UNITED STATES OF AMERICA

BEFORE THE

FEDERAL ENERGY REGULATORY COMMISSION

Reliability Standards for Geomagnetic Disturbances	**)** **)**	**Docket No. RM12-22-000**

COMMENTS OF THE FOUNDATION FOR RESILIENT SOCIETIES

Submitted to FERC on May 1, 2013

Pursuant to the Federal Energy Regulatory Commission's ("FERC" or "Commission") Notice of Proposed Rulemaking (NOPR) issued on October 18, 2012,[1] the Foundation for Resilient Societies respectfully submits Supplemental Comments on the Commission's proposal to direct the North American Electric Reliability Corporation (NERC), the Commission-certified Electric Reliability Organization (ERO), to submit for approval Reliability Standards that address the impact of geomagnetic disturbances (GMD) on the reliable operation of the Bulk-Power System (BPS).

The Foundation for Resilient Societies (or "Foundation") is incorporated in the State of New Hampshire as a non-profit organization engaged in scientific research and education with the goal of protecting technologically-advanced societies from infrequently occurring natural and man-made disasters. All technologically-advanced societies rely on critical infrastructures—electric power generation and transmission, telecommunications, transportation, financial services, petrochemical refining, food production, water, and sanitation, to name just a few. Sustained interruption of any one of these critical infrastructures can result in economic, political, and social chaos. The profit incentive, which normally serves society well, provides inadequate protection from disasters that occur infrequently but have impact beyond the responsibilities of commercial enterprises. The Foundation seeks to identify cost-effective

[1] Reliability Standards for Geomagnetic Disturbances, Notice of Proposed Rulemaking, 141 FERC ¶ 61,045 (2012) ("GMD NOPR").

opportunities to protect societies and then develop policy initiatives. Its Board of Directors consists of persons residing in New Hampshire, Arizona, California, Massachusetts, and Virginia. Information about the Foundation may be found at www.resilientsocieties.org.

BACKGROUND

Necessity and Timing of Supplemental Comments

We file these Supplemental Comments, together with Appendices, in FERC Docket RM12-22-000. We request that all these documents be a part of the Docket record, so as to assist the Commission and Commission Staff in rulemaking and any related FERC Order on GMD.

The filing deadline for FERC Docket RM12-22-000 was December 24, 2013. No FERC Order has yet been made on Docket RM12-22-000. The docket is still open and comments are still being posted in the FERC Online eLibrary. For example, FERC accepted a reply comment by NERC dated January 10, 2013 which is now posted, and a supplemental comment by John G. Kappenman of Storm Analysis Consultants dated April 29, 2013.

The Foundation for Resilient Societies respectfully requests that the Commissioners give full consideration to our Supplemental Comments and reference documents for the following reasons:

1. The GMD Task Force of NERC has had a policy and practice of not investigating past GMD events or their impact on electric utilities. As a result, reports of GMD impacts must be obtained by other means.
2. An emerging scientific consensus is that the Advanced Composition Explorer (ACE) satellite, or any satellite in the Lagrange 1 orbital position, will provide approximately 10 minutes warning time for the fastest moving and most severe Coronal Mass Ejections (CME), such as those that would be part of a 1-in-100-year storm. This consensus was discussed at the February 25-27, 2013 meeting of the GMD Task Force and later published in a March 18, 2013 New York Times article, "Sun Storm Forecast: Tiny Chance of Havoc."

3. Public testimony before the Energy, Utilities and Technology Committee of the Maine State Legislature by Central Maine Power regarding past impacts of GMD events did not take place until March 21, 2013.[2]
4. A public presentation by NextEra Energy regarding GMD impacts at the Seabrook, New Hampshire and Point Beach, Wisconsin nuclear power plants did not take place until April 16, 2013.
5. Geomagnetically Induced Current (GIC) readings taken by the Tennessee Valley Authority (TVA) were not provided to the Foundation for Resilient Societies under the Freedom of Information Act until April 22, 2013.
6. Supplemental Comments by John G. Kappenman of Storm Analysis Consultants on the non-effectiveness of partial power reduction as specified in some so-called GMD operating procedures (hereafter "Operating Procedures") or GMD mitigation guidelines did not become publicly available until April 29, 2013.
7. With rare exception, electric utilities have not released data from their GIC readings, instead keeping this data confidential.[3]
8. With rare exception, the Electric Power Research Institute (EPRI) has not released data from its SUNBURST database of GIC readings, instead keeping this data confidential.[4]
9. NERC has not released data from its Generating Availability Data System (GADS) and Transmission Availability Data System (TADS) databases that could have been used to conduct statistical studies and investigate impacts of GIC upon power transformers.

In summary, new and significant information has become available since the December 24, 2012 docket deadline while other information has continued to be withheld. This new and significant information is directly related to the pending FERC NOPR for GMD protection and should be given full weight by the Commissioners.

Moreover, NERC and the electric utility industry have in their possession data on GIC readings and GMD impacts to the Bulk-Power System, but for the most part this data has not been

[2] By its voluntary and good-faith release of GIC data and system impacts, Central Maine Power has set a new standard among privately owned utilities for appropriate disclosure.
[3] In response to a Freedom of Information Act request by the Foundation for Resilient Societies, Bonneville Power Administration released 20 years of GIC data for 12 monitoring stations in October 2012.
[4] In response to a Freedom of Information Act request by the Foundation for Resilient Societies, Tennessee Valley Authority released GIC data collected under the Electric Power Research Institute (EPRI) SUNBURST program. EPRI should also be favorably recognized for the technical support it provided in conjunction with release of this data.

available for FERC consideration of the pending NOPR. As a result, when GIC readings and GMD impact data do become available these data should be given full weight by the Commissioners.

