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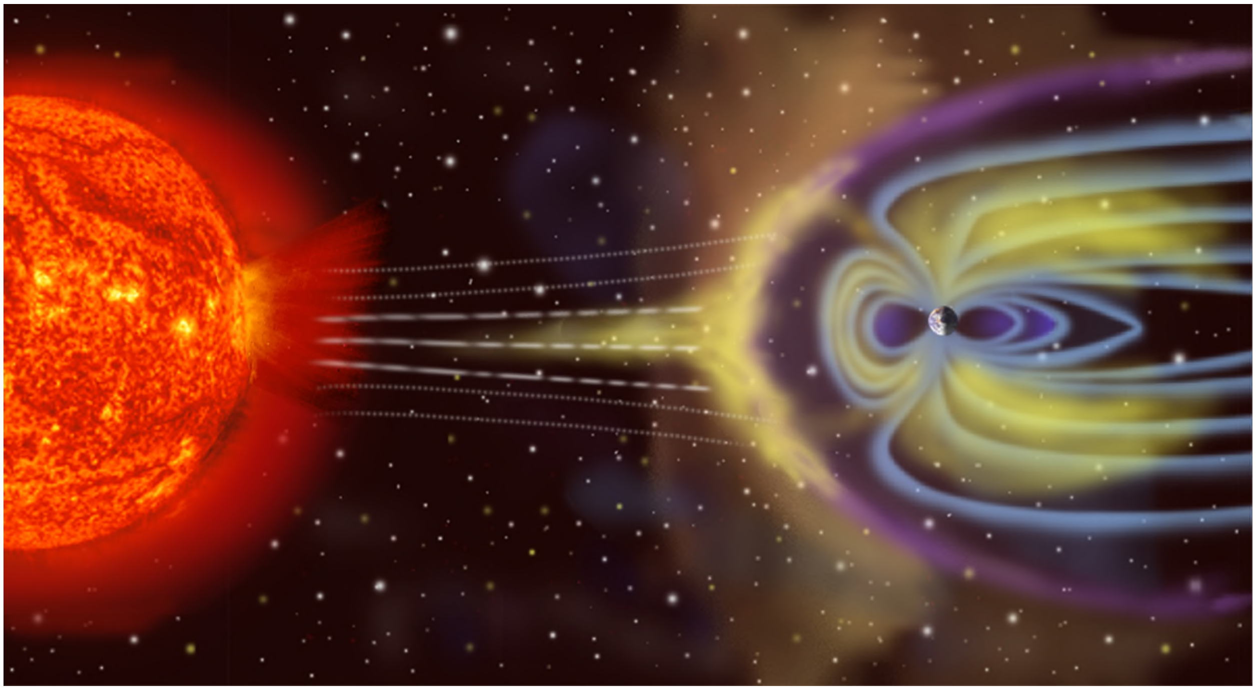
MAINE

2014 Maine GMD/EMP Impacts Assessment

A Report Developed for the Maine Public Utilities Commission



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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 (2nd, 3rd, 4th…). 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

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[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.

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[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.

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[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.

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[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.

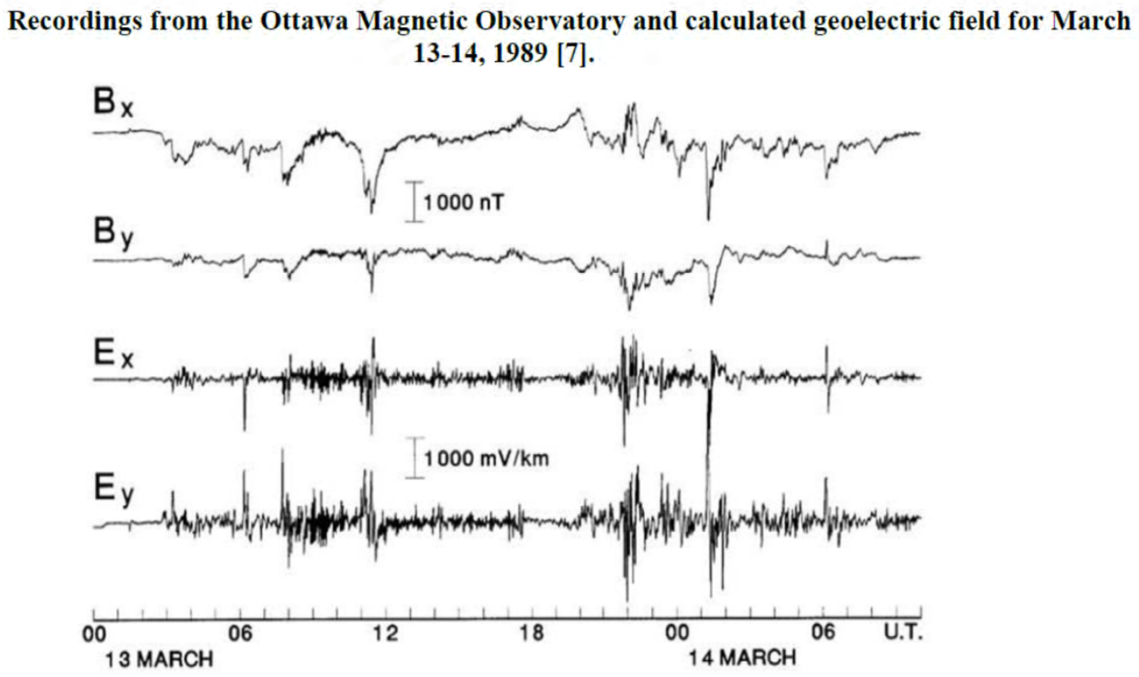
Recordings from the Ottawa Magnetic Observatory and calculated geoelectric field for March 13-14, 1989 [7].

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

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[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.

