmful effects of geomagnetic disturbances; and (B) support the cost-recovery of supplemental reliability improvements to the Maine Power Reliability Program (MPRP).

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Appendix A - Transformer Ownership

Chester unit (345/18kV)	Chester SVC Partnership	joint venture of Central Maine Power, Emera Maine
Orrington #1 (345/115kV)	Maine Electric Power Company (MEPCO),	joint venture of Central Maine Power, Emera Maine
Orrington #2 (345/115kV)	Emera Maine	
Keene Road (345/115kV)	Emera Maine	
Mason Steam (345/115kV)	Central Maine Power	
Maxcy (Coopers Mill) (345/115kV)	Central Maine Power	
McGuire Road(345/115kV)	Central Maine Power	
South Gorham (345/115kV)	Central Maine Power	
Surowiec (345/115kV)	Central Maine Power	
Wyman (Yarmouth) GSUs	NextEra	
Albion Rd (one Auto)	Central Maine Power	
Larrabee Rd (one Auto	Central Maine Power	
Bucksport (3 GSUs)	Bucksport Energy LLC	

Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard

A White Paper by:

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July 30, 2014

Executive Summary

The analysis of the US electric power grid vulnerability to geomagnetic storms was originally conducted as part of the work performed by Metatech Corporation for the Congressional Appointed US EMP Commission, which started their investigations in late 2001. In subsequent work performed for the US Federal Energy Regulatory Commission, a detailed report was released in 2010 of the findings[11]. In October 2012, the FERC ordered the US electric power industry via their standards development organization NERC to develop new standards addressing the impacts of a geomagnetic disturbance to the electric power grid. NERC has now developed a draft standard and has provided limited details on the technical justifications for these standards in a recent NERC White Paper[22].

The most important purpose of design standards is to protect society from the consequences of impacts to vulnerable and critical systems important to society. To perform this function the standards must accurately describe the environment. Such environment design standards are used in all aspects of society to protect against severe excursions of nature that could impact vulnerable systems: floods, hurricanes, fire codes, etc., are relevant examples. In this case, an accurate characterization of the extremes of the geomagnetic storm environment needs to be provided so that power system vulnerabilities against these environments can be accurately assessed. A level that is arbitrarily too low would not allow proper assessment of vulnerability and ultimately would lead to inadequate safeguards that could pose broad consequences to society.

However from our initial reviews of the NERC Draft Standard, the concern was that the levels suggested by NERC were unusually low compared to both recorded disturbances as well as from prior studies. Therefore this white paper will provide a more rigorous review of the NERC benchmark levels. NERC had noted that model validations were not undertaken because direct measurements of geo-electric fields had not been routinely performed anyway in the US. In contrast, Metatech had performed extensive geo-electric field measurement campaigns over decades for storms in Northern Minnesota and had developed validated models for many locations across the US in the course of prior investigations of US power grid vulnerability[3]. Further, various independent observers to the NERC GMD tasks force meetings had urged NERC to collect decades of GIC observations performed by EPRI and independently by power companies as these data could be readily converted to geo-electric fields via simple techniques to provide the basis for validation studies across the US. None of these actions were taken by the NERC GMD Task Force.

It needs to be pointed out that GIC measurements are important witnesses and their evidence is not being considered by the NERC GMD Task Force in the development of these standards. GIC observations provide direct evidence of all of the uncertain and variable parameters including the deep Earth ground response to the driving geomagnetic disturbance environment. Because the GIC measurement is also obtained from the power grid itself, it incorporates all of the meso-scale coupling of the disturbance environments to the assets themselves and the overlying circuit topology that needs

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[1] *Geomagnetic Storms and Their Impacts on the U.S. Power Grid* (**Meta-R-319**), John Kappenman, Metatech Corporation, January 2010. Via weblink from Oak Ridge National Lab, ***wttp://www.ornl.gov/sci/ees/etsd/pes/ferc_emp_gic.shtml***

[2] NERC Benchmark Geomagnetic Disturbance Event Description, ***http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Benchmark_GMD_Event_April21_2.pdf***

[3] Radasky, W. A., M. A. Messier, J. G. Kappenman, S. Norr and R. Parenteau, "Presentation and Analysis of Geomagnetic Storm Signals at High Data Rates", IEEE International Symposium on EMC, August 1993, pp. 156-157.

to be assessed. Separate discreet measurements of geo-electric fields are usually done over short baseline asset arrays which may not accurately characterize the real meso-scale interdependencies that need to be understood. The only challenge is to interpret what the GIC measurement is attempting to tell us, and fortunately this can be readily revealed with only a rudimentary understanding of Ohm's Law, geometry and circuit analysis methods, a tool set that are common electrical engineering techniques. Essentially the problem reduces to: *"if we know the I (or GIC) and we know the R and topology of the circuit, then Ohm's law tells us what the V or geo-electric field was that created that GIC"*. Further since we know the resistance and locations of power system assets with high accuracy, we can also derive the geo-electric field with equally high certainty. These techniques allow superior characterization of deep Earth ground response and can be done immediately across much of the US if GIC measurements were made available. Further these deep Earth ground responses are based upon geological processes and do not change rapidly over time. Therefore even measurements from one storm event can characterize a region. Hence this is a powerful tool for improving the accuracy of models and allows for the development of accurate forward looking standards that are needed to evaluate to high storm intensity levels that have not been measured or yet experienced on present day power grids. Unfortunately this tool has not been utilized by any of the participants in the NERC Standard development process.

It has been noted that the NERC GMD Task Force has adopted geo-electric field modelling techniques that have been previously developed at FMI and are now utilized at NRCan. The same FMI techniques were also integrated into the NASA-CCMC modeling environments and that as development and testing of US physiographic regional ground models were developed, efforts were also undertaken by the USGS and the NOAA SWPC to make sure their geo-electric field models were fully harmonized and able to produce uniform results. However, it appears that none of these organizations really did any analysis to determine if the results being produced were at all accurate in the first place. For example when recently inquired, NRCan indicated they will perhaps begin capturing geo-electric field measurements later this year to validate the base NERC Shield region ground model, a model which provides a conversion for all other ground models. In looking at prior publications of the geo-electric field model carried out in other world locations, it was apparent that the model was greatly and uniformly under-predicting for intense portions of the storms, which are the most important parameters that need to be accurately understood.

In order to examine this more fully, this white paper will provide the results of our recent independent assessment of the NERC geo-electric field and ground models and the draft standard that flows from this foundation. Our findings can be concisely summarized as follows:

- Using the very limited but publicly available GIC measurements, it can be shown how important geo-electric fields over meso-scale regions can be characterized and that these measurements can be accurately assessed using the certainty of Ohm's Law. This provides a very strict constraint on what the minimum geo-electric field levels are during a storm event.

- When comparing these actual geo-electric fields with NERC model derived geo-electric fields, the comparisons show a systematic under-prediction in all cases of the geo-electric field by the NERC model. In the cases examined, the under prediction is particularly a problem for the rapid rates of change of the geomagnetic field (the most important portions of the storm events) and produce errors that range from factor of ~2 to over factor of ~5 understatement of intensity by the NERC models compared to actual geo-electric field measurements. These are enormous errors and are not at all suitable to attempt to embed into Federally-approved design standards.

- These enormous model errors also call into question many of the foundation findings of the NERC GMD draft standard. The flawed geo-electric field model was used to develop the peak geo-electric field levels of the Benchmark model proposed in the standard. Since this model understates the actual geo-electric field intensity for small storms by a factor of 2 to 5, it would also understate the maximum geo-electric field by similar or perhaps even larger levels. Therefore this flaw is entirely integrated into the NERC Draft Standard and its resulting directives are not valid and need to be corrected.

The findings here are also not simply a matter of whether the NERC model agrees with the results of the Metatech model. Rather the important issue is the degree that the NERC model disagrees with actual geo-electric field measurements from actual storm events. These actual measurements are also confirmed within very strict tolerances via Ohm's Law, a fundamental law of nature. The results that the NERC model has provided are not reliable, and efforts by NERC to convince otherwise and that utilization of GIC data cannot be done are simply misplaced. Actual data provides an ultimate check on unverified models and can be more effectively utilized to guide standard development than models because as Richard Feynman once noted; "Nature cannot be fooled"!

Introduction to NERC Model Evaluation and Validation Overview
A series of case study examples will be provided in this White Paper to illustrate the evaluation of geo-electric fields derived from GIC measurements across the US electric power grid. These derived geo-electric field results will then be compared to the NERC estimated geo-electric fields for the same storm events and scenarios. There are an important number of underlying principles to this analysis that can be summarized as follows:

- Using past storms and by modeling detailed power networks and comparing to GIC measurements at particular locations is the best way to validate overall storm-phenomena/power grid models. It accounts for the "interpolation" of the incident measured B-fields (including the angular rotation of the fields with time), the accuracy of the ground model used, the coupling to the power network, and the computation of the current flow at the measurement point.

- Experience has shown that over times of minutes, the geomagnetic field will rotate its direction and therefore every transformer in a network will have a sensitivity to particular vector orientations of the field, and the maximum current measured at a given transformer location will be a function of the rate of change intensity of the geomagnetic field, the resulting geo-electric field this causes and the angle of the field as it changes over the storm event. This is why the rate of change (dB/dt) and GIC at a single transformer will not scale perfectly with the maximum value of dB/dt, but taking into consideration all of these topology and orientation factors, a highly accurate forensic analysis can be performed.

- Geomagnetic storms are not steady state events, rather they are events with aperiodic extreme impulsive disturbances that can occur over many hours or days duration. Modeling these events to derive a geo-electric field is challenging but readily achievable. Since these events are time domain problems, modeling solutions using time-domain methods are recommended. The NERC modeling methods that will be evaluated here have generally been developed using Fourier transform frequency domain methods. In these implementations of Fourier methods, the primary question is the accuracy in dealing with the phase of the Fourier transforms.

- When referring to impulsive geomagnetic field disturbance events, these are typically multiple discrete events with times of several minutes. Note that the collapse of the Quebec power network in March 1989 occurred in 93 seconds. Clearly times of only a few minutes are important and it is vital that the geo-electric field intensity of these transients be accurately portrayed and not understated in a Design Standard type document. For example, a 10 meter dyke defined by the standard does no good, if the actual Tsunami height is 15 meters. Any efforts to claim that models that depict some satisfactory averaging over extended time periods as being sufficient must be vigorously refuted, as these peak inflection points are the most vital aspects of the storm environments that must be accurately determined.

Simulation Model Validation – Maine Grid Examples
In the analysis carried out for the FERC Meta-R-319 report, extensive efforts were undertaken to verify that the simulation models for the US power grid were providing sufficiently accurate results. One of the primary approaches that were utilized to test these models were to perform simulations for forensic analysis purposes and to compare the results with discrete measurements that were available.

One of the forensic simulations was conducted on the Maine grid and provided important verification of the ability of the model in that portion of the US grid to produce accurate estimates. Figure 1 provides a plot of the results of this simulation showing the "Calculated" versus "Measured" GIC (geomagnetically induced current) at the Chester Maine 345kV transformer. This was for a storm which occurred on May 4, 1998 and was driven by the large scale storm conditions as shown in Figure 2.

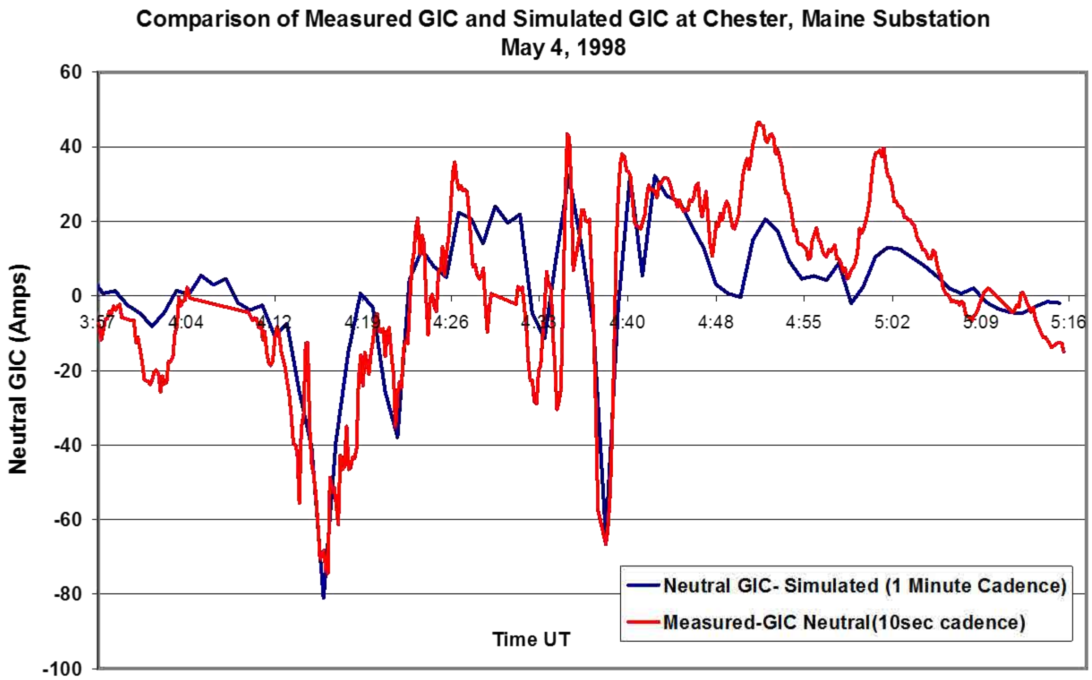


Figure 1 – Plot showing comparison of Simulated versus Measured GIC at Chester Maine 345kV transformer for May 4, 1998 geomagnetic storm. (Source – Meta-R-319)

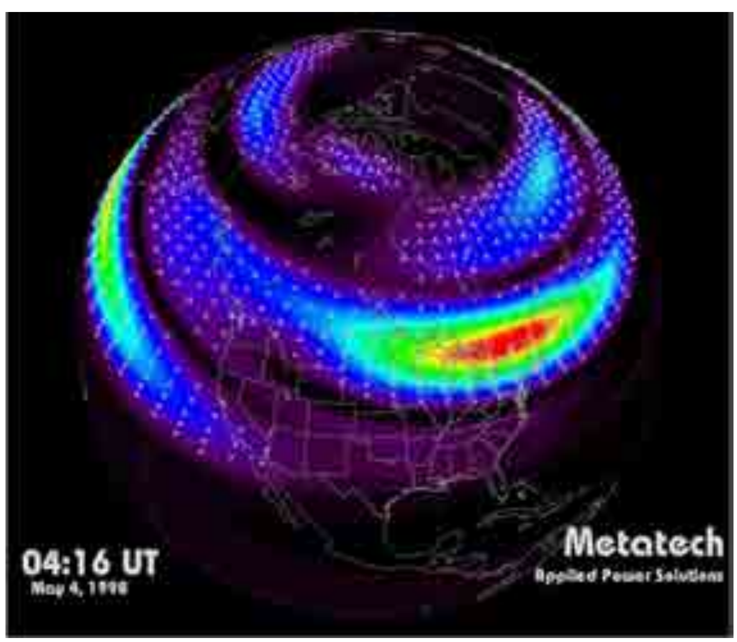


Figure 2 – Map of Geomagnetic Disturbance conditions at 4:16UT during May 4, 1998 storm. (Source – Meta-R-319)

The results in Figure 1 provide a comparison between high sample rate measured GIC (~10 second cadence) versus storm simulations that were limited to 1 minute cadence geomagnetic observatory data inputs (B-fields). Due to this limitation of inputs to the model, the model would not be able to reproduce all of the small scale high frequency variations shown in the measured data. However, the simulation does provide very good accuracy and agreement on major spikes in GIC observed, the most important portion of the simulation results that need to be validated. Figure 3 provides a wider view of the impact of the storm in terms of other GIC flow conditions in the Maine and New England region electric power grid, this is provided at time 4:16UT.

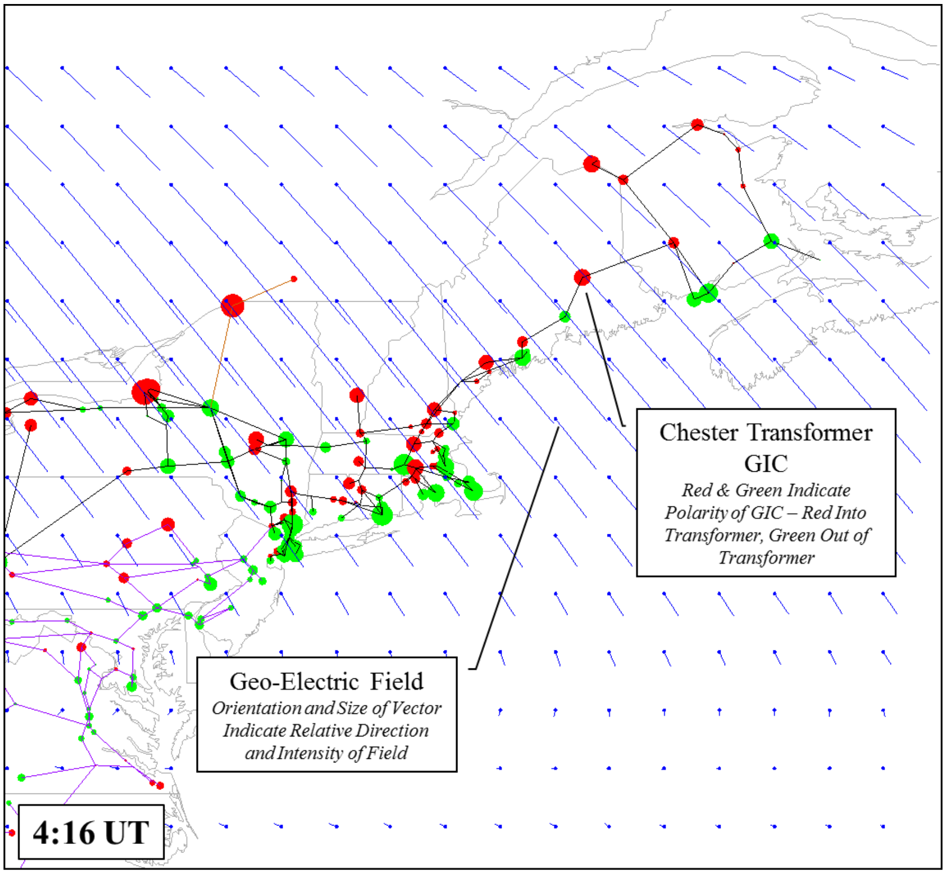


Figure 3 – GIC flows and disturbance conditions in Maine/New England grid at 4:16UT, May 4, 1998. (Source – Meta-R-319)

As this illustration shows, the Chester GIC flow is shown along with comparable GIC flows in a number of other locations in the regional power grid at one minute in time. In addition to impacts to the New England grid, extensive power system impacts were also observed to voltage regulation in upstate New York region due to storm. In this map, the intensity and polarity of GIC flows are depicted by red or green balls and their size, the larger the ball the larger the GIC flow and the danger it presents to the transformer and grid. Also shown are the blue vector arrows which are the orientation and intensity of the geo-electric field which couples to the topology of the electric grid and produces the GIC flow patterns that develop in the grid. It is noted that during the period of this storm, the electric fields rotated and all transformers in the grid would experience a variation in the pattern of GIC flows.

Considerable scientific and engineering examination has been performed since the release of the Meta-R-319 report; the report and other subsequent examinations are in close agreement on a number of important parameters of future severe geomagnetic storm threat conditions. For example, it is now well-accepted that severe storm intensity disturbance intensity can reach level of 5000 nT/min at the latitudes of the Maine power grid. NRCan now provides estimates of geo-electric fields for the nearby Ottawa observatory for storms including the May 4, 1998 storm. The ability therefore exists to do cross-validations with this and other proposed NERC ground models and geo-electric field calculation methods.

Observations of GIC at the Chester Maine substation also provide important observational confirmations that allow empirical projection of GIC levels that are plausible at more severe storm intensities. Earlier this year, the Maine electric utilities provided a limited summary of peak GIC observations from their Chester transformer and storm dates to the Maine Legislature. Figure 4 provides a graphical summary that was derived of the peak GIC and peak disturbance intensities (in nT/min) observed at the Ottawa Canada geomagnetic observatory for a number of reported events. The Maine utilities did not provide accurate time stamps (just date only), so that limits some of the ability to accurately correlate disturbance intensity to GIC peaks as the knowledge of timing is extremely coarse. Also since the Ottawa observatory is approximately 550km west of Chester, there is some uncertainty to local storm intensity specifics near Chester. However as shown, there are clear trend lines and uncertainty bounding of the level of GIC and how the GIC increases for increasing storm intensity. This trend line is quite revealing even with all of the previously mentioned uncertainties on the spatial and temporal aspects of the threat environments.

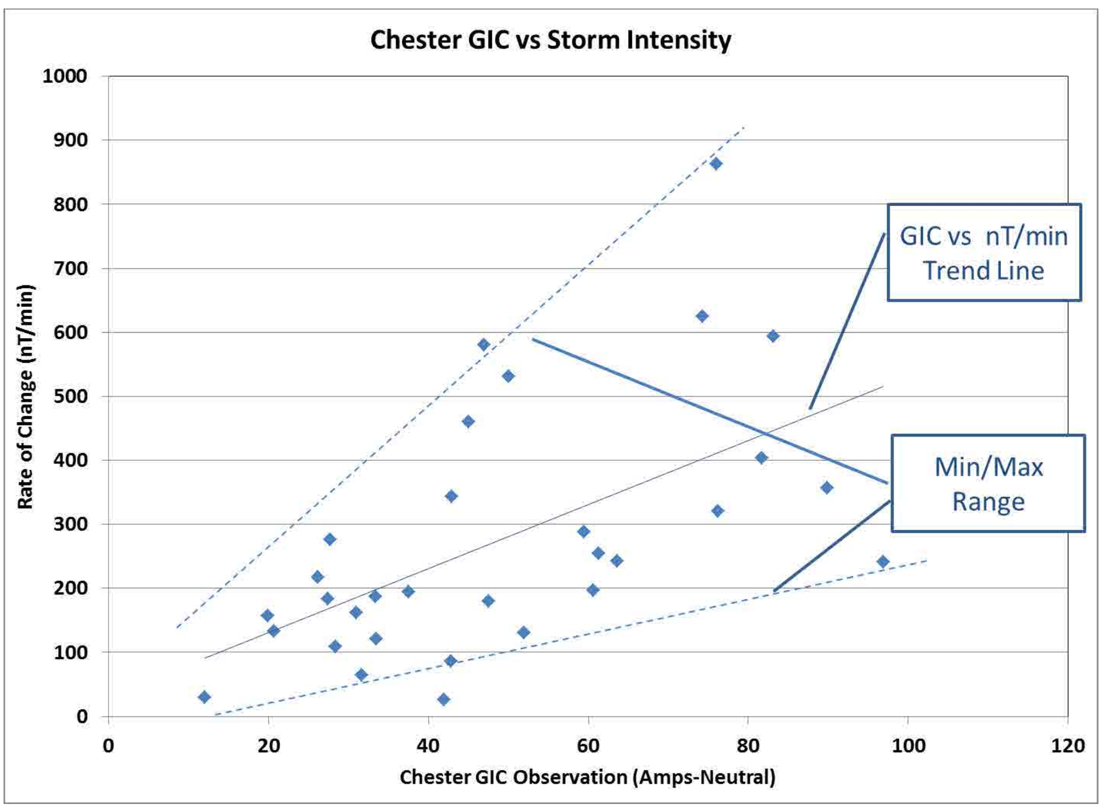


Figure 4 – GIC versus Storm Intensity (nT/min) from multiple observed GIC storm events at Chester Transformer, in this case the GIC timing is extremely coarse.

At higher storm intensities, the geo-electric field increases and if only intensity changes (as opposed to spectral content), then the increase in geo-electric field and resulting GIC will be linear. Because storm intensity for very severe storms can reach ~5000 nT/min, this graph can be linearly extended to project the range of GIC flows in the Chester transformer for these more extreme threat conditions. Figure 5 provides a plot similar to that in Figure 4, only with linear extensions of the GIC flow that this observational data estimates.

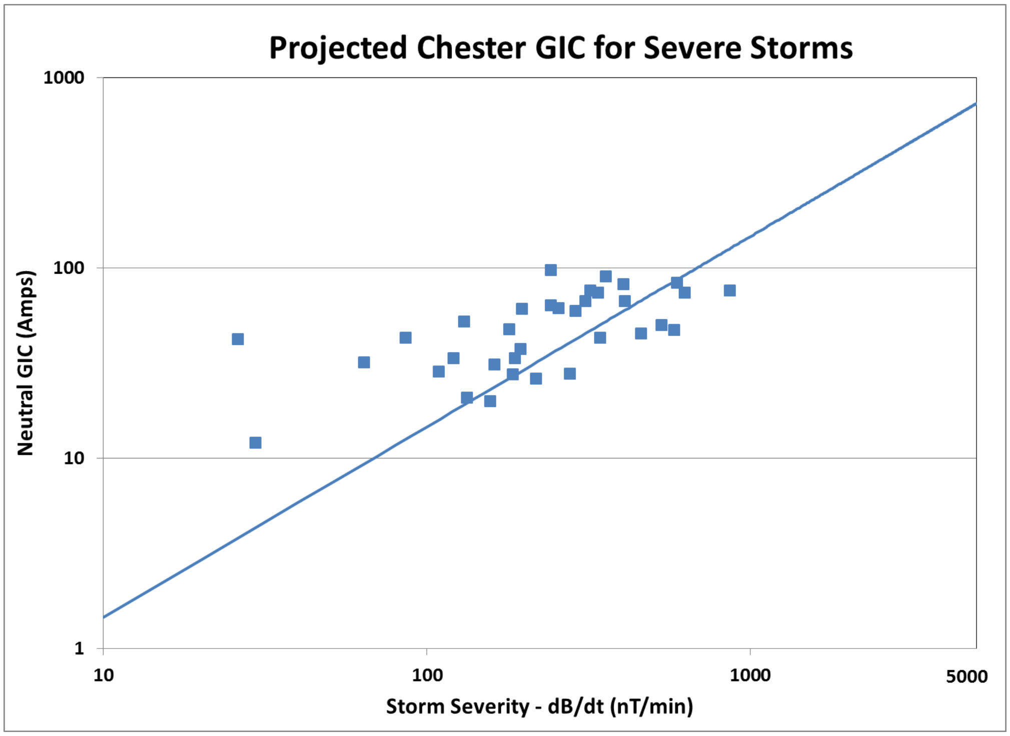


Figure 5 – Projected Chester GIC flow for storm intensity increasing to ~5000 nT/min.

Using these data plotting techniques with the previously noted uncertainties, a more detailed examination can be performed for one of the specific storm events which occurred on May 4, 1998. Figure 6 provides again the earlier described GIC plots from Figure 1. Two particularly important peak times are also highlighted on this plot at 4:16UT and 4:39UT where the recorded GIC reaches peaks respectively of -74.3 Amps and -66.6 Amps. These comparisons also show very close agreement with the simulation model results as well. Therefore the peak data points can be more explicitly examined in detail, as a comparison to how GIC vs dB/dt was plotted in Figure 4. In addition to this GIC observation data, there was also dB/dt data observed from a local magnetometer for this storm, which also greatly reduces the uncertainty of the threat environment.

Having all of this data available will aid in utilizing the power system itself as an antenna that can help resolve the geo-electric field intensity that the complex composition of ground strata generates during this storm event. Further once this response is empirically established, this same ground response can be reliably utilized to project to higher storm intensity and therefore higher GIC levels. This provides a blended effort of model and observational data to extract details on how the same grid and ground strata would behave at higher storm intensity levels. One of the advantages that exists in the modeling of the circuits of the transmission networks are that the resistive impedances of transmission lines and transformers (which are the key GIC flow paths) are very well known and have small uncertainty errors. It is also known that the Chester transformer is non-auto, so GIC flow in the neutral also defines the GIC per phase. There is also no doubt about the locations of assets within the circuit topology. Finally, station grounding resistance can also be determined to relatively high certainty as well. In comparison, ground response as has been previously published in the Meta-R-319 report can vary over large ranges, as much as a factor of 6. Therefore direct observations of ground response are highly important and GIC measurements, as will be discussed, provide an excellent proxy or geophysical data that can be used to derive the complex behavior characteristics of the ground strata. This set of understandings can be applied as a tool to significantly bound this major area of uncertainty.

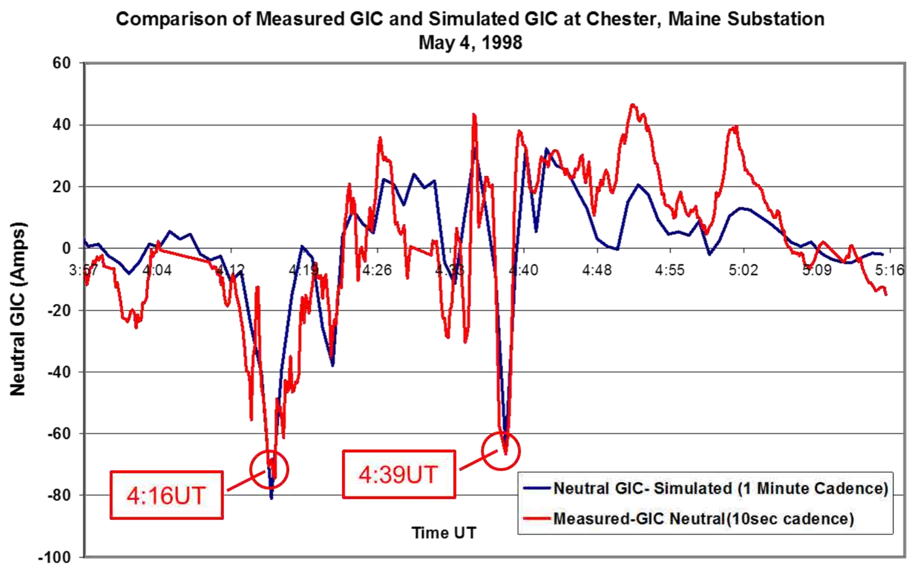


Figure 6 – GIC observation at times 4:16 & 4:39 UT that can be examined in further detail.

Network Model and Calculation of Chester GIC for 1 V/km Geo-Electric Field

Using the Maine region power grid model of the EHV grid, it is possible to examine what the GIC flow would be at the Chester transformer for a specified geo-electric field intensity of 1 V/km. This specified GIC is an intrinsic and precise characteristic of the network that will provide a useful yardstick to calibrate against for actual GIC flows that occurred and from that a more highly bounded geo-electric field intensity range can be determined at this location. Figure 7 provides a plot of the GIC flow in the Chester transformer for a 1 V/km geo-electric field. Since the topology of the transmission network also greatly determines the resulting GIC, this calculation is performed for a full 360 degree rotation of the orientation of the 1 V/km field.

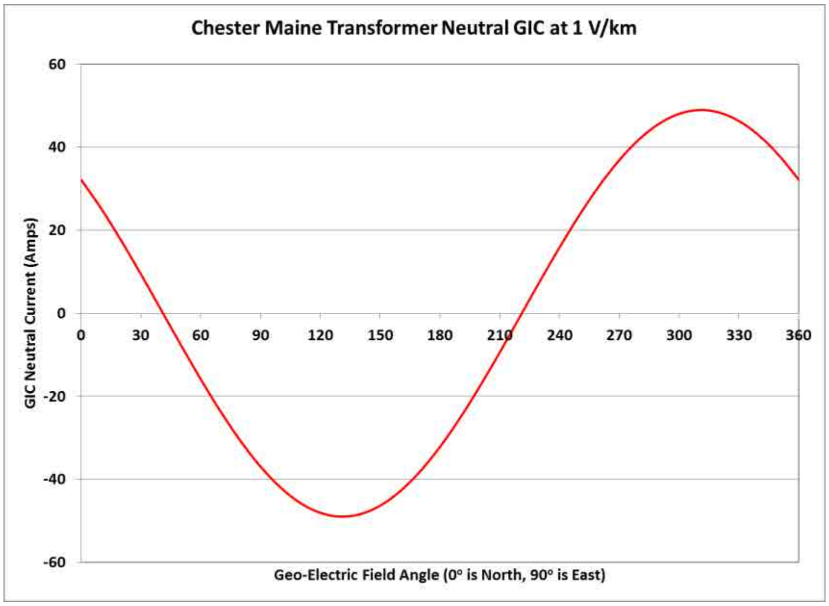


Figure 7 – GIC flow at Chester transformer neutral for 1 V/km geo-electric field at various orientation angles.

As the plot in Figure 7 shows, the peak GIC flow at this location is ~49 Amps which occurs at the 130° and 310° angular orientations of the 1 V/km field.

While the GIC to 1 V/km relationship in Figure 7 is developed from a detailed network model, there are also much simpler methods using a limited knowledge of a portion of the local transmission network that can be used to check the accuracy of the model. This involves a simple circuit analysis to derive the resistance and orientation specifics of just the two major transmission lines connecting to Chester. Each of the two 345kV lines connecting to Chester (from Chester-Orrington and from Chester to Keswick New Brunswick) is shown in the map of Figure 8.

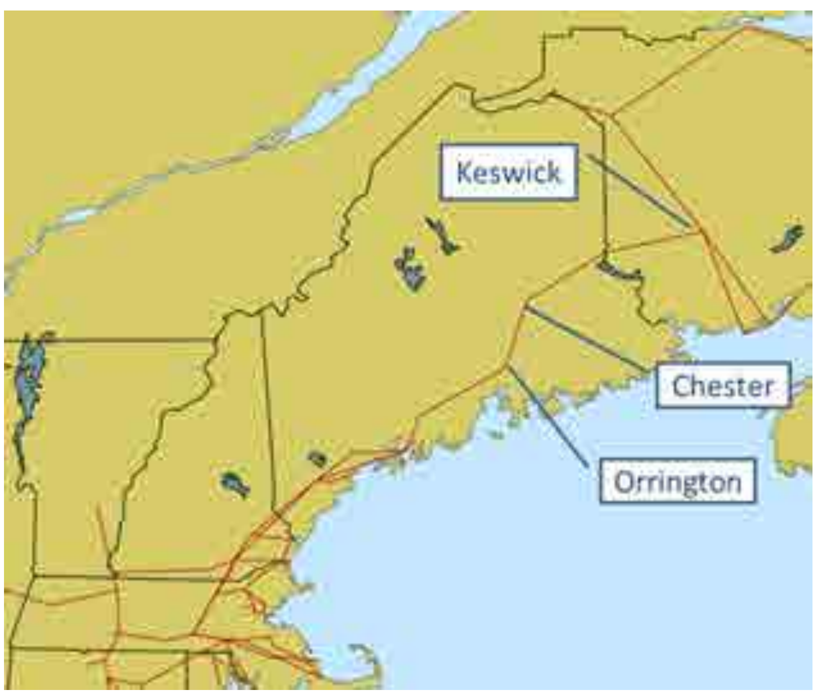


Figure 8 - Map of Chester Maine and 345kV line interconnections.

