Report:

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

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Prepared by:

Emprimus

In Partnership With:

Central Maine Power
Emera Maine

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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

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

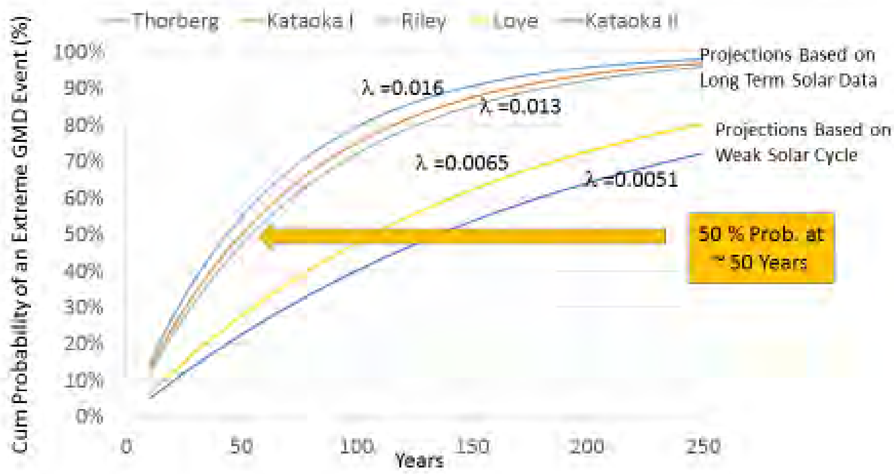
where t is time in years and λ is a single parameter that is selected to fit to the recorded data. These authors also used different sources of long term recorded solar storm data as the basis for their findings. For example; P. Riley used 45 years of magnetic data and 10 years of CME speed data from 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