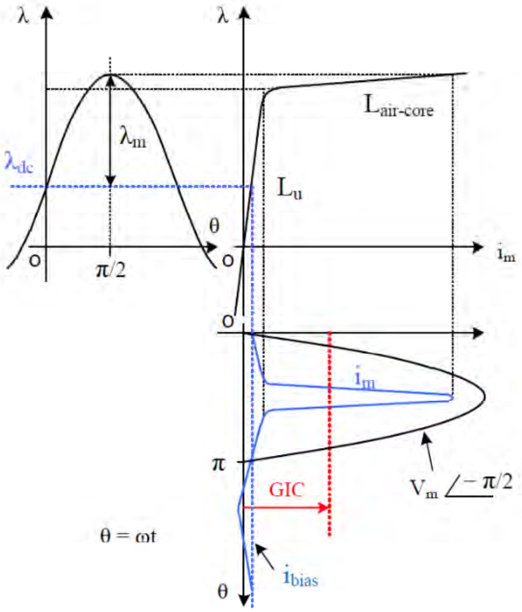

Figure 2: DC offset to Transformer sinusoidal operation (Source: NERC State2 GMD webinar)

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,

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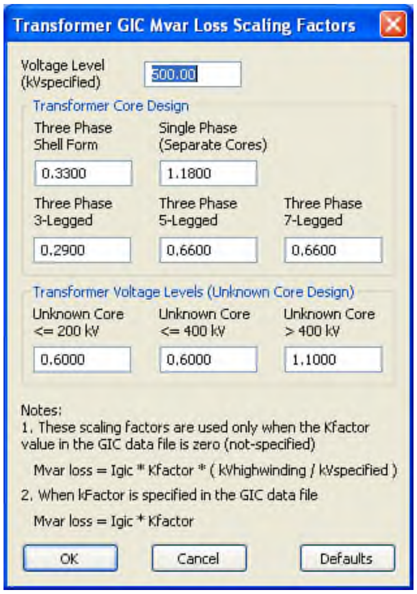
[12] "Geomagnetic Disturbance Planning Guide." Internet: http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GMD%20Planning%20Guide_approved.pdf, December 2013

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].



Voltage Level (kVspecified): 500.00

Transformer Core Design

Three Phase Shell Form	Single Phase (Separate Cores)	
0.3300	1.1800	
Three Phase 3-Legged	**Three Phase 5-Legged**	**Three Phase 7-Legged**
0.2900	0.6600	0.6600

Transformer Voltage Levels (Unknown Core Design)

Unknown Core <= 200 kV	Unknown Core <= 400 kV	Unknown Core > 400 kV
0.6000	0.6000	1.1000

Notes:
1. These scaling factors are used only when the Kfactor value in the GIC data file is zero (not-specified)

Mvar loss = Igic * Kfactor * (kVhighwinding / kVspecified)

2. When kFactor is specified in the GIC data file

Mvar loss = Igic * Kfactor

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.

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[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.

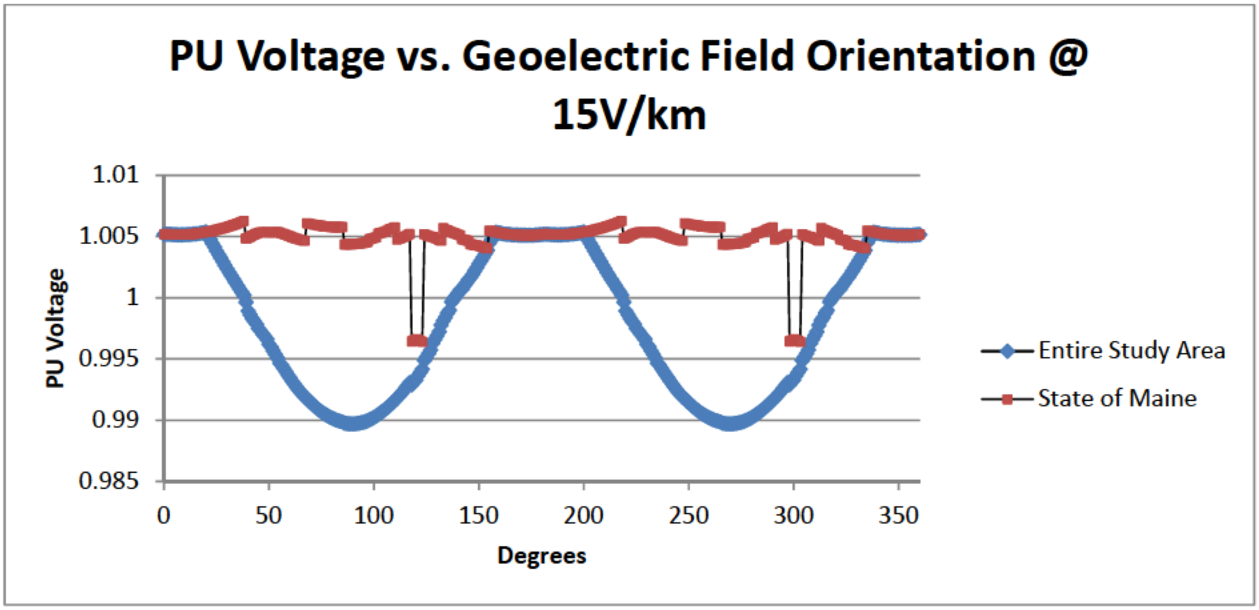

Figure 4: Transmission voltage response to geoelectric field rotation linear representation