For geomagnetic storms, the orientation of specific transmission lines becomes very important in determining their coupling to the geo-electric field which also has a specific orientation. For example if the orientation of a specific line is identical to the orientation of the geo-electric field, then the GIC will be at a relative maximum. Conversely if the orientations of the field and line are orthogonal, then no coupling or GIC flow will occur. In the case of the Chester to Keswick line, the orientation is at an angle of ~70^{o} (with 0^{o} being North) and for the Chester to Orrington line the angle is ~205^{o}. Hence it should be expected that each line will couple differently as the orientation of the geo-electric field changes. Also an important parameter in the calculation of GIC is the line length which also describes the total resistance of this element of the GIC circuit. The point to point distances from Chester are ~80 km to Orrington and ~146 km to Keswick. Figure 9 provides the results of a simple single circuit calculation of the Chester transformer GIC connected to a 345kV transmission line of variable length with a transformer termination at the remote end of that line, the estimated GIC is also shown for the 80 km Orrington line and the 146 km Keswick line using a uniform 1 V/km geo-electric field strength. As shown in this figure, for the two line lengths only a small change in GIC occurs (~11%), even though there is nearly a factor of two difference in line lengths. This calculation assumes a full coupling with the orientation of the geo-electric field, as the geo-electric field changes its orientation to the line with time, and the GIC will change as prescribed via a sine function.

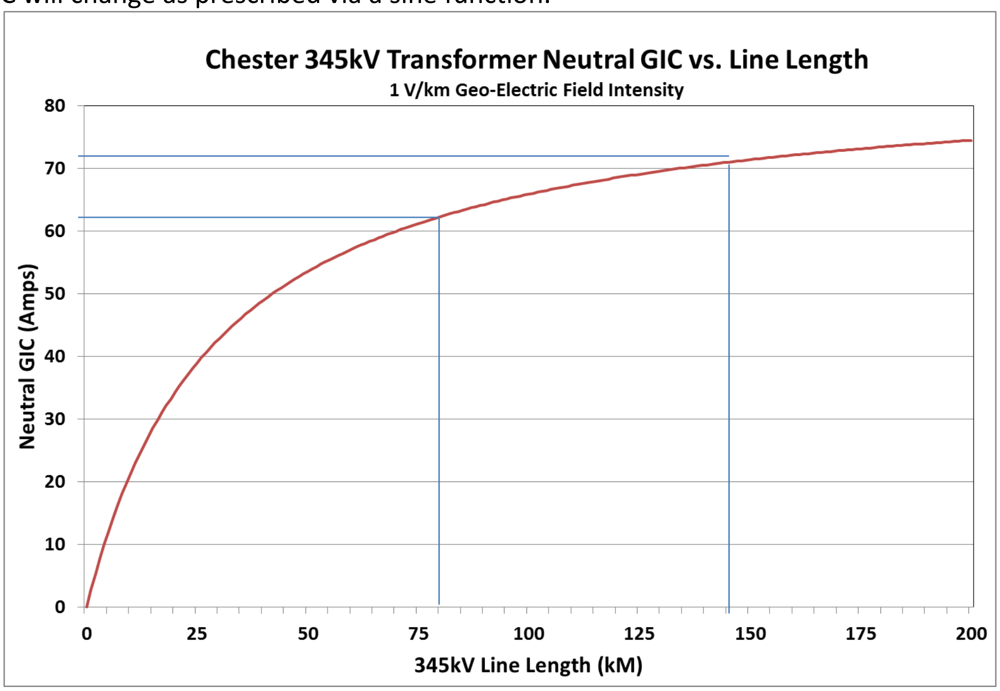


Figure 9 – Calculated Chester GIC for single circuit 345kV transmission line, 80 km Orrington and 146km Keswick noted

Given this simple two line case, a discrete calculation can be performed for each line, and using circuit superposition principles(Kirchoff's Laws), the resulting Chester GIC flow can be plotted as well versus the orientation angle of a uniform 1 V/km geo-electric field. This is shown in Figure 10 for each of the two lines and the resultant GIC flow at Chester.

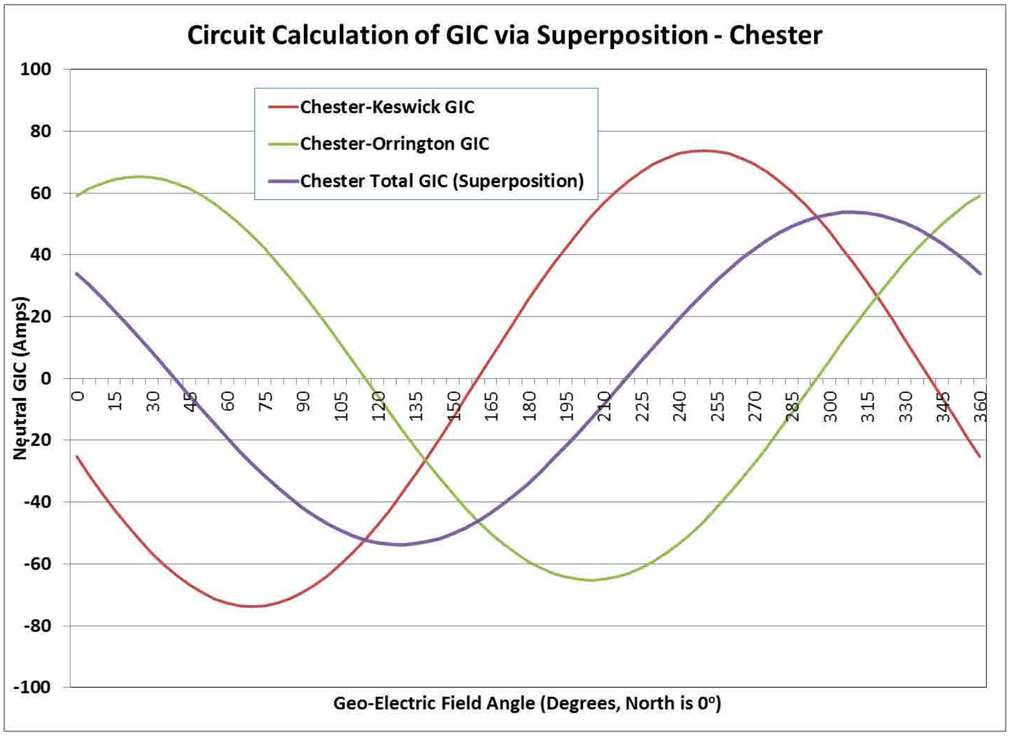


Figure 10 – GIC flow for each line versus geo-electric field angle and Resultant GIC at Chester.

Determining Storm Geo-Electric Field Intensity from Observed GIC

As this Figure 10 illustrates, each line segment will have differing GIC flows versus the orientation of the geo-electric field, and the resultant Chester neutral GIC will also be of lower magnitude and will also have a differing vector angle to each line segment. This simple Ohm's law based circuit calculation can be compared to the more detailed model calculation previously shown in Figure 7, which is shown in Figure 11. As this Figure illustrates, there is very good agreement in GIC flows using the two-line calculation approache (~95% agreement). The detailed model result will be more exact because all of the other network assets are used in the calculation. However, this comparison also shows that the line length parameter dominates the impedance of the circuit and defines the circuit current given the circuit resistances of just a few key components. Knowing both I (or GIC in this case) and R of the circuit allows the ability to precisely determine the driving V or geo-electric field that caused the observed GIC to occur in the transformer.

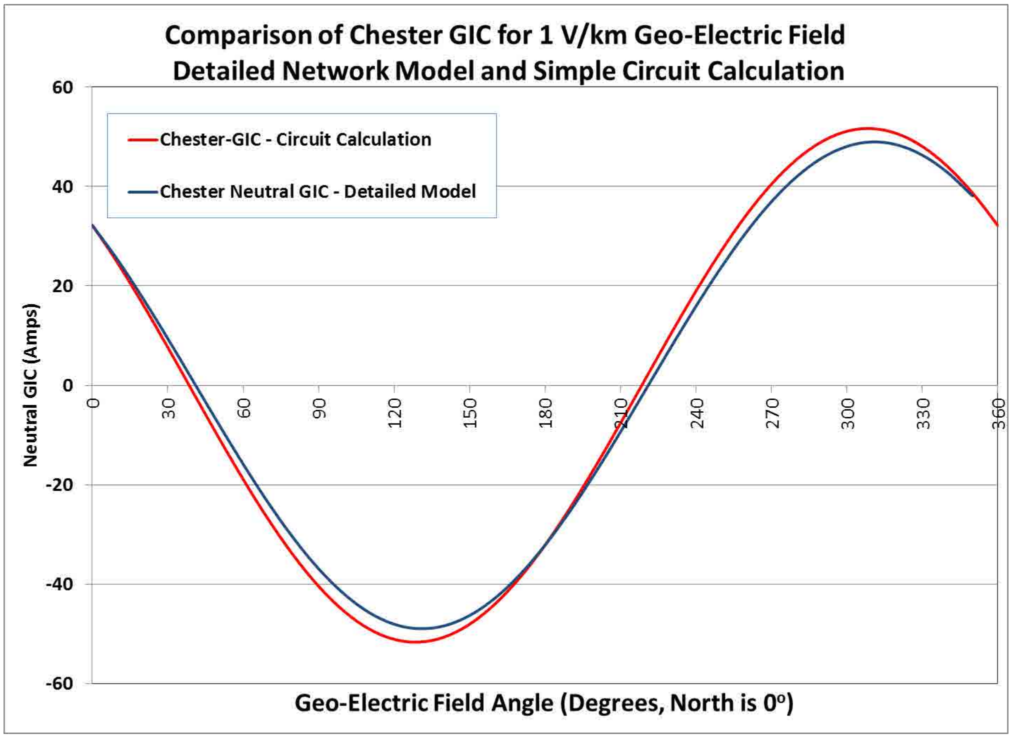


Figure 11 – Comparison of Calculated Chester GIC from detailed model and simple circuit calculation

Using the data from Figures 6 (the observed GIC at Chester) and Figure 11, it can be immediately inferred that the peak GIC levels of -66.6 and -74.3 Amps would have required a geo-electric field intensity of greater than 1 V/km to have occurred to produce such high levels of GIC. This is simply a process of utilizing Ohm's law knowledge to begin to develop an improved understanding of the geo-electric field intensity, an otherwise complex and uncertain field to calculate. In contrast it is not possible to infer the upper bound of geo-electric field, in that at angles where GIC nulls occur (such as 40^o and 220^o) even with a very high geo-electric field will not produce a significant GIC flow. As this point illustrates, these estimates can also be greatly improved by adding a simple understanding of geometry to this calculation. For example at time 4:16 UT, the simulation model results shown previously in Figure 3 illustrates a geo-electric field orientation at the Chester location which is almost exactly at 130^o, the orientation that would produce a peak GIC response at Chester. Using this circuit relationship of current to voltage allows extension to a scaling of the 49 Amp GIC at 1 V/km to a field intensity that would instead result in a 74.3 Amps GIC magnitude. This would lead to the estimated geo-electric field intensity at this 4:16UT time of ~1.5 V/km.

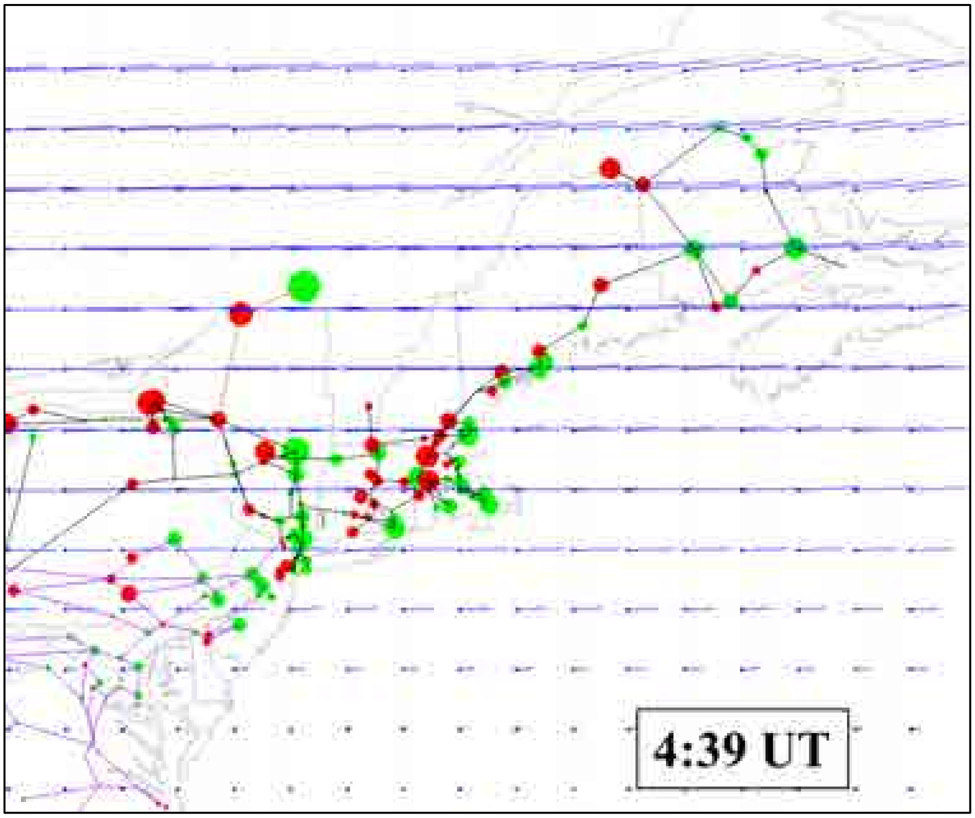


Figure 12 - GIC flows and disturbance conditions in Maine/New England grid at 4:39UT, May 4, 1998.

A similar simplified empirical analysis to confirm model results and expected geo-electric field levels can also be performed at time 4:39UT. Figure 12 provides a simulation output at time 4:39UT which again shows the intensity and geo-electric field angular orientation that would have occurred at this time step. This shows that the field was Eastward oriented or ~90^{o}. Since the characteristic GIC flows at Chester behave as a sine wave for variation of the geo-electric field angle to these circuit assets, a scaling factor based on these angular characteristics can also be applied, which would rerate the field to account for the less-optimal orientation angle at this time. In this case, the 66.6 Amp GIC would be produced by total geo-electric field of ~2 V/km, but only ~1.4 V/km of this total geo-electric field is utilized to produce a GIC flow in the Chester transformer. As this case illustrates, a higher total geo-electric field intensity occurred at 4:39UT than at time 4:16 UT, even though the GIC is lower at 4:39UT. This appears to be counter intuitive. However the event produced a smaller GIC, with the important difference being the angular orientation of the field alone.

As this example illustrates, the observation of GIC when properly placed in context provides an ability to develop an important metric for calculation of the driving geo-electric field that caused the GIC.

Validating the NERC Geo-Electric Field for Ottawa and New England Ground Models

As the previous discussion has revealed, the knowledge of GIC flows combined with the network resistance characteristics and locations of network assets can provide all of the information needed to fully resolve the storm Geo-Electric Field Intensity at any particular time during the storm. In other words knowing I and R allows the application of Ohm's law and geometry to derive V or the Geo-Electric Field. This means that GIC measurements can be utilized to derive the geo-electric field at all observation locations and provide important validations of the NERC Ground Models and Geo-Electric Field calculation methodology.

To better understand how GIC can be used to validate the NERC geo-electric field calculations, the regional nature and footprint of each storm needs to be more fully explained. Figure 13 provides a map of the Ottawa and St John's geomagnetic observatories and their proximity to the Chester substation in Maine. As this map illustrates, Chester is positioned in between these two observatories with Ottawa being ~550 km west of Chester and St. Johns being ~1230 km to the east of Chester.

Figure 13 – Map showing Locations of Chester substation in comparison with Ottawa and St. Johns geomagnetic observatories

During the time period around 4:39UT which resulted in the peak GIC flow at Chester, both the Ottawa and St. John's geomagnetic observatory also recorded similar impulsive disturbance levels. This plot of these two observatories is shown in Figure 14. Because both of these observatories recorded this same coherent impulsive disturbance, this suggests that the observations had to be connected to the same coherent ionospheric electrojet current structure (in this case an intensification of the Westward Electojet Current) that would have extended all the way between these observatories and directly in proximity to Chester, Maine as well.

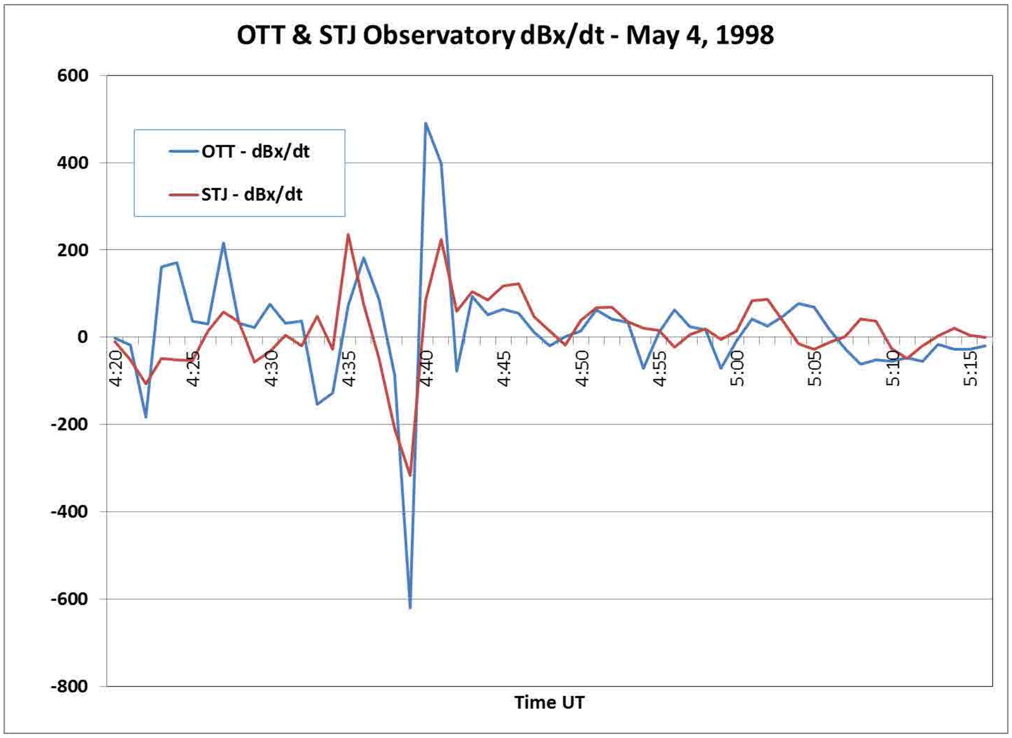


Figure 14 – Observed Impulsive disturbance at Ottawa and St. John's on May 4, 1998 at time 4:39UT.

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.

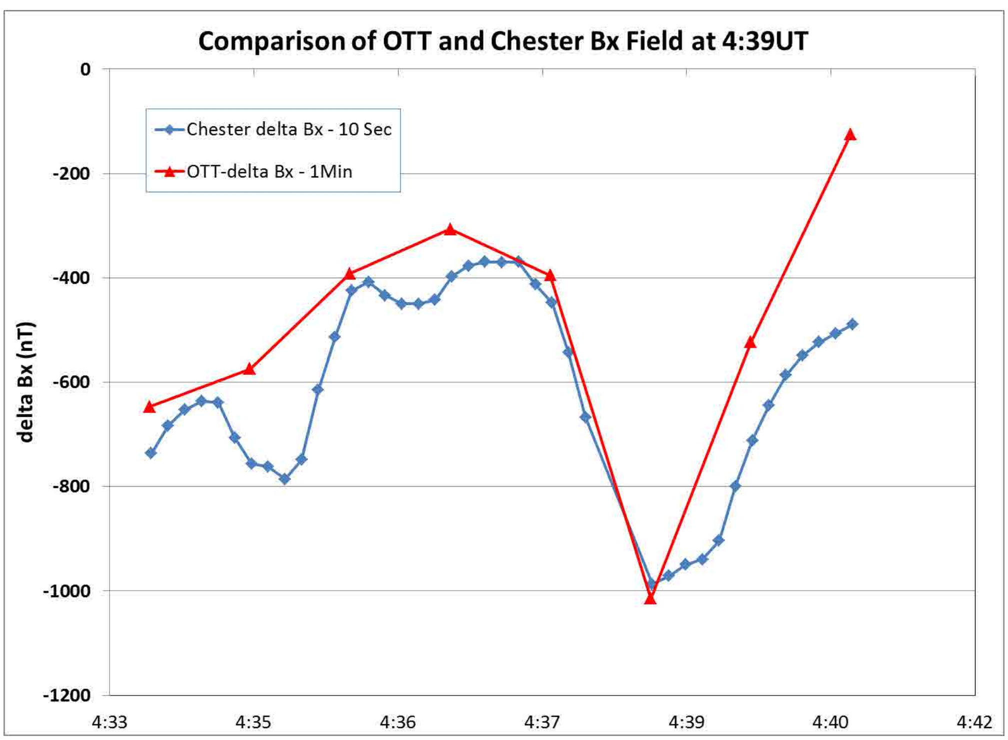


Figure 15 – Observation of Bx at Ottawa and Chester during peak impulse at time 4:39UT.

This close agreement between the observations at Ottawa and at Chester therefore allows the comparison of geo-electric field estimates between these two sites to be compared. As we had previously established using Ohm's Law, the peak geo-electric field must reach ~2 V/km to create the level of GIC observed during this storm. Geo-electric field calculations using a simulation model developed by the NERC GMD Task Force can be compared with the simulated geo-electric field in the Metatech simulation[4]. This comparison is shown in Figure 16. In addition, several portions of this geo-electric field waveform comparison are noted.

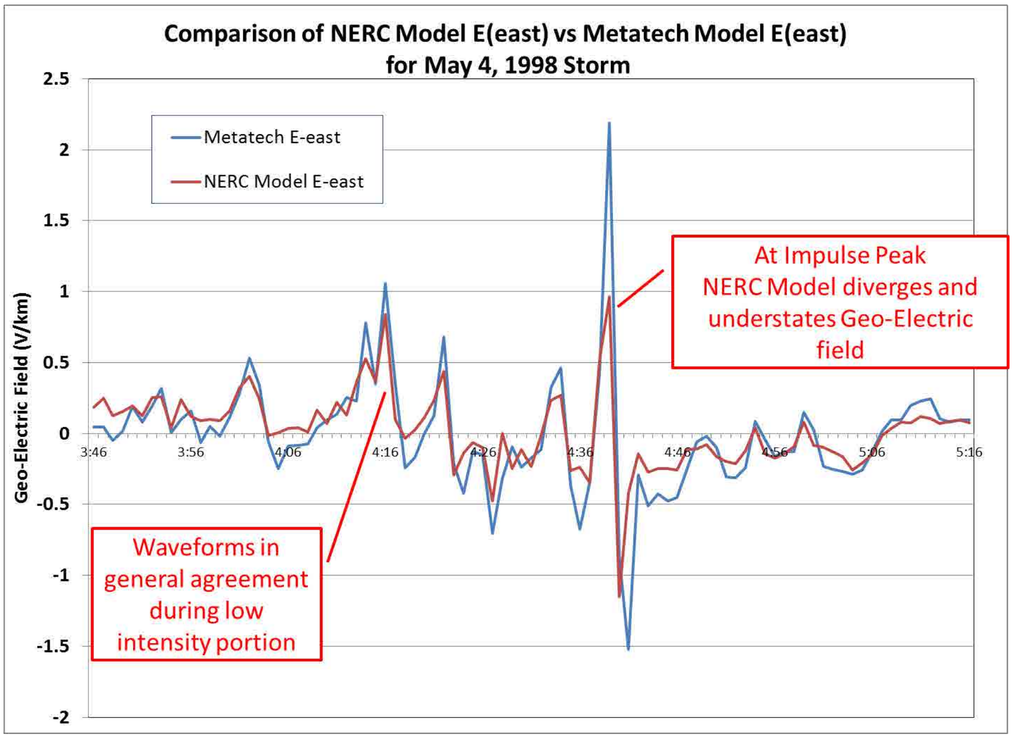


Figure 16 – Comparison of Metatech east-west geo-electric field calculation and NERC east-west geo-electric field calculation for May 4, 1998 storm event.

In the earlier portions of the storm simulation, the relative agreement between the two models for the geo-electric field is quite close. This occurs during a quieter and less intense portion of the storm. However as shown at the large impulse around time 4:39 UT, there is a divergence of agreement between the two models with the NERC modeling method understating the Metatech model results by a significant margin. After that impulse is over, the two models again come into relatively close agreement again. This suggests a problem in the NERC model of understating the intensity for more intense impulsive disturbances. As previously shown, the intensity in dB/dt is ~600 nT/min at time 4:39 UT, while it is generally below 100 to 200 nT/min at all other times during the simulation. Hence this higher intensity may be an important inflexion threshold within the NERC model.

As previously discussed Ohm's Law requires a sufficiently large enough geo-electric field to create the GIC flow observed at this location. Using the NERC model geo-electric fields it is possible to calculate the GIC flow and compare this to the GIC flow calculated for the Metatech model and even to the observed GIC. Figure 17 provides a comparison of the NERC model GIC with that computed in the

[4] Geo-elctric field data for this storm downloaded from NRCan http://www.spaceweather.gc.ca/data-donnee/dl/dl-eng.php#view

Metatech model. Figure 18 compares the same NERC Model GIC result with actual GIC observed at Chester. As both of these figures illustrate, the NERC model results will under predict the GIC at the peak storm intensities. In the case of the peak at time 4:39UT the understatement was similar in both the model comparisons and the observed GIC comparison.

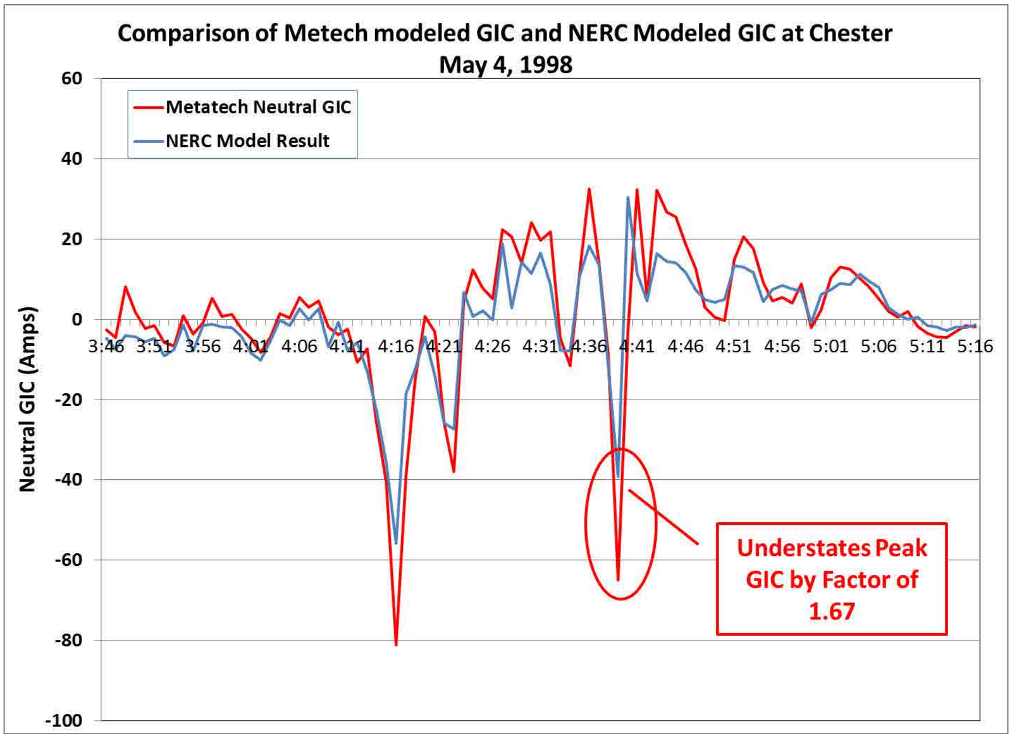


Figure 17 – Comparison of Metatech model GIC to NERC model GIC at Chester.

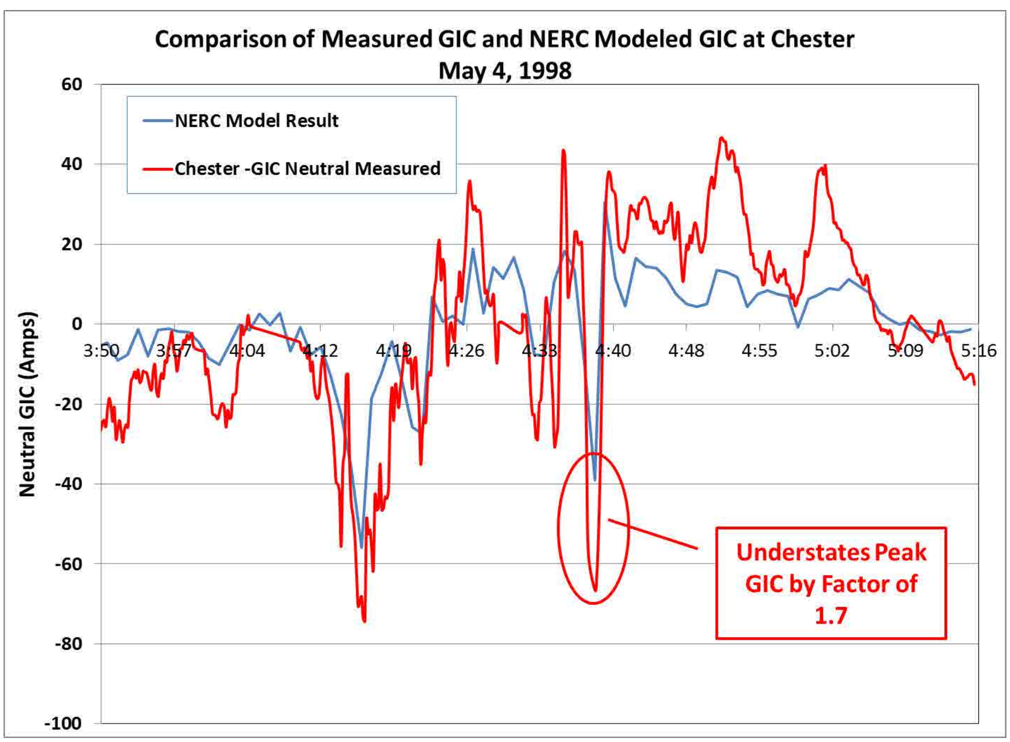


Figure 18 - Comparison of NERC model GIC to observed GIC at Chester.

NERC Model Validation Problems and Other GIC Observations

Seabrook GIC Observations July 13-16, 2012

While a number of GIC observations have been made over the last few decades in the US, very little of this information has been made publicly available. However where there is public information, it is possible to examine that data in a similar manner to the observations in Chester. Last year, observations as provided in Figure 19 were reported for GIC observations at the Seabrook Nuclear Plant[5]. These observations indicated peak GIC intensities during this storm that reached levels of 30 to 40 amps several times during the storm. The peak of 40 Amps occurred on July 16, 2012.

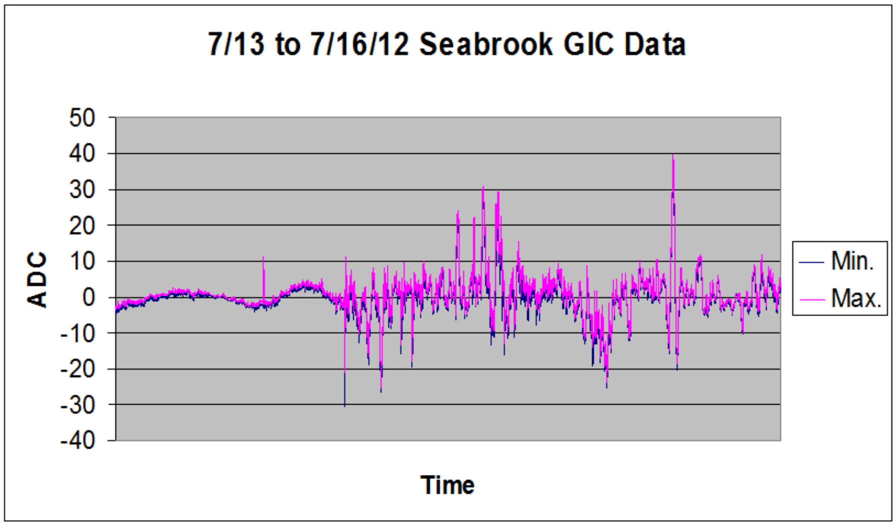


Figure 19 – GIC Observations at Seabrook Nuclear Plant July 13-16, 2012

Seabrook is also located in the New England region and because it is a GSU transformer, the neutral GIC also determines the flow that injects into the 345kV transmission network in that region. Figure 20 provides a map showing the location of Seabrook, and like Chester it will be heavily influenced by the same storm processes that will be observed at the nearby Ottawa observatory. In fact Seabrook is even closer to Ottawa than Chester.

[5] Geomagnetic Disturbance Mitigation for Nuclear Generator Main Power Transformers, Kenneth R. Fleischer, Presented April 16, 20132 at NOAA Space Weather Week Conference, Boulder Co.

Figure 20 – Location of Seabrook Nuclear Plant in New England region 345kV network.

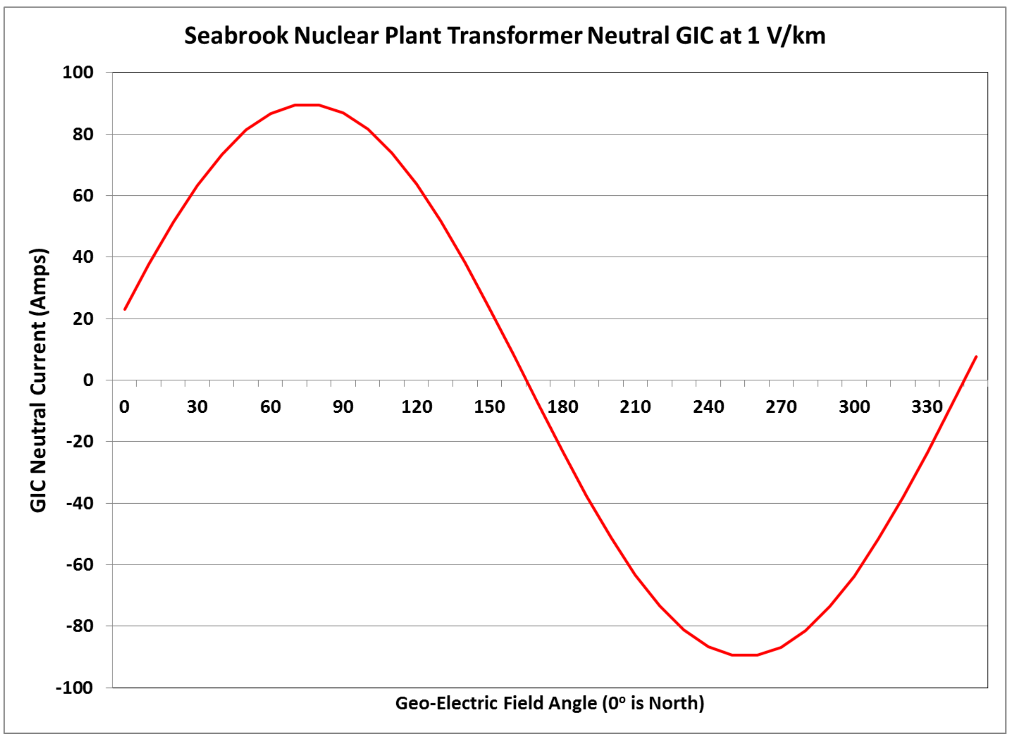


Figure 21 - GIC flow at Seabrook transformer neutral for 1 V/km geo-electric field at various orientation angles.