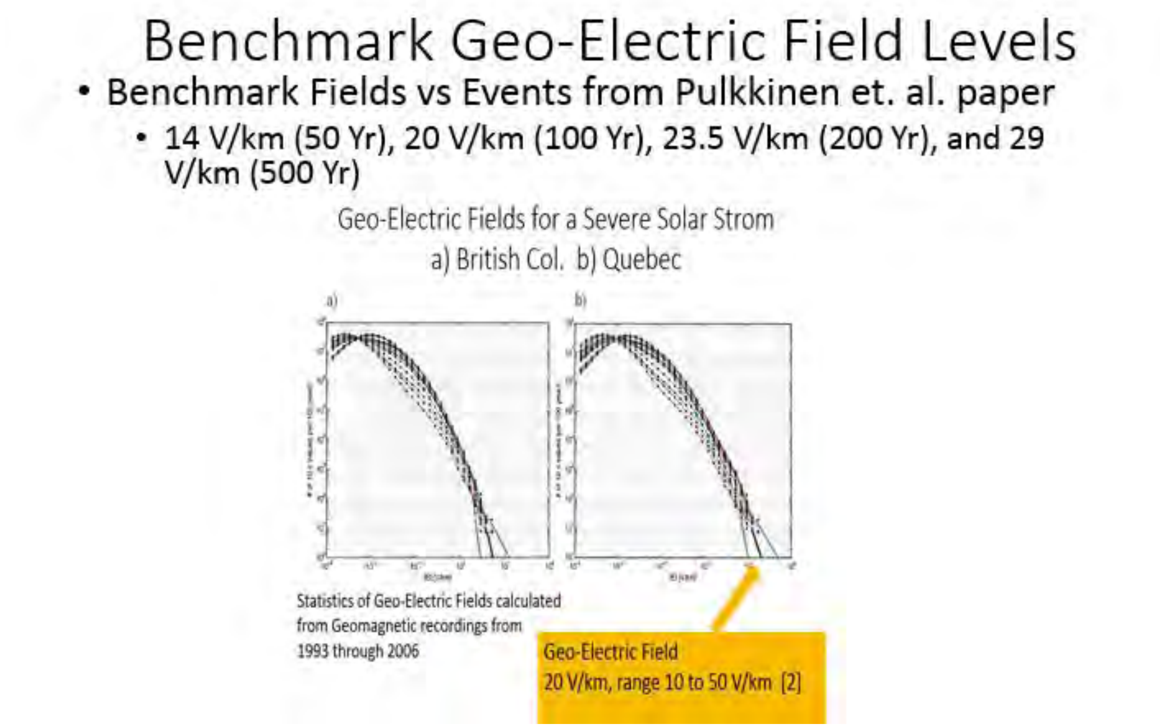
Geo-Electric Field Strengths

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

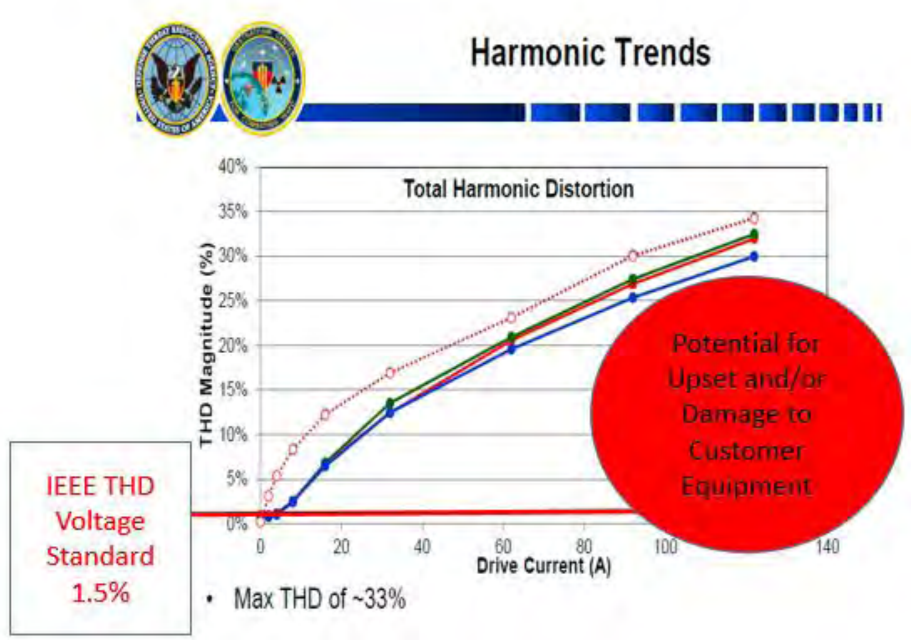
Table 1—Voltage distortion limits

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.



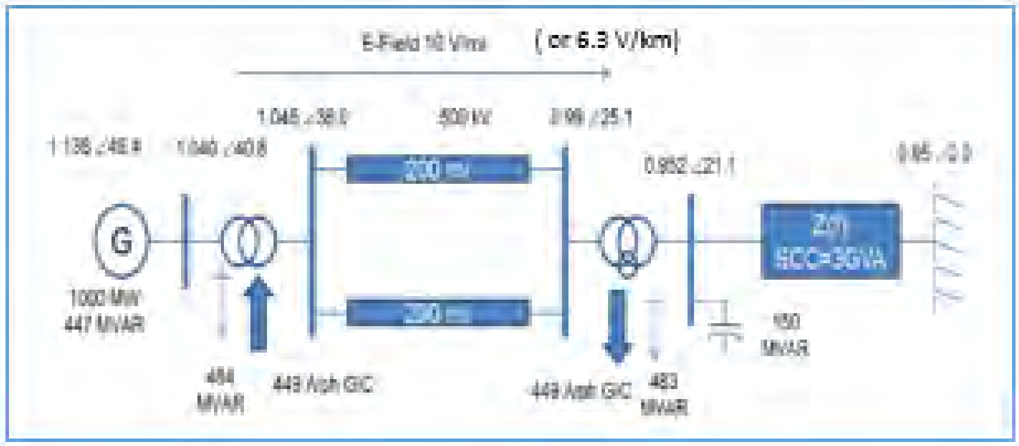
It was observed that at 6 Amps or less the IEEE 519 standard for voltage total harmonic distortion was exceeded. And at 120 Amps of DC injected current the harmonics were above 30 %. Such harmonics are therefore a concern and a potential issue that can result in power equipment and customer equipment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