Investigative Inaction by GMD Task Force of NERC

As part of its duties as the Electric Reliability Organization (ERO), NERC initiated Phase II of its Geomagnetic Disturbance Task Force ("GMD Task Force") to study GMD and provide recommendations in a special assessment report. The Foundation for Resilient Societies and others have repeatedly suggested that NERC and the GMD Task Force ask participating utilities to voluntarily provide GIC data and/or GMD impact reports but utilities generally have not released this data. Most recently, on August 24, 2012, Thomas Popik, Chairman of our Foundation and a participant in NERC's GMD Task Force, sent an email to the entire GMD Task Force asking in part:

> Unfortunately, at the GMD Task Force meetings last summer and fall, we had nearly zero discussion of any information that would be of practical value to utility engineers who need to take protective action during solar storms. In particular, no one talked about specific GIC readings at their plants and what prudent actions would be taken, or have been taken, consistent with this level of GIC.
>
> GIC monitors are now commonly installed on power transformers and surely many members of the GMD Task Force know these readings during past solar storms. This applies to both operators and equipment manufacturers. If people sit mute during the meetings and do not disclose what they know, then engineers like the one I talked to will not have the information to protect their equipment, their jobs, our communities, and our countries.
>
> If you have access to GIC readings for your transformers, I urge you to consult with your management before the GMD Task Force meeting next week and see if you can release this data to the task force. Likewise if you have documented guidelines for operational procedures—including downrating of vulnerable transformers—during solar storms, this would be very helpful and practical information and I urge you to bring it with you to the Atlanta meeting.

As of the date of this filing, the GMD Task Force of NERC has not made any request for voluntary provision of historic GIC data and/or GMD impacts from its participants or of the electric utility industry in general. The GMD Task Force did request and obtain GMD Operating Procedures currently in use by some electric utilities.

COMMENTS

Experience of Central Maine Power with GMD Impacts and Operating Procedures

Upon request of the Energy, Utilities and Technology Committee of the Maine State Legislature, Central Maine Power voluntarily released on March 21, 2013 twenty-four years of GMD impacts on its system and twenty-two years of GIC data at its Chester, Maine substation.[5] Central Maine Power should be commended for this voluntary and good faith release of data which has substantially expanded public knowledge of GMD and its impact on electric grids. The Central Maine Power GMD event disclosure is reproduced in full in Appendix 1 of this comment. Central Maine Power also disclosed its GMD Operating Procedures.

No GIC monitors were installed in the Central Maine Power system at the time of the March 1989 solar storm that caused the Hydro-Quebec Blackout. However, these system impacts were observed, according to the disclosure:

- All Orrington capacitors tripped
- Orrington capacitors would not close back in
- Yarmouth 4 and “MY” Generator VARs went over 300+ MVAR each

By the June 5, 1991 solar storm, a GIC monitor had been installed at the Chester, Maine substation. Below is a summary of the top 10 GIC events from June 1991 to March 2013, ranked by maximum GIC readings.

[5] No GIC readings or GMD impacts were provided by Central Maine Power for the period between 9/8/1994 and 5/4/1998. It is not clear from the disclosure whether no significant GMD occurred during this period, or whether the data are missing.

Top 10 GMD Events for Central Maine Power—1991 to 2013

GIC Rank	Maximum GIC Reading in Amps	Impact Category	GMD Event Dates	Central Maine Power Comments
1	173.4	No Known Impact	06/21/2001	May be an anomaly – one time spike with very little activity before or after spike
2	98.0	No Known Impact	10/24/2003 to 11/05/2003	NKI; 10/29/03 Very large GIC flow but no impacts seen by CMP
3	96.9	SVC Trip	08/24/2005	Chester SVC Filter banks tripped
4	89.9	SVC Trip	11/24/2001	Chester SVC filter banks trip
5	88.0	No Known Impact	11/07/2004 to 11/10/2004	NKI; 11/9/04
6	83.1	No Known Impact	05/15/2005	NKI
7	81.7	SVC Trip	04/06/2000	SVC filter banks trip; distribution customers UPS's not functioning properly in North Coastal areas
8	76.2	Generator Trip	03/30/2001	MIS G1 trip but think it was due to faulty control board – no other evidence for trip
9	76.0	Capacitor Trip	07/15/2000	MS2 declared by ISO; Orrington KC3 trip; 7kV swing on 345kv system; many Auto xfmr LTC operations
10	74.3	Capacitor Trip	05/04/1998	2 caps tripped at Orrington; Orrington Bus @ 328kV

Note: NKI stands for No Known Impact. SVC stands for Static Var Compensator.

As the above table shows, the Central Maine Power system has experienced multiple capacitor and Static Var Compensator (SVC) trips during GMD events. In fact, of the top 10 GMD events over a twenty-two year period, 50% resulted in SVC or capacitor trips. SVC and capacitor trips are caused by production of harmonics within half-cycle saturated power transformers. While transformer manufacturers are now beginning to specify transformers resistant to overheating when subjected to GIC, this data from Central Maine Power shows that harmonic production by transformers is another important GMD effect that must be addressed by system operators. The disclosed GMD impacts also show that harmonics prevented Uninterruptable Power Supplies (UPS) at customer sites from functioning properly during at least one solar storm.

SVC trips were the immediate cause of voltage collapse for Hydro-Quebec in March 1989, a system geographically adjacent to Central Maine Power. The Hydro-Quebec Blackout occurred during an induced electric field of approximately 2 volts/kilometer. According to estimates by both John Kappenman of Storm Analysis Consultants and Antti Pulkkinen of Catholic University, a 1-in-100-year solar storm of intensity equivalent to the 1921 Railroad Storm or 1859 Carrington Event would produce an electric field of approximately one order of magnitude greater.

Central Maine Power and its regional balancing authority, ISO-New England, currently rely on Operating Procedures to protect against solar storms and associated GMD. Operating procedures for ISO-New England were first implemented on February 13, 2003. Nonetheless, these Operating Procedures did not prevent the Chester SVCs from tripping during the August 24, 2005 solar storm.

The current GMD Operating Procedures of Central Maine Power appear to concede that tripping of SVCs and capacitor banks is still likely during solar storms. Section 4.2.2 of the Central Maine Power System Operations Common Control Room Procedure states:

4.2.2 The following actions will be evaluated between ISO-NE and their LCC operators and performed as appropriate to posture the grid accordingly either pre-SMD event or post-SMD event (Note: ISO-NE initiates discussion of below actions at Kp7 or greater, per their SOP-RTMKTS.0120.0050):

- Inhibit the Unbalance protection of the Chester SVC to prevent trips caused by harmonics.