Figure 21 provides a plot of the characteristic GIC flows that would be observed at Seabrook for a uniform 1 V/km geo-electric field for a 360 degree rotation. This is computed similar to the way it was done at Chester. At this location, a 1 V/km geo-electric field produces ~90 Amp GIC at an 80^{o} angle (essentially nearly east-west oriented). Compared to the characteristic GIC plot for Chester (Figures 7 and 11), for a 1 V/km geo-electric field at Seabrook the GIC will be ~50% higher. This is due to the more integrated connections at Seabrook into the New England 345kV grid and lower circuit impedances, as would be expected. This characteristic indicates that for the 40 Amp GIC observation that occurred on July 16, 2012, there must have been a net east-west geo-electric field of ~0.45 V/km to produce this large of a GIC, a requirement dictated by the Ohm's law behavior of the circuit at Seabrook.

Figure 22 provides a plot of the East-West Geo-Electric Field that would be derived using the NERC model from this storm, using the Ottawa observatory geomagnetic field disturbance conditions as the input. As shown the peak field intensity reaches only ~0.1 V/km which is ~4 times too low to produce the actual GIC observed at Seabrook for this storm event. Hence this storm simulation model provides an example of even worse GIC validation attempt than at Chester. (Not shown is that the peak north-south geo-electric field would have been ~0.12 V/km. But these are also too low and would not couple efficiently with the Seabrook region circuits; therefore this was not a factor in the GIC levels at Seabrook.)

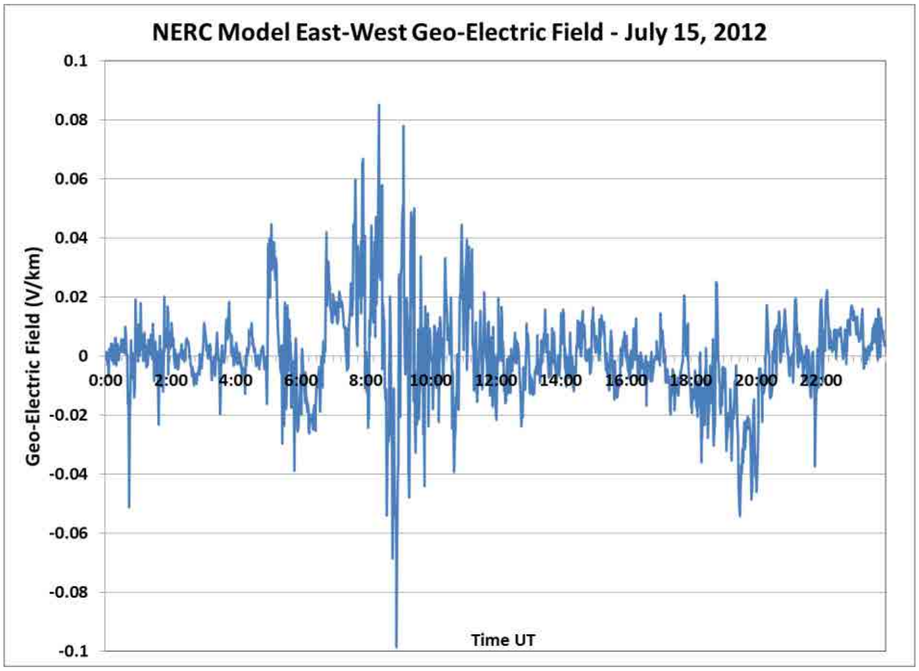


Figure 22 – NERC Model estimated East-West Geo-Electric Field on July 15, 2012 for the NE1 ground model.

BPA Tillamook GIC Observations Oct 30, 2003

In another situation, an examination has been conducted for ground models in the Pacific northwest region of the US. Data on GIC observations in the BPA transmission system have been provided to the Resilient Society Foundation under FOIA provisions and have been provided for analysis and ground model validation purposes. The GIC observations at the BPA Tillamook 230kV substation are examined in this case study. The Tillamook substation is on the western end of the BPA transmission network as shown in the map in Figure 23. There is a single 230kV line from Tillamook to the Carlton substation, but also 3 115kV lines that also connect at Tillamook, two which go in mostly North-South directions and one that connects to the East at Keeler.

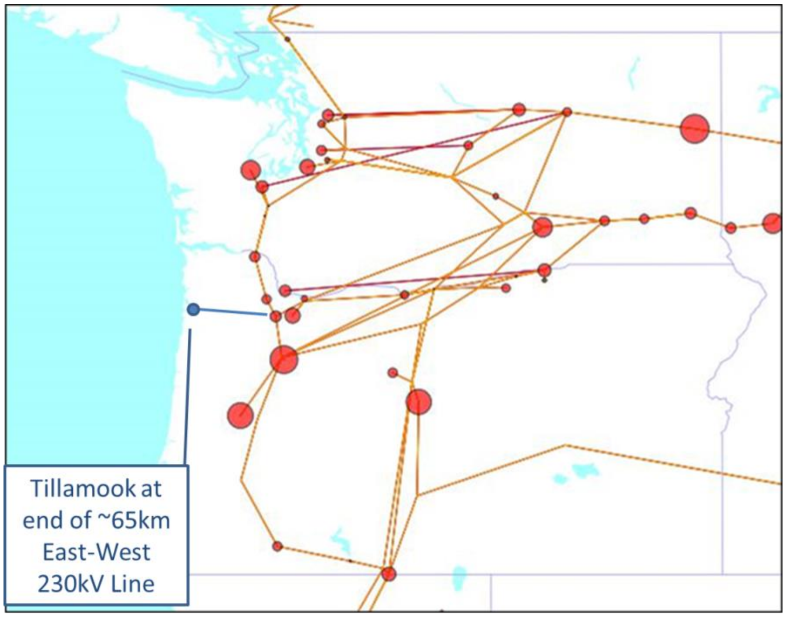


Figure 23 – Map of Tillamook 230kV substation and BPA 500kV network

Figure 24 provides a set of observations of GIC over a 2 hour time period at Tillamook which BPA provided in both 5 minute average and 2 second cadences during the October 30, 2003 storm. As shown in the 2 sec cadence data, the peak GIC approached nearly 50 Amps around time 19:55UT.

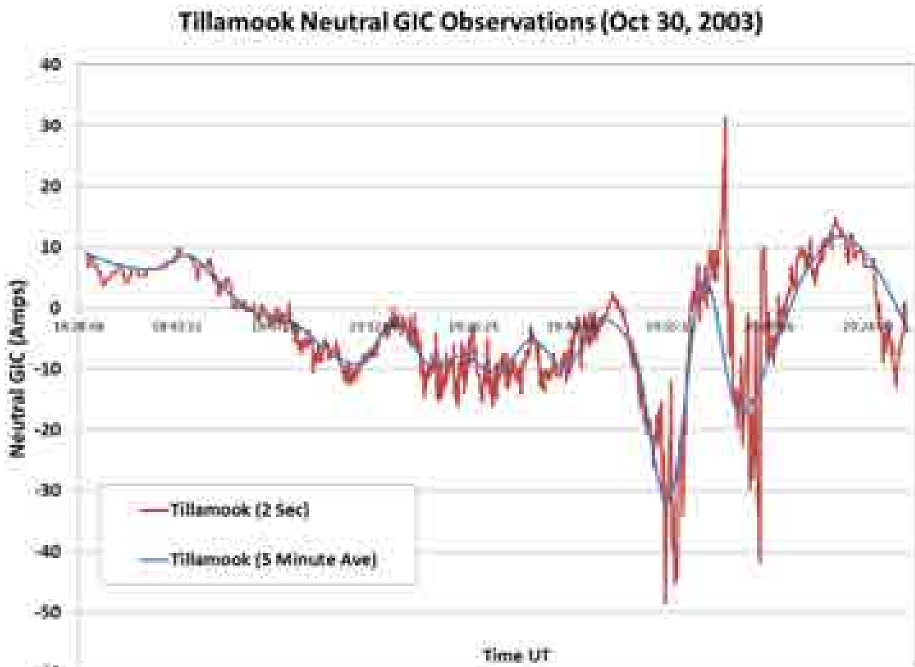


Figure 24 – Tillamook Neutral GIC observations on Oct 30, 2003, both 2 second and 5 minute average levels are shown

The Oct 30, 2003 storm conditions around time 19:55 UT are summarized from regional geomagnetic observatories as shown in Figure 25. This summary indicates that a region of intensification did encroach down into the Tillamook proximity at this time and would have been responsible for the peak GIC flows observed at this time, though Tillamook was not exposed to the worst case storm intensities.

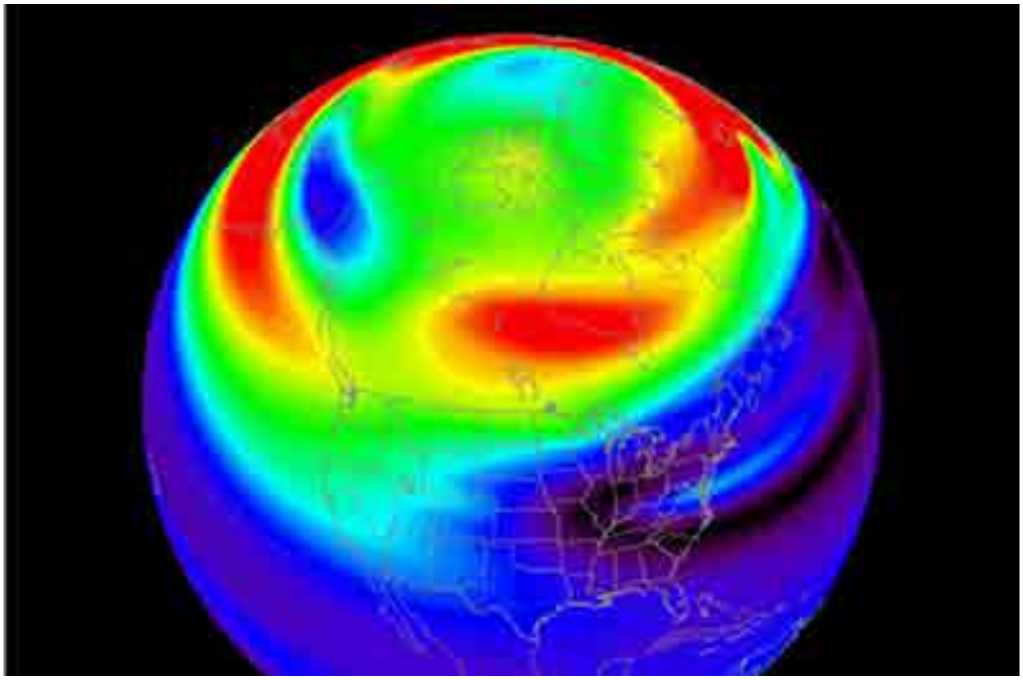


Figure 25 – Regional storm conditions at time 19:55UT October 30, 2003 at time of peak Tillamook GIC flows

Using methods similar to those developed for the Chester station and the various BPA physical data sources available, the characteristic GIC flows for the Tillamook 230kV autotransformer can be calculated for a rotated 1 V/km geo-electric field. The results for this are shown in Figure 26 and the peak GIC reaches a level of ~38 Amps for a predominantly east-west oriented geo-electric field. Therefore when examining the GIC levels observed at Tillamook on Oct 30, 2003, Ohm's law would constrain that the minimum geo-electric field in this region would need to exceed 1 V/km (in at least the east-west direction) to produce the nearly 50 Amps GIC peaks.

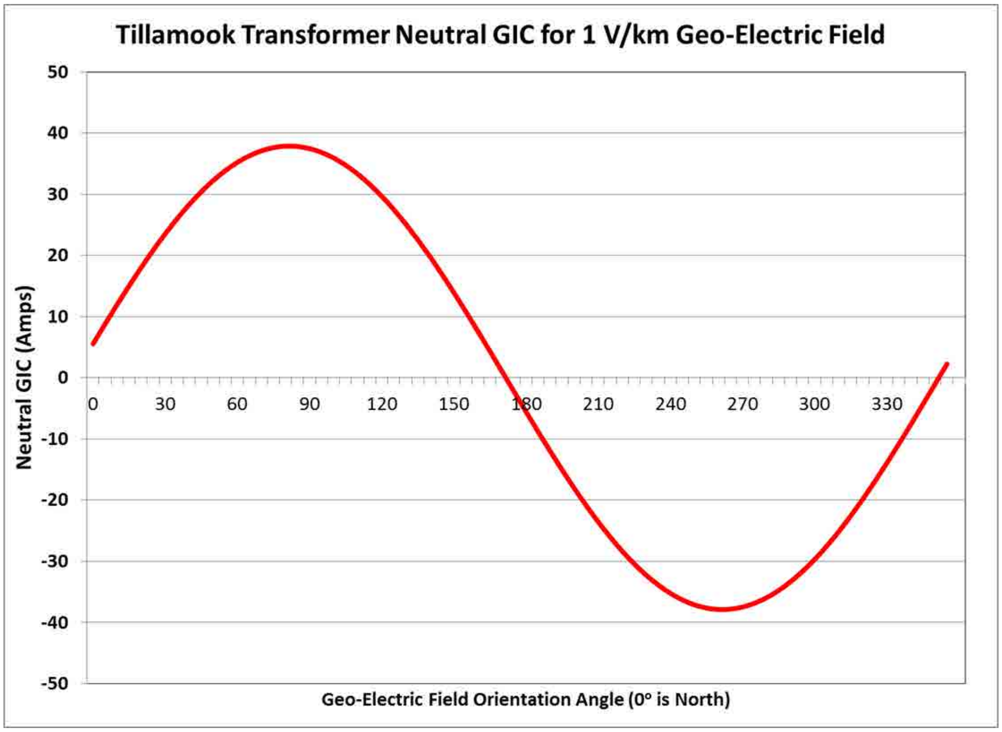


Figure 26 - GIC flow at Tillamook transformer neutral for 1 V/km geo-electric field at various orientation angles.

The NERC model calculations for East-West geo-electric field using the PB1 model are shown in Figure 27 for the same time interval as shown in Figure 24 for the Tillamook high GIC observations, but since the Tillamook GIC flow characteristics are defined in Figure 26, it is possible to utilize this to derive the minimum East-West geo-electric field responsible for producing the GIC flows in Figure 24. These results are also presented in Figure 27 with the NERC model predictions for this storm.

As Figure 27 shows, the peak geo-electric field as strictly constrained by Ohm's law must exceed 1 V/km during portions of the GIC flow where the Tillamook GIC exceeded ~38 amps level. At all times, the NERC model geo-electric field did not exceed even 0.25 V/km. As this comparison illustrates, the NERC model greatly understates the peak geo-electric field intensities at the peak GIC flow portions of the storm. In some cases this understatement is more than a factor of 4 to 5 times too small. This degree of divergence is also worse than what was observed at Chester Maine and is similar to the error level noted for Seabrook.

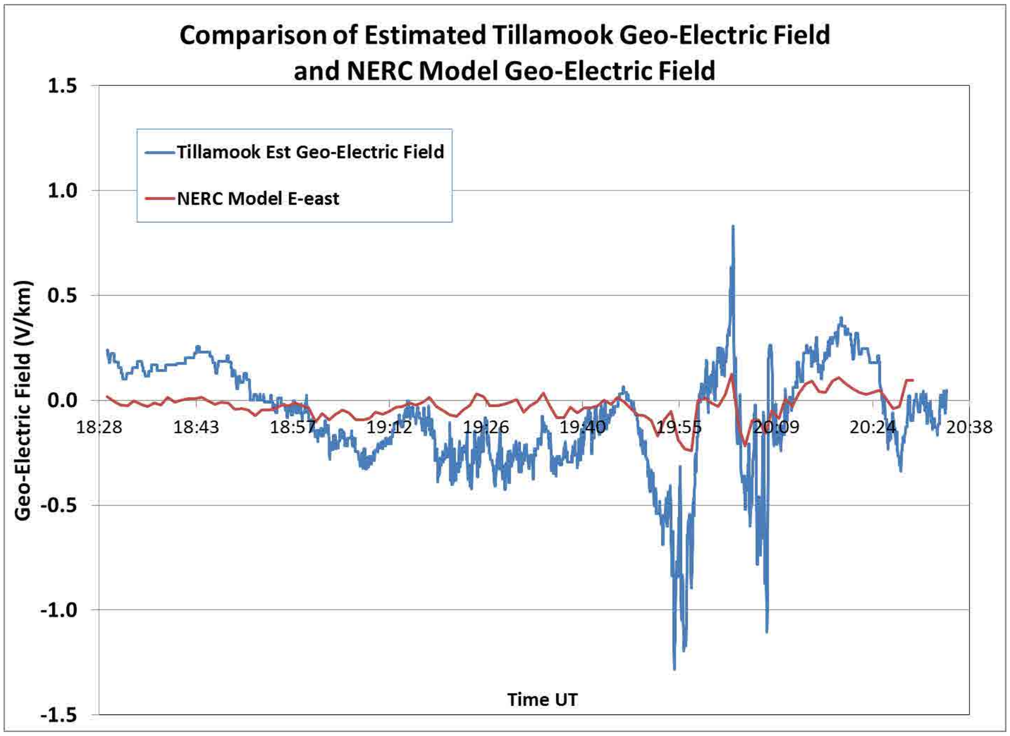
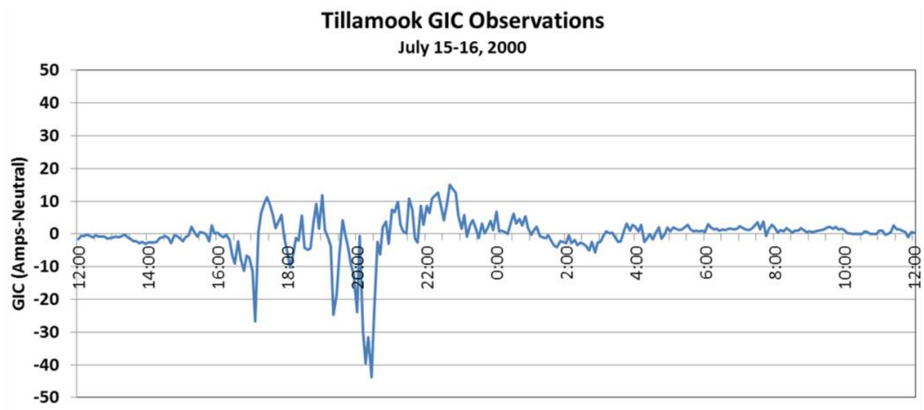


Figure 27 – Comparison of NERC Model geo-electric field with estimated geo-electric field needed to produce Tillamook GIC flows for the Oct 30, 2003 storm

There are other storms available with similar levels of GIC measurements observed at the Tillamook substation and 230kV line. Because this 230kV line is an East-West orientated line, GIC observed there will be largely driven by North-South variations (or dBx/dt) in the geo-magnetic field which subsequently produces an East-West geo-electric field. Figure 28 provides a plot of the nearest geomagnetic observatory (Victoria, ~340 km north of Tillamook) and the Tillamook GIC observed during an important storm on July 15-16, 2000. These geomagnetic disturbance conditions reach a peak of just over 150 nT/min resulting in GIC flows (5 min averaging) reaching -43.5 Amps at time 20:25UT. Figure 29 provides a detailed regional summary which show the more global storm conditions that were occurring at time 20:25UT over North America. As this Figure illustrates, the most severe storm conditions were located quite far to the North, so the GIC observed for these conditions could have been driven to much higher levels had the intensity extended further southward.

From the GIC observations for this storm, the minimal Geo-Electric field levels necessary to produce the GIC flows observed at Tillamook can be again calculated. This can also again be compared with the estimates used by NERC in modeling this storm event, this comparison is shown in Figure 30. In the comparison of the NERC model geo-electric field with the actual geo-electric field as derived from GIC measurements, the NERC model again greatly under predicts peak V/km intensities, by as much as a factor of ~5 or more at peak intensities times. These results are similar to the results from the Oct 30, 2003 storm as shown in Figure 27 and further confirm that the NERC models will not accurately depict storm conditions.



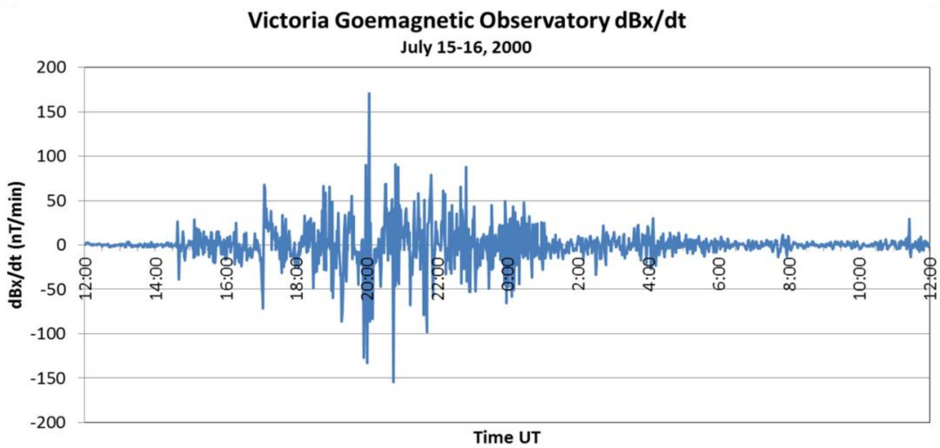


Figure 28 – Observed Tillamook GIC and Victoria dBx/dt for storm on July 15-16, 2000.

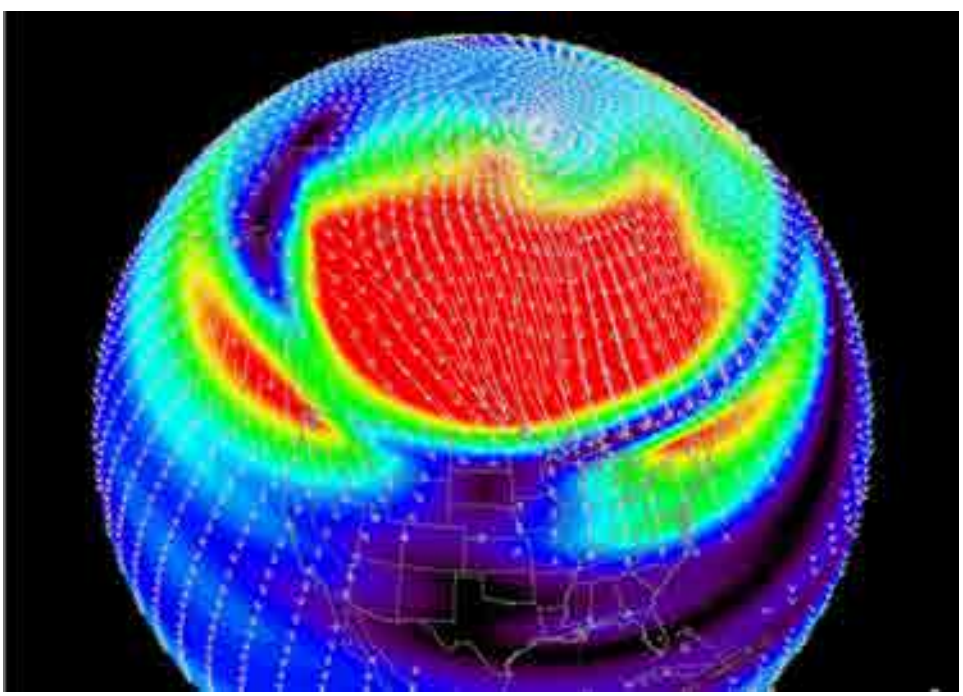


Figure 29 - July 15, 2000 at time 20:25UT storm conditions at time of Tillamook -43.5 Amp GIC Peak.

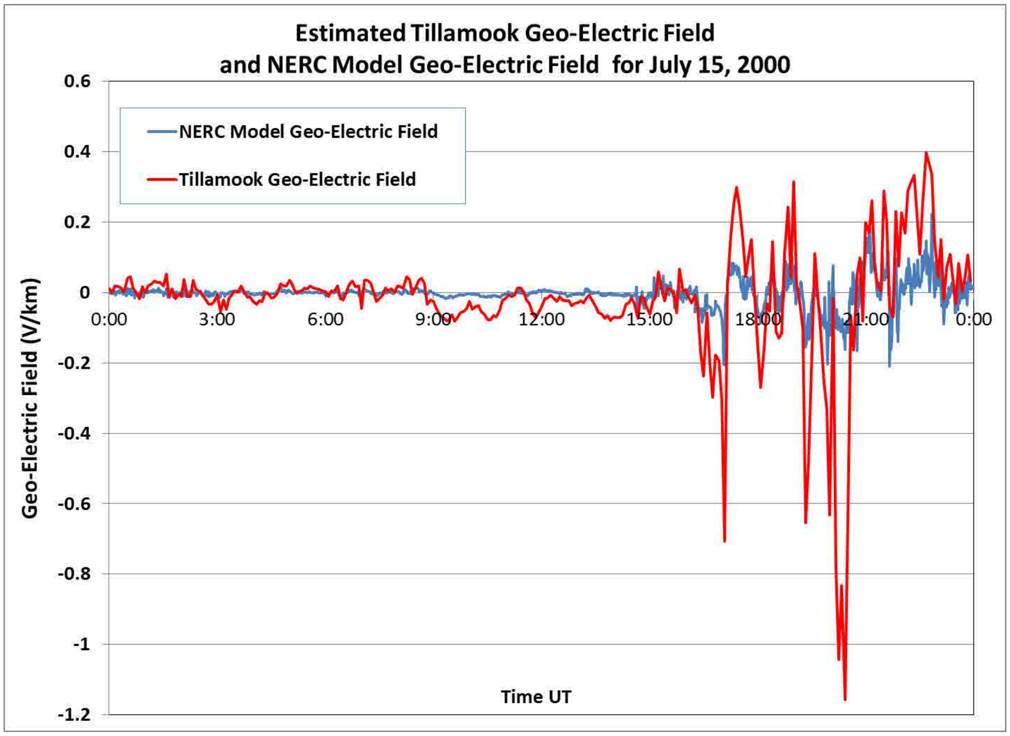


Figure 30 - Comparison of NERC Model geo-electric field with estimated geo-electric field needed to produce Tillamook GIC flows for the July 15, 2000 storm

Other Instances of Geo-Electric Field Modeling Concerns

The NERC geo-electric field simulation tools had their genesis out of the Finnish Meteorology Institute and have since been adopted at NASA (A. Pulkkinen) and also at Natural Resources Canada and many other locations around the world. Pulkkinen in particular was a key NERC GMD Task Force science investigator, a key EPRI science investigator along with staff from NRCan. Pulkkinen was also a member of the NERC GMD Standards Task Force, where the draft standards incorporating these tool sets are fully integrated into the science analysis and are recommended tools for system analysis. In the entirety of the NERC GMD task force investigations, no evidence has been made available by the NERC GMD Task Force of rigorous validations of the suite of ground models and derived relationships that have been published. USGS scientist involved in the effort asked for more power industry efforts to do model validations at several NERC GMD meetings, with no active participants and no subsequent publications supporting the ability to verify these models.

These FMI/NRCan-based geo-electric field modeling approaches use a Fourier transform method[6]. Fourier transforms are well-conditioned for periodic signals, not the very aperiodic events associated with abrupt, high intensity impulsive disturbances typical for severe geomagnetic storms. Therefore a Fourier approach needs to be carefully considered and tested rigorously to assure fidelity in output resolution for severe impulsive geomagnetic field disturbances. An additional geo-electric field modeling approach has been developed by Luis Marti based upon Recursive Convolution[7]. Unfortunately no independent validation for this model was noted in their IEEE paper on the model, rather it was only

[6] How to Calculate Electric Fields to Determine Geomagnetically-Induced Currents. EPRI, Palo Alto, CA: 2013. 3002002149.

[7] Calculation of Induced Electric Field During a Geomagnetic Storm Using Recursive Convolution, Luis Marti, A. Rezaei-Zare, and D. Boteler, IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 29, NO. 2, APRIL 2014

tuned to agree with the FMI/NRCan geo-electric field model output results. In addition, staff from the NOAA SWPC and USGS were also provided tool sets that were tuned to the NASA-CCMC/NRCan geo-electric field models so that the results that each examined would be the same. Hence no real independent assessments were ever apparently undertaken by all of these organizations. Therefore all of the various NERC GMD models appear to produce results that will consistently understate the true geo-electric field intensity.

In looking at recent publications by Pulkkinen, et. al., a paper titled “Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden”[8] was published in the Space Weather Journal in 2008. In this paper the authors presented results from several storm events that were similar in intensity to the May 4, 1998 storm that was discussed in a prior section of this report. Figure 31 is a set of plots from Figure 7 of their paper showing the disturbance intensity (dB/dt in nT/min) in the bottom plot and the measured and calculated GIC in the top plot. As illustrated in this Figure, the storm intensity is similar to that experienced in Maine during the May 4, 1998 storm at ~500 nT/min. In regards to the comparison of the Measured and Calculated GIC the simulation model greatly under predicts the actual measured GIC during the most intense portion of the storm around hour 23 UT by substantial margins (factor of 3 or more). This is the same symptomatic outcome observed in the NERC model results and provides another independent assessment with possible inherent problems with this modeling approach.

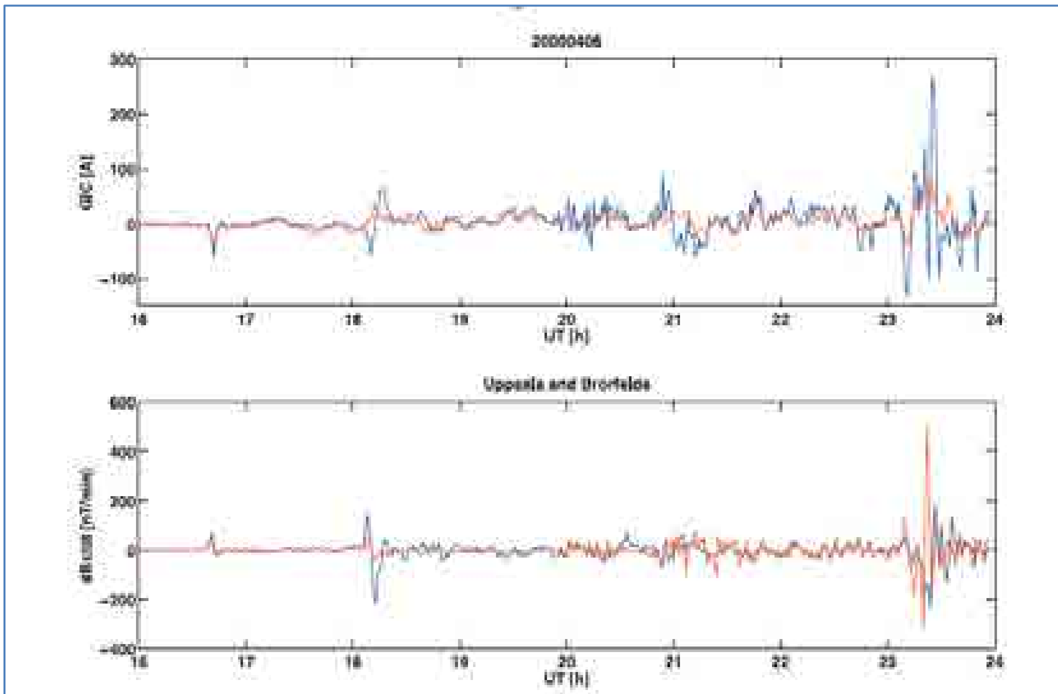


Figure 7. The top curve shows the measured (blue) and calculated (red) GIC at Simpevarp-2 (6 April 2000). The bottom curve shows dB_x/dt from Uppsala (blue) and Brorfelde (red).

Figure 31 – Plot Figure 7 from Pulkkinen, et.al.,paper “Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden” published 2008 showing storm intensity and GIC comparisons

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[8] Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden, M. Wik, A. Viljanen, R. Pirjola, A. Pulkkinen, P. Wintoft, and H. Lundstedt, SPACE WEATHER, VOL. 6, S07005, doi:10.1029/2007SW000343, 2008

In another example from this same paper, a figure shown below as Figure 32 provides a comparison plot of the Measured and Calculated GIC during the July 15, 2000 storm at the same transformer in southern Sweden. The GIC results as in all prior comparisons greatly diverge during the occurrence of the largest and most sudden impulsive disturbance events, such as those between 21 and 22 UT.

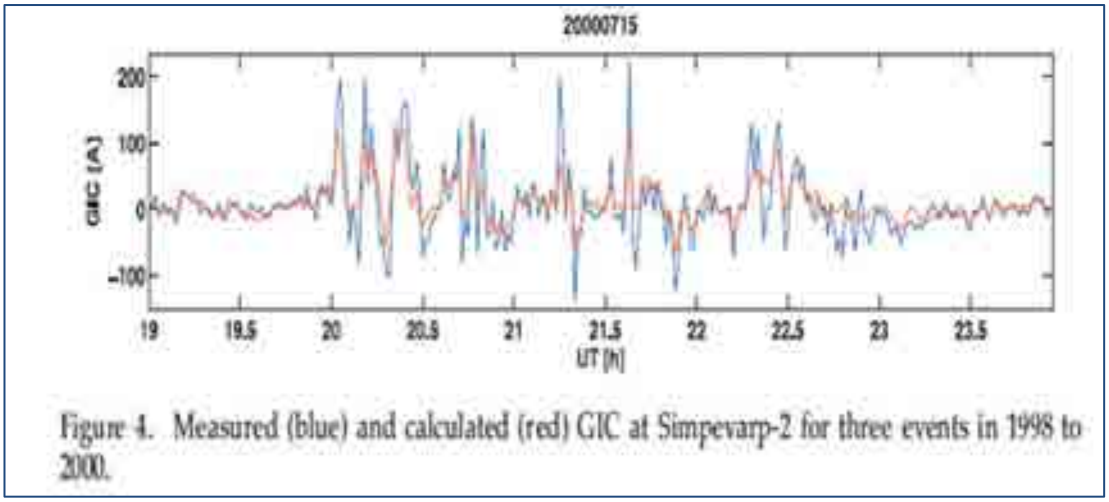

Figure 32 - Plot Figure 4 from Pulkkinen, et.al.,Paper "Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden" published 2008 showing GIC comparisons

Conclusions – Draft NERC Standards are Not Accurate and Greatly Understate Risks

As these examples illustrate the results of calculations of geo-electric fields by the NERC models and any subsequent NERC predicted GIC's appear to exhibit the same problems of significantly under predicting for intense storm disturbances. In all locations that were examined the results of the models consistently under predicted what Ohm's Law establishes as the actual geo-electric field. This is a systemic problem that is likely related to inherent modeling deficiencies, and exists in all models in the NERC GMD Task Force and likely in many other locations around the world.