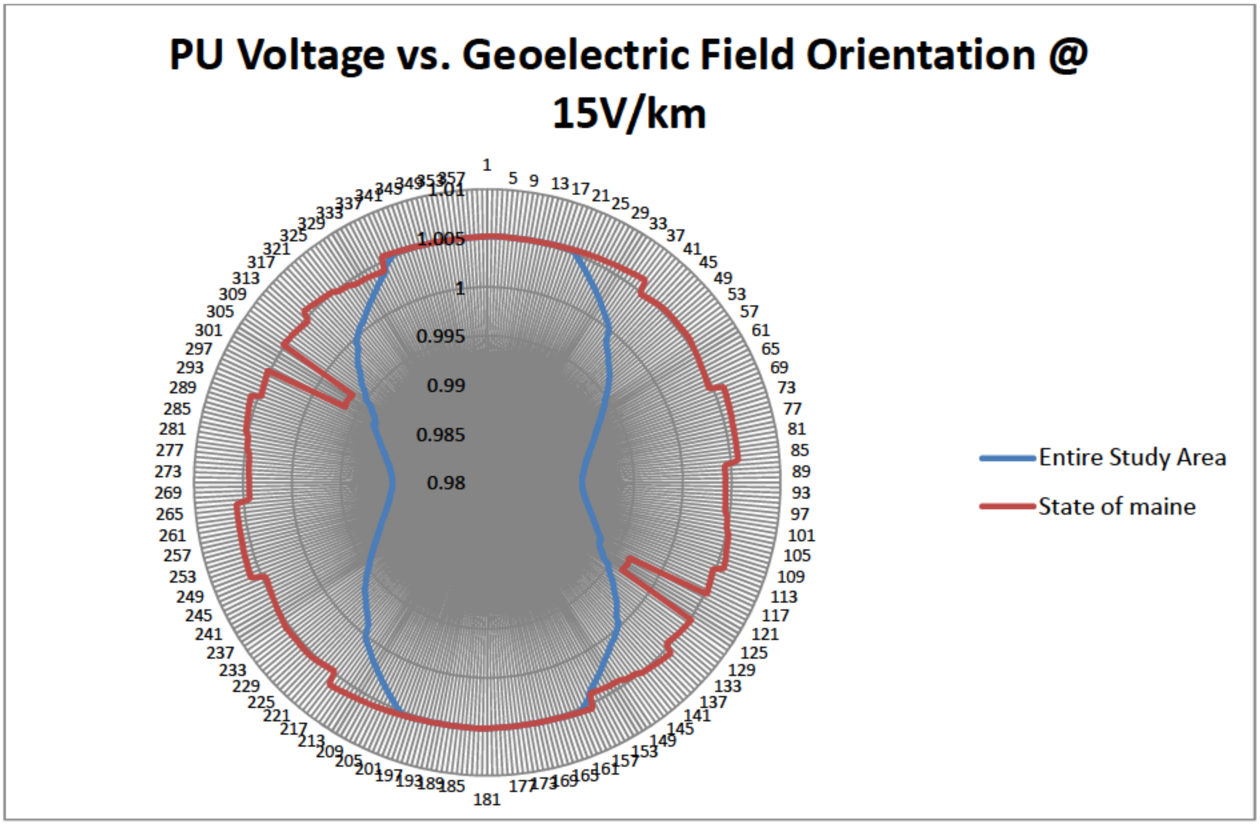

Figure 5: Transmission voltage response to geoelectric field rotation polar representation

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.

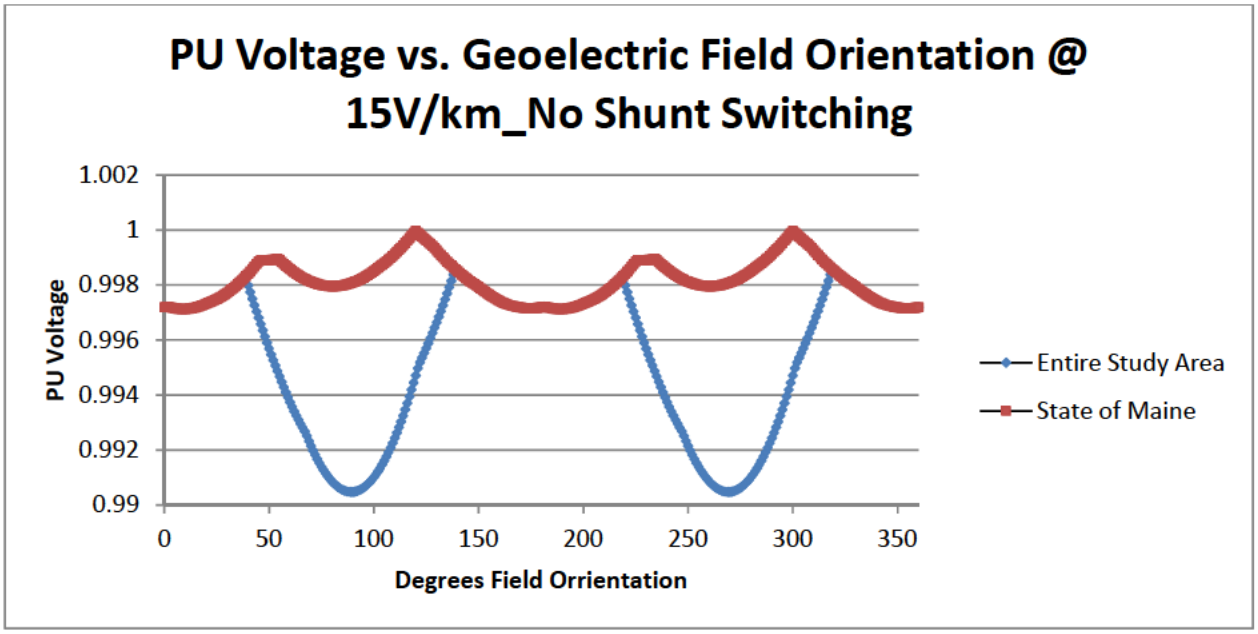

Figure 6: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching linear representation

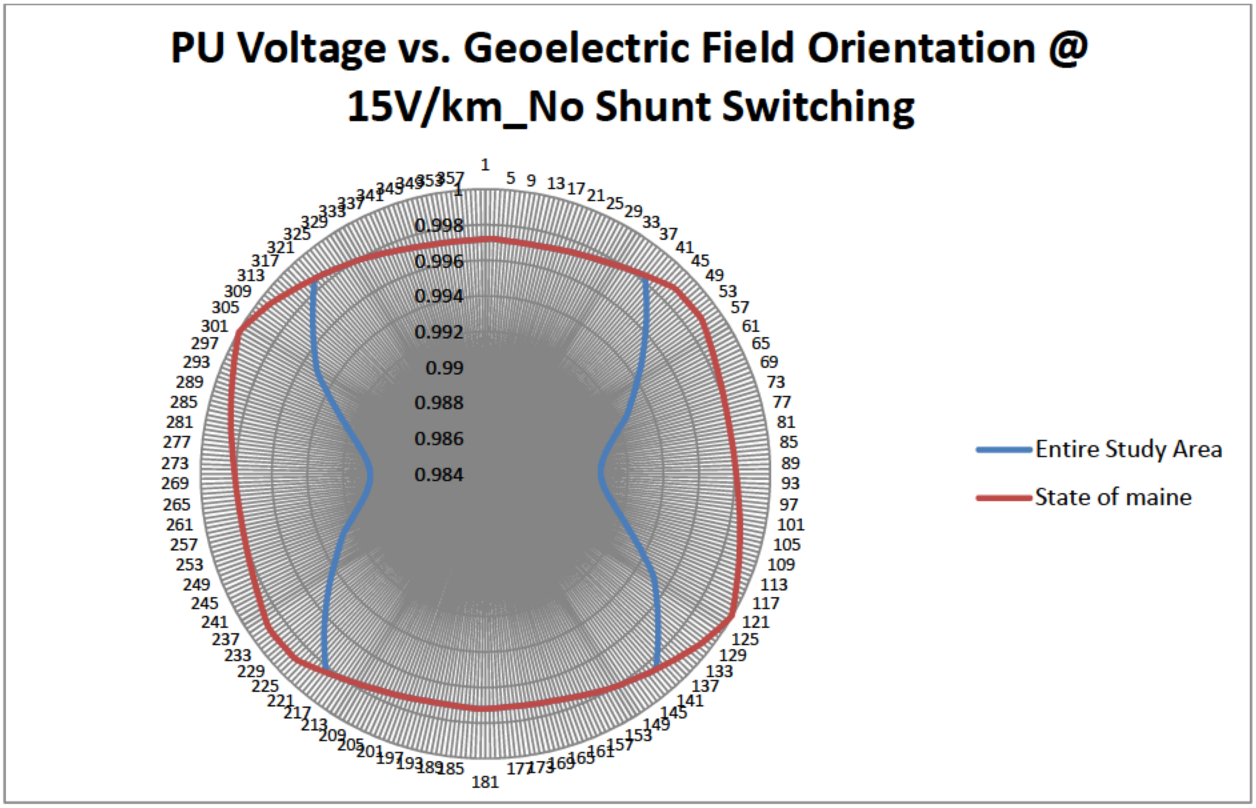

Figure 7: Transmission voltage response to geoelectric field rotation without reactive device or LTC switching polar representation

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.