  …

- Take pre-contingency measures for the loss of the Chester SVC and/or Orrington capacitors.

In summary, this recent disclosure by Central Maine Power shows that solar storms and associated GMD have had major effects on its system, with significant SVC and capacitor trips during relatively minor solar storms producing GIC of less than 100 amps. ISO-New England Operating Procedures implemented in 2003 did not prevent tripping of the Chester SVC during a 2005 solar storm. Central Maine Power compensates for the inability of Operating Procedures to mitigate harmonics by requiring unspecified “pre-contingency measures” for tripping of equipment. Additionally, in a grid posturing action whose prudence could be questioned, normally-needed system protection—such as “unbalance protection”—would be inhibited by their GMD Operating Procedures.

When considering this recent disclosure of GMD impacts by Central Maine Power, and the track record of its Operating Procedures, one must remember that Maine has not experienced a truly severe solar storm during the time period of recorded GIC readings—such as the 1921 Railroad Storm or the 1859 Carrington Event. Such a storm is likely to produce GIC of magnitude 5-10 times greater than the March 1989 storm, with greater potential for production of harmonics, equipment tripping, cascading blackout, and permanent damage to critical equipment.

NextEra Disclosures of Transformer Noise at Seabrook and Point Beach

NextEra Energy gave a presentation on GMD impacts at Seabrook, New Hampshire and Point Beach, Wisconsin nuclear power plants to the Space Weather Workshop held in Boulder, Colorado on April 16-19, 2013. While we disagree with the conclusions of NextEra, this company should be commended for its voluntary and good faith release of information which has substantially expanded public knowledge of GMD and its impact on generation facilities. Selected slides of the NextEra presentation are reproduced in Appendix 2 of this comment.

NextEra confirmed that Seabrook and Point Beach are GIC “hot spots,” with observed GIC of 80 amps and 68 amps, respectively, during the October 29, 2003 solar storm. During a storm of intensity equivalent to the 1921 Railroad Storm or 1859 Carrington Event, GIC of hundreds or even thousands of amps might be induced at these locations.

NextEra disclosed "growling" noises coming from Generator Step Up (GSU) transformers at both Seabrook and Point Beach during past GMD events. These growling noises are indicative of vibration within transformers. NextEra indicates that during the October 29, 2003 solar storm, GSU transformer noise diminished when GIC was reduced to 4 amps by opening a line. Vibration and associated audible noise have been commonly reported by other utilities when power transformers are subjected to GIC. Below is a table of transformer noise events during the March 1989 solar storm:

Transformer Noise Events During March 1989 Solar Storm

Event #	Date	System	Category	Comments
5	03/12/1989	So Cal Edison	noise	115/55 kV transformer nr Bishop
19	03/13/1989	PJM Interconnection	noise	Calvert Cliffs GSU transformer
66	03/13/1989	PJM Interconnection	noise	Calvert Cliffs GSU transformer
77	03/13/1989	Portland GE	noise	360 Hz noise at Boardman
84	03/13/1989	PJM Interconnection	noise	Calvert Cliffs GSU transformer
90	03/13/1989	So Cal Edison	noise	500/220 kV transformer at Mira Loma
105	03/13/1989	Bonneville Power Adm	noise	Ross substation nr Vancouver WA
114	03/13/1989	Wisconsin Electric	noise	Low frequency noise at Point Beach

Source: Excerpts from NERC file on March 13, 1989 geomagnetic storm, available at http://www.nerc.com/files/1989-Quebec-Disturbance.pdf

Mechanical components within transformers are subjected to 120 hertz vibration in normal operation. But when subjected to GIC, half cycle saturation produces 60 hertz vibration and harmonics at multiples of 60 hertz. Structural members and other mechanical components, designed to be non-resonant and damped at 120 hertz, can activate resonance at these abnormal frequencies and produce “growling” noises.

Common postmortem indicators of excessive vibration in mechanical systems include:

- Loosing of fasteners such as bolts, screws, and clamps
- Chafing of non-metal components such as insulation
- Misalignment of mechanical components
- Metal fatigue and eventual fracture, especially at stress points such as joints, bends, welds, notches, and holes

One could also reasonably expect to see the same postmortem indicators in power transformers subjected to excessive vibration. In particular, if vibration were causing transformer premature failures during or shortly after GMD events, one would expect to see telltale signs during root-cause analysis. In fact, a GSU transformer at Seabrook failed only one day after a GMD event from November 8-9, 1998. The subsequent root-cause analysis showed that the Seabrook transformer failed due to a loose bolt.[6]

Moving beyond this single data point of a Seabrook GSU failure, a 2003 study of transformer failures by Hartford Steam Boiler, "Analysis of Transformer Failures," for the years 1997 through 2001 demonstrated that GSU transformer loss claims in the high GMD year of 2000 were six times the GSU transformer loss claims for the average of four surrounding years with lower GMD activity.[7] Moreover, the study also showed that the No. 1 known cause of power transformer failures is "insulation" and the No. 3 known cause is "loose connection."

It is certainly plausible that a failure mode during GMD events could be chafing or displacement of paper tape winding insulation or other insulation components and associated dielectric failure, ultimately resulting in overall transformer failure. It is also plausible that some proportion of "loose connection" failures could be attributable to vibration during GMD events. More statistical study with larger sample sizes should be conducted to investigate these preliminary correlations.

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[6] See "Seabrook Station Unit 1: Damage To Generator Step-Up Transformer Identified 10 November 1998 Immediately Following Geomagnetic Storm Shocks Of November 7-9, 1998" filed on FERC docket AD12-13-000 by the Foundation for Resilient Societies.