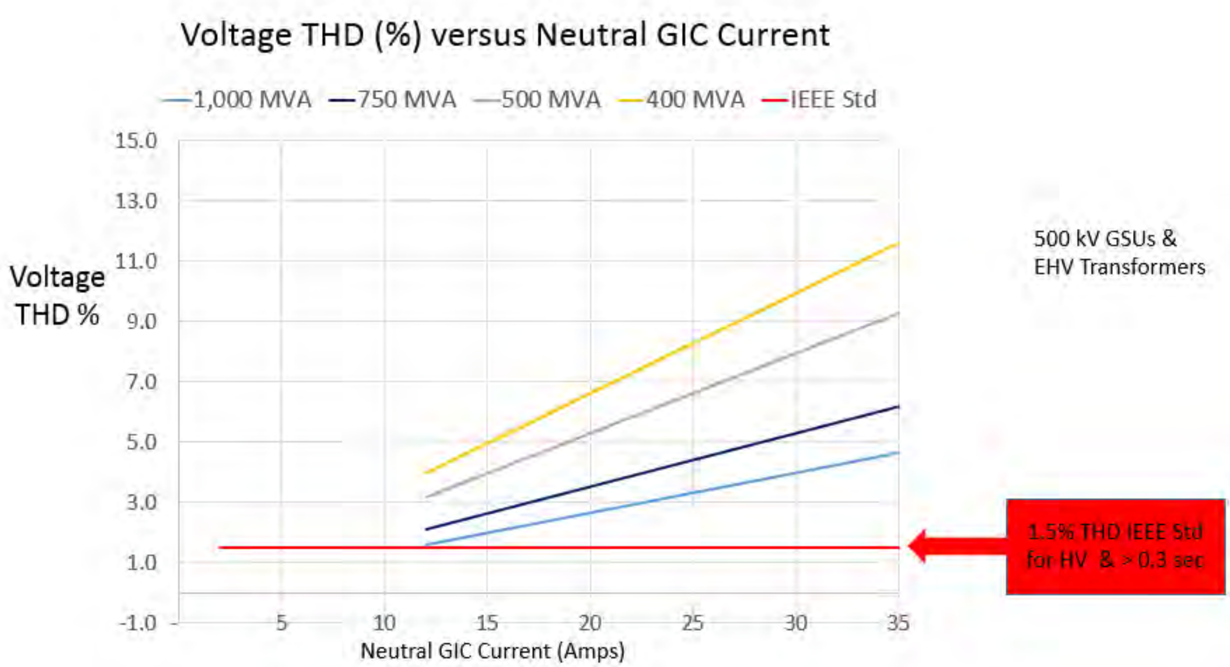
The Walling report then goes on to examine GMD induced voltage harmonics in a hypothetical 500 kV network with single phase GSU and EHV transformers (400 to 1,000 MVA). This hypothetical network is shown in figure 5.

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 2^{nd} and 3^{rd} components. These will propagate with less loss than the higher components ($> 3^{rd}$) 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
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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
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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

Principles

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)

Modeling

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.

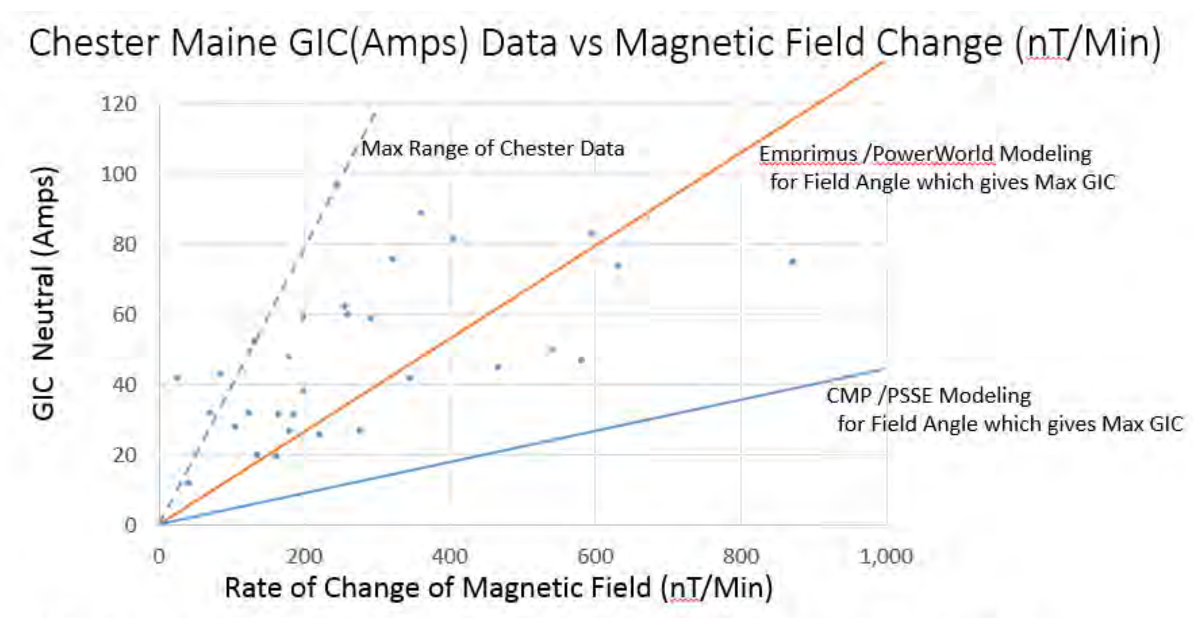
Also shown in the graph below are the Emprimus /PowerWorld and CMP / PSSE modeling results for the GIC currents at the Chester substation. It should be noted that numerous input parameters to these two modeling efforts were different and no attempt was made to make an accurate comparison of the two software 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.



Modeling Results Assumes that a 2 V/km Field equates to a 480 nT/Min Rate of Change of Magnetic Field.
And a 2 V/km Field is a 1/10 intensity of a one in 100 Year GMD Storm and a 1/20 intensity of an EMP E3 intensity.