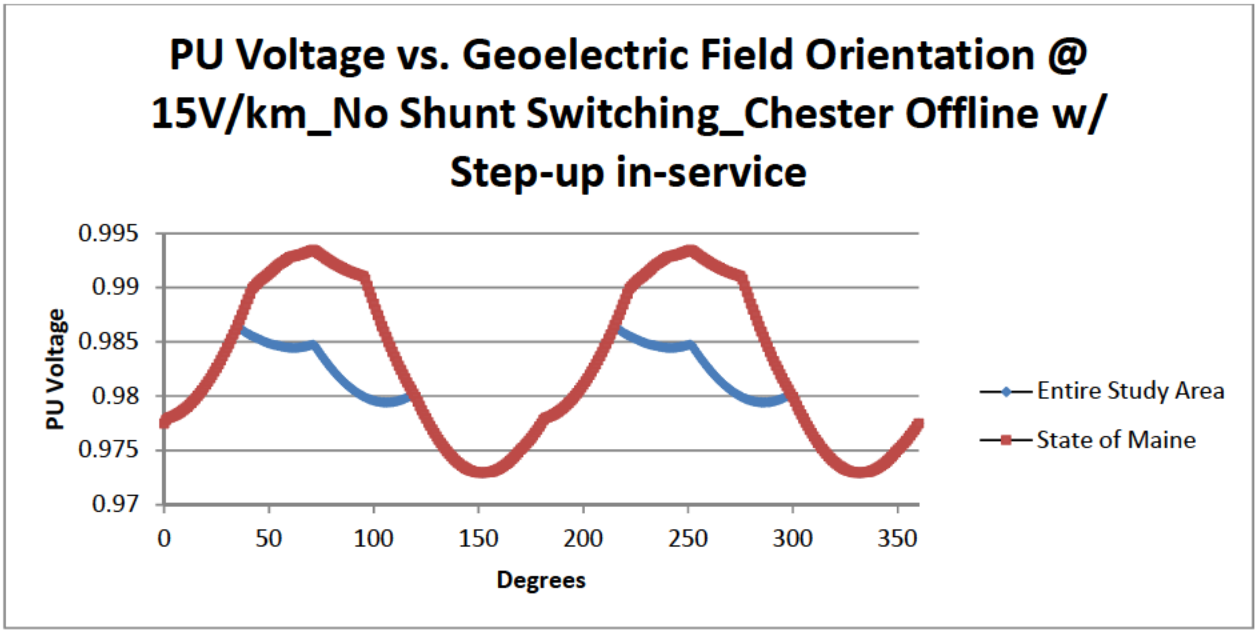

Figure 8: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching and Chester offline (step-up energized) linear representation

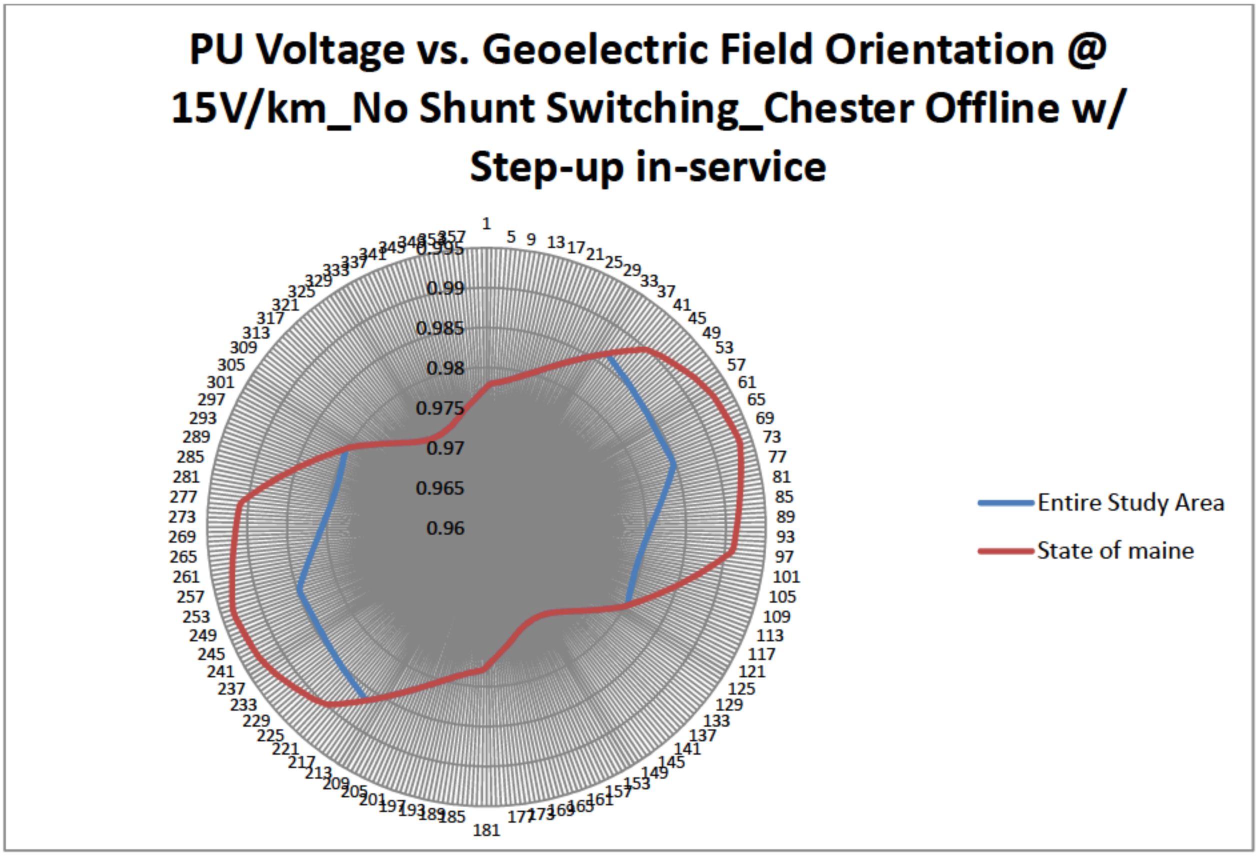

Figure 9: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching and Chester offline (step-up energized) polar representation

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.