This has significant implications for nearly all of the findings of the NERC GMD Task Force. These erroneous modeling approaches were utilized to examine the peak geo-electric field outputs to much higher disturbance intensities for severe storms. For example the underlying analysis performed by NERC Standard Task Force members Pulkkinen and Bernabeu[9] for the 100 Year storm peaks utilized the faulty geo-electric field calculation model to derive the peak geo-electric fields for the reference Quebec ground models. This would drastically understate the peak intensity of the storm events by the same factor of 2 to 5 ratios as noted in the prior case study analysis. Therefore the standard proposing the NERC Reference Field level of between 3 to 8 V/km would be an enormous under-estimation and result in an enormous miss-calculation of risks to society. The same modelling errors are part of all earlier Pulkkinen/Pirjola[10] derived science assessments which also examined these peaks and 100 year storm statistics. As all prior validations within this report have established, the NERC geo-electric field model under predicts geo-electric field by a factor of 2 to 5 for the most important portions of storm events. Hence these errors have been entirely baked into the NERC GMD Task Force cake and their draft standards as well. Therefore the entirety of the Draft Standard does not provide accurate assessments

[9] 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.

[10] Pulkkinen, A., R. Pirjola, and A. Viljanen, Statistics of extreme geomagnetically induced current events, Space Weather, 6, S07001, doi:10.1029/2008SW000388, 2008.

of the geo-electric field environments that will actually occur across the US. It has also been shown in this White Paper that undertaking a more rigorous development of validated geo-electric field standards can be done in a simple and efficient manner and that such data to drive these more rigorous findings already exists in many portions of the US. Efforts on the part of NERC's standard team and the industry to withhold this material information are counter-productive to the overarching requirements to assure public safety against severe geomagnetic storm events. Such fundamental and significant flaws in technical calculations and procedural actions should not be a part of any proposed standard and a redraft must be undertaken.

UNITTED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

Reliability Standard for	**)**	**Docket No. RM14-1-000**
Geomagnetic Disturbance Operations	**)**	

SUPPLEMENTAL INFORMATION SUPPORTING REQUEST FOR REHEARING OF FERC ORDER NO. 797, RELIABILITY STANDARD FOR GEOMAGNETIC DISTURBANCE OPERATIONS, 147 FERC ¶ 61209, JUNE 19, 2014 AND MOTION FOR REMAND

Submitted to FERC on August 18, 2014

The Foundation for Resilient Societies, Inc. (hereafter "Resilient Societies") files, for the benefit of the Commissioners and all parties to FERC Docket RM14-1-000, this request to accept late filing of subsequently-developed facts and graphic representations of facts that comply with the standard of FERC Rules of Practice and Procedure Rule 907, 18 C.F.R. sec. 385.907, "New Facts and Issues." In particular, Resilient Societies provides facts relating to the location, ownership, and range of effective instrumentation of Geomagnetic Induced Current ("GIC") monitors deployed throughout the U.S. Bulk Power System as of August 2014.

In its Order No. 797 of June 19, 2014 (Geomagnetic Disturbance Operations), the Commission found information on GIC monitors to be lacking in the record. Compiled data on GIC monitors throughout the United States was not available to the public, nor known, nor reasonable knowable, when Resilient Societies filed its timely comments on March 24, 2014 and its timely Petition for Rehearing on July 21, 2014.

The facts as herein above could have been requested of electric utilities under existing FERC authority and in support of rulemaking under Docket RM14-1-000. Because FERC chose to not exercise its information-collection authority, it fell to a private non-profit, Resilient Societies, to make up the information gap. Understandably, our information collection took extra time.

In order for Resilient Societies to compile information on existing GIC monitors, we had to search a wide range of information sources, including presentations by electric utility engineers to industry forums, operating procedures of Reliability Coordinators, and transmission upgrade plans for regulated utilities. Resilient Societies made Freedom of Information (FOIA) requests and other informal requests of utilities under the control of the U.S. Government. Resilient Societies contacted industry experts that might know of the locations of GIC monitors and their dates of installation. Collected data then had to be painstakingly matched and confirmed with geospatial information on transmission substations and generation facilities. While some source documents were available prior to the filing deadlines on the docket, other key information was not received by Resilient Societies until August 2014, including count of shipped GIC monitors, the number of installed monitors at certain points in time, locations of monitors installed by Tennessee Valley Authority, and locations of monitors sponsored by U.S. Department of Energy. Additionally, in August 2014 we obtained assistance of Storm Analysis Consultants, Inc. in checking our work and determining ranges of effective instrumentation. In summary, these facts and their aggregation regarding the location, ownership, and range of effective instrumentation of GIC monitors deployed throughout the U.S. Bulk Power System as of August 2014 constitute: "Facts or issues that were not known and could not, with the exercise of due care, have been known to the intervenor at the time they would otherwise have been raised during the prior proceedings." 18 C.F.R. sec. 385.907(c)(2)(i)(A).(New Facts and Issues, FERC Rule 907.)

Resilient Societies also observes that Draft 1 of NERC Standard TPL-007-001 (“Transmission System Planned Performance for Geomagnetic Disturbance Events”), developed under Stage 2 of standard setting under FERC Order 797, is dated June 3, 2014. Draft Standard TPL-007-001 contains no requirements for GIC monitoring nor any requirements for sharing of GIC data with Reliability Coordinators. The content of draft Standard TPL-007-001 was not known to Resilient Societies at the time of its March 24, 2014 comments on Docket RM14-1-000. However, the lack of required GIC monitoring and data sharing with Reliability Coordinators in the Stage 2 NERC standard would have been known to the FERC Commissioners at the time of their June 19, 2014 Order 797 which stated, “The issue of monitoring requirements properly belongs in the Second Stage GMD Reliability Standards.”

FERC has the authority to improve a proposed reliability standard, by granting a Petition for Rehearing, if the submission into the record of newly-developed facts enables the Commission to achieve a more workable and practical set of operating procedures to fulfill the purposes of a Commission Order.[1]

Results of Recent Investigation of Existing GIC Monitoring

Based on its investigation, Resilient Societies now provides counts of GIC monitor locations by utility and state, including information on NERC Registered Entity status as Balancing Authority and Generator Operator. The total count obtained by Resilient Societies, 102 monitors, roughly corresponds with the total of Eclipse units shipped by the Advanced Power Technologies (83),[2] the approximate number of pre-existing SUNBURST[3] installations as disclosed by Department of Energy (10), and the number of Bonneville Power Administration (BPA) installations using technology other than the Eclipse product (12).[4]

Resilient Societies also provides a United States map of GIC monitor locations and associated areas of effective instrumentation contrasted with regions susceptible to system collapse due to effects of GIC disturbance as documented in "Geomagnetic Storms and Their Impacts on the U.S. Power Grid,".[5]

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[1] "[T]he agency may well improve its decisions on larger policy issues if it has in front of it the facts of a particular party, even if the policy ultimately chosen applies generally to all similarly-situated parties." *Philadelphia Gas Works* v. *FERC*, 989 F.2d 1246 at 1250 (D.C. Cir. 1993). "Of course, FERC can consider new facts and circumstances ….but it must identify the facts, circumstances, and equitable factors on which it relies. See *Atchinson, Topeka & Santa Fe Ry.* v. *Wichita Bd. Of Trade*, 412 U.S. 800, 809 (1973)." "Nothing in the Administrative Procedures Act prohibits an agency from changing its mind, if that change aids it in its appointed task." *Montana Power Co.* v. *EPA*, 608 F.2d 334, 347-349 (9th Cir. 1979).

[2] Because of its policy on customer confidentiality, Advanced Power Technologies declined to disclose the identity of its customers or the locations of installed GIC monitors. Based on our research, we believe that the Eclipse™ product of Advanced Power Technologies priced at approximately $15,000 per unit accounts for the vast majority of GIC monitors recently installed.

[3] SUNBURST is a GIC monitoring program managed by the Electric Power Research Institute. Resilient Societies emailed EPRI to ask for information about its network of monitors, but has received no reply as of this filing.

[4] Results of the Freedom of Information Act request to BPA indicate that their GIC monitoring program dates back to 1993.

[5] Source for Figure 1, bottom, is John Kappenman, Geomagnetic Storms and Their Impacts on the U.S. Power Grid, Goleta, CA: Metatech Corp, for Oak Ridge National Laboratory, Jan. 2010, Report Meta-R-319, Figure 3-25, "100 Year geomagnetic storm – 50 degree geomagnetic disturbance scenario," p. 3-26.

Location and Ownership of GIC Monitors
within United States

StateName	Utility Name	Balancing Authority	Generator Operator	Monitor Count
Alabama	Southern Company	Yes	Yes	1
Alabama	Tennessee Valley Authority	Yes	Yes	2
Arizona	Salt River Project	Yes	Yes	1
California	LA Department of Water and Power	Yes	Yes	1
California	Southern California Edison		Yes	1
Connecticut	United Illuminating Company			4
Idaho	American Electric Power		Yes	1
Idaho	Bonneville Power Administration	Yes		1
Idaho	Idaho Power	Yes	Yes	5
Illinois	Ameren	Yes	Yes	1
Illinois	Exelon/ComEd			3
Illinois	MidAmerican Energy	Yes	Yes	1
Indiana	American Electric Power		Yes	4
Indiana	Duke Energy	Yes	Yes	1
Iowa	Western Area Power Administration	Yes		1
Kansas	Kansas City Power & Light		Yes	1
Kentucky	Tennessee Valley Authority	Yes	Yes	1
Maine	Central Maine Power			1
Maryland	Exelon/Baltimore Gas & Electric			2
Maryland	Exelon/PECO		Yes	1
Maryland	FirstEnergy		Yes	2
Michigan	American Transmission Company			2
Mississippi	Tennessee Valley Authority	Yes	Yes	1
Montana	Bonneville Power Administration	Yes		1
New Hampshire	NextEra		Yes	1
New Jersey	FirstEnergy		Yes	1
New Jersey	PSEG		Yes	1
New York	Con Edison		Yes	4
New York	National Grid			1
New York	New York Power Authority		Yes	7
North Carolina	Duke Energy	Yes	Yes	1

Location and Ownership of GIC Monitors (continued)

within United States

StateName	Utility Name	Balancing Authority	Generator Operator	Monitor Count
Ohio	American Electric Power		Yes	2
Ohio	FirstEnergy		Yes	2
Oregon	Bonneville Power Administration	Yes		4
Pennsylvania	Exelon/PECO		Yes	4
Pennsylvania	FirstEnergy		Yes	3
Rhode Island	National Grid			1
Tennessee	Tennessee Valley Authority	Yes	Yes	4
Texas	Centerpoint			2
Virginia	American Electric Power		Yes	1
Virginia	Dominion (VA Electric & Power)		Yes	7
Virginia	FirstEnergy		Yes	1
Virginia	LG&E and KU	Yes	Yes	1
Washington	Bonneville Power Administration	Yes		6
West Virginia	American Electric Power		Yes	1
West Virginia	FirstEnergy		Yes	3
Wisconsin	American Transmission Company			3
Wisconsin	NextEra		Yes	1
Total				**102**

Sources: Data compiled by the Foundation for Resilient Societies, Inc. from FOIA requests and responses; Regional Coordinator publications; EPRI SUNBURST press releases; NERC GMD Task Force presentations; U.S. Department of Energy release of data in August 2014; voluntary U.S. electric utility publications; and Google Earth data as of August 2014,

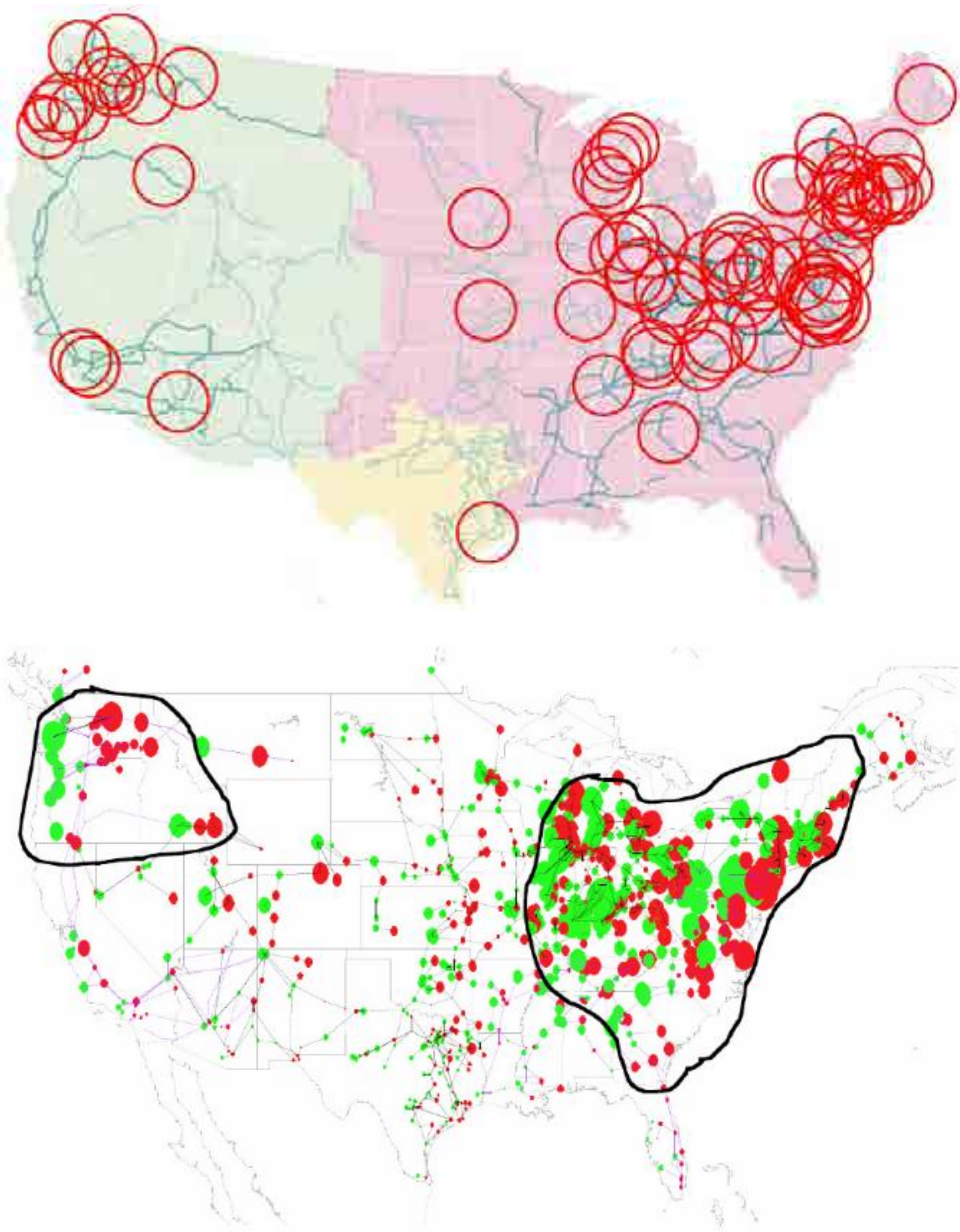

Figure 1. Location of GIC Monitors (top) vs. Areas Susceptible to Collapse from GIC (bottom)

Sharing of Real-Time GIC Data with Reliability Coordinators

In FERC Order 797 the Commission ruled:

> 36. We are not persuaded that the First Stage GMD Reliability Standards should require all responsible entities to monitor GICs or mandate sharing GIC monitoring data with reliability coordinators, as Foundation contends. As explained above, we directed NERC to develop only operational procedures in the First Stage GMD Reliability Standards, and to develop more comprehensive protections in the Second Stage GMD Reliability Standards. The issue of monitoring requirements properly belongs in the Second Stage GMD Reliability Standards.

Since the date of our original request for rehearing, NERC has written the Stage 2 GMD Reliability Standards and conducted its first vote in standard-setting. As subsequent facts show, the Stage 2 draft standard contains no requirement for GIC monitoring or sharing of real-time GIC data with Reliability Coordinators. Moreover, our recent investigation shows existing GIC monitoring that could be used for prudent grid coordination and operation under both Stage 1 and Stage 2 standards.

Generator Operators as Applicable Entities in Standard EOP-010-1

In FERC Order 797 the Commission ruled:

> 29. With respect to generator operators, there is no dispute that GSU transformers are susceptible to geomagnetically-induced currents. While generator operators are not listed as applicable entities in Reliability Standard EOP-010-1, NERC explains that generator operators will have to act during a GMD event when directed by a reliability coordinator, in accordance with its reliability coordinator's GMD Operating Plan, or by a transmission operator, in accordance with its transmission operator's GMD Operating Procedures or Operating Processes. We are not persuaded that generator operators should be required to act independently under Reliability Standard EOP-010-1. While generator operators might be, as Foundation asserts, increasingly installing GIC monitoring equipment, there is no evidence in the record regarding the proportion of generator operators with GIC monitoring capabilities. Accordingly, we agree with NERC that at least some generator operators would not have the technical basis to address a GMD event and would instead need to rely on reliability coordinators and transmission operators for direction. We also note that the Geomagnetic Disturbance Operating Procedure Template for generator operators developed by the NERC GMD Task Force, which the Foundation's comments reference, conditions some of its suggested actions on the generator operator having adequate monitoring systems. In sum, we are not persuaded by Foundation's comments

> and, rather, determine that there is adequate justification in the record for not including balancing authorities and generator operators in the applicability section of Reliability Standard EOP-010-1.

Contrary to assertions in the FERC ruling, our investigation shows that large Balancing Authorities and Generator Operators in the most vulnerable parts of the United States do have adequate GIC monitoring systems to take action on their own. We now place this information in the record. Surely some planning and action is better than no action at all by any Balancing Authority or Generator Operator; all Balancing Authorities and Generator Operators should not be exempted from standards because some have lagged in installing GIC monitors.

Moreover, the counts of locations and ownership of GIC monitors now submitted by Resilient Societies in this Rulemaking demonstrate that roughly 69 percent, or more than 2 of 3 GIC monitors installed within the U.S. Bulk-Power System are controlled by NERC Entities registered as "Generator Operator." Generator Operators are the most likely to know of impacts of a severe solar storms on Generator Step Up (GSU) transformers with long replacement times.

In contrast, we did not find a single instance of Reliability Coordinators owning or operating GIC monitors.[6] Reliability Coordinators are the least likely – of Reliability Coordinators, Transmission Operators, Balancing Authorities, and Generator Operators – to have real-time information about geomagnetic (GMD) storm impacts on critical equipment, and the least likely to be in a position to have real-time data for prudent decision-making to mitigate severe solar weather.

Were FERC to mandate sharing of GIC monitor data with Reliability Coordinators, the Reliability Coordinators might have more adequate information for prudent real-time decision-making. But NERC Standard EOP-010-1 ("Geomagnetic Disturbance Operations") does not mandate reporting of GIC monitor data to Reliability Coordinators and other FERC-approved standards do not presently require this either. So the current system of "GMD operating procedures" as codified in NERC Standard does not assure prudent decision-making or protection for the public.

[6] GMD operating procedures for two Reliability Coordinators, PJM and ISO-New England describe reliance on GIC monitors owned and operated by utilities within their footprints. In some cases, reporting of GIC data is not in real time, but by telephone.

Validation of NERC Benchmark GMD Event and Ongoing Modeling

Had FERC used its existing authority to obtain measured GIC data from utilities, this data could have been used to validate the NERC Benchmark GMD Event for Stage 2 standard-setting. Moreover, had a requirement for GIC monitoring been included in the Stage 1 GMD standard, data from GIC monitors could have been used to validate ongoing GMD modeling at utilities.

Using data obtained from existing GIC monitors obtained through the efforts of Resilient Societies and others, John Kappenman of Storm Analysis Consultants and Dr. William Radasky of Metatech performed a validation of the NERC Benchmark GMD Event currently being used in Stage 2 standard setting under FERC Order 779. Their analysis shows that the NERC Benchmark GMD Event is too low by a factor of 2 to 5.

Without requirements for installation and operation of GIC monitors, at *de minimus costs* to electric utilities, and without mandatory reporting of GIC data to Reliability Coordinators, Balancing Authorities, Transmission Operators, and the Department of Energy Operations Center, the FERC-approved GMD operating procedures are doomed to failure in a severe solar storm.

A nationwide system of installed, low-cost GIC monitors, combined with pre-existing instrumentation of the health-status of high voltage transformers,[7] might enable workable operating procedures, in contrast with the operating procedures approved in FERC Order No. 797.

When one combines the inadequacy of Stage 1 GMD operating procedures with modeling of "benchmark" solar events that under-estimate the magnitude of GIC by a factor of 2 to 5, the Commissioners can reasonably anticipate Stage 2 standards that will discourage installation of

[7] Two basic indicators of transformer conditions and failure risks are (1) measurement of dissolved gases, and (2) measurement of transformer temperature. A baseline GIC monitor sells at approximately $10,000 per unit. For $15,000, enhanced GIC monitors also report on dissolved gases and transformer temperature. The associated SCADA controller enables automatic reporting as alarm thresholds are passed. So, for relatively low cost, GIC monitors could report data to Reliability Coordinators, Balancing Authorities, Transmission Operators, and the DOE Operations Center. Already, BPA reports GIC data from 12 monitors in near real-time on a webpage available to the public at http://transmission.test.bpa.gov/BUSINESS/OPERATIONS/gic/gic.aspx.

needed hardware protection and perpetuate unworkable GMD operating procedures. The combination will result in an electric grid that will be needlessly unprotected from severe solar storms, despite the good intentions of FERC Orders No. 779 and 797.

If real-time GIC data at major Generator Operator sites and at major transmission sites within the Bulk-Power System are not reported to Reliability Coordinators and not reported to the DOE Operations Center, how will the President be able to prudently exercise existing authority to de-energize generation facilities at risk of catastrophic loss? How will the Secretary of Energy be able to prudently exercise interconnection authority under Section 202(c) of the Federal Power Act?[8] Ignorance and lack of data, when timely action is necessary, are barriers to timely prevention of grid separation, cascading outages, and the permanent loss of grid-critical equipment over large regions of the grid.

The full text of the Kappenman-Radasky White Paper, "Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard," is included as Appendix 1 to this filing. This whitepaper, dated July 30, 2014, was not available at the time of our comments on March 24, 2014 and our Petition for Rehearing on July 21, 2014.

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[8] See Resilient Societies' Petition for Rehearing, timely-filed on July 21, 2014 in FERC Docket RM14-1-000. These Additional Facts with Respect to GIC Monitor Availability, or Absence at Regional Coordinator sites relate, *inter alia*, to Petitioner's Request for Rehearing:

Issue 4, proposing that requiring GIC Detectors and Requiring GIC data reporting is essential for effective GMD operating procedures;

Issue 5, asserting that delay of mandatory GIC monitoring and reporting will unreasonably delay the benefits of GMD operating procedures;

Issue 7, asserting that FERC Order No. 797 unreasonably relies upon Reliability Coordinators (lacking their own GIC monitors) and without right to receive near-real-time GIC monitoring data from other entities, and unreasonably exempts Balancing Authorities and Generator Operators, which together operate 83 of the 102 deployed GIC monitors known to be deployed in the U.S. Bulk-Power System;

Issue 8, Interference with prudent exercise of existing Presidential Authority to order de-energizing of gas fired and federally operated generating facilities in an energy supply emergency;

Issue 9, Interference with the prudent exercise of existing authority of the Secretary of Energy to reconnect or interconnect transmission capabilities under Section 202(c) of the Federal Power Act;

Issue 11, Unsubstantiated assumption of viability of two-way communications in a severe solar storm between Reliability Coordinators, apparently none directly operating GIC monitors, and Generator Operators, operating fully 70 of 102 known GIC monitors (or 69%) but being excluded from mandatory participation in GMD operating procedures, and having no present duty to report GIC data in near-real-time to Reliability Coordinators or Balancing Authorities, or Transmission Operators, or the DOE Operations Center.

Conclusion

We ask that the Commissioners, seeing this previously unavailable information on GIC monitor deployments and the potential improvement of operating procedures for solar storms, would conclude that sharing data from existing GIC monitors to inform Reliability Coordinators in real-time during solar storms is operationally feasible, advantageous to public safety, and should be required in Standard EOP-010-1.

We ask that the Commissioners, seeing this previously unavailable information, would conclude that existing GIC monitors can be used to inform Balancing Authorities, Generator Operators, and the DOE Operations Center during solar storms and that Balancing Authorities and Generator Operators should be applicable entities in Standard EOP-010-1.

We ask that the Commissioners, seeing the gaps in GIC monitor coverage of large regions of the Bulk-Power System, and recognizing the *de minimus* costs of installing GIC monitors at grid-critical equipment, would, through Rehearing of Order No. 797, mandate that NERC develop standards for mandatory installation of GIC monitors and mandatory reporting of GIC data to relevant entities.

We ask that the Commissioners, seeing the failure of the NERC Benchmark Event model to predict solar storm intensities that are compatible with empirical observations, across many regions and over several decades, direct NERC to utilize data from existing GIC monitors to revise and revalidate the NERC Benchmark GMD Event presented by NERC as a whitepaper in Stage 2 Standard Setting under FERC Order 779.

Respectfully submitted by:

Thomas S. Popik, Chairman,

William R. Harris, Secretary,

For the

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APPENDIX 1

Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard

A White Paper by:

John G. Kappenman, Storm Analysis Consultants

and

Dr. Willam A. Radasky, Metatech Corporation

July 30, 2014

Executive Summary

The analysis of the US electric power grid vulnerability to geomagnetic storms was originally conducted as part of the work performed by Metatech Corporation for the Congressional Appointed US EMP Commission, which started their investigations in late 2001. In subsequent work performed for the US Federal Energy Regulatory Commission, a detailed report was released in 2010 of the findings[11]. In October 2012, the FERC ordered the US electric power industry via their standards development organization NERC to develop new standards addressing the impacts of a geomagnetic disturbance to the electric power grid. NERC has now developed a draft standard and has provided limited details on the technical justifications for these standards in a recent NERC White Paper[22].

The most important purpose of design standards is to protect society from the consequences of impacts to vulnerable and critical systems important to society. To perform this function the standards must accurately describe the environment. Such environment design standards are used in all aspects of society to protect against severe excursions of nature that could impact vulnerable systems: floods, hurricanes, fire codes, etc., are relevant examples. In this case, an accurate characterization of the extremes of the geomagnetic storm environment needs to be provided so that power system vulnerabilities against these environments can be accurately assessed. A level that is arbitrarily too low would not allow proper assessment of vulnerability and ultimately would lead to inadequate safeguards that could pose broad consequences to society.

However from our initial reviews of the NERC Draft Standard, the concern was that the levels suggested by NERC were unusually low compared to both recorded disturbances as well as from prior studies. Therefore this white paper will provide a more rigorous review of the NERC benchmark levels. NERC had noted that model validations were not undertaken because direct measurements of geo-electric fields had not been routinely performed anyway in the US. In contrast, Metatech had performed extensive geo-electric field measurement campaigns over decades for storms in Northern Minnesota and had developed validated models for many locations across the US in the course of prior investigations of US power grid vulnerability[3]. Further, various independent observers to the NERC GMD tasks force meetings had urged NERC to collect decades of GIC observations performed by EPRI and independently by power companies as these data could be readily converted to geo-electric fields via simple techniques to provide the basis for validation studies across the US. None of these actions were taken by the NERC GMD Task Force.

It needs to be pointed out that GIC measurements are important witnesses and their evidence is not being considered by the NERC GMD Task Force in the development of these standards. GIC observations provide direct evidence of all of the uncertain and variable parameters including the deep Earth ground response to the driving geomagnetic disturbance environment. Because the GIC measurement is also obtained from the power grid itself, it incorporates all of the meso-scale coupling of the disturbance environments to the assets themselves and the overlying circuit topology that needs to be assessed. Separate discreet measurements of geo-electric fields are usually done over short

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[1] *Geomagnetic Storms and Their Impacts on the U.S. Power Grid* (**Meta-R-319**), John Kappenman, Metatech Corporation, January 2010. Via weblink from Oak Ridge National Lab, *wttp://www.ornl.gov/sci/ees/etsd/pes/ferc_emp_gic.shtml*

[2] NERC Benchmark Geomagnetic Disturbance Event Description, *http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Benchmark_GMD_Event_April21_2.pdf*

[3] Radasky, W. A., M. A. Messier, J. G. Kappenman, S. Norr and R. Parenteau, "Presentation and Analysis of Geomagnetic Storm Signals at High Data Rates", IEEE International Symposium on EMC, August 1993, pp. 156-157.

baseline asset arrays which may not accurately characterize the real meso-scale interdependencies that need to be understood. The only challenge is to interpret what the GIC measurement is attempting to tell us, and fortunately this can be readily revealed with only a rudimentary understanding of Ohm's Law, geometry and circuit analysis methods, a tool set that are common electrical engineering techniques. Essentially the problem reduces to: *"if we know the I (or GIC) and we know the R and topology of the circuit, then Ohm's law tells us what the V or geo-electric field was that created that GIC"*. Further since we know the resistance and locations of power system assets with high accuracy, we can also derive the geo-electric field with equally high certainty. These techniques allow superior characterization of deep Earth ground response and can be done immediately across much of the US if GIC measurements were made available. Further these deep Earth ground responses are based upon geological processes and do not change rapidly over time. Therefore even measurements from one storm event can characterize a region. Hence this is a powerful tool for improving the accuracy of models and allows for the development of accurate forward looking standards that are needed to evaluate to high storm intensity levels that have not been measured or yet experienced on present day power grids. Unfortunately this tool has not been utilized by any of the participants in the NERC Standard development process.

It has been noted that the NERC GMD Task Force has adopted geo-electric field modelling techniques that have been previously developed at FMI and are now utilized at NRCan. The same FMI techniques were also integrated into the NASA-CCMC modeling environments and that as development and testing of US physiographic regional ground models were developed, efforts were also undertaken by the USGS and the NOAA SWPC to make sure their geo-electric field models were fully harmonized and able to produce uniform results. However, it appears that none of these organizations really did any analysis to determine if the results being produced were at all accurate in the first place. For example when recently inquired, NRCan indicated they will perhaps begin capturing geo-electric field measurements later this year to validate the base NERC Shield region ground model, a model which provides a conversion for all other ground models. In looking at prior publications of the geo-electric field model carried out in other world locations, it was apparent that the model was greatly and uniformly under-predicting for intense portions of the storms, which are the most important parameters that need to be accurately understood.

In order to examine this more fully, this white paper will provide the results of our recent independent assessment of the NERC geo-electric field and ground models and the draft standard that flows from this foundation. Our findings can be concisely summarized as follows:

- Using the very limited but publicly available GIC measurements, it can be shown how important geo-electric fields over meso-scale regions can be characterized and that these measurements can be accurately assessed using the certainty of Ohm's Law. This provides a very strict constraint on what the minimum geo-electric field levels are during a storm event.

- When comparing these actual geo-electric fields with NERC model derived geo-electric fields, the comparisons show a systematic under-prediction in all cases of the geo-electric field by the NERC model. In the cases examined, the under prediction is particularly a problem for the rapid rates of change of the geomagnetic field (the most important portions of the storm events) and produce errors that range from factor of ~2 to over factor of ~5 understatement of intensity by the NERC models compared to actual geo-electric field measurements. These are enormous errors and are not at all suitable to attempt to embed into Federally-approved design standards.

- These enormous model errors also call into question many of the foundation findings of the NERC GMD draft standard. The flawed geo-electric field model was used to develop the peak geo-electric field levels of the Benchmark model proposed in the standard. Since this model understates the actual geo-electric field intensity for small storms by a factor of 2 to 5, it would also understate the maximum geo-electric field by similar or perhaps even larger levels. Therefore this flaw is entirely integrated into the NERC Draft Standard and its resulting directives are not valid and need to be corrected.

The findings here are also not simply a matter of whether the NERC model agrees with the results of the Metatech model. Rather the important issue is the degree that the NERC model disagrees with actual geo-electric field measurements from actual storm events. These actual measurements are also confirmed within very strict tolerances via Ohm's Law, a fundamental law of nature. The results that the NERC model has provided are not reliable, and efforts by NERC to convince otherwise and that utilization of GIC data cannot be done are simply misplaced. Actual data provides an ultimate check on unverified models and can be more effectively utilized to guide standard development than models because as Richard Feynman once noted; "Nature cannot be fooled"!

Introduction to NERC Model Evaluation and Validation Overview

A series of case study examples will be provided in this White Paper to illustrate the evaluation of geo-electric fields derived from GIC measurements across the US electric power grid. These derived geo-electric field results will then be compared to the NERC estimated geo-electric fields for the same storm events and scenarios. There are an important number of underlying principles to this analysis that can be summarized as follows:

- Using past storms and by modeling detailed power networks and comparing to GIC measurements at particular locations is the best way to validate overall storm-phenomena/power grid models. It accounts for the "interpolation" of the incident measured B-fields (including the angular rotation of the fields with time), the accuracy of the ground model used, the coupling to the power network, and the computation of the current flow at the measurement point.

- Experience has shown that over times of minutes, the geomagnetic field will rotate its direction and therefore every transformer in a network will have a sensitivity to particular vector orientations of the field, and the maximum current measured at a given transformer location will be a function of the rate of change intensity of the geomagnetic field, the resulting geo-electric field this causes and the angle of the field as it changes over the storm event. This is why the rate of change (dB/dt) and GIC at a single transformer will not scale perfectly with the maximum value of dB/dt, but taking into consideration all of these topology and orientation factors, a highly accurate forensic analysis can be performed.

- Geomagnetic storms are not steady state events, rather they are events with aperiodic extreme impulsive disturbances that can occur over many hours or days duration. Modeling these events to derive a geo-electric field is challenging but readily achievable. Since these events are time domain problems, modeling solutions using time-domain methods are recommended. The NERC modeling methods that will be evaluated here have generally been developed using Fourier transform frequency domain methods. In these implementations of Fourier methods, the primary question is the accuracy in dealing with the phase of the Fourier transforms.

- When referring to impulsive geomagnetic field disturbance events, these are typically multiple discrete events with times of several minutes. Note that the collapse of the Quebec power network in March 1989 occurred in 93 seconds. Clearly times of only a few minutes are important and it is vital that the geo-electric field intensity of these transients be accurately portrayed and not understated in a Design Standard type document. For example, a 10 meter dyke defined by the standard does no good, if the actual Tsunami height is 15 meters. Any efforts to claim that models that depict some satisfactory averaging over extended time periods as being sufficient must be vigorously refuted, as these peak inflection points are the most vital aspects of the storm environments that must be accurately determined.

Simulation Model Validation – Maine Grid Examples

In the analysis carried out for the FERC Meta-R-319 report, extensive efforts were undertaken to verify that the simulation models for the US power grid were providing sufficiently accurate results. One of the primary approaches that were utilized to test these models were to perform simulations for forensic analysis purposes and to compare the results with discrete measurements that were available.

One of the forensic simulations was conducted on the Maine grid and provided important verification of the ability of the model in that portion of the US grid to produce accurate estimates. Figure 1 provides a plot of the results of this simulation showing the "Calculated" versus "Measured" GIC (geomagnetically induced current) at the Chester Maine 345kV transformer. This was for a storm which occurred on May 4, 1998 and was driven by the large scale storm conditions as shown in Figure 2.