[7] W. H. Bartley, "Analysis of Transformer Failures," Hartford Steam Boiler, IMIA-WGP 33(03), Stockholm, 2003

Previous studies of transformer failure modality due to GMD have concentrated on transformer heating due to flux displacement, but not vibration effects. Studies of GIC waveforms—including our own study of TVA data later in this comment—show that GIC can have a long-duration, low amplitude waveform, with occasional high amplitude spikes.

Some transformer designers have been doubtful that long-duration, low amplitude GIC with only brief spikes would cause damaging heat buildup in high thermal mass transformers. Transformer vibration as an alternative failure modality could explain transformer failures during or shortly after long-duration, low amplitude GIC events—the failures of multiple transformers in South Africa after the 2003 solar storms being a prominent example. And even short duration, high amplitude GIC could cause damaging vibration, because mechanical systems typically reach resonance in just a few cycles of a forcing function.

Minnesota Power conducted tests of transformers injected with direct current to simulate GIC conditions in 1981 and published the results in IEEE Special Publication 90TH0291-5 PWR. Three single-phase transformers of varying designs were tested, with acoustic monitoring of audible noise produced by the transformers. Figure 8, reproduced from the original paper, shows the changes in audible noise as varying levels of direct current were injected into one of the test transformers.

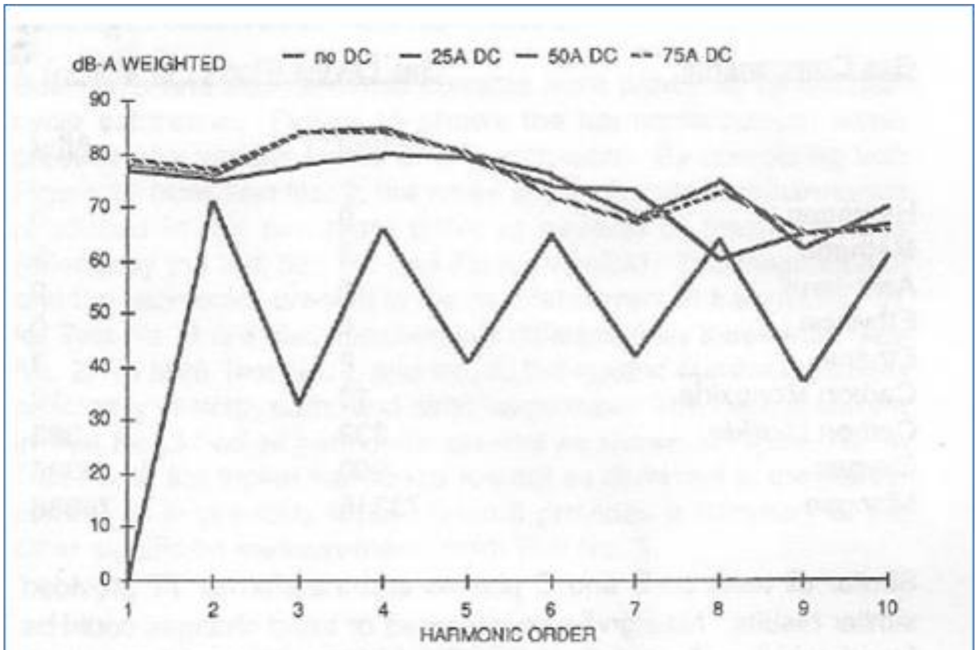

Figure 8. Audible Noise From Transformer (8T) During Test #1

The solid line in Figure 8 represents audible noise at various harmonic orders under normal operation. For the purposes of this analysis, Harmonic Order 1 is the transformer excitation frequency of 60 hertz. Familiar no-load transformer hum is caused by magnetostriction that occurs at the peak and trough of each 60 hertz cycle; as a result under normal operation only the second harmonic of 120 hertz is audible—noise at the fundamental of 60 cycles is nearly zero.

Upon injection of direct current, half-cycle saturation in the test transformer produced magnetostriction at the peak of each AC cycle.(Half-cycle saturation could also occur at the trough of each AC cycle, depending on the polarity of the DC bias current.) As the Figure 8 indicates, audible noise appeared at the fundamental of 60 hertz. In normal operation, 60 hertz noise was essentially zero, but during even the lowest level of DC injection, there was a 70 decibel increase in audible noise. Notably, the level of audible noise at the odd harmonics was also substantially increased under DC injection, as much as 40 decibels for the third harmonic and slightly less for the higher order harmonics. Noise at the even harmonics also increased by as much as 20 decibels. Decibels follow a logarithmic scale times 10; an increase of 20 decibels implies an increase in sound energy of 100 times and an increase of 40 decibels implies an increase in sound energy of 10,000 times. Because audible noise is directly related to vibration within the transformer, it is reasonable to expect that energy dissipated in vibration in the test transformer increased by several orders of magnitude at each of the odd harmonics and by approximately a factor of 10 at the even harmonics.

Minnesota Power produced a video of the transformer tests with a soundtrack of audible noise produced by the test transformer. A clip from this video can be accessed at the below link and is an integral part of this docket comment. (This video is most reliably viewed with the Internet Explorer browser.)

Video Clip of DC Injection Test of Power Transformer

When DC of 25 amps is injected into the test transformer, an increase in audible high frequency noise can be clearly heard. The noise appears to have a clattering or rattling nature, which is unusual from an apparatus that is designed to have no internal moving parts.[8]

In the Minnesota Power tests, a DC injection of only 25 amps was sufficient to drive the transformer into half-cycle saturation and increase audible noise. Notably, the amplitude of audible noise at greater DC injections of 50 amps and 75 amps was not significantly greater. Based on this limited empirical evidence, it appears that transformers may have a threshold for half cycle saturation and associated vibration and noise, without a linear "dose-response" relationship. This could explain observations of power transformer failures during or immediately after relatively small GMD events, such as the November 8-9, 1998 GMD event followed by a November 10 GSU transformer failure at Seabrook nuclear plant. Multiple transformers also failed in South Africa after a long duration GMD event that caused only moderate GIC. It is intuitively obvious that long duration exposure to vibration has a greater

[8] When a layperson is confronted with a loud rattling sound in an automobile, the prudent reaction is to slowly drive to a nearby repair shop for diagnosis. When grid operators have been confronted with loud sounds from power transformers during GMD events, too often the reaction has been, "Drive on!"

likelihood of causing insulation chafing, fastener loosing, metal fatigue, and other internal insult to power transformers.