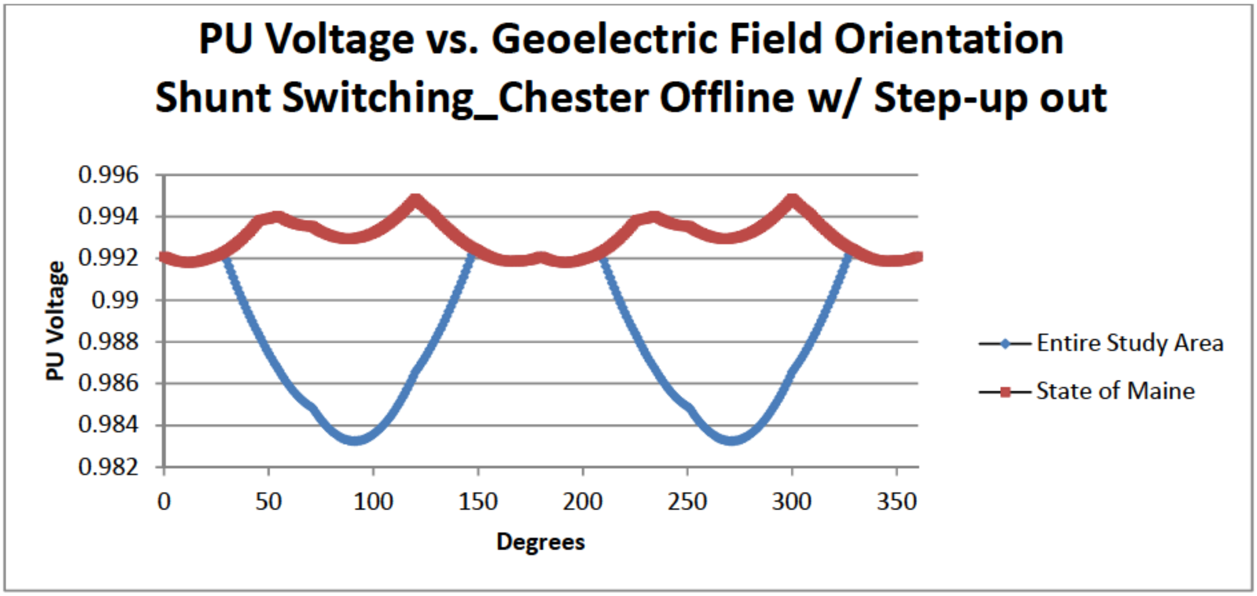

Figure 10: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching and Chester offline (step-up de-energized) linear representation

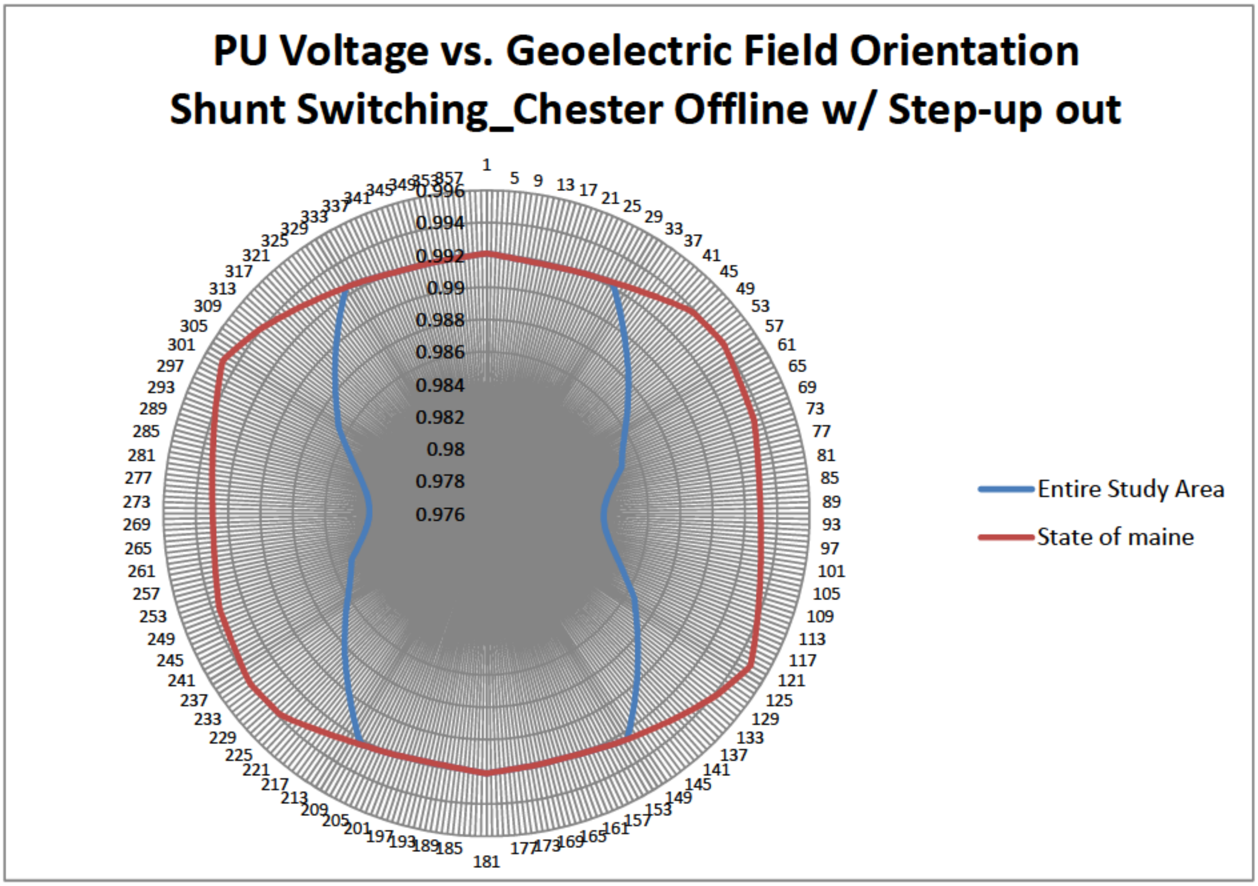

Figure 11: Transmission voltage response to geoelectric field rotation W/0 reactive device or LTC switching and Chester offline (step-up de-energized) polar representation

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	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
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