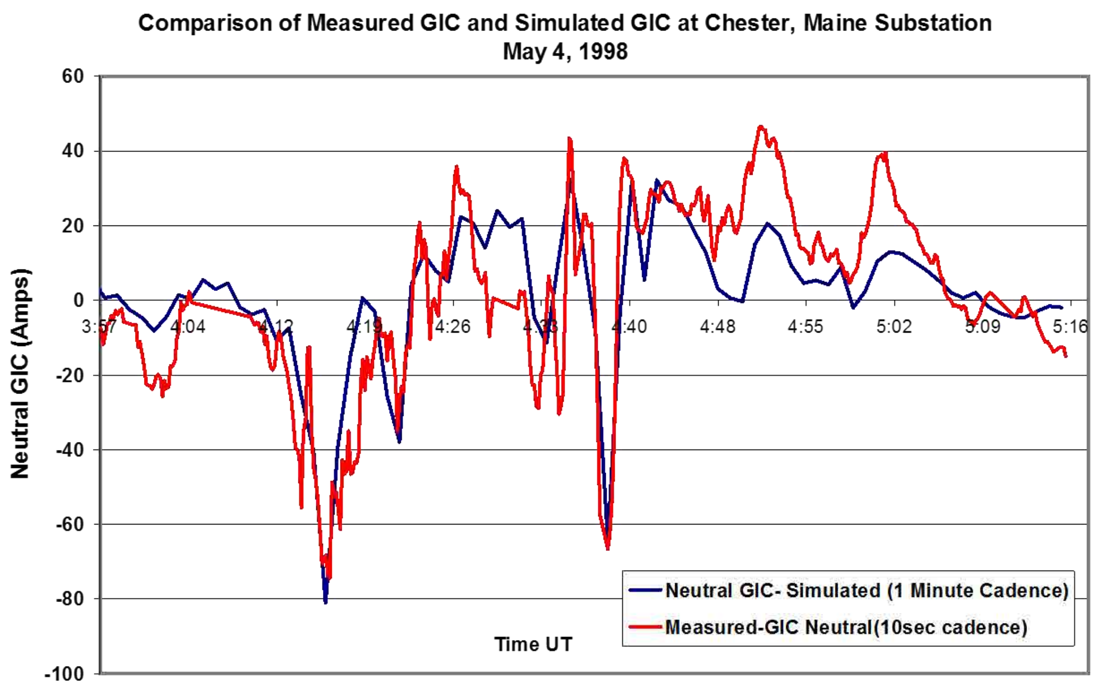


Figure 1 – Plot showing comparison of Simulated versus Measured GIC at Chester Maine 345kV transformer for May 4, 1998 geomagnetic storm. (Source – Meta-R-319)

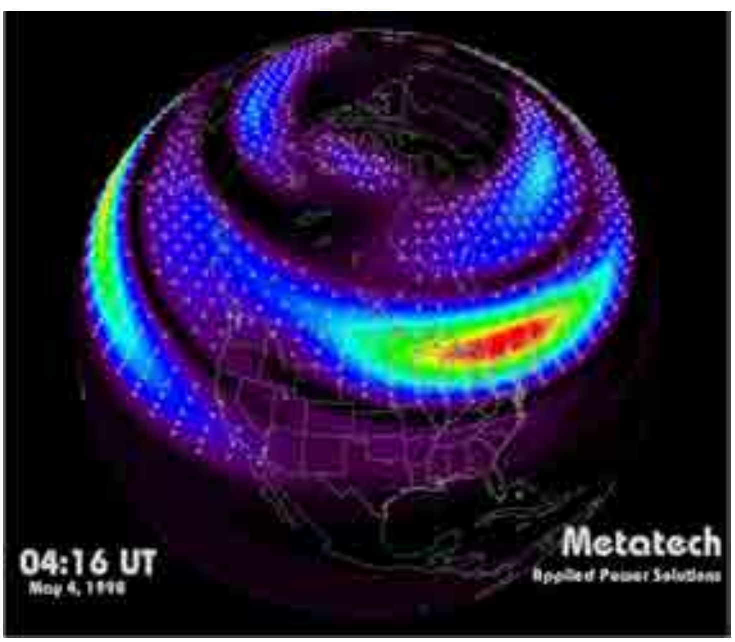


Figure 2 – Map of Geomagnetic Disturbance conditions at 4:16UT during May 4, 1998 storm. (Source – Meta-R-319)

The results in Figure 1 provide a comparison between high sample rate measured GIC (~10 second cadence) versus storm simulations that were limited to 1 minute cadence geomagnetic observatory data inputs (B-fields). Due to this limitation of inputs to the model, the model would not be able to reproduce all of the small scale high frequency variations shown in the measured data. However, the simulation does provide very good accuracy and agreement on major spikes in GIC observed, the most important portion of the simulation results that need to be validated. Figure 3 provides a wider view of the impact of the storm in terms of other GIC flow conditions in the Maine and New England region electric power grid, this is provided at time 4:16UT.

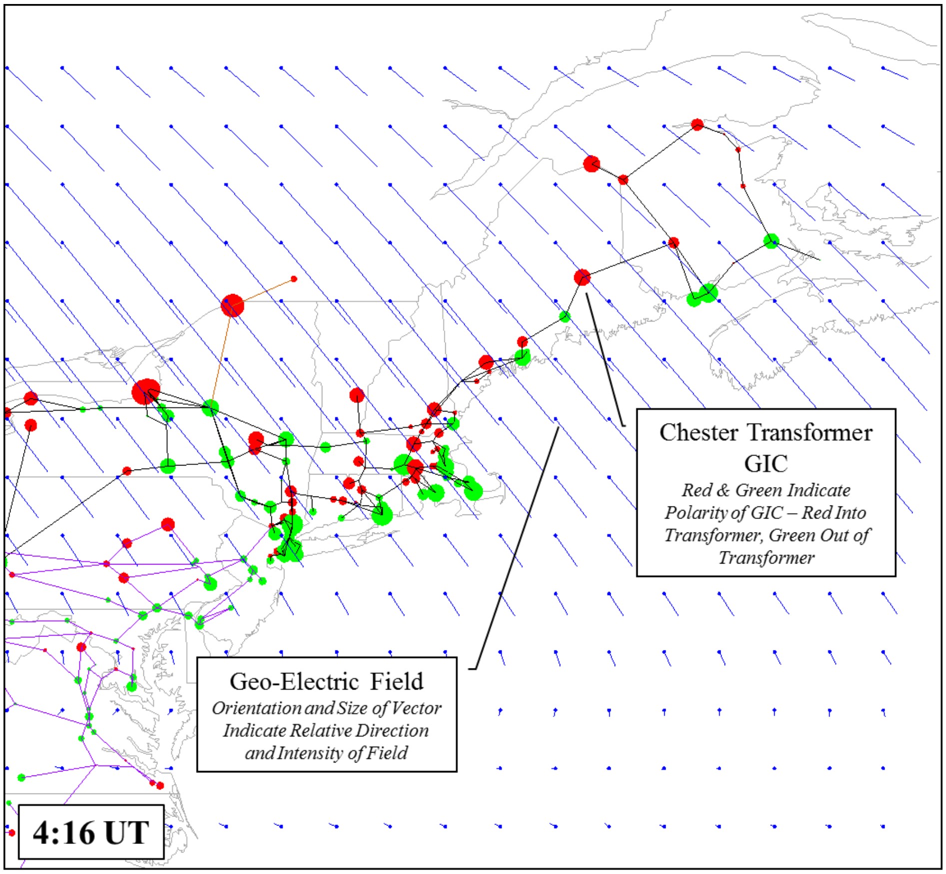


Figure 3 – GIC flows and disturbance conditions in Maine/New England grid at 4:16UT, May 4, 1998. (Source – Meta-R-319)

As this illustration shows, the Chester GIC flow is shown along with comparable GIC flows in a number of other locations in the regional power grid at one minute in time. In addition to impacts to the New England grid, extensive power system impacts were also observed to voltage regulation in upstate New York region due to storm. In this map, the intensity and polarity of GIC flows are depicted by red or green balls and their size, the larger the ball the larger the GIC flow and the danger it presents to the transformer and grid. Also shown are the blue vector arrows which are the orientation and intensity of the geo-electric field which couples to the topology of the electric grid and produces the GIC flow patterns that develop in the grid. It is noted that during the period of this storm, the electric fields rotated and all transformers in the grid would experience a variation in the pattern of GIC flows.

Considerable scientific and engineering examination has been performed since the release of the Meta-R-319 report; the report and other subsequent examinations are in close agreement on a number of important parameters of future severe geomagnetic storm threat conditions. For example, it is now well-accepted that severe storm intensity disturbance intensity can reach level of 5000 nT/min at the latitudes of the Maine power grid. NRCan now provides estimates of geo-electric fields for the nearby Ottawa observatory for storms including the May 4, 1998 storm. The ability therefore exists to do cross-validations with this and other proposed NERC ground models and geo-electric field calculation methods.

Observations of GIC at the Chester Maine substation also provide important observational confirmations that allow empirical projection of GIC levels that are plausible at more severe storm intensities. Earlier this year, the Maine electric utilities provided a limited summary of peak GIC observations from their Chester transformer and storm dates to the Maine Legislature. Figure 4 provides a graphical summary that was derived of the peak GIC and peak disturbance intensities (in nT/min) observed at the Ottawa Canada geomagnetic observatory for a number of reported events. The Maine utilities did not provide accurate time stamps (just date only), so that limits some of the ability to accurately correlate disturbance intensity to GIC peaks as the knowledge of timing is extremely coarse. Also since the Ottawa observatory is approximately 550km west of Chester, there is some uncertainty to local storm intensity specifics near Chester. However as shown, there are clear trend lines and uncertainty bounding of the level of GIC and how the GIC increases for increasing storm intensity. This trend line is quite revealing even with all of the previously mentioned uncertainties on the spatial and temporal aspects of the threat environments.

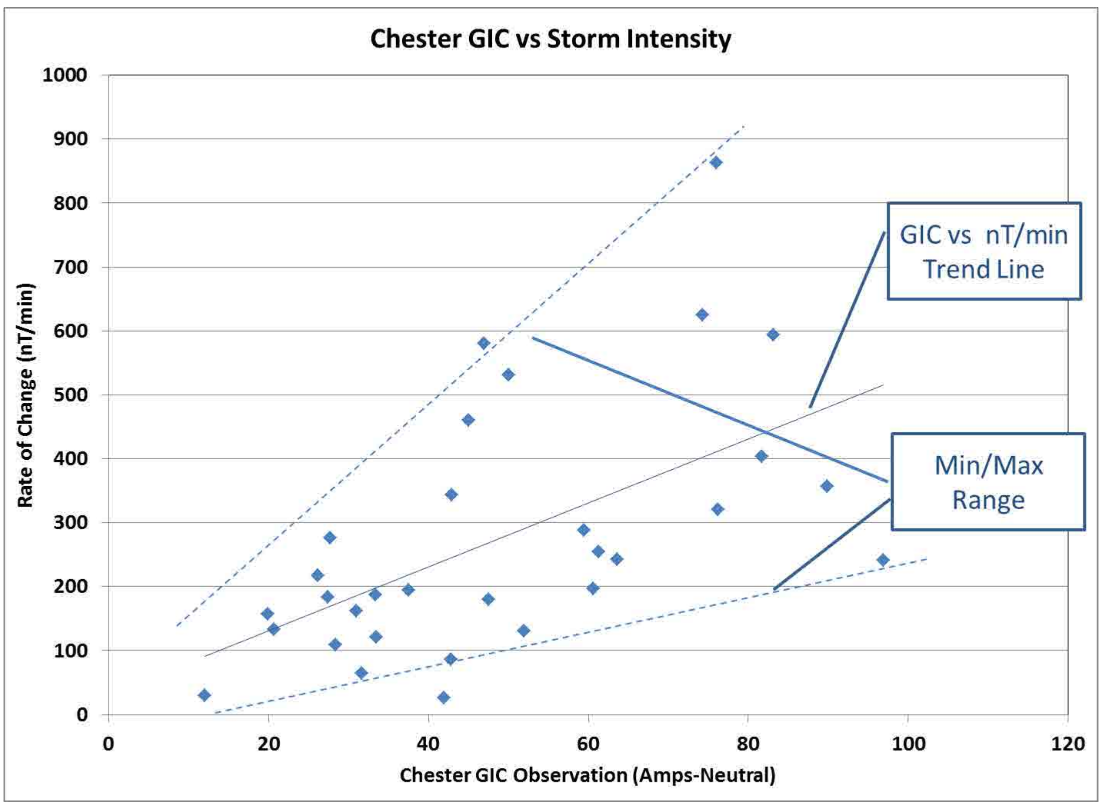


Figure 4 – GIC versus Storm Intensity (nT/min) from multiple observed GIC storm events at Chester Transformer, in this case the GIC timing is extremely coarse.

At higher storm intensities, the geo-electric field increases and if only intensity changes (as opposed to spectral content), then the increase in geo-electric field and resulting GIC will be linear. Because storm intensity for very severe storms can reach ~5000 nT/min, this graph can be linearly extended to project the range of GIC flows in the Chester transformer for these more extreme threat conditions. Figure 5 provides a plot similar to that in Figure 4, only with linear extensions of the GIC flow that this observational data estimates.

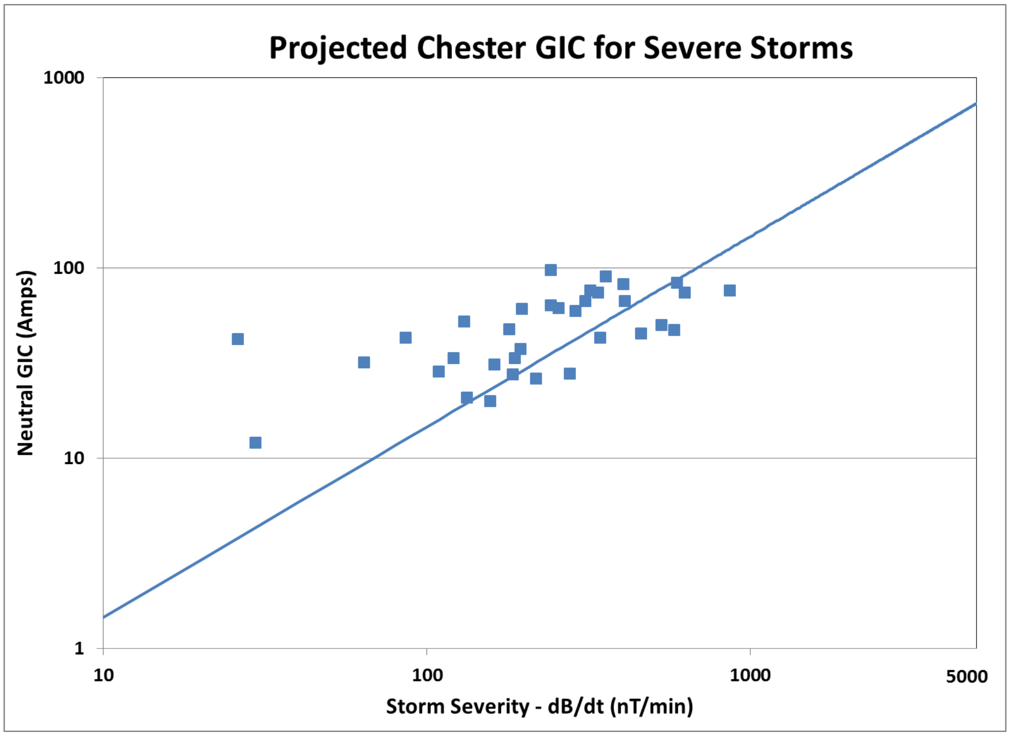


Figure 5 – Projected Chester GIC flow for storm intensity increasing to ~5000 nT/min.

Using these data plotting techniques with the previously noted uncertainties, a more detailed examination can be performed for one of the specific storm events which occurred on May 4, 1998. Figure 6 provides again the earlier described GIC plots from Figure 1. Two particularly important peak times are also highlighted on this plot at 4:16UT and 4:39UT where the recorded GIC reaches peaks respectively of -74.3 Amps and -66.6 Amps. These comparisons also show very close agreement with the simulation model results as well. Therefore the peak data points can be more explicitly examined in detail, as a comparison to how GIC vs dB/dt was plotted in Figure 4. In addition to this GIC observation data, there was also dB/dt data observed from a local magnetometer for this storm, which also greatly reduces the uncertainty of the threat environment.

Having all of this data available will aid in utilizing the power system itself as an antenna that can help resolve the geo-electric field intensity that the complex composition of ground strata generates during this storm event. Further once this response is empirically established, this same ground response can be reliably utilized to project to higher storm intensity and therefore higher GIC levels. This provides a blended effort of model and observational data to extract details on how the same grid and ground strata would behave at higher storm intensity levels. One of the advantages that exists in the modeling of the circuits of the transmission networks are that the resistive impedances of transmission lines and transformers (which are the key GIC flow paths) are very well known and have small uncertainty errors. It is also known that the Chester transformer is non-auto, so GIC flow in the neutral also defines the GIC per phase. There is also no doubt about the locations of assets within the circuit topology. Finally, station grounding resistance can also be determined to relatively high certainty as well. In comparison, ground response as has been previously published in the Meta-R-319 report can vary over large ranges, as much as a factor of 6. Therefore direct observations of ground response are highly important and GIC measurements, as will be discussed, provide an excellent proxy or geophysical data that can be used to derive the complex behavior characteristics of the ground strata. This set of understandings can be applied as a tool to significantly bound this major area of uncertainty.

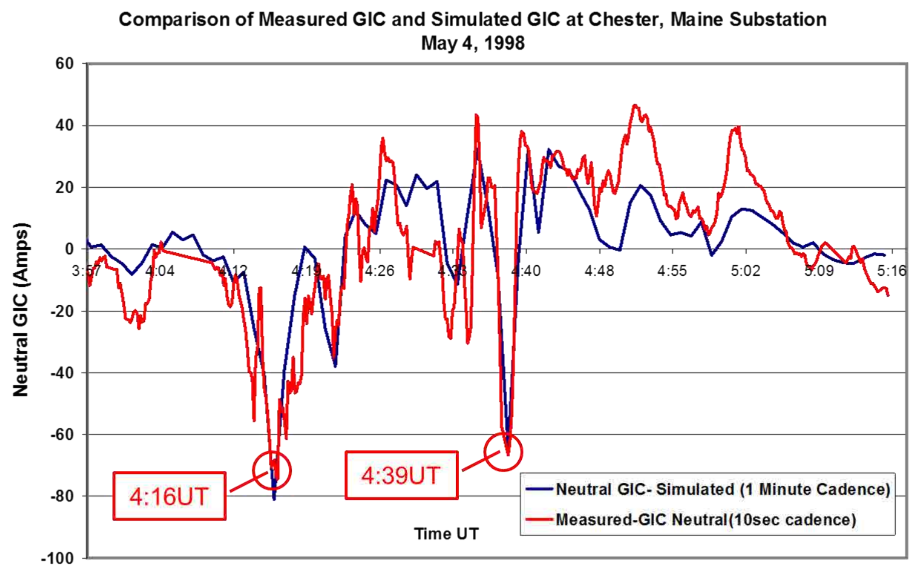


Figure 6 – GIC observation at times 4:16 & 4:39 UT that can be examined in further detail.

Network Model and Calculation of Chester GIC for 1 V/km Geo-Electric Field

Using the Maine region power grid model of the EHV grid, it is possible to examine what the GIC flow would be at the Chester transformer for a specified geo-electric field intensity of 1 V/km. This specified GIC is an intrinsic and precise characteristic of the network that will provide a useful yardstick to calibrate against for actual GIC flows that occurred and from that a more highly bounded geo-electric field intensity range can be determined at this location. Figure 7 provides a plot of the GIC flow in the Chester transformer for a 1 V/km geo-electric field. Since the topology of the transmission network also greatly determines the resulting GIC, this calculation is performed for a full 360 degree rotation of the orientation of the 1 V/km field.

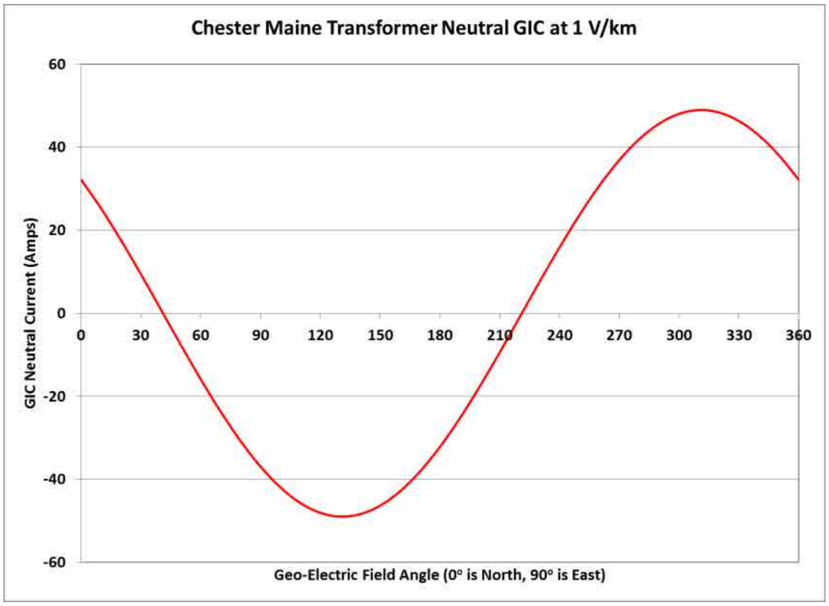


Figure 7 – GIC flow at Chester transformer neutral for 1 V/km geo-electric field at various orientation angles.

As the plot in Figure 7 shows, the peak GIC flow at this location is ~49 Amps which occurs at the 130^{o} and 310^{o} angular orientations of the 1 V/km field.

While the GIC to 1 V/km relationship in Figure 7 is developed from a detailed network model, there are also much simpler methods using a limited knowledge of a portion of the local transmission network that can be used to check the accuracy of the model. This involves a simple circuit analysis to derive the resistance and orientation specifics of just the two major transmission lines connecting to Chester. Each of the two 345kV lines connecting to Chester (from Chester-Orrington and from Chester to Keswick New Brunswick) is shown in the map of Figure 8.

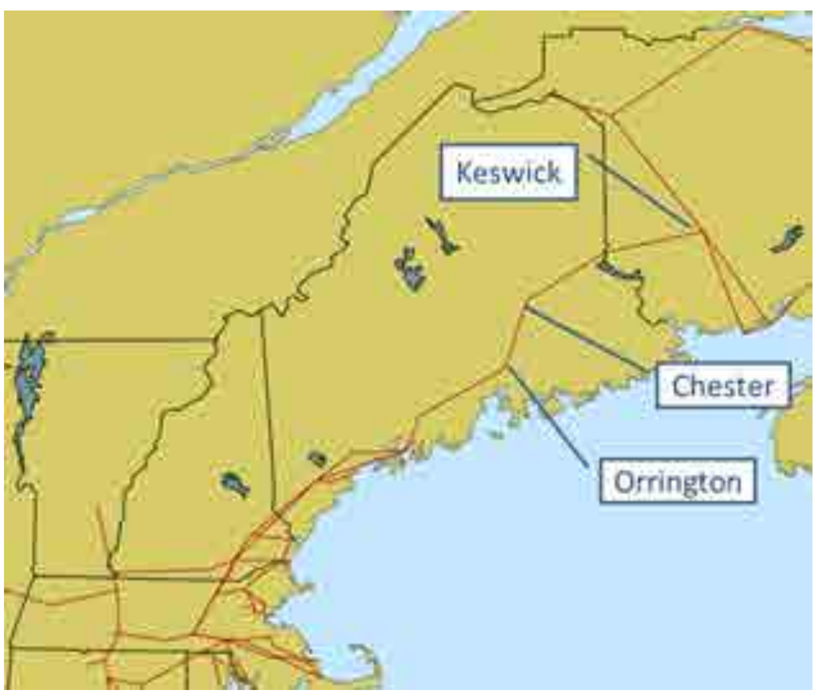


Figure 8 - Map of Chester Maine and 345kV line interconnections.

For geomagnetic storms, the orientation of specific transmission lines becomes very important in determining their coupling to the geo-electric field which also has a specific orientation. For example if the orientation of a specific line is identical to the orientation of the geo-electric field, then the GIC will be at a relative maximum. Conversely if the orientations of the field and line are orthogonal, then no coupling or GIC flow will occur. In the case of the Chester to Keswick line, the orientation is at an angle of ~70^o (with 0^o being North) and for the Chester to Orrington line the angle is ~205^o. Hence it should be expected that each line will couple differently as the orientation of the geo-electric field changes. Also an important parameter in the calculation of GIC is the line length which also describes the total resistance of this element of the GIC circuit. The point to point distances from Chester are ~80 km to Orrington and ~146 km to Keswick. Figure 9 provides the results of a simple single circuit calculation of the Chester transformer GIC connected to a 345kV transmission line of variable length with a transformer termination at the remote end of that line, the estimated GIC is also shown for the 80 km Orrington line and the 146 km Keswick line using a uniform 1 V/km geo-electric field strength. As shown in this figure, for the two line lengths only a small change in GIC occurs (~11%), even though there is nearly a factor of two difference in line lengths. This calculation assumes a full coupling with the orientation of the geo-electric field, as the geo-electric field changes its orientation to the line with time, and the GIC will change as prescribed via a sine function.

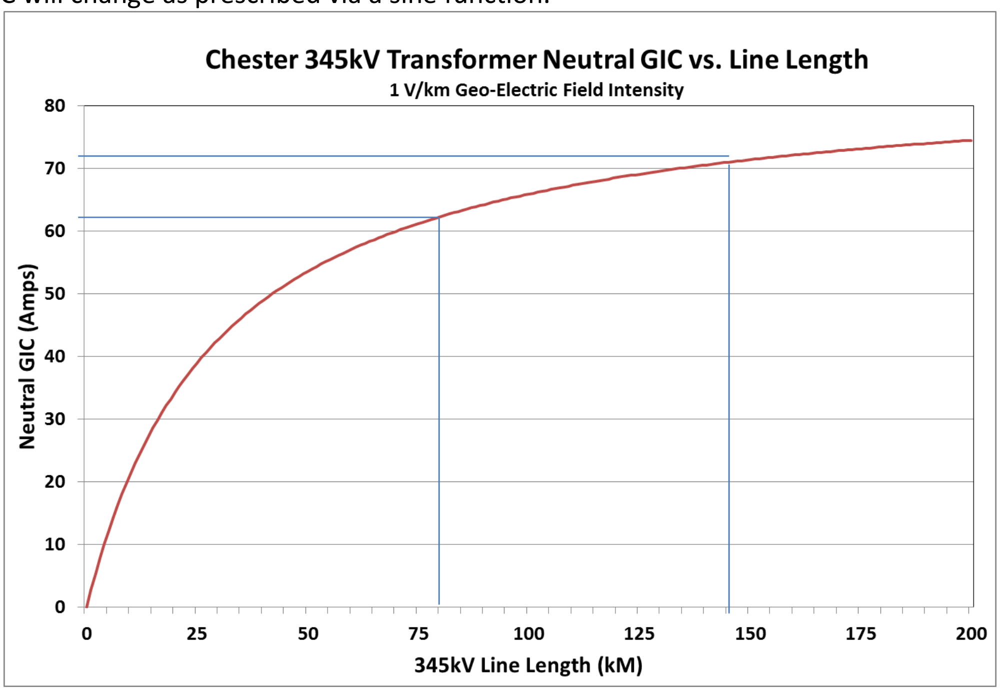


Figure 9 – Calculated Chester GIC for single circuit 345kV transmission line, 80 km Orrington and 146km Keswick noted

Given this simple two line case, a discrete calculation can be performed for each line, and using circuit superposition principles (Kirchoff's Laws), the resulting Chester GIC flow can be plotted as well versus the orientation angle of a uniform 1 V/km geo-electric field. This is shown in Figure 10 for each of the two lines and the resultant GIC flow at Chester.

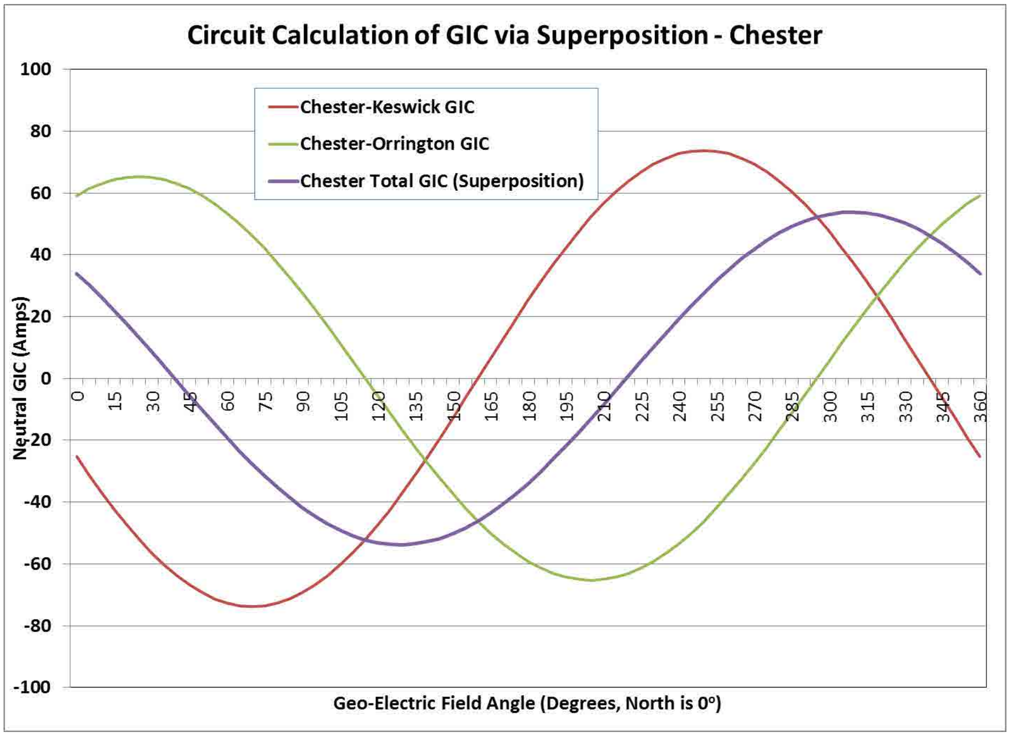


Figure 10 – GIC flow for each line versus geo-electric field angle and Resultant GIC at Chester.

Determining Storm Geo-Electric Field Intensity from Observed GIC

As this Figure 10 illustrates, each line segment will have differing GIC flows versus the orientation of the geo-electric field, and the resultant Chester neutral GIC will also be of lower magnitude and will also have a differing vector angle to each line segment. This simple Ohm's law based circuit calculation can be compared to the more detailed model calculation previously shown in Figure 7, which is shown in Figure 11. As this Figure illustrates, there is very good agreement in GIC flows using the two-line calculation approach (~95% agreement). The detailed model result will be more exact because all of the other network assets are used in the calculation. However, this comparison also shows that the line length parameter dominates the impedance of the circuit and defines the circuit current given the circuit resistances of just a few key components. Knowing both I (or GIC in this case) and R of the circuit allows the ability to precisely determine the driving V or geo-electric field that caused the observed GIC to occur in the transformer.

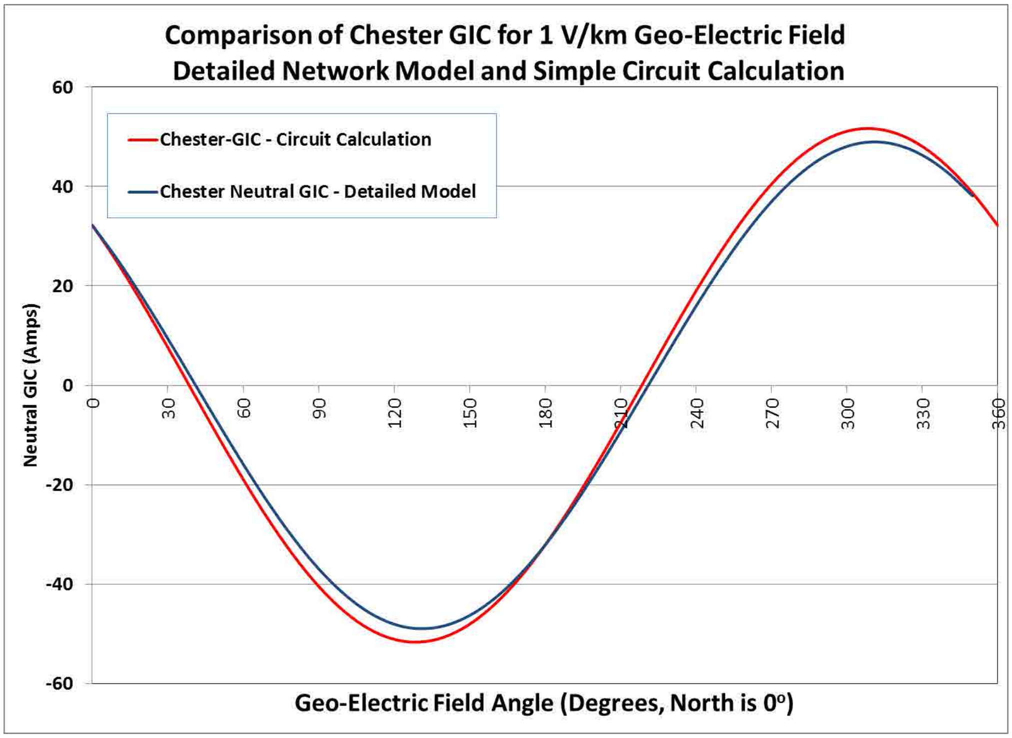


Figure 11 – Comparison of Calculated Chester GIC from detailed model and simple circuit calculation

Using the data from Figures 6 (the observed GIC at Chester) and Figure 11, it can be immediately inferred that the peak GIC levels of -66.6 and -74.3 Amps would have required a geo-electric field intensity of greater than 1 V/km to have occurred to produce such high levels of GIC. This is simply a process of utilizing Ohm's law knowledge to begin to develop an improved understanding of the geo-electric field intensity, an otherwise complex and uncertain field to calculate. In contrast it is not possible to infer the upper bound of geo-electric field, in that at angles where GIC nulls occur (such as 40^{o} and 220^{o}) even with a very high geo-electric field will not produce a significant GIC flow. As this point illustrates, these estimates can also be greatly improved by adding a simple understanding of geometry to this calculation. For example at time 4:16 UT, the simulation model results shown previously in Figure 3 illustrates a geo-electric field orientation at the Chester location which is almost exactly at 130^{o}, the orientation that would produce a peak GIC response at Chester. Using this circuit relationship of current to voltage allows extension to a scaling of the 49 Amp GIC at 1 V/km to a field intensity that would instead result in a 74.3 Amps GIC magnitude. This would lead to the estimated geo-electric field intensity at this 4:16UT time of ~1.5 V/km.