Transformer vibration should be investigated by FERC, NERC, or other investigative bodies as a possible GIC-induced failure mode. For transformers that have previously failed during or shortly after GMD events, examination of root-cause failure reports would be particularly helpful. But just as management of the NERC GMD Task Force has resisted asking utility operators for disclosure of GIC readings, it has also resisted requesting transformer root-cause failure reports.

The NERC GMD Task Force is now asking grid operators to participate in a voluntary program to test power transformers under DC injection. Appendix 3 contains the document describing this test program. Notably, the test specification contains absolutely no plans for modeling or testing of transformer vibration—only thermal modeling and testing is planned. It is doubtful that the NERC test program will find transformer vibration to be a potential failure mode, especially if there is no requirement for vibration instrumentation in the test specification.

In summary, the specific example of a “loose bolt” transformer failure at Seabrook immediately after a GMD event—now augmented with additional disclosure of significant “growling" of the Seabrook and Point Beach transformers during GMD events—shows that transformer vibration cannot be discounted as a possible GMD failure mode. Empirical data from the Minnesota Power tests of power transformers show large increases in audible noise during even moderate levels of DC injection.

Inadequate Warning Time from GIC Readings for Operating Procedures

GMD Operating Procedures commonly have operator action “triggers” or “thresholds” based on NOAA solar storm forecasts relying on satellite data or, alternatively, GIC readings within control areas. For example, the GMD Operating Procedures of ISO-New England contain these triggers:

> <u>**Condition(s) to perform this step:**</u>
>
> Notification of an Actual GMD event of intensity 7 or greater with GIC activity of 10 Amps or greater.
>
> Or notified of a GMD Alert of intensity 7 or greater with a probability of 40% or greater with GIC activity of 10 Amps or greater.

As part of its charter to study GMD and develop recommendations, the GMD Task Force of NERC produced a Geomagnetic Disturbance Operating Procedure Template for Transmission Operators and another largely similar template for Generation Operators. Both NERC GMD Operating Procedure Templates were approved by the NERC Planning Committee on March 6, 2013.

The "triggers" of the Transmission Operators Template are:

> The following are triggers that could be used to initiate operator action:
>
> - External:
>   - NOAA Space Weather Prediction Center or other organization issues:
>   - Geomagnetic storm Watch (1-3 day lead time)
>   - Geomagnetic storm Warning (as early as 15-60 minutes before a storm, and updated as solar storm characteristics change)
>   - Geomagnetic storm Alert (current geomagnetic conditions updated as k-index thresholds are crossed)
> - Internal:
>   - Generator:
>   - Reactive power reserves
>   - System voltage/MVAR swings/current harmonics

- Generator Step-Up (GSU) Transformer:
    - GIC measuring devices
    - Abnormal temperature rise (hot-spot) and/or sudden significant gassing (where on-line DGA available)
    - MVAR losses