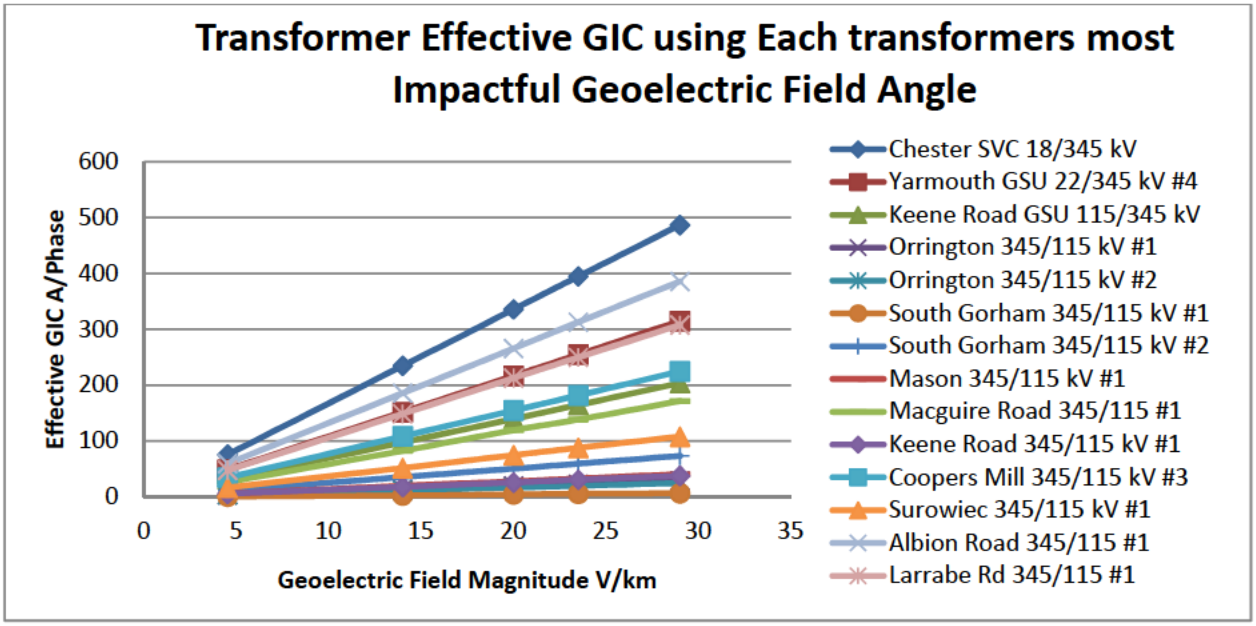

Figure 12: Effective GIC in transformers vs. geoelectric field

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[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.

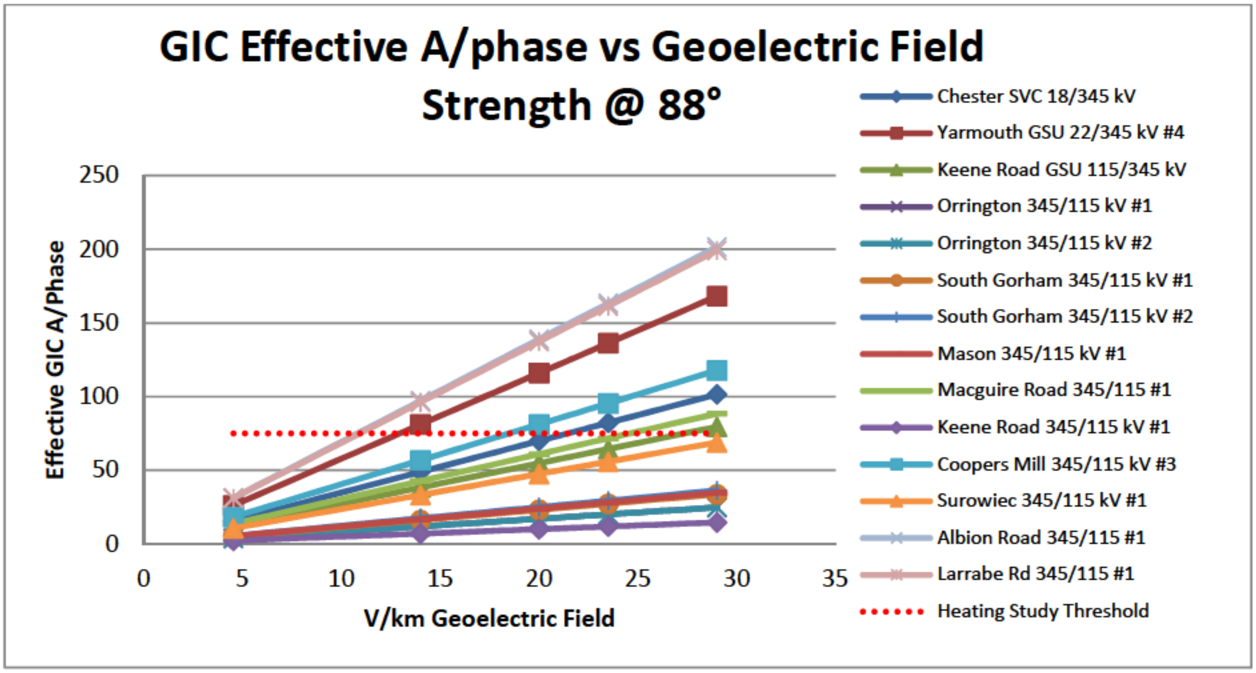

Figure 13: Effective GIC in transformers Vs. geoelectric field

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.