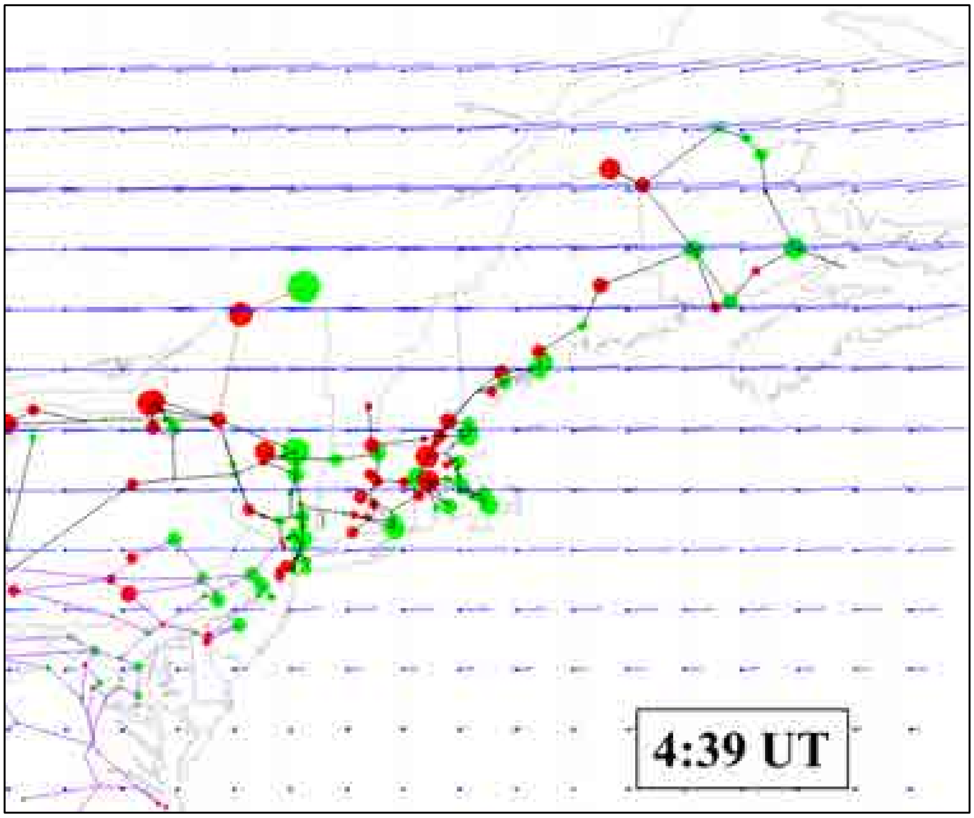


Figure 12 - GIC flows and disturbance conditions in Maine/New England grid at 4:39UT, May 4, 1998.

A similar simplified empirical analysis to confirm model results and expected geo-electric field levels can also be performed at time 4:39UT. Figure 12 provides a simulation output at time 4:39UT which again shows the intensity and geo-electric field angular orientation that would have occurred at this time step. This shows that the field was Eastward oriented or ~90^{o}. Since the characteristic GIC flows at Chester behave as a sine wave for variation of the geo-electric field angle to these circuit assets, a scaling factor based on these angular characteristics can also be applied, which would rerate the field to account for the less-optimal orientation angle at this time. In this case, the 66.6 Amp GIC would be produced by total geo-electric field of ~2 V/km, but only ~1.4 V/km of this total geo-electric field is utilized to produce a GIC flow in the Chester transformer. As this case illustrates, a higher total geo-electric field intensity occurred at 4:39UT than at time 4:16 UT, even though the GIC is lower at 4:39UT. This appears to be counter intuitive. However the event produced a smaller GIC, with the important difference being the angular orientation of the field alone.

As this example illustrates, the observation of GIC when properly placed in context provides an ability to develop an important metric for calculation of the driving geo-electric field that caused the GIC.

Validating the NERC Geo-Electric Field for Ottawa and New England Ground Models

As the previous discussion has revealed, the knowledge of GIC flows combined with the network resistance characteristics and locations of network assets can provide all of the information needed to fully resolve the storm Geo-Electric Field Intensity at any particular time during the storm. In other words knowing I and R allows the application of Ohm's law and geometry to derive V or the Geo-Electric Field. This means that GIC measurements can be utilized to derive the geo-electric field at all observation locations and provide important validations of the NERC Ground Models and Geo-Electric Field calculation methodology.

To better understand how GIC can be used to validate the NERC geo-electric field calculations, the regional nature and footprint of each storm needs to be more fully explained. Figure 13 provides a map of the Ottawa and St John's geomagnetic observatories and their proximity to the Chester substation in Maine. As this map illustrates, Chester is positioned in between these two observatories with Ottawa being ~550 km west of Chester and St. Johns being ~1230 km to the east of Chester.

Figure 13 – Map showing Locations of Chester substation in comparison with Ottawa and St. Johns geomagnetic observatories

During the time period around 4:39UT which resulted in the peak GIC flow at Chester, both the Ottawa and St. John's geomagnetic observatory also recorded similar impulsive disturbance levels. This plot of these two observatories is shown in Figure 14. Because both of these observatories recorded this same coherent impulsive disturbance, this suggests that the observations had to be connected to the same coherent ionospheric electrojet current structure (in this case an intensification of the Westward Electojet Current) that would have extended all the way between these observatories and directly in proximity to Chester, Maine as well.

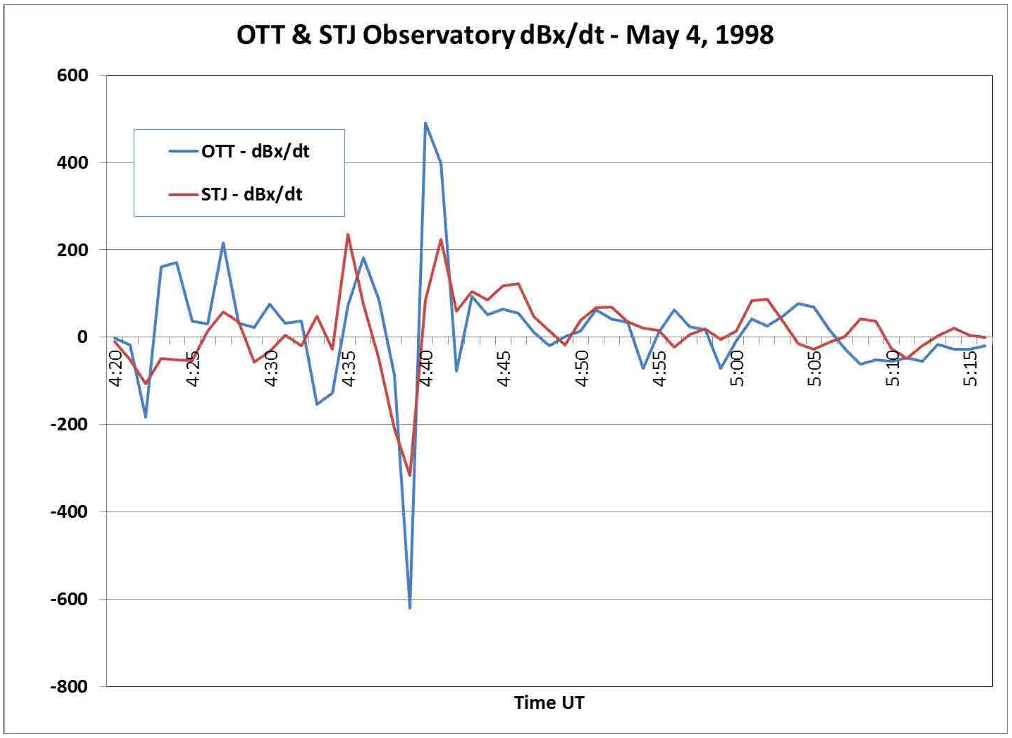


Figure 14 – Observed Impulsive disturbance at Ottawa and St. John's on May 4, 1998 at time 4:39UT.

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.

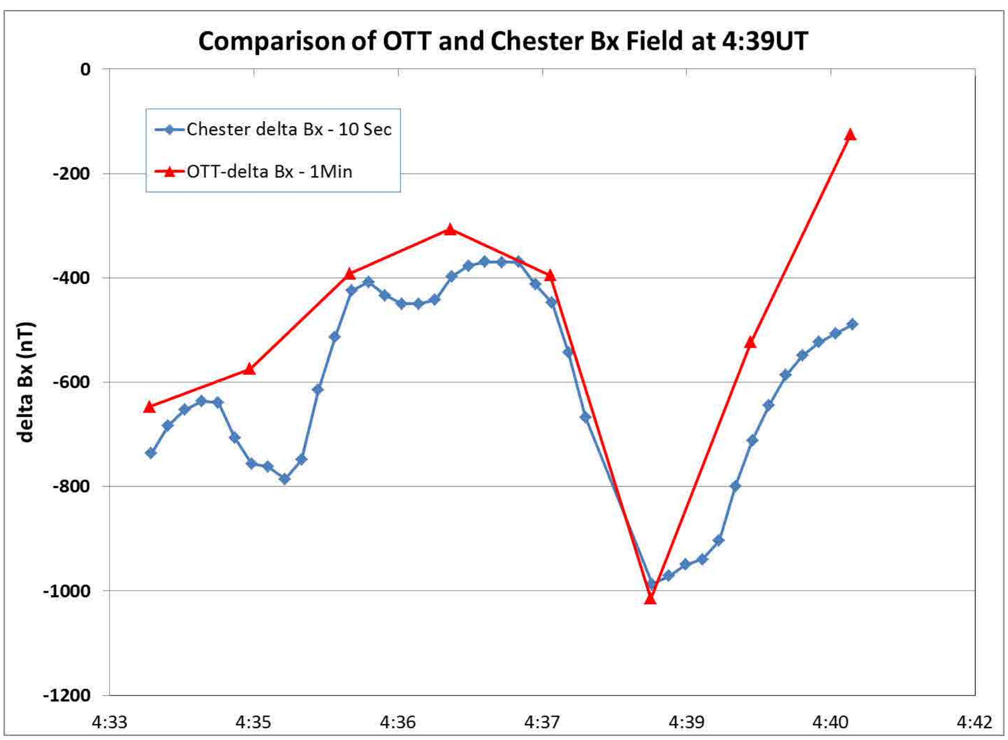


Figure 15 – Observation of Bx at Ottawa and Chester during peak impulse at time 4:39UT.

This close agreement between the observations at Ottawa and at Chester therefore allows the comparison of geo-electric field estimates between these two sites to be compared. As we had previously established using Ohm's Law, the peak geo-electric field must reach ~2 V/km to create the level of GIC observed during this storm. Geo-electric field calculations using a simulation model developed by the NERC GMD Task Force can be compared with the simulated geo-electric field in the Metatech simulation[4]. This comparison is shown in Figure 16. In addition, several portions of this geo-electric field waveform comparison are noted.

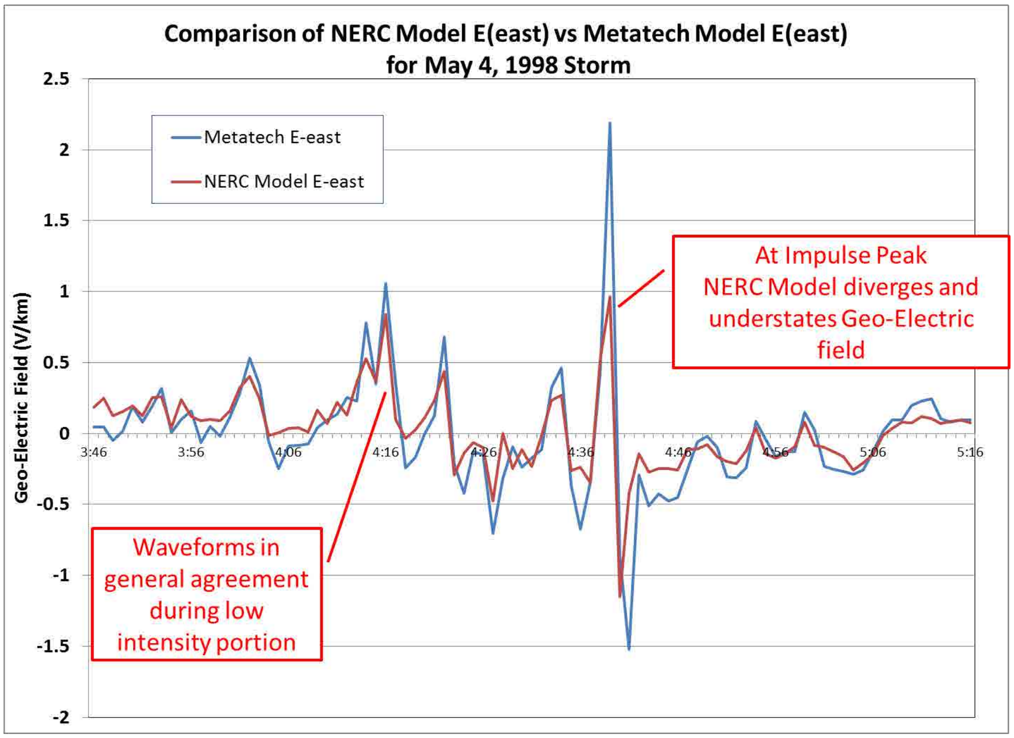


Figure 16 – Comparison of Metatech east-west geo-electric field calculation and NERC east-west geo-electric field calculation for May 4, 1998 storm event.

In the earlier portions of the storm simulation, the relative agreement between the two models for the geo-electric field is quite close. This occurs during a quieter and less intense portion of the storm. However as shown at the large impulse around time 4:39 UT, there is a divergence of agreement between the two models with the NERC modeling method understating the Metatech model results by a significant margin. After that impulse is over, the two models again come into relatively close agreement again. This suggests a problem in the NERC model of understating the intensity for more intense impulsive disturbances. As previously shown, the intensity in dB/dt is ~600 nT/min at time 4:39 UT, while it is generally below 100 to 200 nT/min at all other times during the simulation. Hence this higher intensity may be an important inflexion threshold within the NERC model.

As previously discussed Ohm's Law requires a sufficiently large enough geo-electric field to create the GIC flow observed at this location. Using the NERC model geo-electric fields it is possible to calculate the GIC flow and compare this to the GIC flow calculated for the Metatech model and even to the observed GIC. Figure 17 provides a comparison of the NERC model GIC with that computed in the Metatech model. Figure 18 compares the same NERC Model GIC result with actual GIC observed at

[4] Geo-elctric field data for this storm downloaded from NRCan http://www.spaceweather.gc.ca/data-donnee/dl/dl-eng.php#view

Chester. As both of these figures illustrate, the NERC model results will under predict the GIC at the peak storm intensities. In the case of the peak at time 4:39UT the understatement was similar in both the model comparisons and the observed GIC comparison.

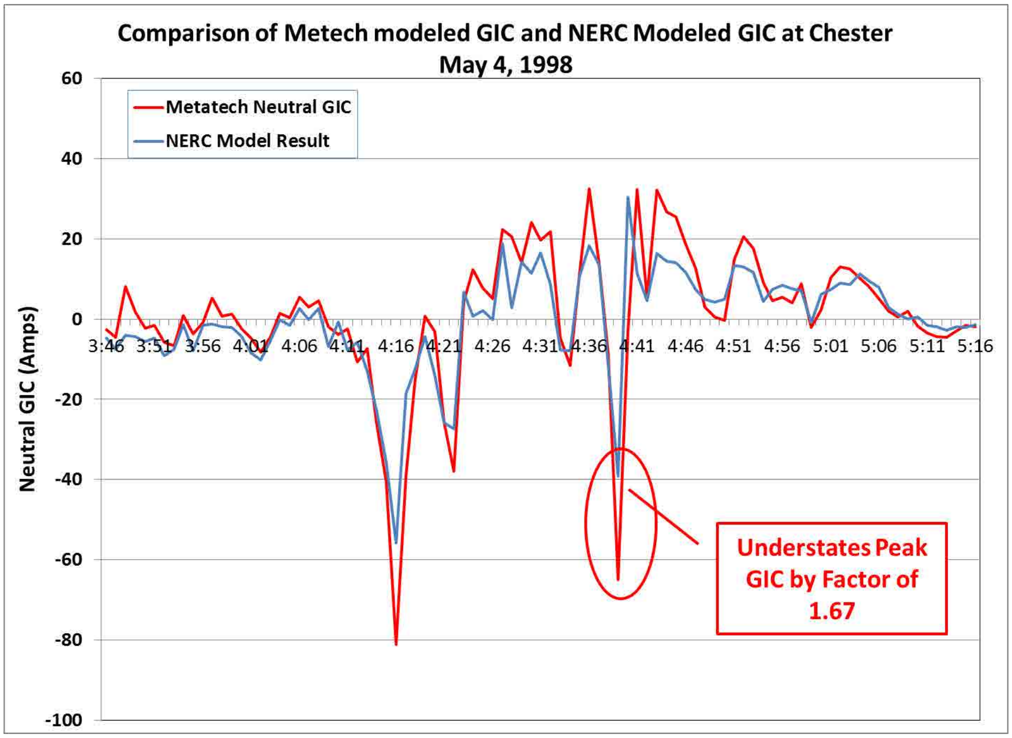


Figure 17 – Comparison of Metatech model GIC to NERC model GIC at Chester.

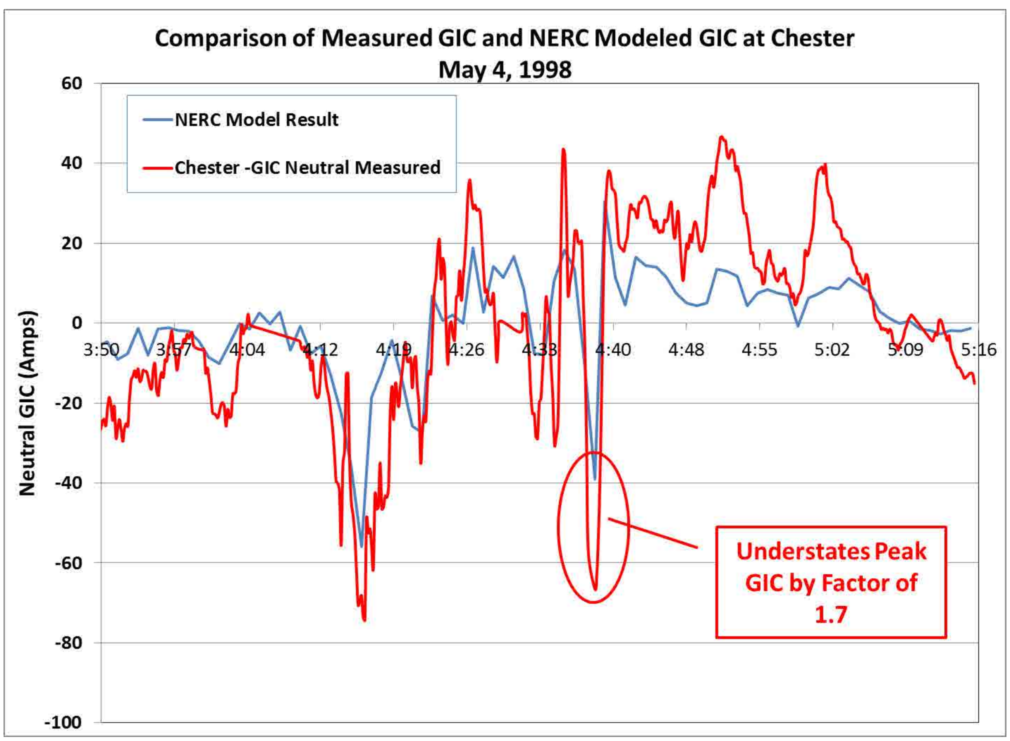


Figure 18 - Comparison of NERC model GIC to observed GIC at Chester.

NERC Model Validation Problems and Other GIC Observations

Seabrook GIC Observations July 13-16, 2012

While a number of GIC observations have been made over the last few decades in the US, very little of this information has been made publicly available. However where there is public information, it is possible to examine that data in a similar manner to the observations in Chester. Last year, observations as provided in Figure 19 were reported for GIC observations at the Seabrook Nuclear Plant[5]. These observations indicated peak GIC intensities during this storm that reached levels of 30 to 40 amps several times during the storm. The peak of 40 Amps occurred on July 16, 2012.

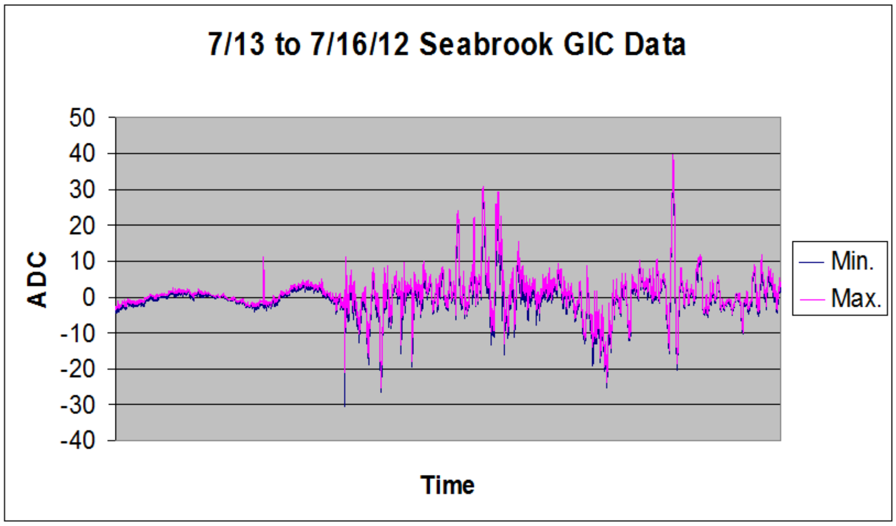


Figure 19 – GIC Observations at Seabrook Nuclear Plant July 13-16, 2012

Seabrook is also located in the New England region and because it is a GSU transformer, the neutral GIC also determines the flow that injects into the 345kV transmission network in that region. Figure 20 provides a map showing the location of Seabrook, and like Chester it will be heavily influenced by the same storm processes that will be observed at the nearby Ottawa observatory. In fact Seabrook is even closer to Ottawa than Chester.

[5] Geomagnetic Disturbance Mitigation for Nuclear Generator Main Power Transformers, Kenneth R. Fleischer, Presented April 16, 20132 at NOAA Space Weather Week Conference, Boulder Co.

Figure 20 – Location of Seabrook Nuclear Plant in New England region 345kV network.

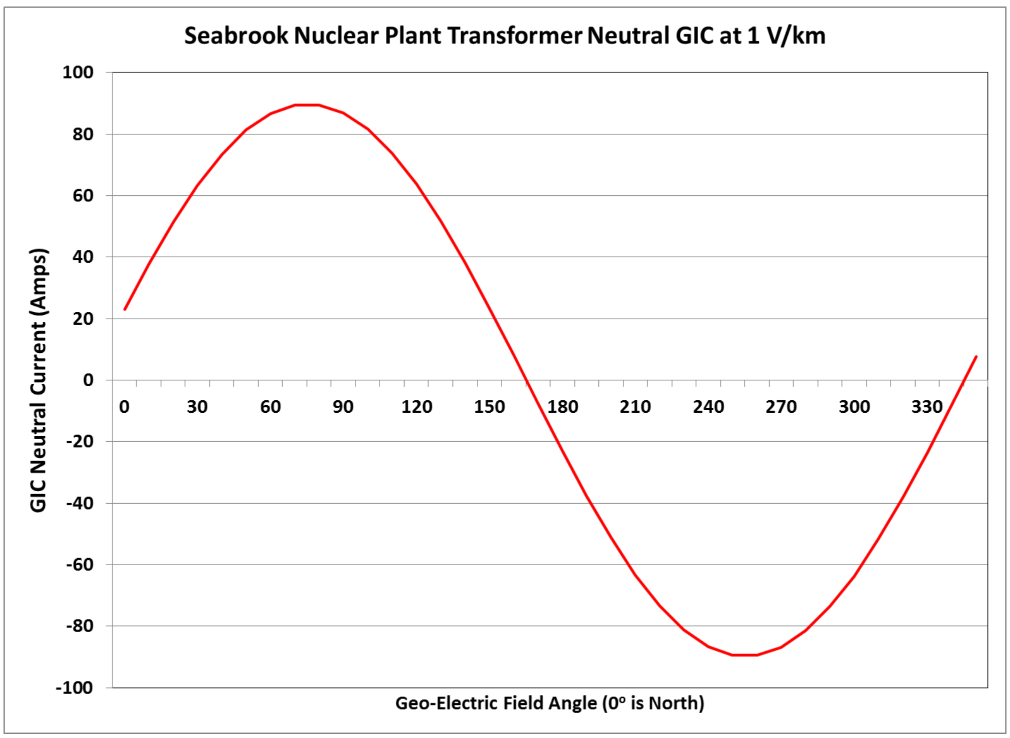


Figure 21 - GIC flow at Seabrook transformer neutral for 1 V/km geo-electric field at various orientation angles.

Figure 21 provides a plot of the characteristic GIC flows that would be observed at Seabrook for a uniform 1 V/km geo-electric field for a 360 degree rotation. This is computed similar to the way it was done at Chester. At this location, a 1 V/km geo-electric field produces ~90 Amp GIC at an 80° angle (essentially nearly east-west oriented). Compared to the characteristic GIC plot for Chester (Figures 7 and 11), for a 1 V/km geo-electric field at Seabrook the GIC will be ~50% higher. This is due to the more integrated connections at Seabrook into the New England 345kV grid and lower circuit impedances, as would be expected. This characteristic indicates that for the 40 Amp GIC observation that occurred on July 16, 2012, there must have been a net east-west geo-electric field of ~0.45 V/km to produce this large of a GIC, a requirement dictated by the Ohm's law behavior of the circuit at Seabrook.

Figure 22 provides a plot of the East-West Geo-Electric Field that would be derived using the NERC model from this storm, using the Ottawa observatory geomagnetic field disturbance conditions as the input. As shown the peak field intensity reaches only ~0.1 V/km which is ~4 times too low to produce the actual GIC observed at Seabrook for this storm event. Hence this storm simulation model provides an example of even worse GIC validation attempt than at Chester. (Not shown is that the peak north-south geo-electric field would have been ~0.12 V/km. But these are also too low and would not couple efficiently with the Seabrook region circuits; therefore this was not a factor in the GIC levels at Seabrook.)

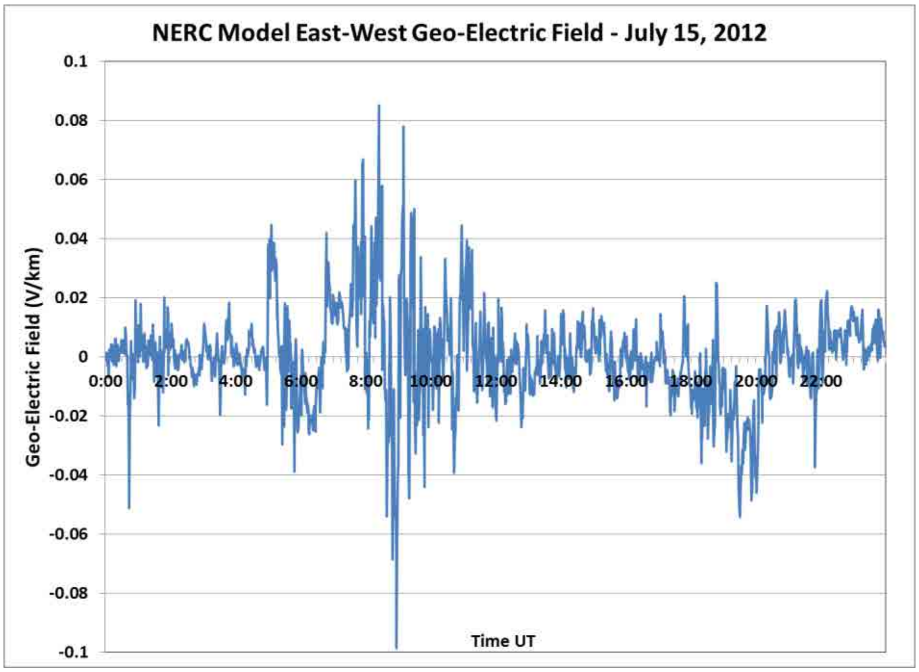


Figure 22 – NERC Model estimated East-West Geo-Electric Field on July 15, 2012 for the NE1 ground model.

BPA Tillamook GIC Observations Oct 30, 2003

In another situation, an examination has been conducted for ground models in the Pacific northwest region of the US. Data on GIC observations in the BPA transmission system have been provided to the Resilient Society Foundation under FOIA provisions and have been provided for analysis and ground model validation purposes. The GIC observations at the BPA Tillamook 230kV substation are examined in this case study. The Tillamook substation is on the western end of the BPA transmission network as shown in the map in Figure 23. There is a single 230kV line from Tillamook to the Carlton substation, but also 3 115kV lines that also connect at Tillamook, two which go in mostly North-South directions and one that connects to the East at Keeler.

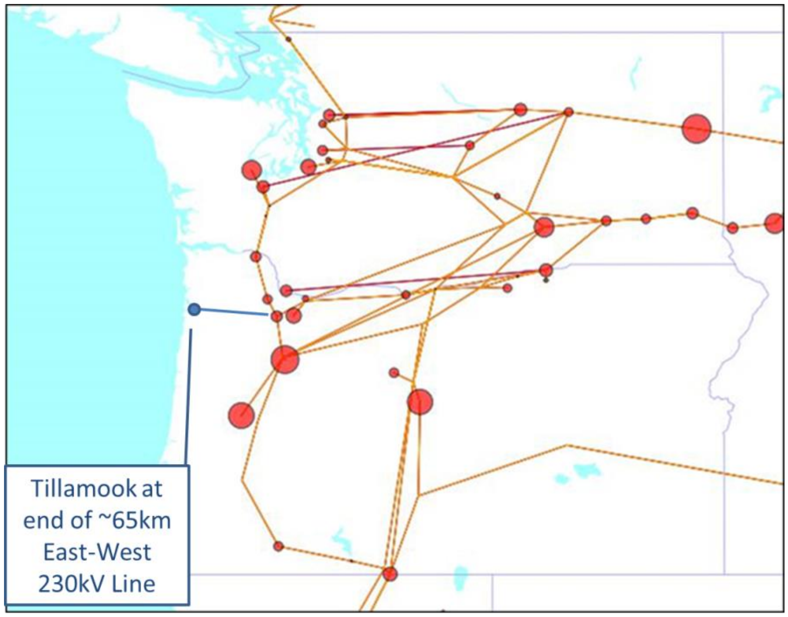


Figure 23 – Map of Tillamook 230kV substation and BPA 500kV network

Figure 24 provides a set of observations of GIC over a 2 hour time period at Tillamook which BPA provided in both 5 minute average and 2 second cadences during the October 30, 2003 storm. As shown in the 2 sec cadence data, the peak GIC approached nearly 50 Amps around time 19:55UT.

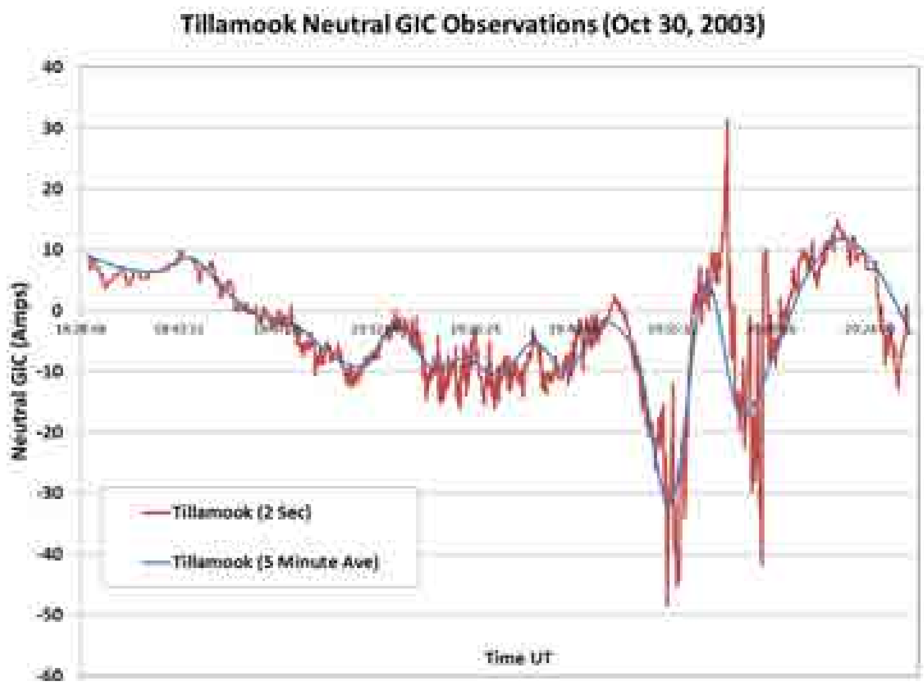


Figure 24 – Tillamook Neutral GIC observations on Oct 30, 2003, both 2 second and 5 minute average levels are shown

The Oct 30, 2003 storm conditions around time 19:55 UT are summarized from regional geomagnetic observatories as shown in Figure 25. This summary indicates that a region of intensification did encroach down into the Tillamook proximity at this time and would have been responsible for the peak GIC flows observed at this time, though Tillamook was not exposed to the worst case storm intensities.

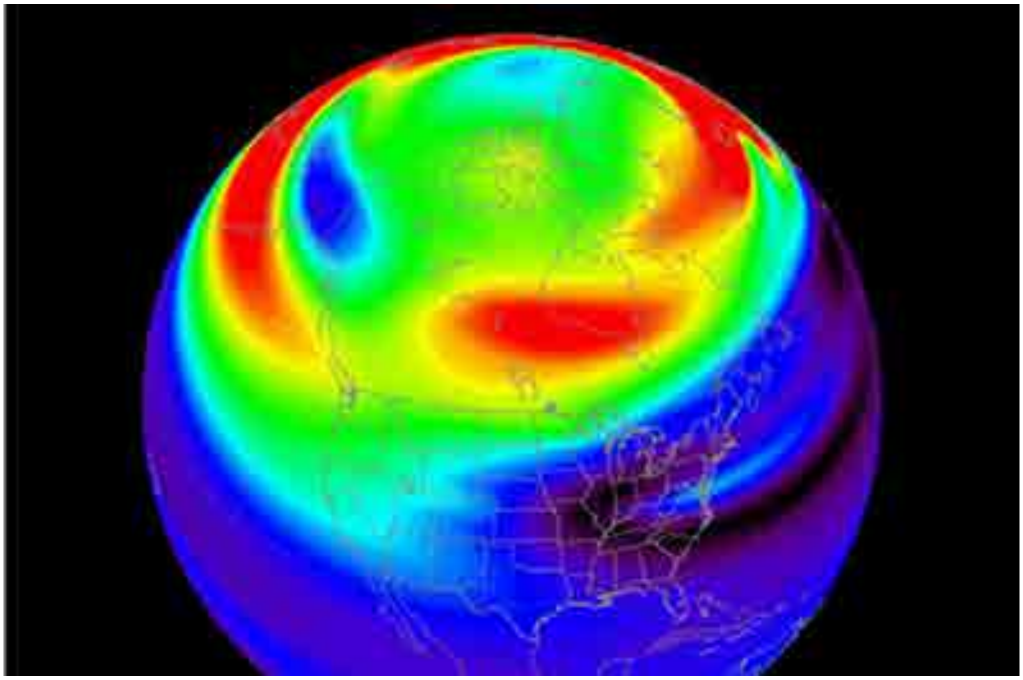


Figure 25 – Regional storm conditions at time 19:55UT October 30, 2003 at time of peak Tillamook GIC flows

Using methods similar to those developed for the Chester station and the various BPA physical data sources available, the characteristic GIC flows for the Tillamook 230kV autotransformer can be calculated for a rotated 1 V/km geo-electric field. The results for this are shown in Figure 26 and the peak GIC reaches a level of ~38 Amps for a predominantly east-west oriented geo-electric field. Therefore when examining the GIC levels observed at Tillamook on Oct 30, 2003, Ohm's law would constrain that the minimum geo-electric field in this region would need to exceed 1 V/km (in at least the east-west direction) to produce the nearly 50 Amps GIC peaks.