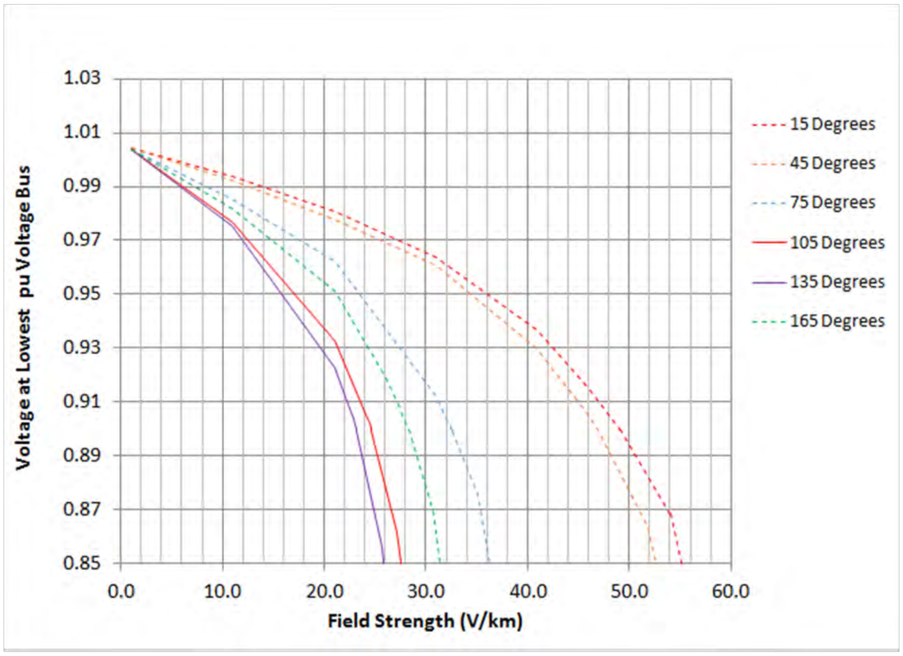
Selection of K-Factor Transformer Saturation Parameter

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.