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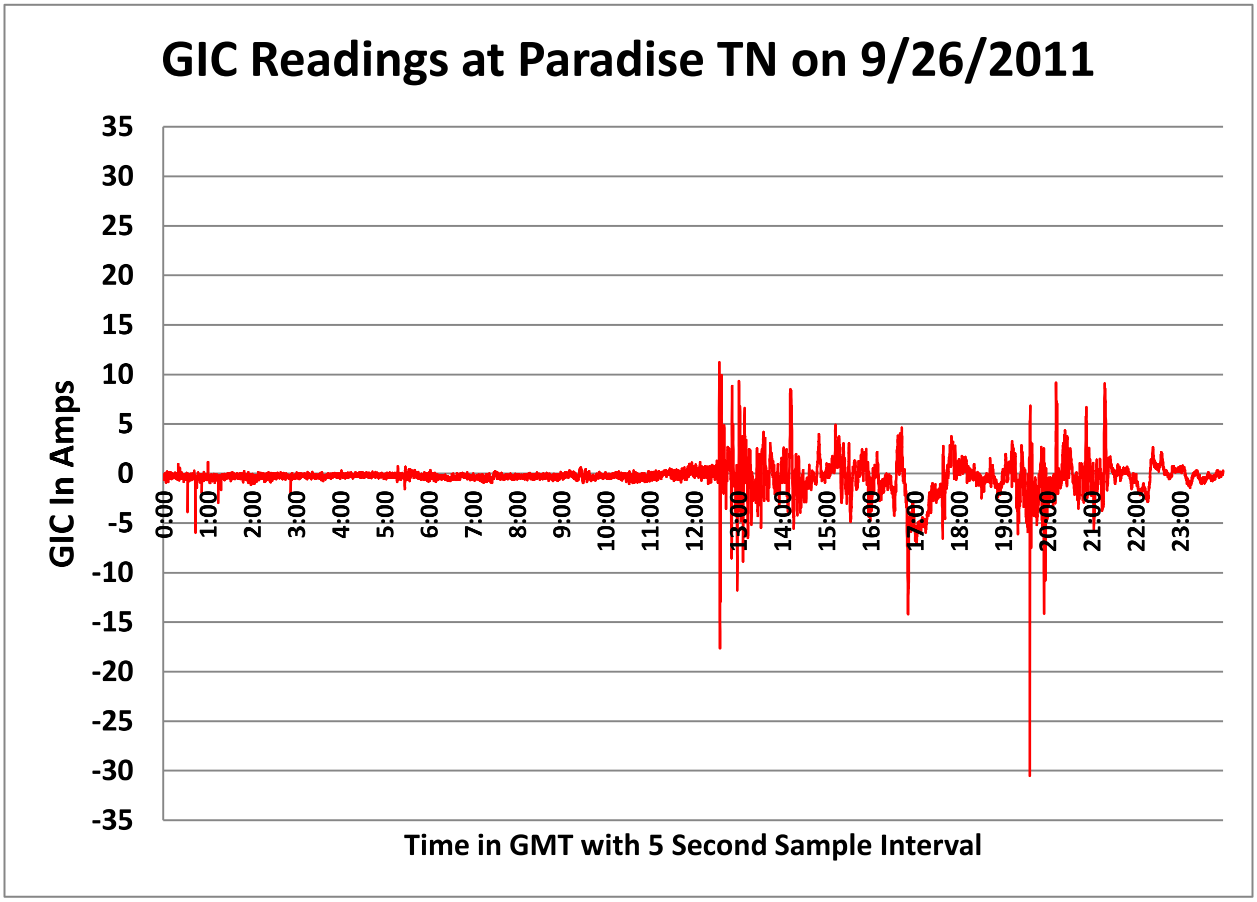
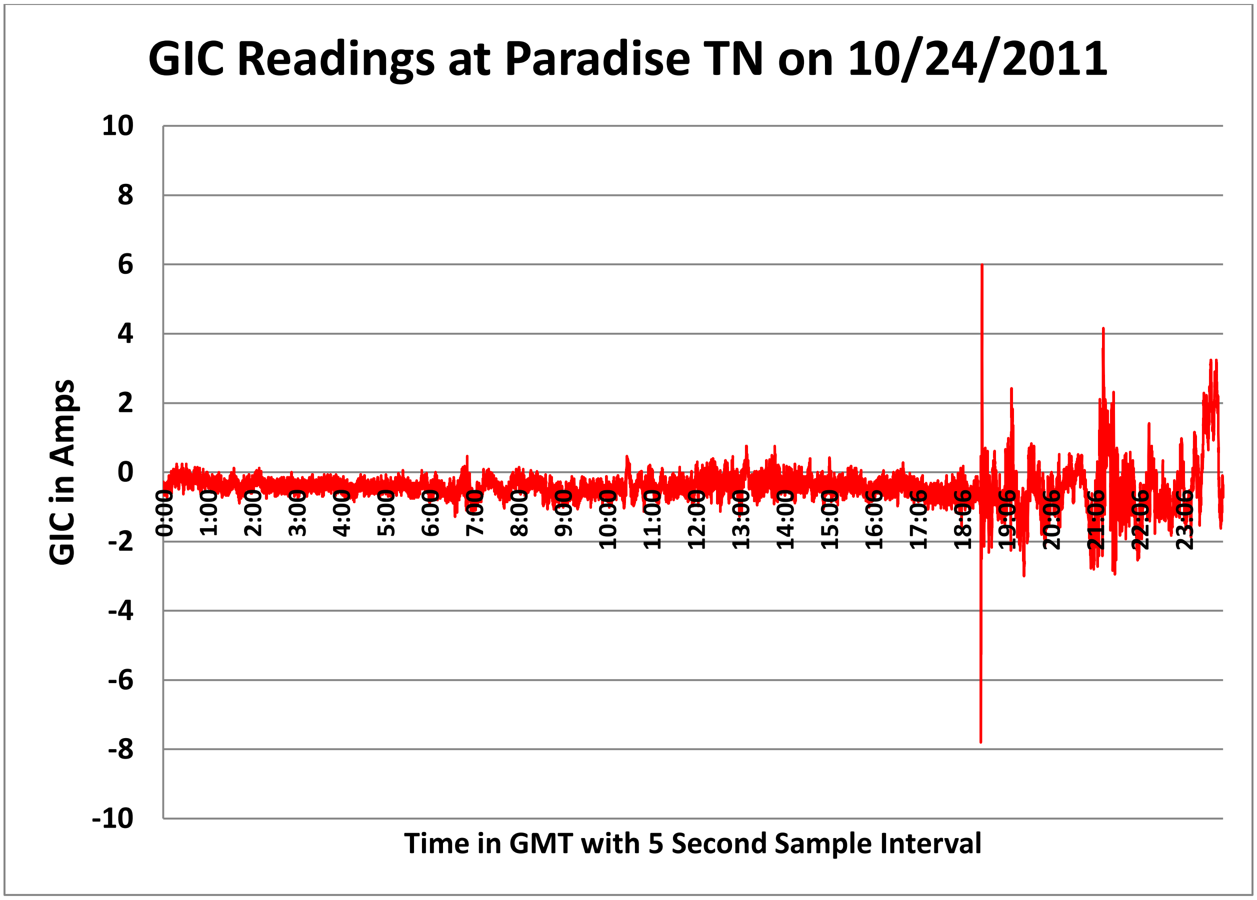
    - Geomagnetic storm Warning (as early as 15-60 minutes before a storm, and updated as solar storm characteristics change)
    - Geomagnetic storm Alert (current geomagnetic conditions updated as k-index thresholds are crossed)
- Internal:
    - System-wide:
        - Reactive power reserves
        - System voltage/MVAR swings/current harmonics
    - Equipment-level:
        - GIC measuring devices
        - Abnormal temperature rise (hot-spot) and/or sudden significant gassing (where on-line DGA available) in transformers
        - System or equipment relay action (e.g., capacitor bank tripping)

The current scientific consensus is that a satellite in the Lagrange 1 orbital position would give approximately ten minutes warning of a fast-moving 1-in-100-year solar storm of intensity equivalent to the 1921 Railroad Storm or the 1859 Carrington Event. Therefore, "GIC measuring devices" might give the only alternative advance warning, as other "triggers"—such as voltage, MVAR, harmonics, hot-spot measurements, and transformer gassing—are real-time indicators, not advance warnings. Our Foundation set out to investigate the realistic warning time that GIC readings might provide operators.