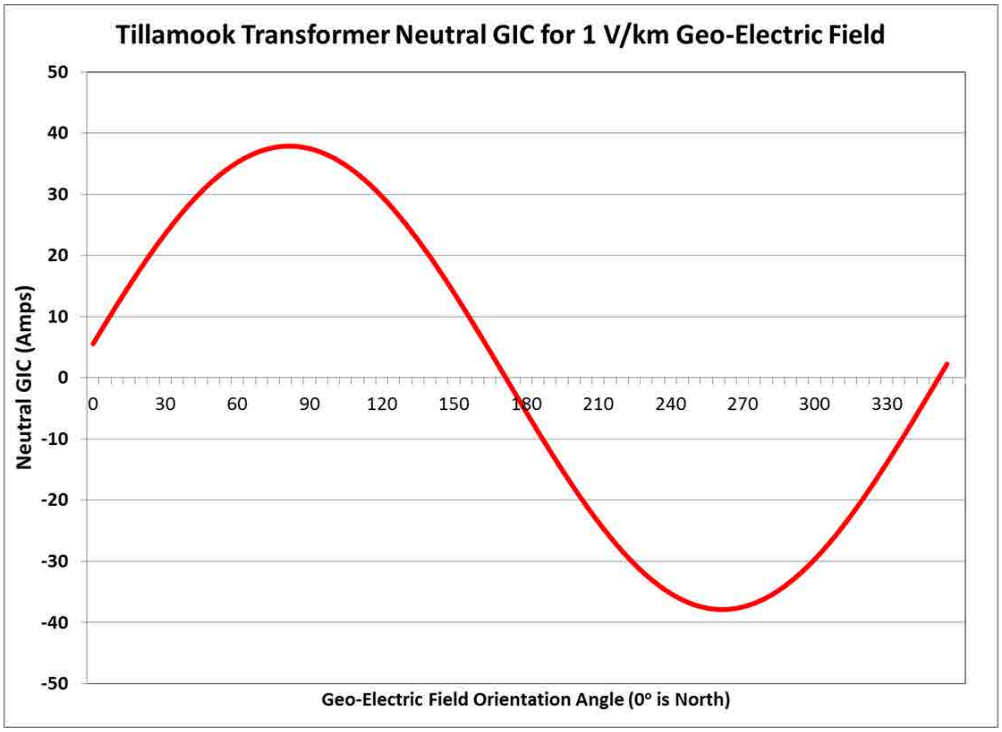


Figure 26 - GIC flow at Tillamook transformer neutral for 1 V/km geo-electric field at various orientation angles.

The NERC model calculations for East-West geo-electric field using the PB1 model are shown in Figure 27 for the same time interval as shown in Figure 24 for the Tillamook high GIC observations, but since the Tillamook GIC flow characteristics are defined in Figure 26, it is possible to utilize this to derive the minimum East-West geo-electric field responsible for producing the GIC flows in Figure 24. These results are also presented in Figure 27 with the NERC model predictions for this storm.

As Figure 27 shows, the peak geo-electric field as strictly constrained by Ohm's law must exceed 1 V/km during portions of the GIC flow where the Tillamook GIC exceeded ~38 amps level. At all times, the NERC model geo-electric field did not exceed even 0.25 V/km. As this comparison illustrates, the NERC model greatly understates the peak geo-electric field intensities at the peak GIC flow portions of the storm. In some cases this understatement is more than a factor of 4 to 5 times too small. This degree of divergence is also worse than what was observed at Chester Maine and is similar to the error level noted for Seabrook.

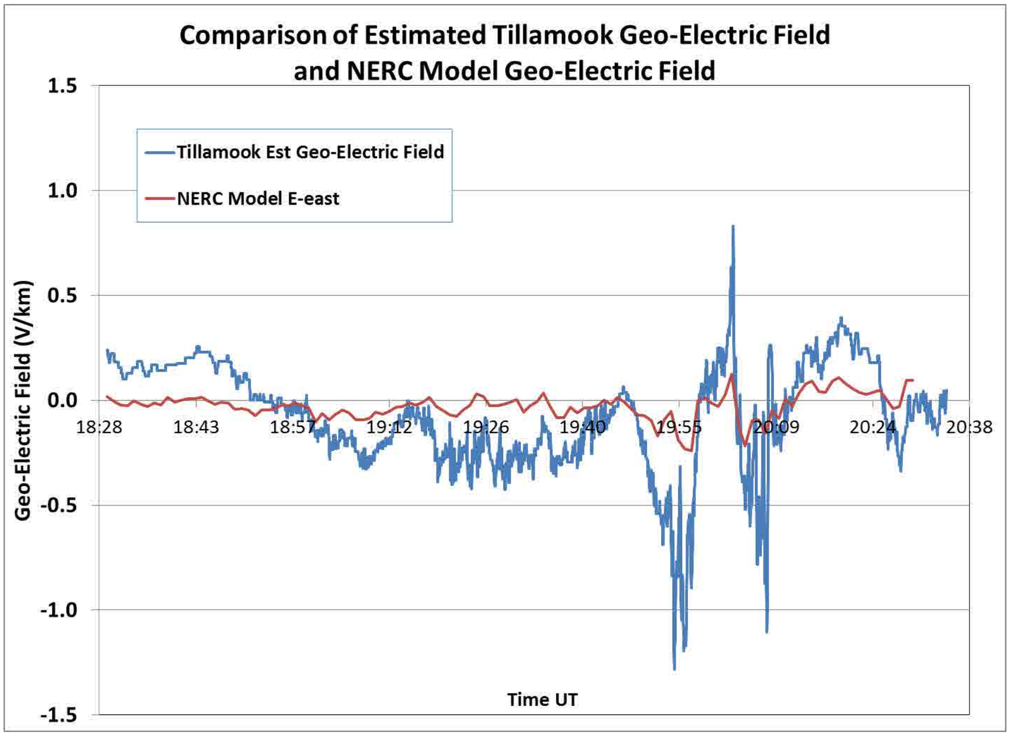
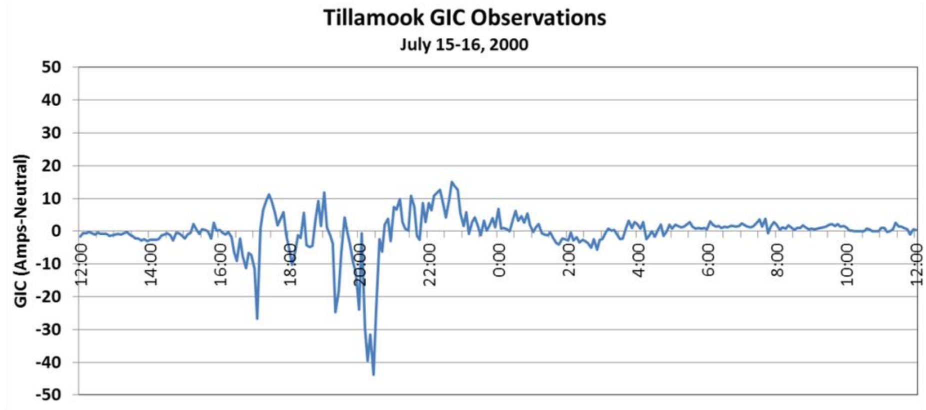


Figure 27 – Comparison of NERC Model geo-electric field with estimated geo-electric field needed to produce Tillamook GIC flows for the Oct 30, 2003 storm

There are other storms available with similar levels of GIC measurements observed at the Tillamook substation and 230kV line. Because this 230kV line is an East-West orientated line, GIC observed there will be largely driven by North-South variations (or dBx/dt) in the geo-magnetic field which subsequently produces an East-West geo-electric field. Figure 28 provides a plot of the nearest geomagnetic observatory (Victoria, ~340 km north of Tillamook) and the Tillamook GIC observed during an important storm on July 15-16, 2000. These geomagnetic disturbance conditions reach a peak of just over 150 nT/min resulting in GIC flows (5 min averaging) reaching -43.5 Amps at time 20:25UT. Figure 29 provides a detailed regional summary which show the more global storm conditions that were occurring at time 20:25UT over North America. As this Figure illustrates, the most severe storm conditions were located quite far to the North, so the GIC observed for these conditions could have been driven to much higher levels had the intensity extended further southward.

From the GIC observations for this storm, the minimal Geo-Electric field levels necessary to produce the GIC flows observed at Tillamook can be again calculated. This can also again be compared with the estimates used by NERC in modeling this storm event, this comparison is shown in Figure 30. In the comparison of the NERC model geo-electric field with the actual geo-electric field as derived from GIC measurements, the NERC model again greatly under predicts peak V/km intensities, by as much as a factor of ~5 or more at peak intensities times. These results are similar to the results from the Oct 30, 2003 storm as shown in Figure 27 and further confirm that the NERC models will not accurately depict storm conditions.



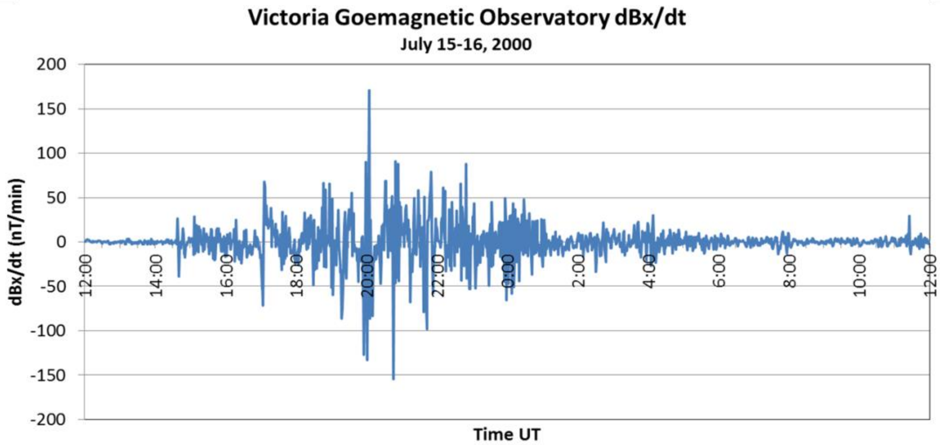


Figure 28 – Observed Tillamook GIC and Victoria dBx/dt for storm on July 15-16, 2000.

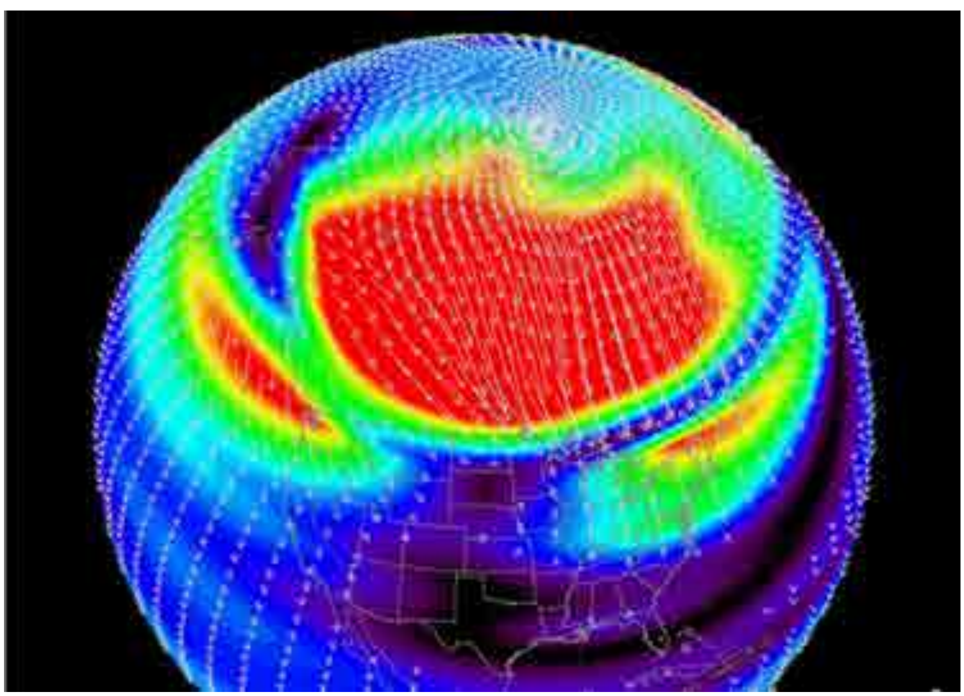


Figure 29 - July 15, 2000 at time 20:25UT storm conditions at time of Tillamook -43.5 Amp GIC Peak.

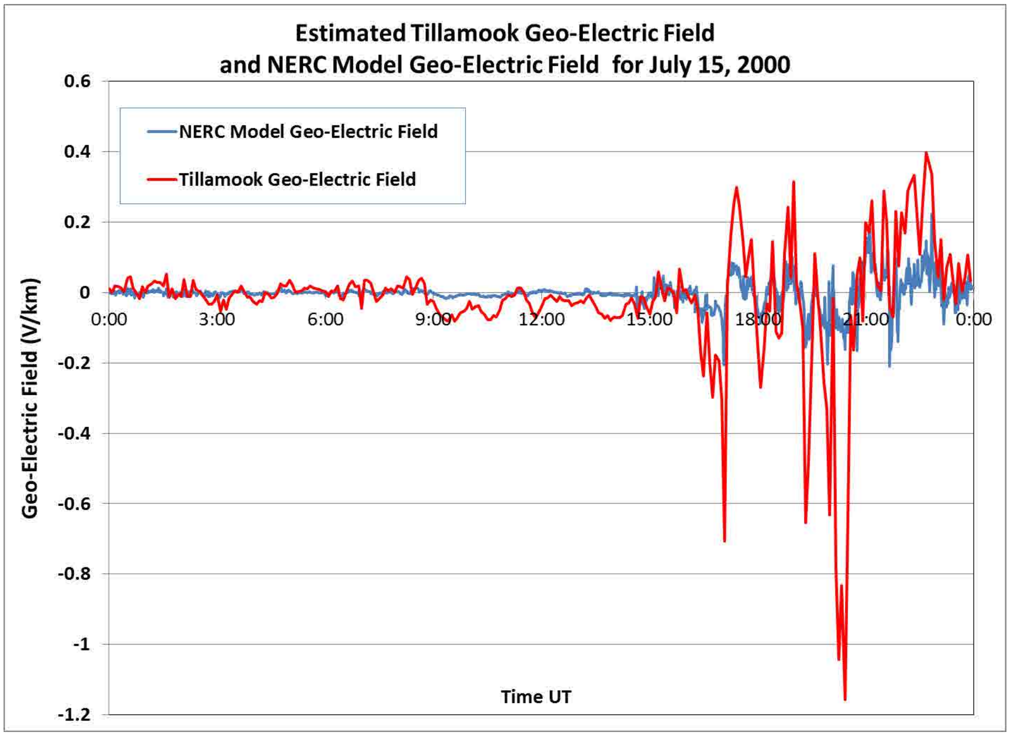


Figure 30 - Comparison of NERC Model geo-electric field with estimated geo-electric field needed to produce Tillamook GIC flows for the July 15, 2000 storm

Other Instances of Geo-Electric Field Modeling Concerns

The NERC geo-electric field simulation tools had their genesis out of the Finnish Meteorology Institute and have since been adopted at NASA (A. Pulkkinen) and also at Natural Resources Canada and many other locations around the world. Pulkkinen in particular was a key NERC GMD Task Force science investigator, a key EPRI science investigator along with staff from NRCan. Pulkkinen was also a member of the NERC GMD Standards Task Force, where the draft standards incorporating these tool sets are fully integrated into the science analysis and are recommended tools for system analysis. In the entirety of the NERC GMD task force investigations, no evidence has been made available by the NERC GMD Task Force of rigorous validations of the suite of ground models and derived relationships that have been published. USGS scientist involved in the effort asked for more power industry efforts to do model validations at several NERC GMD meetings, with no active participants and no subsequent publications supporting the ability to verify these models.

These FMI/NRCan-based geo-electric field modeling approaches use a Fourier transform method[6]. Fourier transforms are well-conditioned for periodic signals, not the very aperiodic events associated with abrupt, high intensity impulsive disturbances typical for severe geomagnetic storms. Therefore a Fourier approach needs to be carefully considered and tested rigorously to assure fidelity in output resolution for severe impulsive geomagnetic field disturbances. An additional geo-electric field modeling approach has been developed by Luis Marti based upon Recursive Convolution[7]. Unfortunately no independent validation for this model was noted in their IEEE paper on the model, rather it was only

[6] How to Calculate Electric Fields to Determine Geomagnetically-Induced Currents. EPRI, Palo Alto, CA: 2013. 3002002149.

[7] Calculation of Induced Electric Field During a Geomagnetic Storm Using Recursive Convolution, Luis Marti, A. Rezaei-Zare, and D. Boteler, IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 29, NO. 2, APRIL 2014

tuned to agree with the FMI/NRCan geo-electric field model output results. In addition, staff from the NOAA SWPC and USGS were also provided tool sets that were tuned to the NASA-CCMC/NRCan geo-electric field models so that the results that each examined would be the same. Hence no real independent assessments were ever apparently undertaken by all of these organizations. Therefore all of the various NERC GMD models appear to produce results that will consistently understate the true geo-electric field intensity.

In looking at recent publications by Pulkkinen, et. al., a paper titled "Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden"[8] was published in the Space Weather Journal in 2008. In this paper the authors presented results from several storm events that were similar in intensity to the May 4, 1998 storm that was discussed in a prior section of this report. Figure 31 is a set of plots from Figure 7 of their paper showing the disturbance intensity (dB/dt in nT/min) in the bottom plot and the measured and calculated GIC in the top plot. As illustrated in this Figure, the storm intensity is similar to that experienced in Maine during the May 4, 1998 storm at ~500 nT/min. In regards to the comparison of the Measured and Calculated GIC the simulation model greatly under predicts the actual measured GIC during the most intense portion of the storm around hour 23 UT by substantial margins (factor of 3 or more). This is the same symptomatic outcome observed in the NERC model results and provides another independent assessment with possible inherent problems with this modeling approach.

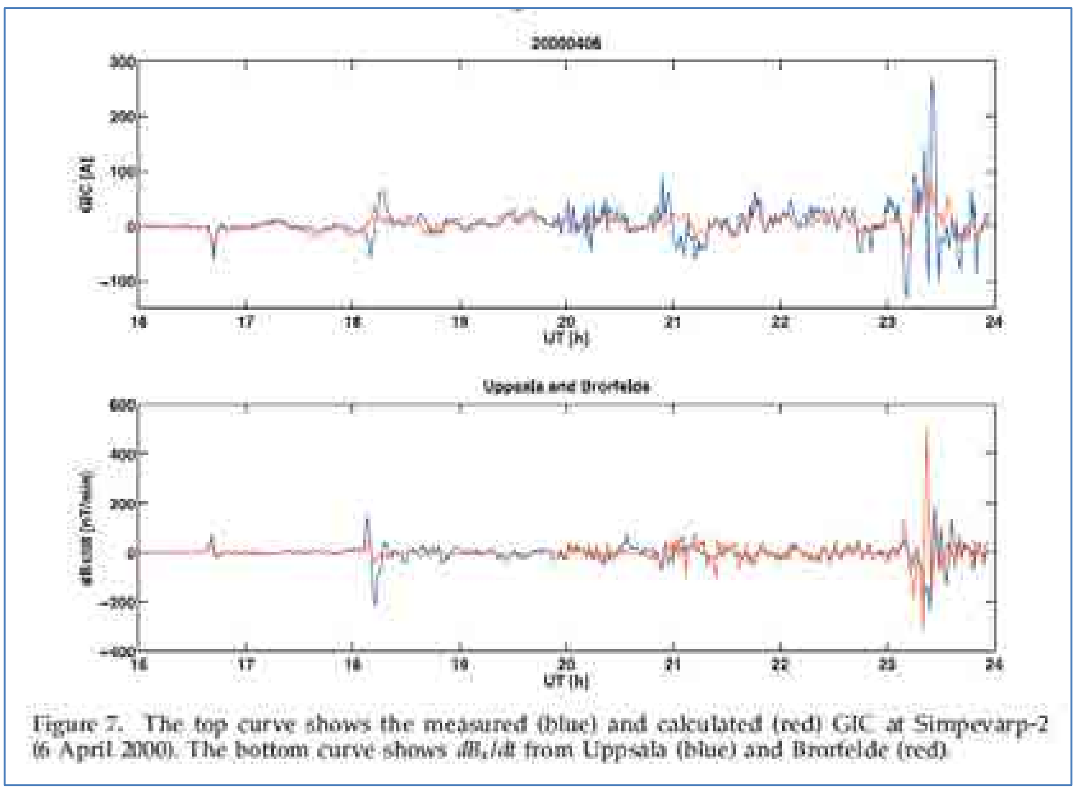


Figure 31 – Plot Figure 7 from Pulkkinen, et.al.,paper "Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden" published 2008 showing storm intensity and GIC comparisons

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[8] Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden, M. Wik, A. Viljanen, R. Pirjola, A. Pulkkinen, P. Wintoft, and H. Lundstedt, SPACE WEATHER, VOL. 6, S07005, doi:10.1029/2007SW000343, 2008

In another example from this same paper, a figure shown below as Figure 32 provides a comparison plot of the Measured and Calculated GIC during the July 15, 2000 storm at the same transformer in southern Sweden. The GIC results as in all prior comparisons greatly diverge during the occurrence of the largest and most sudden impulsive disturbance events, such as those between 21 and 22 UT.

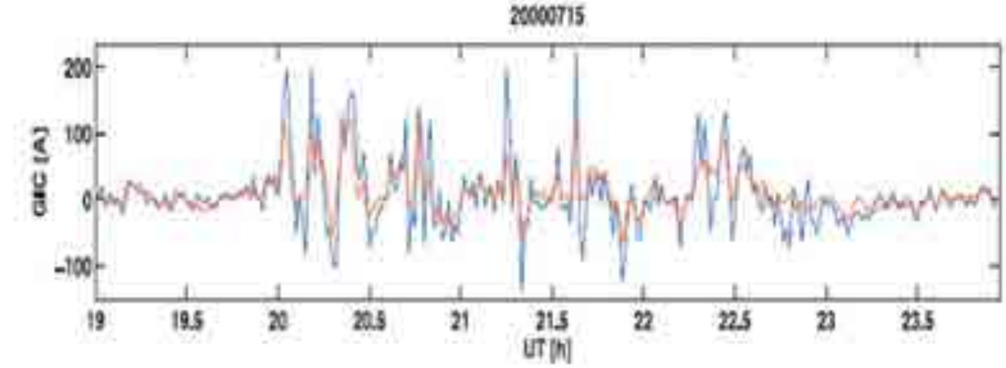

Figure 4. Measured (blue) and calculated (red) GIC at Simpevarp-2 for three events in 1998 to 2000.

Figure 32 - Plot Figure 4 from Pulkkinen, et.al.,Paper "Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden" published 2008 showing GIC comparisons

Conclusions – Draft NERC Standards are Not Accurate and Greatly Understate Risks

As these examples illustrate the results of calculations of geo-electric fields by the NERC models and any subsequent NERC predicted GIC's appear to exhibit the same problems of significantly under predicting for intense storm disturbances. In all locations that were examined the results of the models consistently under predicted what Ohm's Law establishes as the actual geo-electric field. This is a systemic problem that is likely related to inherent modeling deficiencies, and exists in all models in the NERC GMD Task Force and likely in many other locations around the world.

This has significant implications for nearly all of the findings of the NERC GMD Task Force. These erroneous modeling approaches were utilized to examine the peak geo-electric field outputs to much higher disturbance intensities for severe storms. For example the underlying analysis performed by NERC Standard Task Force members Pulkkinen and Bernabeu[9] for the 100 Year storm peaks utilized the faulty geo-electric field calculation model to derive the peak geo-electric fields for the reference Quebec ground models. This would drastically understate the peak intensity of the storm events by the same factor of 2 to 5 ratios as noted in the prior case study analysis. Therefore the standard proposing the NERC Reference Field level of between 3 to 8 V/km would be an enormous under-estimation and result in an enormous miss-calculation of risks to society. The same modelling errors are part of all earlier Pulkkinen/Pirjola[10] derived science assessments which also examined these peaks and 100 year storm statistics. As all prior validations within this report have established, the NERC geo-electric field model under predicts geo-electric field by a factor of 2 to 5 for the most important portions of storm events. Hence these errors have been entirely baked into the NERC GMD Task Force cake and their draft standards as well. Therefore the entirety of the Draft Standard does not provide accurate assessments

[9] 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.

[10] Pulkkinen, A., R. Pirjola, and A. Viljanen, Statistics of extreme geomagnetically induced current events, Space Weather, 6, S07001, doi:10.1029/2008SW000388, 2008.

of the geo-electric field environments that will actually occur across the US. It has also been shown in this White Paper that undertaking a more rigorous development of validated geo-electric field standards can be done in a simple and efficient manner and that such data to drive these more rigorous findings already exists in many portions of the US. Efforts on the part of NERC's standard team and the industry to withhold this material information are counter-productive to the overarching requirements to assure public safety against severe geomagnetic storm events. Such fundamental and significant flaws in technical calculations and procedural actions should not be a part of any proposed standard and a redraft must be undertaken.

NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

February 18, 2015

Mr. William R. (Bill) Harris
Mr. Thomas S. Popik
Foundation for Resilient Societies, Inc.
52 Technology Way
Nashua, New Hampshire 03060
via Federal Express
and via Email to wm.r.harris@gmail.com and
thomasp@resilientsocieties.org

Re: Level 1 Appeal, Proposed Reliability Standard TPL-007-1
(Project 2013-03 Geomagnetic Disturbance Mitigation)

Dear Messrs. Harris and Popik:

As the Director of Standards for the North American Electric Reliability Corporation ("NERC"), I am in receipt of the complaint of Foundation for Resilient Societies, Inc. (the "Foundation") submitted on January 4, 2015 and as revised on January 5, 2015 (the "Complaint"), pursuant to Section 8 of NERC's Standard Processes Manual (the "SPM"), initiating a "Level 1 Appeal" as set forth in the SPM relating to the development of proposed Reliability Standard TPL-007-1. This response is being provided to Foundation within 45 days of receipt of the Complaint, in accordance with the SPM.

In the Complaint, Foundation asserts that the standard drafting team failed to address certain risks, include certain measures, or perform certain analyses in developing the proposed standard and the accompanying Benchmark Geomagnetic Disturbance ("GMD") Event. Foundation also asserts that NERC failed to perform "essential quality control" with respect to the proposed standard, and that the standard drafting team did not fully address its prior comments submitted during the standard development process.

NERC's goal is to provide an open and transparent process for the development of Reliability Standards, and NERC appreciates Foundation's ongoing participation in the standard development process. NERC has reviewed the complete record of development for proposed Reliability Standard TPL-007-1 (part of Project 2013-03 Geomagnetic Disturbance Mitigation) and the information contained in Foundation's Complaint in order to determine whether NERC's SPM was followed during the development of the proposed standard. NERC's review is limited to a review of procedural action or inaction; the appeals

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process does not permit reconsideration of issues concerning the substantive, technical components of a Reliability Standard developed through the standard development process and approved by the NERC Board of Trustees.

For the reasons discussed more fully in the enclosed Disposition of Appeal, NERC finds no basis for any assertions that NERC failed to follow the SPM during the development of proposed Reliability Standard TPL-007-1. Therefore, NERC finds that Foundation has not demonstrated that it has or will experience any adverse impact as a result of a procedural action or inaction associated with the Reliability Standards process, as required by Section 8 of the SPM.

This response concludes Foundation's Level 1 Appeal. Under Section 8.1 of the SPM, if Foundation accepts this response as a satisfactory resolution of the issue, both Foundation's Complaint and this response shall be made a part of the public record of associated with the Reliability Standard.

Thank you for your participation in the standard development process.

Sincerely,

Valerie Agnew

Valerie Agnew
Director of Standards

Enclosure

DISPOSITION OF LEVEL 1 APPEAL
FOUNDATION FOR RESILIENT SOCIETIES, INC.
TPL-007-1 (Project 2013-03 Geomagnetic Disturbance Mitigation)
FEBRUARY 18, 2015

On January 4, 2015, and as revised on January 5, 2015, Foundation for Resilient Societies, Inc. (the "Foundation") submitted a complaint styled *First Stage Appeal to the Director of Standards of the North American Electric Reliability Corporation (NERC) Pursuant to the NERC Standard Processes Manual Rev. 3, Seeking Amendments to a NERC-Proposed Reliability Standard NERC Standard TPL-007-1, Transmission System Planned Performance for Geomagnetic Disturbance Events* to the Director of Standards for the North American Electric Reliability Corporation ("NERC") (the "Complaint"), pursuant to Section 8 of NERC's Standard Processes Manual ("SPM"), initiating a "Level 1 Appeal" as set forth in the SPM.[1]

In the Complaint, Foundation asserts that the standard drafting team (or "SDT") failed to address certain risks, include certain measures, or perform certain analyses in developing proposed standard TPL-007-1 and the accompanying Benchmark Geomagnetic Disturbance ("GMD") Event. Foundation also asserts that NERC failed to perform "essential quality control" with respect to the proposed standard, and that the standard drafting team did not fully address its prior comments submitted during the standard development process.

For the reasons discussed more fully below, NERC finds no basis for any assertions that NERC failed to follow the SPM during the development of proposed Reliability Standard TPL-007-1. Therefore NERC finds that Foundation has not demonstrated that it has or will experience any adverse impact as a result of a procedural action or inaction associated with the Reliability Standards process. NERC concludes that Foundation has not made the necessary showing to sustain an appeal under Section 8 of the SPM. Foundation's Level 1 Appeal is concluded.

I. The Reliability Standards Development Process

NERC develops Reliability Standards in accordance with Section 300 (Reliability Standards Development) of its Rules of Procedure and the NERC SPM.[2] In its ERO Certification Order, the Federal Energy Regulatory Commission ("FERC") found that NERC's proposed rules provide for reasonable notice and opportunity for public comment, due process, openness, and a balance of interests in developing Reliability Standards and thus addresses certain of the criteria for approving Reliability Standards.[3] The development process is open to any person or entity with a legitimate interest in the reliability of the Bulk-Power System. NERC considers the comments

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1 A complete list of files received from Foundation is attached hereto as Attachment 1.

2 The NERC Rules of Procedure are available at http://www.nerc.com/AboutNERC/Pages/Rules-of-Procedure.aspx.
The NERC Standard Processes Manual v. 3, Appendix 3A to the NERC Rules of Procedure (eff. Jun. 26, 2013) is available at http://www.nerc.com/comm/SC/Documents/Appendix_3A_StandardsProcessesManual.pdf.

3 116 FERC ¶ 61,062 at P 250 (2006).

of all stakeholders, and a vote of stakeholders and the NERC Board of Trustees is required to approve a Reliability Standard before the Reliability Standard is submitted to FERC for approval.

Section 8.0 of the SPM describes the Reliability Standards appeals process as follows:

> Any entity that has directly and materially affected interests and that has been or will be adversely affected by any procedural action or inaction related to the development, approval, revision, reaffirmation, retirement or withdrawal of a Reliability Standard, definition, Variance, associated implementation plan, or Interpretation shall have the right to appeal. This appeals process applies only to the NERC Reliability Standards processes as defined in [the SPM], not to the technical content of the Reliability Standards action.
>
> The burden of proof to show adverse effect shall be on the appellant. Appeals shall be made in writing within 30 days of the date of the action purported to cause the adverse effect, except appeals for inaction, which may be made at any time. The final decisions of any appeal shall be documented in writing and made public.

Importantly, and as stated above, the right to appeal is limited to only appeals of actions or inactions related to the standard development processes set forth in the SPM. The SPM explicitly states that the appeals process does not apply to the technical content of the Reliability Standards action.

The process for appealing procedural action or inaction consists of two levels. To pursue a Level 1 Appeal, the appellant must submit a written complaint to the Director of Standards "that describes the procedural action or inaction" which the appellant is appealing, as well as the "actual or potential adverse impact to the appellant" that this procedural action or in action will or may cause. The Director of Standards is required to provide a response within 45 days after receipt of the complaint. If a resolution is reached, the complaint and the response will be made a part of the public record associated with the Reliability Standard.

If a resolution is not reached through the Level 1 Appeal, the appellant may pursue a Level 2 Appeal before a panel of five members appointed by the NERC Board of Trustees. The requirements and procedures for Level 2 Appeals are described in Section 8.2 of the SPM. However, even at the Level 2 Appeal stage, the panel may not revise, approve, disapprove, or adopt a Reliability Standard, as those responsibilities remain with the ballot pool and Board of Trustees.

II. Project 2013-03 Geomagnetic Disturbance Mitigation

In Order No. 779, the Commission directed NERC to develop a set of Reliability Standards to address GMDs in two stages.[4] In the first stage, NERC developed Reliability Standard EOP-010-1, requiring owners and operators of the Bulk-Power System to develop and implement operational procedures to mitigate the effects of GMDs consistent with the reliable operation of the Bulk-Power System.[5] In the second stage, NERC developed proposed Reliability Standard TPL-007-1, requiring owners and operators of the Bulk-Power System to conduct initial and on-going vulnerability assessments of the potential impact of benchmark GMD events on Bulk-Power System equipment and the Bulk-Power System as a whole.

A complete record of the standard development history for proposed Reliability Standard TPL-007-1 is available on NERC's website.[6] A brief summary of the postings, comment periods, and ballots is provided for reference below:

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

5 FERC approved Reliability Standard EOP-010-1 in Order No. 797. *See* Order No. 797, *Reliability Standard for Geomagnetic Disturbance Operations*, 147 FERC ¶ 61,209, *reh'g denied*, Order No. 797-A, 149 FERC ¶ 61,027 (2014).

6 Project 2013-03 Geomagnetic Disturbance Mitigation, *available at* http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx. The summary of development history and complete record of development is provided as Exhibit I to the Petition of the North American Electric Reliability Corporation for Approval of Proposed Reliability Standard TPL-007-1 Transmission System Planned Performance for Geomagnetic Disturbance Events, Dkt. No. RM15-11-000 (Jan. 21, 2015).