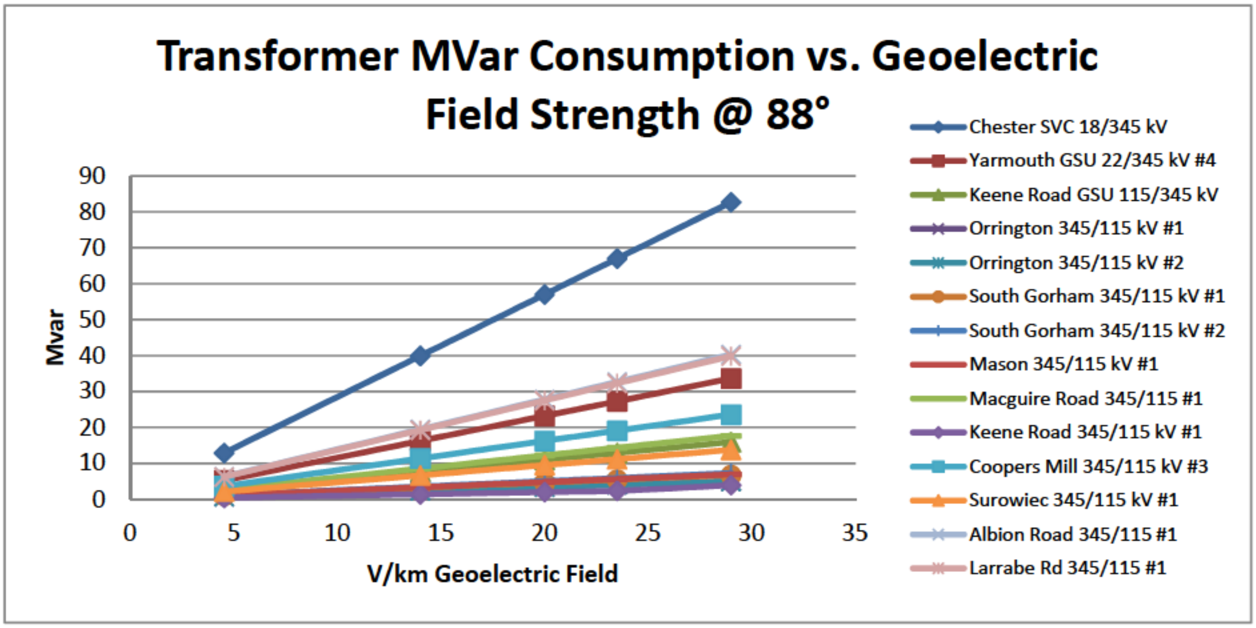

Figure 14: Transformer Mvar consumption vs. geoelectric field

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.

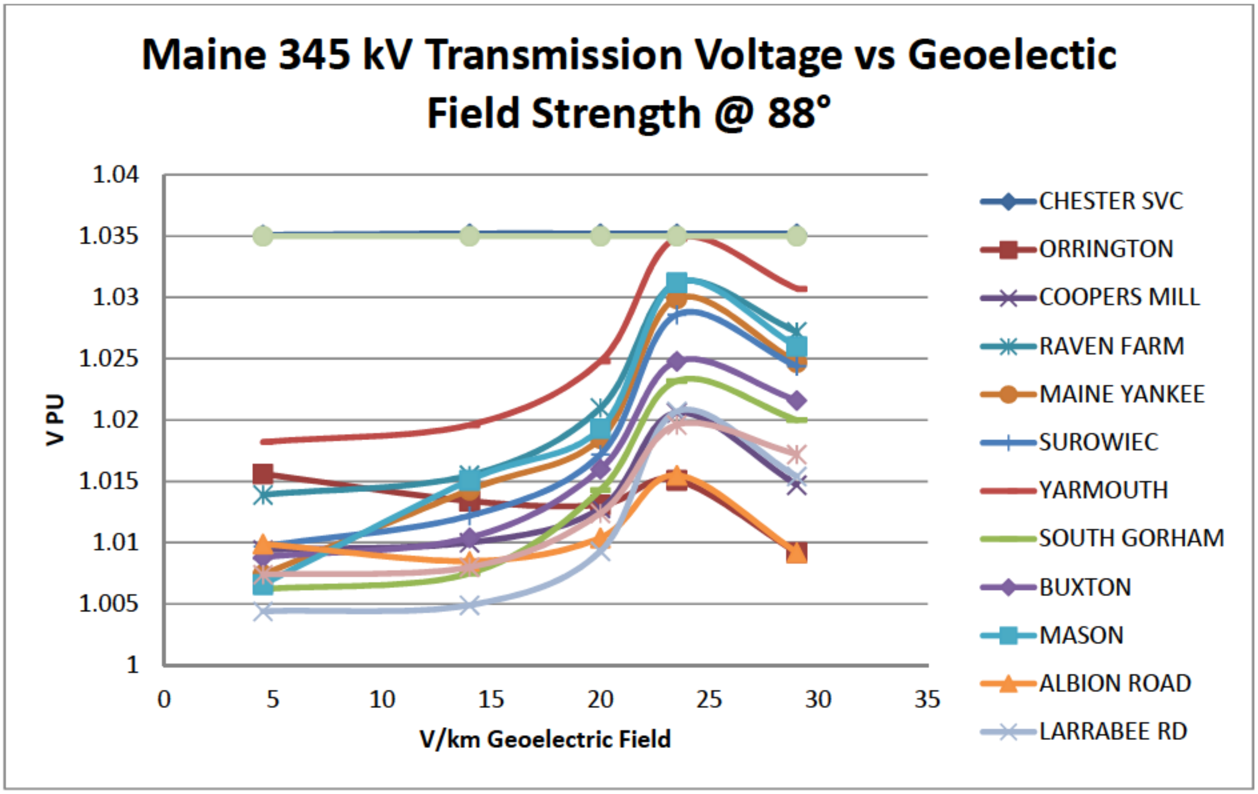

Figure 15: Maine transmission voltage vs. geoelectric field at 88°

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.

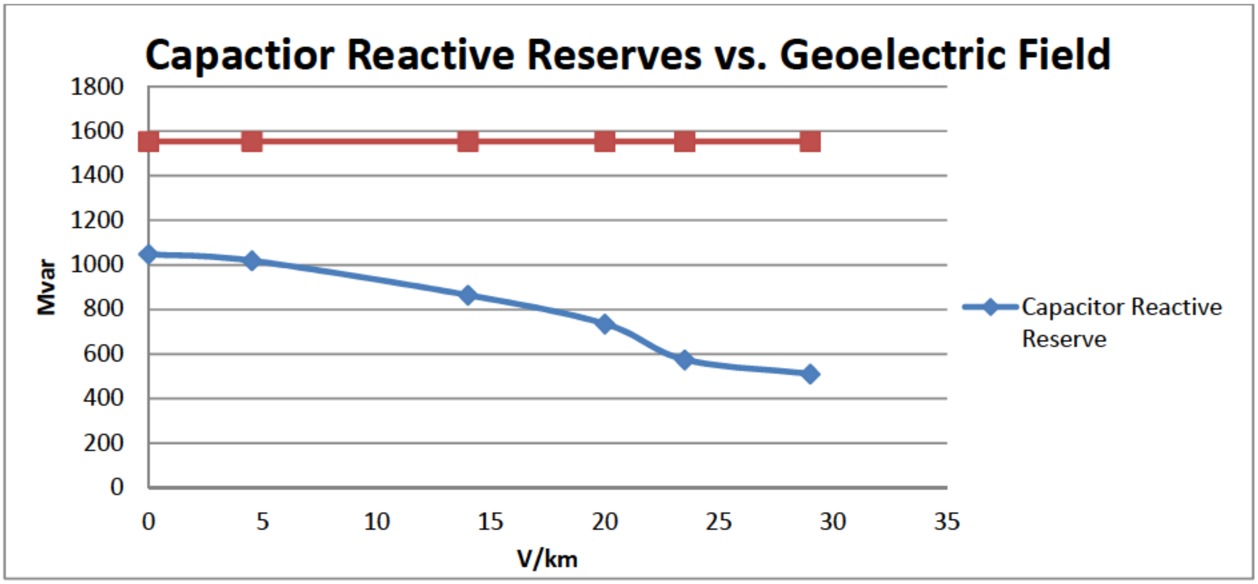

Figure 16: Installed Reactive Capacity and Reactive Output vs. geoelectric field Magnitude at 88°

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.