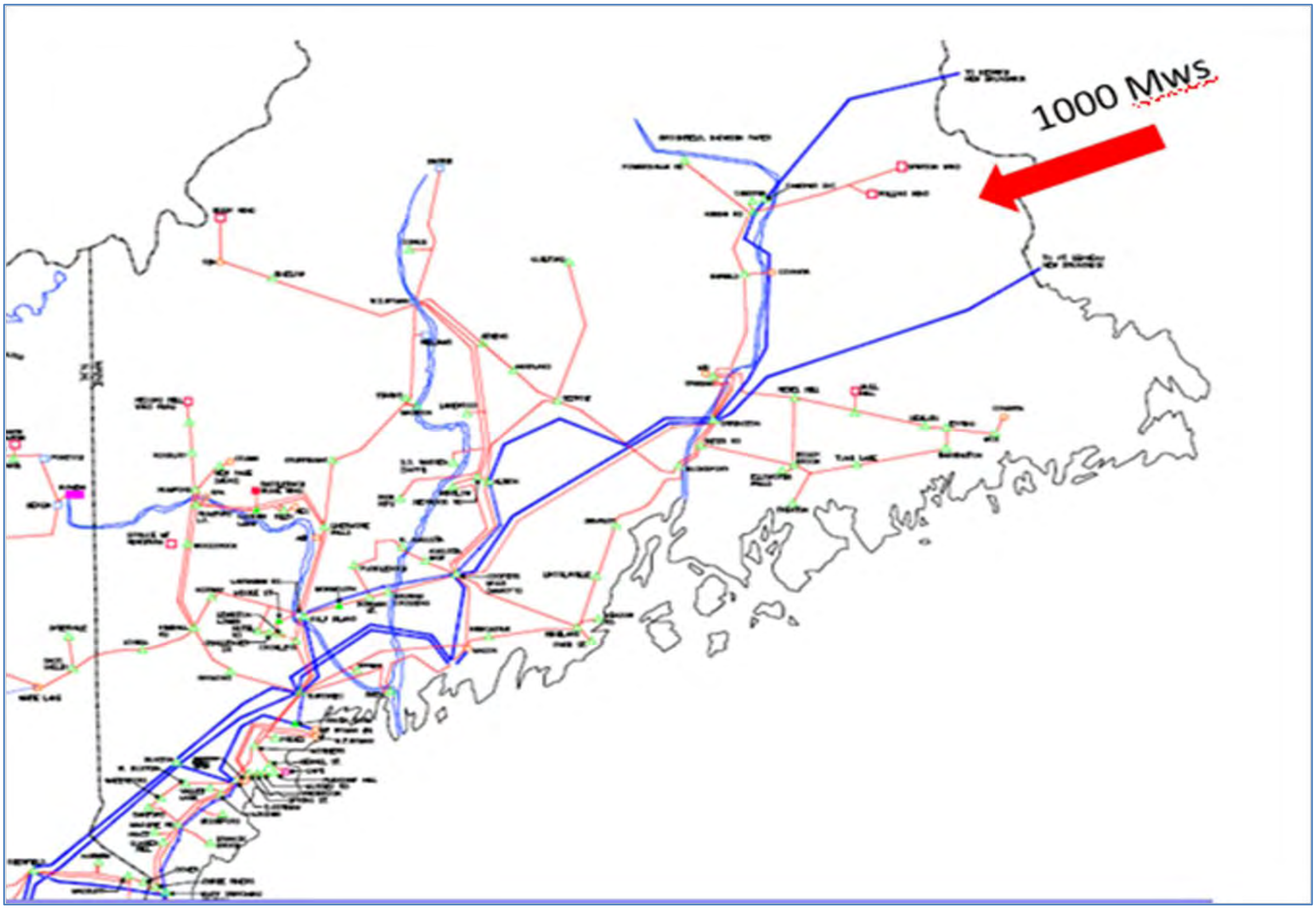


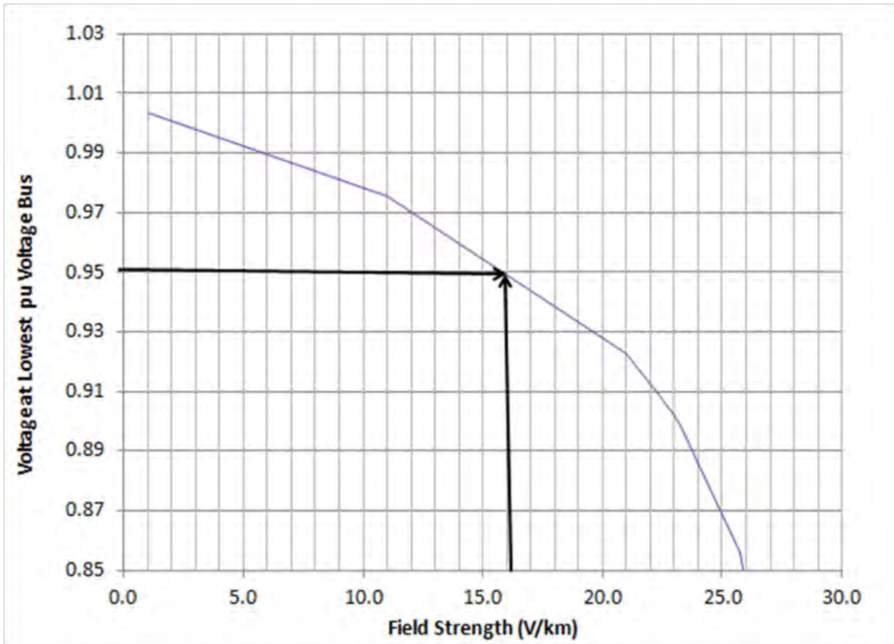
Figure 2 – Maine Bulk Electric Power System Map

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>

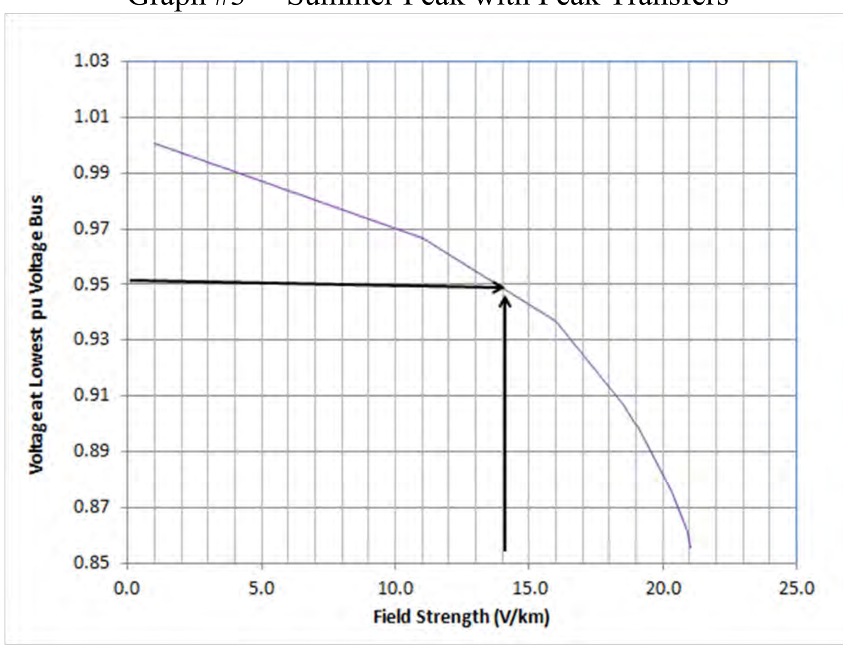
The Summer Peak case with normal firm transfer study results are shown in Graph #2. The voltage collapse is determined from the lowest voltage in the BES that drops below a given voltage level. For this case shown in graph #2 the 95% voltage point occurs at an E-field of 16 V/km for the NE to SW field 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