Action	Date
Standard Authorization Request Posted for Formal Comment Period Approved by Standards Committee	 June 27, 2013 – August 12, 2013 June 21, 2013
First Posting of TPL-007-1 Informal Comment Period	 April 22, 2014 – May 21, 2014
Second Posting of TPL-007-1 Formal Comment Period Initial Ballot & Non-Binding Poll	 June 13, 2014 – July 30, 2014 July 21, 2014 – July 30, 2014
Third Posting of TPL-007-1 Formal Comment Period Additional Ballot & Non-Binding Poll	 August 27, 2014 – October 10, 2014 October 1, 2014 – October 10, 2014
Fourth Posting of TPL-007-1 Formal Comment Period Additional Ballot & Non-Binding Poll	 October 28, 2014 – November 21, 2014[7] November 12, 2014 – November 21, 2014
Final Ballot	December 5, 2014 – December 16, 2014[8]

Having received a quorum and sufficient affirmative votes for approval, proposed Reliability Standard TPL-007-1 was approved by the NERC Board of Trustees on December 17, 2014. On January 21, 2015, NERC submitted the proposed standard, along with the associated implementation plan, associated Violation Risk Factors and Violation Severity Levels, and the proposed definition of "Geomagnetic Disturbance Vulnerability Assessment" or "GMD Vulnerability Assessment," to FERC for approval.

III. Discussion

In this Level 1 Appeal, NERC looks to the record to determine whether its FERC-approved standard development process was followed during the development of the proposed standard. The appeals process does not permit reconsideration of the merit or desirability of the substantive technical content of a proposed standard.

Foundation asserts a number of failures in the standard development process for proposed Reliability Standard TPL-007-1. Foundation has not cited any specific section of the SPM in support of any of the assertions contained in its Complaint. However, to effectuate a complete resolution of the issues raised in the Complaint, NERC has addressed those assertions that could reasonably be construed as implicating procedural action or inaction on the merits. NERC has construed Foundation's assertions as falling within four distinct categories as follows: (a)

[7] On its regularly-scheduled October 22, 2014 teleconference, the Standards Committee authorized a waiver of the Standard Process, shortening the next formal comment period (and any subsequent additional formal comment periods) for draft standard TPL-007-1 from 45 days to 25 days.

[8] The final ballot close date was extended one day to December 16, 2014 due to a NERC.com maintenance outage that occurred Saturday, December 13, 2014.

objections to the technical content of proposed Reliability Standard TPL-007-1; (b) assertions that NERC Reliability Standards staff failed to perform "essential 'quality control'"; (c) assertions implicating potential anticompetitive effects; and (d) assertions regarding the failure to respond to comments submitted during the standard development process, where a response is required by the SPM.

For the reasons that are described more fully below, NERC finds that Foundation has not demonstrated that it has or will experience any adverse impact as a result of a procedural action or inaction associated with the Reliability Standards process related to the development of proposed Reliability Standard TPL-007-1, as required by Section 8 of the SPM.

A. Technical Matters are Excluded from the Scope of the Appeals Process

Many of Foundation's alleged "inactions or omissions" in the Complaint do not relate to any specific procedural action or inaction, but instead seek to address the merits of the technical content of the proposed standard. For example, among other similar technical-related objections, Foundation asserts that the standard development process failed to include risks posed by harmonic production in transformers and impacts to other grid equipment in the Benchmark GMD Event model;[9] failed to include magnetostriction and other vibrational hazards in its benchmark modeling;[10] and failed to validate the benchmark model against historical GIC data in the United States.[11] At various points, Foundation requests that NERC review technical papers that purportedly support its arguments for why the proposed standard is technically deficient.[12] The nature of Foundation's various objections is underscored by Foundation's requested relief, which is for NERC "to correct deficiencies that [Foundation has] cited or enumerated" in the proposed standard.[13]

NERC does not address the merits of the technical arguments presented by Foundation herein, because such consideration is not permitted under the limited appeal right provided by Section 8 of the SPM.

The SPM provides that certain procedures developed to govern the development of Reliability Standards will be followed. These procedures are designed to provide for open participation, balance, transparency, consideration of views and objections, and consensus building in the development of Reliability Standards, among other things.[14] As an additional procedural safeguard, Section 8 of the SPM provides a limited appeal right to an entity that asserts it has or will be harmed by a procedural defect (i.e. action or inaction) during the standard

9 Complaint at 1, 7.

10 Complaint at 2, 7.

11 Complaint at 2, 12.

12 *See, e.g.,* Complaint at 15.

13 Complaint at 17.

14 The "essential attributes" of NERC's standard development process are described in Section 1.4 of the SPM.

development process. This limited appeal right is designed to ensure that the standard development process was conducted in accordance with the procedures set forth in the SPM.

The SPM provides for a fair and open process in which stakeholder views and objections are welcomed and afforded prompt consideration. However, the SPM does not guarantee that every participant will be satisfied with the final outcome of the process. The SPM creates no right of appeal for entities wishing to advance additional debate regarding the merits of the technical content of a proposed standard. Indeed, Section 8.0 explicitly provides that the appeals process does not apply "to the technical content of the Reliability Standards action." Further, the appeals process does not permit, as an outcome, the revision, approval, disapproval, or adoption of a Reliability Standard, as those responsibilities remain with the ballot pool and Board of Trustees. As the appeals process does not apply to the technical content of a Reliability Standards action, NERC does not find basis for appeal in Foundation's Complaint regarding the alleged technical deficiencies in proposed Reliability Standard TPL-007-1.

B. Foundation's "Quality Control" Assertions Are Without Basis

In two instances, Foundation asserts that NERC Reliability Standards staff has failed to perform "essential 'quality control'" in the development of the proposed standard. For the reasons that set forth below, NERC finds no basis for either assertion.

As Foundation has cited no specific portion of the SPM as providing the procedural action or inaction of which it complains, NERC shall construe Foundation's arguments regarding failure of "quality control" as asserting an action or inaction under Section 4.6, which pertains to "quality reviews." Section 4.6 of the SPM addresses the responsibility of NERC staff to conduct quality reviews as follows:

> **4.6: Conduct Quality Review**
> The NERC Reliability Standards Staff shall coordinate a quality review of the Reliability Standard, implementation plan, and VRFs and VSLs in parallel with the development of the Reliability Standard and implementation plan, to assess whether the documents are within the scope of the associated [Standard Authorization Request], whether the Reliability Standard is clear and enforceable as written, and whether the Reliability Standard meets the criteria specified in NERC's Benchmarks for Excellent Standards and criteria for governmental approval of Reliability Standards. The drafting team shall consider the results of the quality review, decide upon appropriate changes, and recommend to the Standards Committee whether the documents are ready for formal posting and balloting.

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First, Foundation asserts that the Office of Standards and the Director of Standards failed to perform "essential 'quality control' to assure that the essential goals and mandates of Order No. 779 are met by the proposed NERC Standard TPL-007-1."[15]

NERC staff coordinated a quality review of the Reliability Standard as required by Section 4.6 of the SPM. This quality review included an assessment of whether the proposed standard is within the scope of the Standard Authorization Request (SAR). The SAR for Project 2013-03 Geomagnetic Disturbance Mitigation specified that the Reliability Standard(s) developed or revised through the project would respond to the directives in FERC Order No. 779. In addition, the standard drafting team maintained a Consideration of Directives document to describe how each directive in Order No. 779 was addressed in TPL-007-1 and the supporting material. Therefore, NERC finds no basis to support Foundation's assertion of failure of "quality control" with respect to the Order No. 779 directives.

Second, Foundation asserts that it was a failure of "essential 'quality control'" to allow "Standard Drafting Team use of a modeled GIC limit of 75 amps per phase for thermal assessment of transformers when the source for this 75 amp limit is an unapproved IEEE standard still in progress."[16]

As noted above, NERC staff coordinated a quality review of the proposed standard as required by Section 4.6. The quality review included an assessment of whether the proposed standard meets NERC's Benchmarks for Excellent Standards and the criteria for governmental approval.[17] Among other things, this assessment included a review to determine whether the proposed standard is based upon sound engineering and operating judgment, analysis, or experience, as determined by expert practitioners in the particular field. The standard drafting team that developed proposed Reliability Standard TPL-007-1 consists of engineers, planners, and operators that are at the forefront of the industry's GMD activities. Industry experts determined that the proposed standard is technically sound.[18] The 75 A per phase screening criterion is supported by a technical white paper with cited references that was prepared by members of the standard drafting team with a high level of technical expertise in power transformers. The white paper describes analysis and simulations of power transformer thermal models derived from available measurement data to support its conclusion that 75 A per phase is a conservative screening criterion. Also, and as discussed more fully below, Foundation's assertion that the

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[15] *See generally* Complaint at 2; for specific objections, see Complaint at 10, 15-16, and 17.

[16] Complaint at 2; *see also* Complaint at 16.

[17] NERC, Ten Benchmarks of an Excellent Reliability Standards, *available at* http://www.nerc.com/files/10_Benchmarks_of_Excellent_Reliability_Standards.pdf; *Rules Concerning Certification of the Electric Reliability Organization; and Procedures for the Establishment, Approval, and Enforcement of Electric Reliability Standards,* Order No. 672, FERC Stats. & Regs. ¶ 31,204, *order on reh'g,* Order No. 672-A, FERC Stats. & Regs. ¶ 31,212 (2006) ("Order No. 672).

[18] The formal ballot and comment periods also served as an additional procedural check regarding the technical soundness of the proposed Reliability Standard.

screening criterion is based on an unapproved Institute of Electrical and Electronics Engineers (IEEE) standard is incorrect. Therefore, NERC finds no basis to support Foundation's assertion of failure of "quality control" with respect to the 75 A screening criterion for transformer thermal impact assessments.

Furthermore, NERC finds that, to the extent that Foundation's "quality control" assertions are actually seeking to appeal the technical content of the Reliability Standard action, such matters are outside the scope of the appeals process.[19]

For the reasons cited above, NERC finds that Foundation has not demonstrated that it has or will experience any adverse impact as a result of a procedural action or inaction associated with the Reliability Standards process related to a purported failure of "quality control."

C. Foundation's Assertions Regarding Anticompetitive Effect are Without Basis

Foundation asserts that it was error to fail "to require public release of [geomagnetically-induced current (GIC)] monitor levels, or designated GIC warning threshold levels, so as to preclude market manipulation and potential antitrust violations resulting from NERC Reliability Standard-setting."[20] Foundation suggests that, by not requiring the sharing of GIC monitoring data with all market participants and the public, that the proposed standard may create an anticompetitive practice by favoring certain participants over others in the wholesale electricity markets.

NERC finds that Foundation has offered no support for its assertion that NERC's failure to require disclosure of GIC monitoring information in a Reliability Standard could have anticompetitive effects in the wholesale electricity markets. Further, NERC finds that Foundation has offered no explanation of how this purported failure represents a procedural action or inaction relating to one or more processes in the SPM that has or will have an adverse effect on Foundation.

Nevertheless, NERC responds as follows. NERC staff coordinated a quality review of the Reliability Standard as required by Section 4.6 of the SPM. This quality review included an assessment of whether the proposed standard meets the criteria for governmental approval. NERC considered competition issues and found that the proposed standard causes no undue negative effect on competition or restriction of the grid beyond any restriction necessary for reliability in accordance with Order No. 672.[21] Proposed Reliability Standard TPL-007-1 requires the same performance by each of the applicable entities. It does not give any market participant

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19 *See* Section III.A, above.

20 Complaint at 2 and 10-12.

21 Order No. 672 at P 332. Similarly, Section 2.3 of the SPM provides for consideration of certain market interface principles "to ensure that Reliability Standards are written such that they achieve their reliability objective without causing undue restrictions or undue impacts on competitive electricity markets."

an unfair competitive advantage, nor does it preclude market solutions to achieving compliance. The proposed standard neither prescribes nor prohibits the use of GIC monitoring. In other words, participation in a collaborative GIC monitoring network such as the Electric Power Research Institute's SUNBURST network is not necessary for compliance with the standard.

For the reasons cited above, NERC finds that Foundation has not demonstrated that it has or will experience any adverse impact as a result of a procedural action or inaction associated with the Reliability Standards process related to a purported failure to require the public release of GIC monitoring data.

D. Foundation's Comments Were Considered and Responded to throughout the Standard Development Process

Foundation asserts that NERC has failed to fully address its prior comments regarding various issues noted in its Complaint during the standard development process.[22]

Foundation does not cite a specific provision of the SPM to support its assertions. However, Sections 4.12 and 4.13 of the SPM provide that the standard drafting team must respond, in writing, to every stakeholder written comment submitted in response to a ballot prior to a Final Ballot, unless the standard drafting team has identified that significant revisions to the Reliability Standard are necessary and the revised standard will be posted for another public comment period and ballot. Pursuant to Section 4.5, there is no requirement for the standard drafting team to respond in writing to comments submitted during informal comment periods.

Although Foundation only cites one specific comment to which it feels the standard drafting team has not properly responded,[23] NERC has reviewed the complete record of development for proposed Reliability Standard TPL-007-1. NERC finds that the standard drafting team made a good faith effort to resolve all objections to the proposed standard and responded in writing to the comments of Foundation where required by the SPM. Therefore, NERC finds that Foundation's assertion that the standard drafting team failed to "fully address" its prior comments about the issues identified in the appeal is without basis.

For these reasons, and as discussed more fully below, NERC finds that Foundation has not demonstrated that it has or will experience any adverse impact as a result of a procedural action or inaction associated with a failure to respond to its comments during the standard development process.

A discussion of the submitted comments relating to the issues identified in the Complaint, as well as the standard drafting team's response to those comments, is provided below.

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22 Complaint at 2.

23 *See* Complaint at 16.

1. *Comment: Failure to include in the NERC GMD Whitepapers Benchmarks for Harmonic Production Arising from Solar GMD Events.*[24]

SmartSenseCom, Inc. submitted comments during the formal comment period from October 28, 2014 through November 21, 2014, recommending that TPL-007 be modified to account for the impact of System harmonics and VAR consumption.

The standard drafting team responded to SmartSenseCom, Inc. as follows:

> 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".[25]

The Complaint also refers to an Emprimus report of December 2014. A citation to the draft version of this report was provided by Foundation in its comments submitted in the formal comment period ending November 21, 2014, with the comment "[the draft report] includes an assessment of avoided costs, hence financial benefits, of installing neutral ground blocking devices.... 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."[26]

The standard drafting team responded to this cost-related comment as discussed below.

2. *Comment: Failure to Provide Methods to Estimate VAR (Reactive Power) Consumption Arising from Solar GMD Events.*[27]

NERC has reviewed the complete record of development and finds that Foundation did not submit comments regarding this specific issue during the standard development process.

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24 Complaint at 7.

25 Consideration of Comments Posted December 5, 2014 at 28-38 (SmartSenseCom, Inc. comments) and 38-39 (standard drafting team response), *available at* http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Comment%20Report%20_2013-03_GMD_12052014.pdf.

26 Consideration of Comments Posted December 5, 2014 at 71.

27 Complaint at 7.

3. ***Comment: Failure to Include Magnetostriction and Other Vibrational Risks to Operability of Transformers, Stators, Turbines, and Other Grid Equipment.***[28]

Foundation submitted a comment regarding vibration effects during the 45-day formal comment period from June 13, 2014 through July 30, 2014, stating as follows: "There have been many reports of vibration effects on transformers and vibration could be causing failures even without heating. The effects of shock or vibration do not require long time constants; near immediate damage might occur after a "GIC shock."[29]

As a result of comments received during this formal comment period, the standard drafting team revised the standard, implementation plan, and reference material to incorporate a number of stakeholder recommendations. Although Section 4.12 of the SPM states that the drafting team is not required to respond in writing to comments from the previous posting when it has identified the need to make significant changes to the standard, the standard drafting team provided summary responses to the comments received in order to facilitate stakeholder understanding.

Thus, the standard drafting team responded as follows: "A commenter stated that the standard should also include assessments for shock or vibration impacts. Vibration is not considered in the standard because available information is sparse, mostly anecdotal and not likely to have a wide area impact on the network."[30]

Foundation again provided comments regarding vibration effects during the 45-day formal comment period from August 27, 2014 through October 10, 2014. The standard drafting team considered the comments and responded as follows: "The standard addresses the assessment parameters of order 779. Vibration impacts are not included in the standard. Available information is sparse and mostly anecdotal. Available information does not suggest vibration would likely have a wide area impact." The standard drafting team also noted that it had previously responded to comments on vibration, and that its goal was to provide serious consideration to all comments submitted during the standards development process.[31]

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28 Complaint at 7-10.

29 Consideration of Comments Posted August 27, 2014 at 58*, available at* http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Response_to_Comments_2013-03_GMD_082714_posted_version.pdf.

30 Consideration of Comments Posted August 27, 2014 at 55.

31 Consideration of Comments Posted October 28, 2014 at 25-31 (Foundation comments) and 31-32 (standard drafting team response), *available at* http://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/Consideration_of_Comments_GMD_TPL-007-1_10292014.pdf.

4. ***Comment: Failure to Establish Reliability Standards for Mandatory Installation and Operation of Geomagnetic[ally] Induced Current (GIC) Monitors.***[32]

The Complaint assigns error for failing to consider deployment of GIC monitors as a part of the mitigation process for GMD events from a "quality control" perspective. The "quality control" issue is addressed above.

With respect to consideration of comments, NERC finds that the standard drafting team responded to Foundation's written comments on the specific issue of using GIC monitors for mitigation submitted during the standard development process.

In written comments submitted during the formal comment period from October 28, 2014 through November 21, 2014, Foundation "express[ed] concern that the combination of NERC Standards in Phase 1 [approved standard EOP-010-1] and Phase 2 [proposed standard TPL-007-1], providing no mandatory GIC monitor installations and data sharing with Regional Coordinators, and with state and federal operations center, effectively precludes time-urgent mitigation during severe solar storms...."[33]

The standard drafting team considered the comment and responded as follows:

> 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 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 [Task Force] GMD Planning Guide and the 2012 GMD Report.[34]

[32] Complaint at 10.

[33] Consideration of Comments Posted December 5, 2014 at 72.

[34] Consideration of Comments Posted December 5, 2014 at 73-74.

5. *Comment: Failure to Require Public Release of GIC Monitor Levels, or Designated GIC Warning Threshold Levels, So As to Preclude Market Manipulation and Potential Antitrust Violations Resulting from NERC Reliability Standard-Setting.* [35]

NERC has addressed anticompetitive effects, as discussed above.

NERC has reviewed the complete record of development and finds that Foundation did not submit comments regarding this specific issue during the standard development process.

6. *Comment: Failure to Validate the NERC Benchmark Model for Geomagnetic Disturbance Assessments against Actual Historical GIC Data within the U.S.* [36]

NERC has reviewed the complete record of development and finds that the standard drafting team has responded to all comments submitted by or referenced by Foundation during formal comment periods regarding the scientific validity of the Benchmark Geomagnetic Disturbance (GMD) Event.

Foundation November 21, 2014 Comments

In its comments submitted during the formal comment period from October 28, 2014 through November 21, 2014, Foundation commented that the Benchmark GMD Event "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.'"[37]

The standard drafting team considered these comments, and citing published research supporting the use of this observation data, responded as follows: "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."[38]

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[35] Complaint at 10-12.

[36] Complaint at 12-16.

[37] Consideration of Comments Posted December 5, 2014 at 21.

[38] Consideration of Comments Posted December 5, 2014 at 27-28.

Foundation July 2014 Comments

Foundation submitted comments during the 45-day formal comment period from June 13, 2014 through July 30, 2014 objecting to the use of the Northern Europe magnetometer information. As noted above, the standard drafting team provided summary responses to the comments received during this comment period in order to facilitate stakeholder understanding, even though Section 4.12 of the SPM provides that written responses were not required. The standard drafting team stated as follows:

> A data set of high resolution modern magnetometer observations that has been used extensively in space weather research was used in the benchmark analysis. The SDT maintains that spatial averaging is supported by the magnetometer data and justified for determining the wide-area impacts on the power system. The North American magnetometer network is too sparse to be used as the basis of spatial averaging. Nevertheless, the statistical storm peaks recorded in North America are consistent with those recorded in Europe.[39]

Kappenman & Radasky July 30, 2014 White Paper

Also during the formal comment period ending July 30, 2014, Kappenman submitted a white paper by Kappenman and Radasky titled "Examination of NERC GMD Standards and Validation of Ground Models and Geoelectric Fields Proposed in this NERC GMD Standard." The white paper challenged the standard drafting team's technical approach to determining the benchmark GMD event and compared calculations of geoelectric fields from GIC data using U.S. Geological Survey ground models and proprietary ground models.[40]

The standard drafting team considered the comments and responded as follows:

> **A commenter stated that the plane wave method used to calculate geoelectric fields from geomagnetic field data produces incorrect results and it systematically produces low geoelectric field values.** The plane wave method that was utilized in the generation of the NERC GMD benchmark event has been applied extensively in GIC studies over the past several decades. 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).

[39] Consideration of Comments Posted August 27, 2014 at 27.

[40] Consideration of Comments Posted August 27, 2014 (appended, immediately following p. 138).

> Further, although the plane wave method assumes a one-dimensional (1D) ground conductivity structure, the method has been shown to be applicable even in highly non-1D situations if an effective 1D ground conductivity is used (Thomson et al., 2005; Ngwira et al., 2008; Pulkkinen et al. 2010) . . . . Comparisons with measured data are valuable tools to validate and improve earth models. There are efforts in the industry to validate and adjust average earth models on the basis of GIC and magnetometer measurements. This type of validation has to be done carefully in order to avoid numerical issues caused by using data with different sampling rates and thus mask differences due to inaccuracies in the earth model to be validated. The example presented by the commenter used downsampled 1 minute geomagnetic field data from the OTT geomagnetic observatory on May 4 1998 to calculate the geoelectric field from the "NERC" model. When the same calculations are carried out using 5 second geomagnetic field data from the same observatory, calculated geoelectric field peak maxima increase by a factor of 1.5 to 1.9. The use of 1 minute magnetometer data will always result in lower calculated peak maxima.[41]

Kappenman & Birnbach November 2014 Comments

During the formal comment period from October 28, 2014 through November 21, 2014, Kappenman and Birnbach submitted comments to supplement the white paper submitted during the formal comment period ending July 30, 2014.[42]

The standard drafting team considered these comments and responded as follows:

> 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

[41] Consideration of Comments Posted August 27, 2014 at 26-27.

[42] Consideration of Comments Posted December 5, 2014 (appended).

> 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.
>
> 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.[43]

Emprimus November 20, 2014 Comments

Emprimus submitted comments during the formal comment period ending November 21, 2014, stating: "The NERC Benchmark formula modified further for latitude and soil does not give results that are anywhere near actual data." The comments included a calculation of geoelectric fields in a low latitude area based on GIC information published in a journal article.[44]

The standard drafting team considered Emprimus's comments and responded as follows:

> 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.[45]

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[43] Consideration of Comments Posted December 5, 2014 at 87.

[44] Consideration of Comments Posted December 5, 2014 (appended, immediately following p. 89).

[45] Consideration of Comments Posted December 5, 2014 at 88.

Electric Infrastructure Security (EIS) Council October 10, 2014 Comments

EIS Council submitted comments during the 45-day formal comment period from August 27, 2014 through October 10, 2014 that described aspects of the proposed benchmark GMD event that it believed was technically inadequate, including the mathematical techniques, validation, use of the 1989 GMD event, and geomagnetic latitude scaling.[46]

The standard drafting team considered these comments and responded as follows:

> 1. The proposed benchmark continues the work of the GMD [Task Force] and is responsive to FERC Order No. 779 which directs protection against instability, uncontrolled separation, or cascading failures as a result of a benchmark GMD event. For this application, GIC flows should not be based upon statistics derived from single localized observations as advocated by the commenter.
>
> 2. There is no direct evidence about the geoelectric field amplitudes for the 1921 Railroad Storm. Absence of recorded data precludes rigorous comparison. The frequency content of the March 1989 storm has been shown in the white paper to a conservative selection from available data.
>
> 3. The analogy to bridge design is not valid for considering wide area effects directed by Order No. 779.
>
> 4. The March 1989 event provides one parameter of the benchmark GMD event. The commenter is incorrect in referring to this event as the benchmark. The March 1989 event provides a conservative waveshape for transformer thermal impact assessment. The magnitude of the benchmark (used in power flow analysis and transformer thermal impact assessment) is a 100-year event determined through statistical analysis of magnetometer data.[47]

In addition, the standard drafting team previously explained the technical basis for the geomagnetic latitude scaling as follows:

> **Geomagnetic latitude scaling validity. Commenters questioned the technical basis for alpha scaling factors.** As indicated in the Benchmark GMD Event white paper, the alpha scaling factors are based on global geomagnetic field observations of 12 major or extreme geomagnetic storms since the late 1980s (Thomson et al.,

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[46] Consideration of Comments Posted October 28, 2014 (appended).

[47] Consideration of Comments Posted October 28, 2014 at 104.

> 2011; Pulkkinen et al., 2012; Ngwira et al., 2013). For all observed storm events, the maximum expansion of the auroral region was identified and the corresponding time derivatives of the ground magnetic field (dB/dt) or geoelectric field magnitudes were computed. The approximate factor of 10 fall of the dB/dt and associated geoelectric field magnitudes between geomagnetic latitudes from 60 degrees to 40 degrees represent the general trend that was observed for all studied storm events at the time of the maximum expansion of the auroral region. In summary, the selected geomagnetic latitude scaling is based on global geomagnetic field observations of major or extreme storm events and represents approximate field scaling at the time of the maximum expansion of the auroral region.[48]

Additional Issues Raised in the First Instance on Appeal

Foundation suggests that the standard drafting team rejected the use of interpolation to estimate geoelectric field strength in North America and references a 2013 paper by Wei, Homeier, and Gannon.[49] Comments regarding this specific issue were not submitted during the standard development process for the standard drafting team to consider.

Foundation also cites several times to an EIS Council filing to the State of Maine in October 2014.[50] NERC has reviewed the complete record of development and finds that this filing was not submitted to the standard drafting team for consideration in the standards development process. However, the standard drafting team responded to the comments submitted by EIS Council in October 2014, as discussed above.

7. *Comment: Failure in Quality Control and Failure to Consider Technical Objections in Our Comments to a Modeled GIC Limit of 75 Amps per Phase for Exemption of Transformers from Thermal Impact Assessment.*[51]

The Complaint assigns error to NERC for failing to consider technical objections to a modeled GIC limit of 75 Amps per phase from a "quality control" perspective. The "quality control" issue is addressed above.

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[48] Consideration of Comments Posted August 27, 2014 at 26.

[49] Complaint at 15.

[50] *See, e.g.*, Complaint at 14.

[51] Complaint at 16.

Additionally, Foundation asserts that the standard drafting team "did not appropriately respond" to its comments submitted November 21, 2014 regarding the 75 A screening criterion, as cited on page 16 of the Complaint.

NERC has reviewed the complete record of development and finds that the standard drafting team responded to Foundation's written comments. Specifically, the standard drafting team responded to Foundation as follows:

> 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 [subject matter experts]. The justification is documented in the thermal screening criterion white paper.[52]

Further, Foundation is incorrect when it states that the standard drafting team did not present technical evidence that a 75 A per phase screening criterion is supported, other than to reference a standard-setting at IEEE that is still in progress.[53] The 75 A per phase screening criterion is based on simulation, analysis, and references cited in the Screening Criterion for Transformer Thermal Impact Assessment white paper – as cited in the standard drafting team's response.

8. *Comment: Failure to Perform Cost-Benefit Analysis of Grid Protection Options.*[54]

The Complaint assigns error to NERC for failing to meet the cost-benefit mandate of Order No. 779. Issues relating to Order No. 779 are addressed above.

Furthermore, NERC finds that the standard drafting team responded to Foundation's written comments regarding this issue submitted during the standard development process.

In its comments submitted during the formal comment period from October 28, 2014 through November 21, 2014, Foundation stated, "[t]o date, no element of the standard performs the cost-benefit mandate of FERC Order. No. 779." Foundation also referred the standard drafting team to a filing in a Maine Public Utilities Commission docket,[55] with the comment: "Cost-benefit

[52] Consideration of Comments Posted December 5, 2014 at 28.

[53] Complaint at 17.

[54] Complaint at 16-17.

[55] Specifically, Foundation referred the standard drafting team to Item 31 filed in Docket 2013-00415, consisting of three documents: a draft document titled "2014 Maine GMD/EMP Impacts Assessment" prepared by Justin Michlig – Central Maine Power Co.; a document titled "Effects of GMD & EMP on the State of Maine Power Grid (Nov. 12, 2014)," prepared by Emprimus in partnership with Central Maine Power and Emera Maine; and

analysis could and should be applied on a regional basis, in the NERC model and with criteria for application by NERC registered entities."[56]

The standard drafting team considered this comment and responded as follows:

> 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 [Federal Power Act] requires a particular cost-benefit showing.[57]

IV. Conclusion

For the reasons stated above, NERC finds that Foundation has not demonstrated that it has or will experience any adverse impact as a result of a procedural action or inaction associated with the Reliability Standards process related to the development of proposed Reliability Standard TPL-007-1, as required by Section 8 of the SPM.

This response concludes Foundation's Level 1 Appeal. NERC thanks Foundation for its participation in the standard development process.

Dated: February 18, 2015

a cover letter dated November 21, 2014 from Central Maine Power to the Maine Public Utilities Commission, indicating that it was transmitting a rough draft of the report. In the same comments, Foundation also referred the standard drafting team to Item 30 in that docket, consisting of a letter dated November 11, 2014 from Foundation to Central Maine Power Company.

[56] Consideration of Comments Posted December 5, 2014 at 71-72.

[57] Consideration of Comments Posted December 5, 2014 at 73.

ATTACHMENT 1

In support of its Level 1 Appeal, Foundation submitted the following documents:

- an email from William R. Harris, dated January 4, 2015 at 10:55 p.m., subject line *Timely-filed Phase 1 Appeal of NERC Proposed Standard TPL-007-1 (Phase 2) is attached*
    - an attachment, *Resilient Soc NERC Appeal 01042015_Final.docx*
- an email from William R. Harris, dated January 4, 2015 at 11:20 p.m., subject line *Attached are 2d Copy of the Resilient Foundation Phase 1 Appeal and Central Maine Power Rpt & Kappenman-Radasky Rpt*
    - an attachment, *Resilient Soc NERC Appeal 01042015_Final.docx*
    - an attachment, *Central Maine Power 2014 Maine GMD & EMP Impacts Assessment 12232014.pdf*
    - an attachment, *Kappenman & Radasky White Paper July 2014.pdf*
- an email from William R. Harris, dated January 4, 2015 at 11:32 p.m., subject line *Additional Attachments to be included in Record of Phase 1 Appeal by Resilient Societies*
    - an attachment, *Comments of Kappenman Birnbach 10102014Corrected.docx*
    - an attachment, *Resilient Societies Additional Facts081814.pdf*
    - an attachment, *EISCouncilCommentsforMPUCDocket2013-004510413.pdf*
- an email from William R. Harris, dated January 4, 2015 at 11:36 p.m., subject line *Additional Appendices to be included in the Record of Resilient Societies' Phase 1 Appeal*
    - an attachment, *Resilient Societies Group Comments on GMD Standard TPL-007-1 Final Additional Signatory.pdf*
    - an attachment, *Supplemental comments of the Foundation for Resilient Societies.docx*
- an email from William R. Harris, dated January 5, 2015 at 6:43 p.m., subject line *Filing of Corrected Copy of Resilient Societies' Stage 1 Appeal & Corrected Emprimus Report Jan 5, 2015*
    - an attachment, *Resilient Soc NERC Appeal 01042015_Corrected01052015.docx*
    - an attachment, *Emprimus Report to Maine PUC Rev01052015.pdf*

Foundation for Resilient Societies
52 Technology Way
Nashua NH 03060

February 26, 2015

Ms. Valerie Agnew
Director of Standards
North American Electric Reliability Corporation
3353 Peachtree Road, N.E.
Atlanta, Georgia 30326

Dear Ms. Agnew:

This is a follow-up to our telephone conversation of February 25, 2015.

I write to confirm that the Foundation for Resilient Societies, Inc. (hereafter "Resilient Societies"), upon review of the Letter and attachments that you transmitted on February 18, 2015, responding to our Stage 1 Appeal of NERC-proposed Standard TPL-007-1 - "Transmission System Planned Performance for Geomagnetic Disturbance Events" - intends to proceed with a Stage 2 Appeal.

We will proceed in accordance with the NERC Standards Processes Manual as revised June 26, 2013. We await information that you will provide, identifying the time and place for our presentation of a Stage 2 Appeal to a subcommittee of the Board of Trustees that you or other NERC officials will designate. Other organizations may also wish to present their concerns about the standard development process for proposed Standard TPL-007-1.

We appreciate the comments and explanations that you provided. However, both because of the importance of this proposed reliability standard and its inadequacies, and the procedural and quality control issues raised by its process of development, Resilient Societies seeks the opportunity to submit documentary materials and to make a presentation before a designated subcommittee of the NERC Board of Trustees.

Respectfully submitted by:

Wm. R. Harris

William R. (Bill) Harris
Secretary, and

Thomas S. Popik

Thomas S. Popik
Chairman, for the
FOUNDATION FOR RESILIENT SOCIETIES, INC.
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Copies transmitted electronically on February 26, 2015
to:
Ms. Valerie Agnew, Director of Standards, NERC valerie.agnew@nerc.net
Mr. Mark G. Lauby, Senior Vice President &
Chief Reliability Officer, NERC mark.lauby@nerc.net

Copy transmitted by U.S. Mail to:

Ms. Valerie Agnew
Director of Standards
North American Electric Reliability Corporation
3353 Peachtree Road, N.E. STE 600
Atlanta, GA 30326-1436

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Valerie Agnew
Senior Director of Standards

March 31, 2015

Mr. William R. (Bill) Harris
Mr. Thomas S. Popik
Foundation for Resilient Societies, Inc.
52 Technology Way
Nashua, New Hampshire 03060
via First Class Mail
via Email to wm.r.harris@gmail.com and
thomasp@resilientsocieties.org

Re: Level 2 Appeal, Proposed Reliability Standard TPL-007-1
(Project 2013-03 Geomagnetic Disturbance Mitigation)

Dear Messrs. Harris and Popik:

NERC is in receipt of the February 26, 2015 letter from the Foundation for Resilient Societies, Inc. (the "Foundation") initiating a Level 2 Appeal pursuant to Section 8.2 of the NERC Standard Processes Manual regarding the development of proposed Reliability Standard TPL-007-1.

By written consent dated March 31, 2015, the NERC Board of Trustees appointed the following members of the NERC Board of Trustees to serve as the Level 2 Appeals Panel for the Foundation's Level 2 Appeal:

Ken Peterson, Chair
Fred Gorbet
Paul Barber
Dave Goulding
Doug Jaeger

In accordance with Section 8.2 of the NERC Standard Processes Manual, NERC Reliability Standards staff shall post the Foundation's complaint and other relevant materials and provide at least 30 days' notice of the meeting of the Level 2 Appeals Panel.

The Foundation will be notified when the time and place for the meeting of the Level 2 Appeals Panel have been set.

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

Thank you for your participation in the standard development process.

Sincerely,

Valerie Agnew
Senior Director of Standards

cc: Mark G. Lauby, Senior Vice President and Chief Reliability Officer, NERC