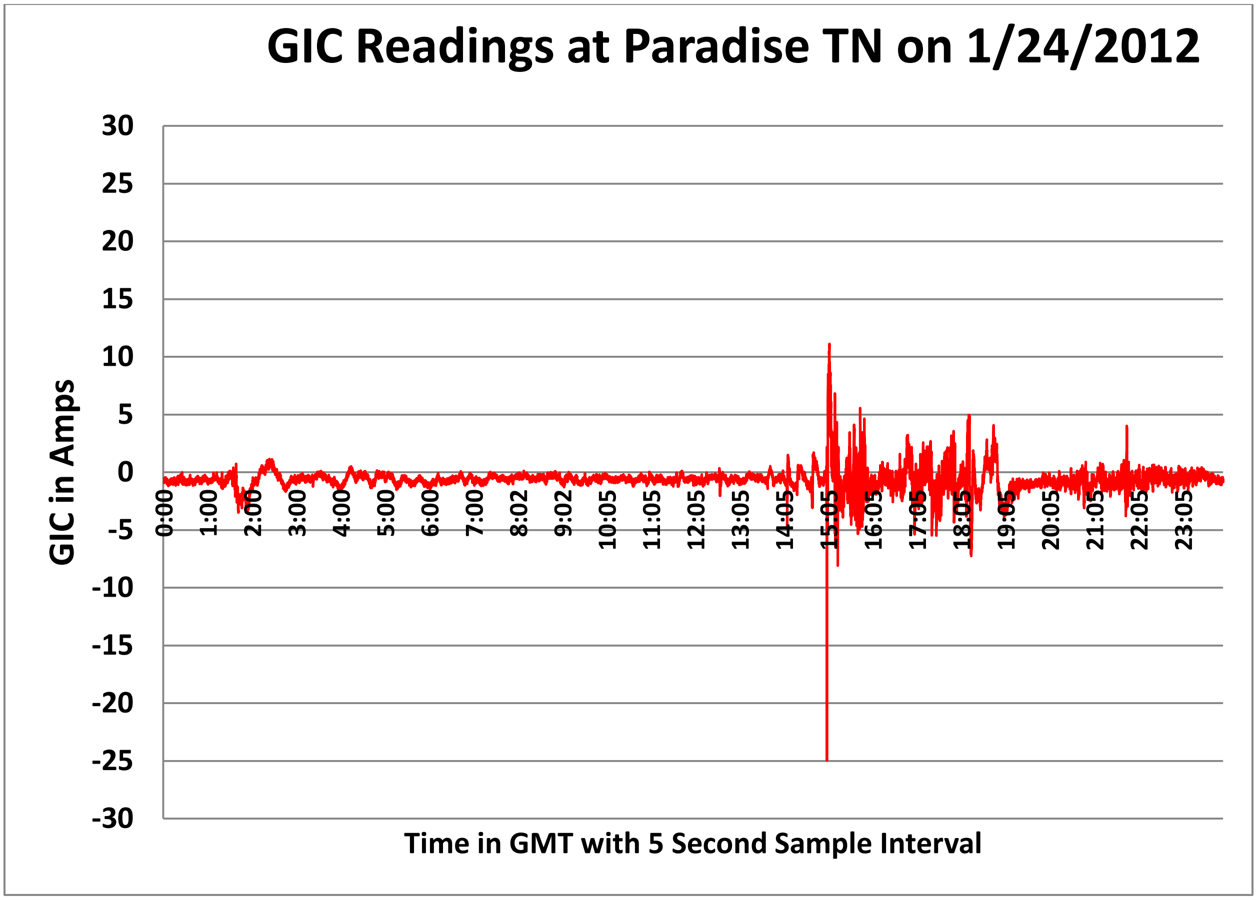
The Foundation for Resilient Societies made a request under the Freedom of Information Act for GIC readings at sites controlled by the TVA. We obtained GIC readings for the Paradise, Tennessee generation facility for five solar storms during 2011 and 2012. TVA should be commended for prudently installing GIC monitors and making the readings available in a usable electronic format. Graphical data for GIC readings at Paradise is presented below.



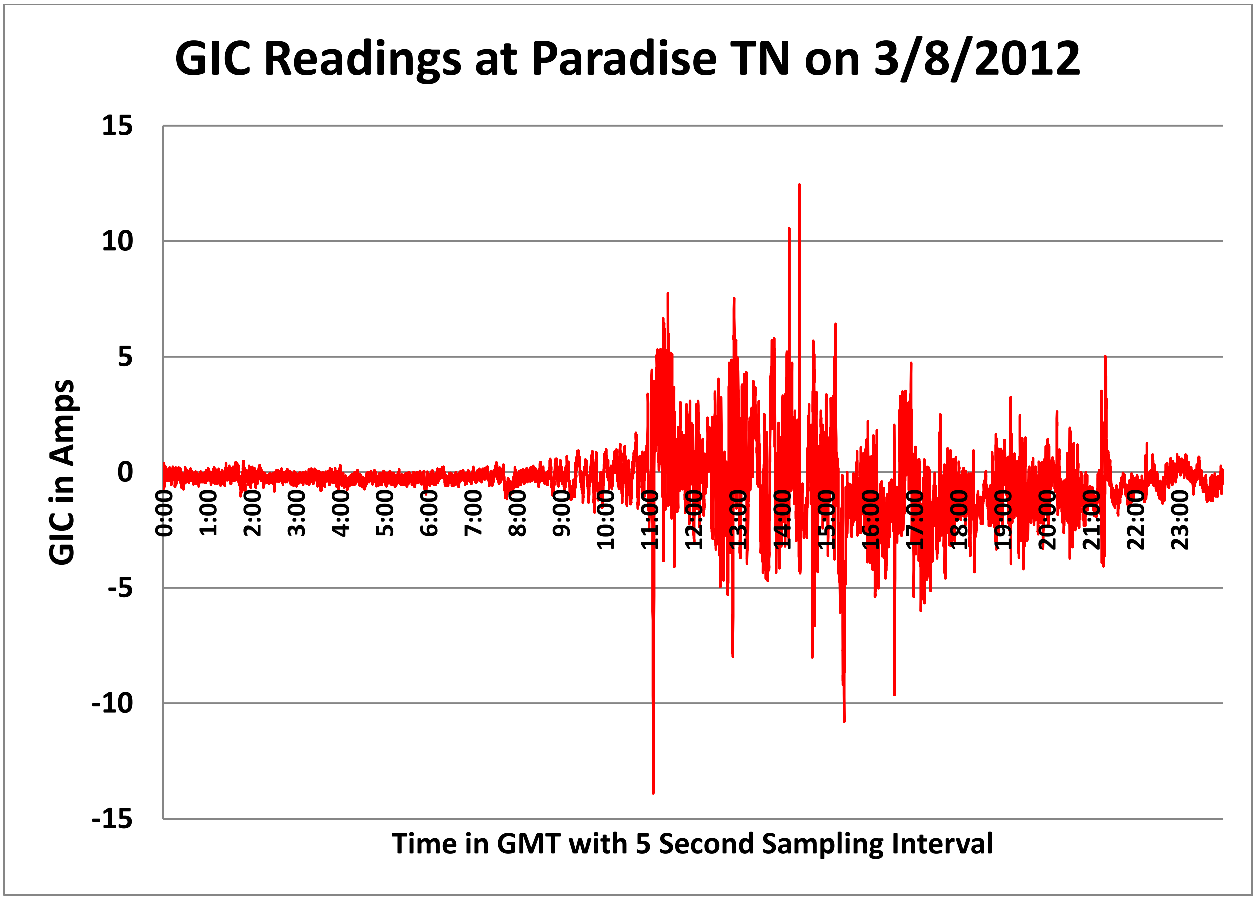
The September 26, 2011 solar storm commenced with a pulse shortly after 12:35 GMT. Absolute value GIC readings rose from 0.18 amps at 12:35:00 GMT to a peak of 17.64 amps in approximately 2 minutes.