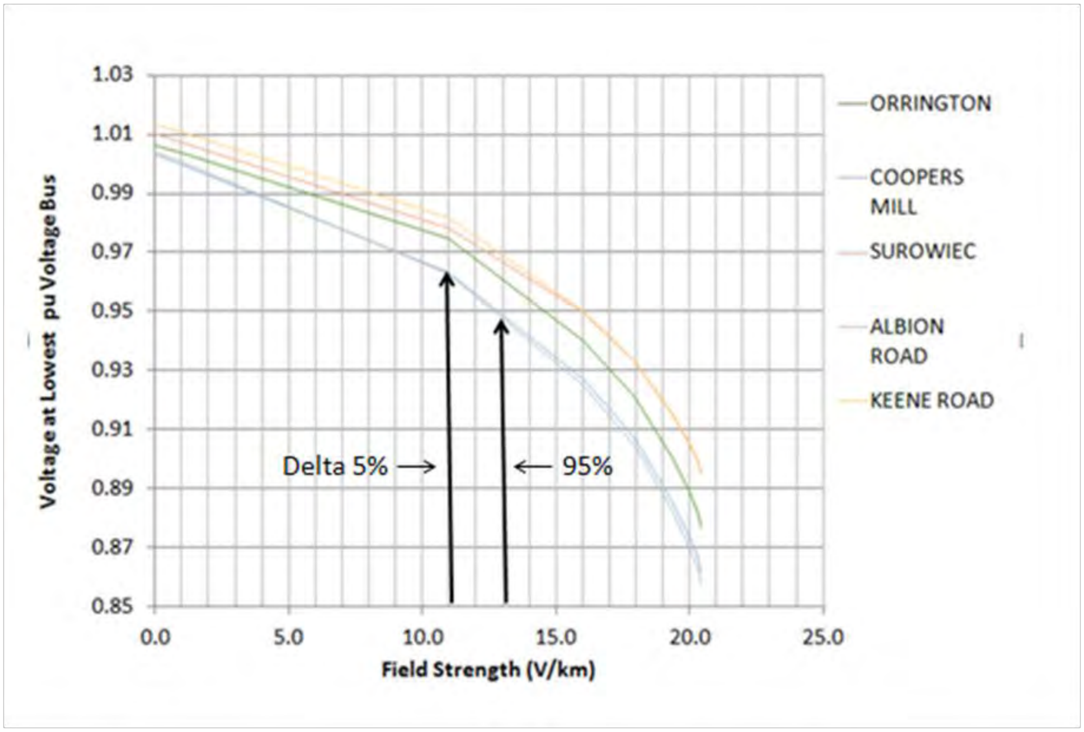
The Summer Peak case with peak transfers study results are shown in Graph #3. The 95% voltage point occurs at an E-field of 14 (placeholder) V/km.

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.

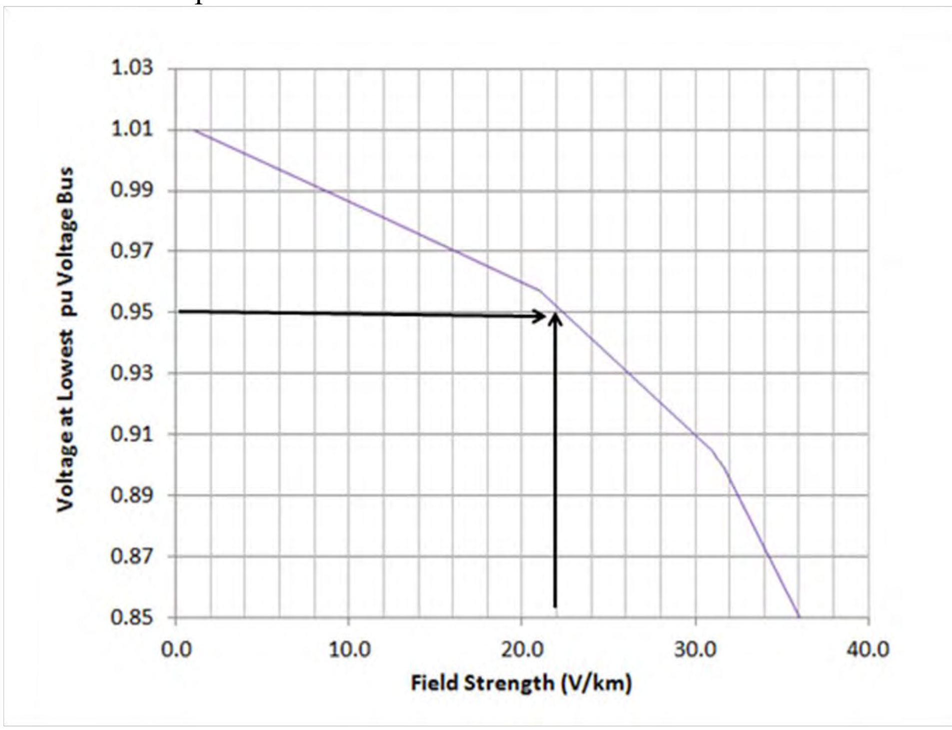
Table #1 – GIC currents for Summer Peak conditions with Normal and Peak Transfers