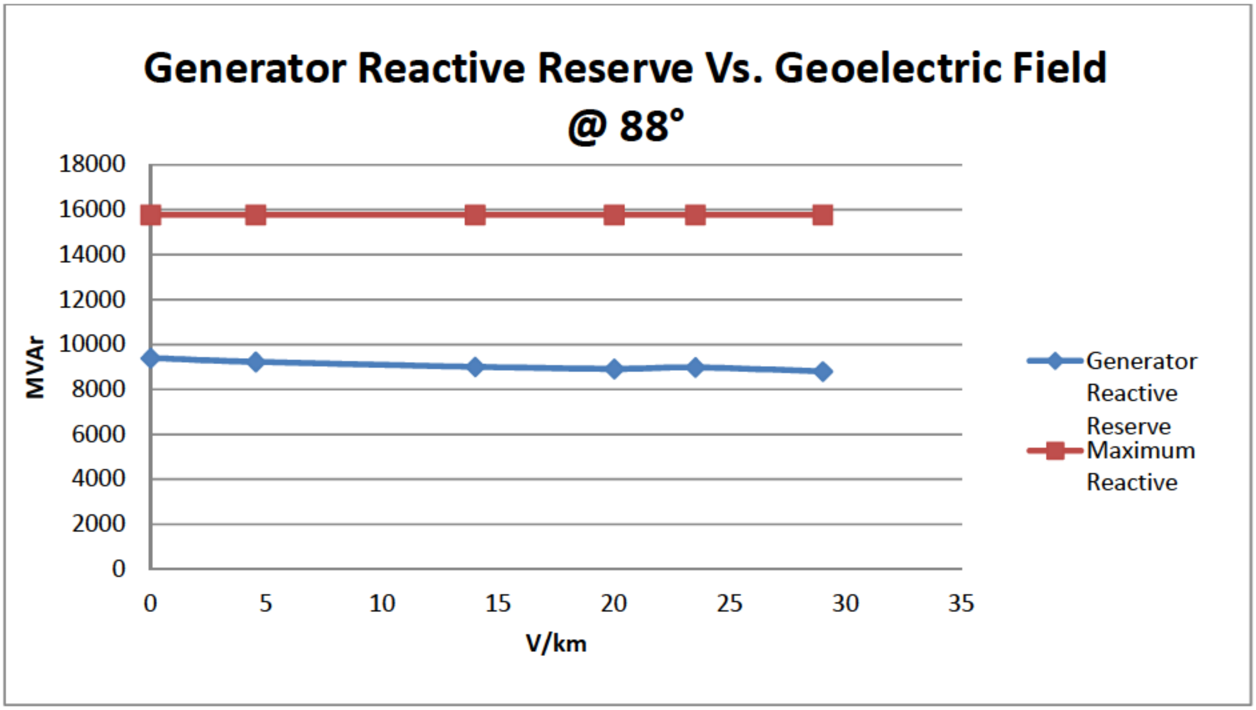

Figure 17: Generator Reactive Reserve

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.

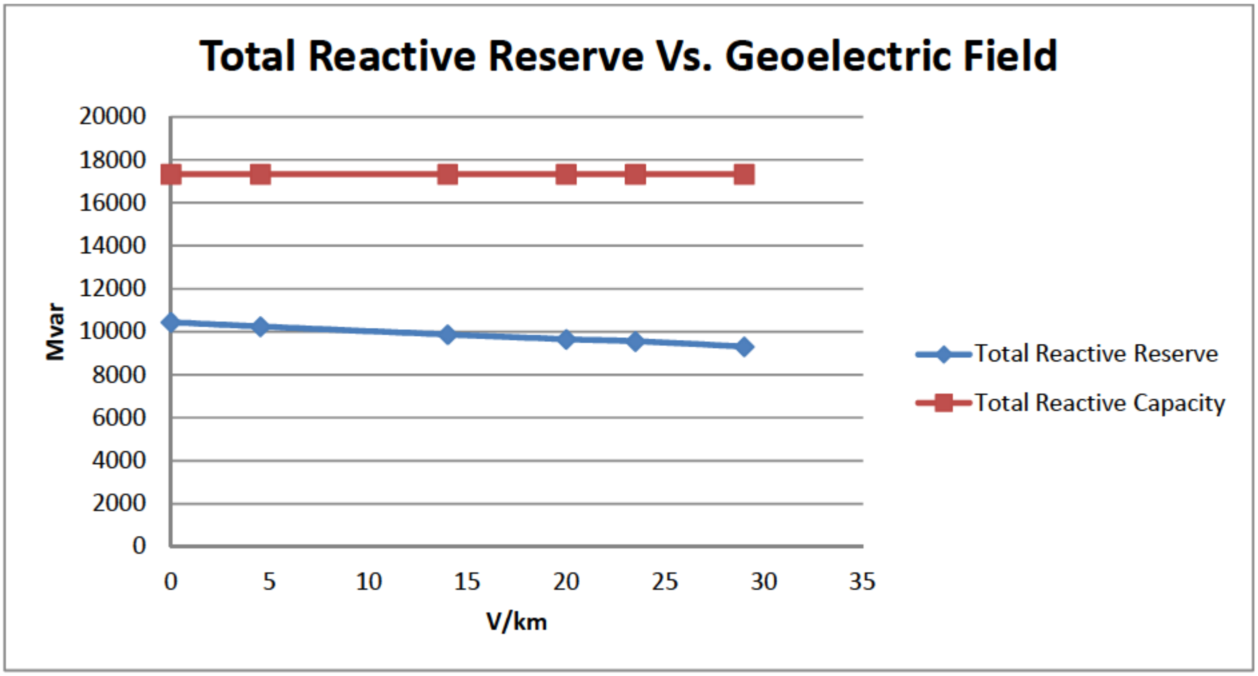

Figure 18: Total Reactive Reserve

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

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[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,[100001,100002,100004,100005,100007,100050,100051,100052,100086,100087,100088,10008
9,100090,100091,100092,100095,100098],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,[100001,100002,100004,100005,100007,100050,100051,100052,100086,100087,1000
88,100089,100090,100091,100092,100095,100098,103001,103710,103712,104054,104063,190230,190231,190237],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		