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

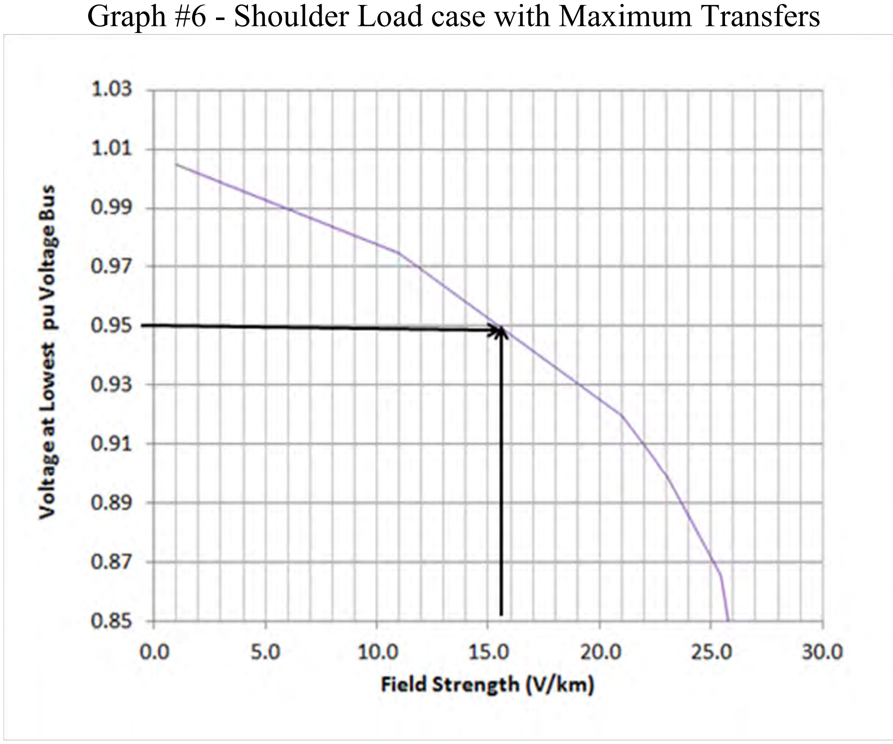
The Shoulder Load case with normal firm transfers study results are shown in Graph #5. The 95% voltage point occurs at an E-field of 21 V/km for the NE to SW field direction.

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.

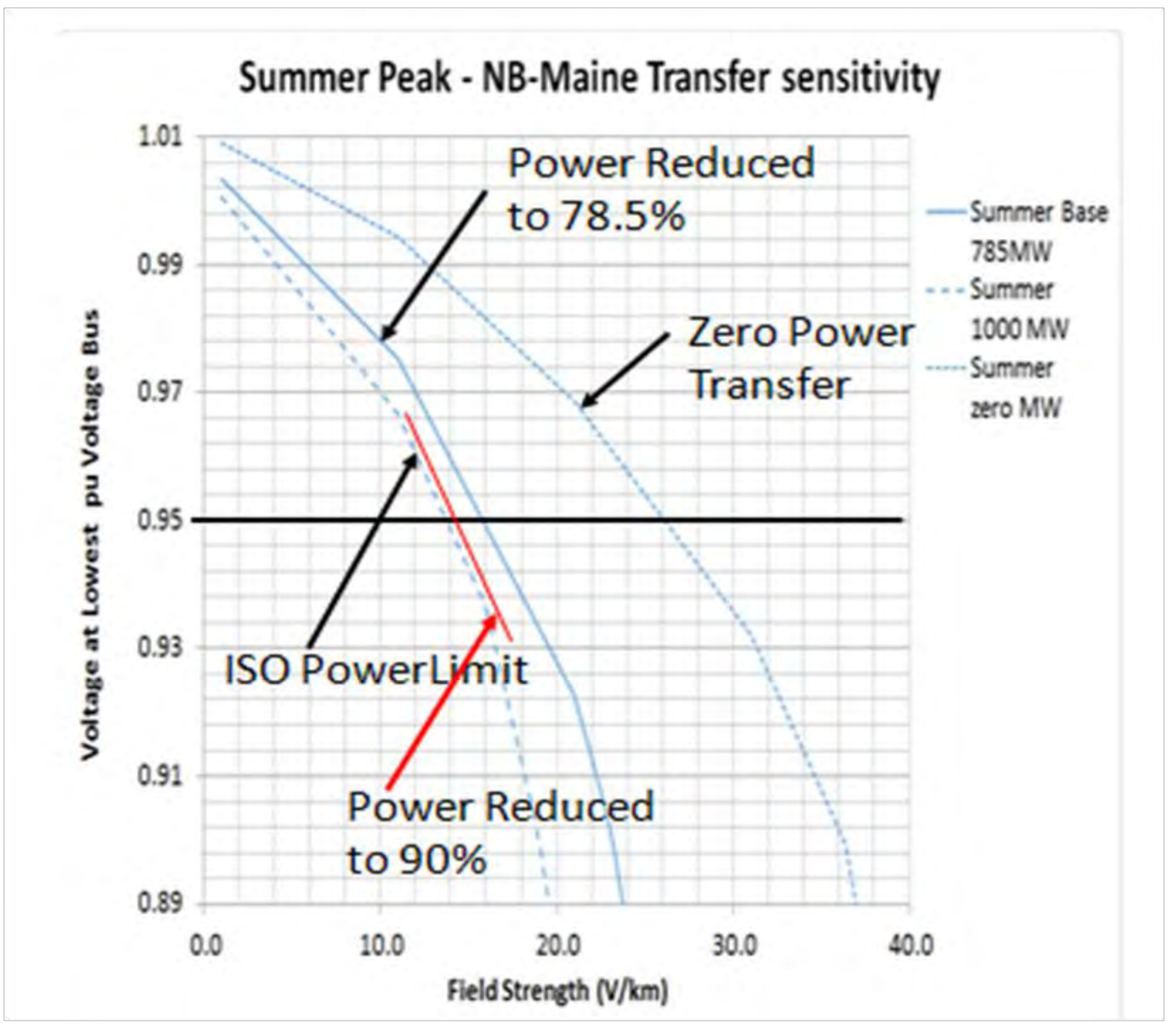
Contingent Operations

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.



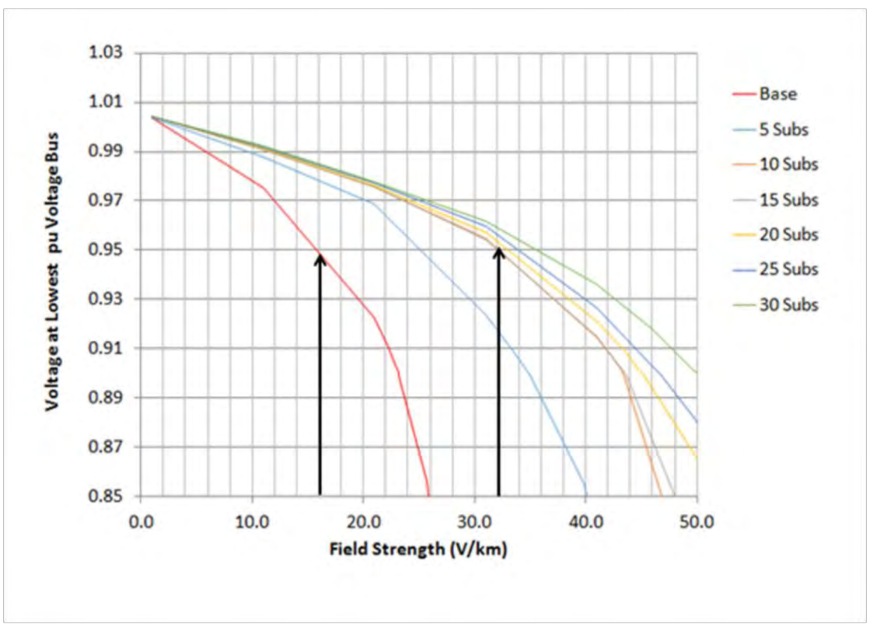
The conclusion from this graph is that an adjustment reducing the flow from 100 to 90% on the New Brunswick interface has little impact on the voltage collapse point. To have a significant impact the ISO NE must request more than a reduction to 50% of the flow on the interface. Since the operating procedures 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	