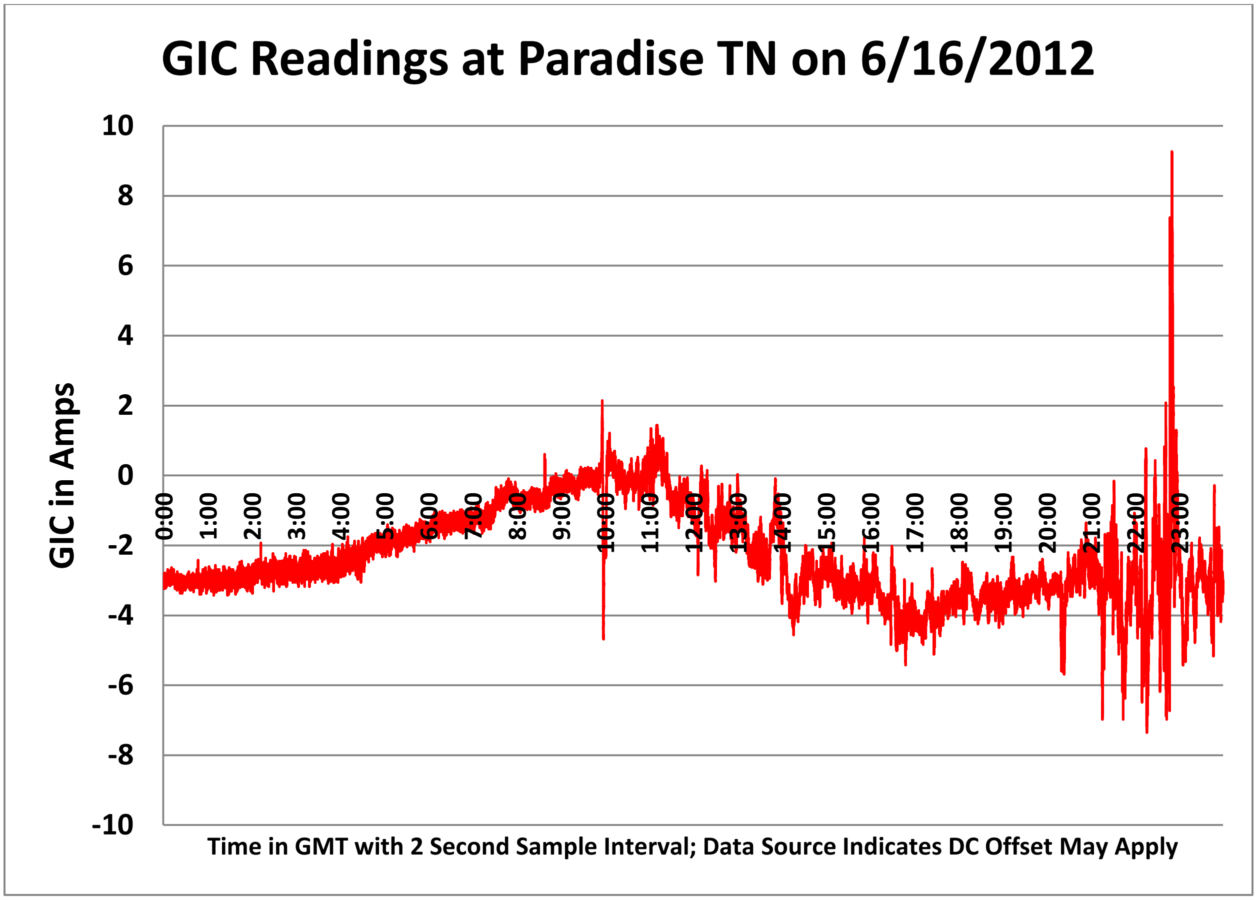
The October 24, 2011 solar storm commenced with a pulse shortly after 18:31 GMT. Absolute value GIC readings rose from 0.76 amps at 18:31:00 GMT to a peak of 7.55 amps in less than 2 minutes.



The January 1, 2012 solar storm commenced with a pulse shortly after 15:03 GMT. Absolute value GIC readings rose from 0.55 amps at 15:03:00 GMT to a peak of 24.95 amps in 25 seconds.



The March 8, 2012 solar storm commenced with a pulse shortly after 11:03 GMT. Absolute value GIC readings rose from 0.73 amps at 11:03:00 GMT to a peak of 13.84 amps in less than 4 minutes.



The July 16, 2012 solar storm had a gradual onset. A large positive spike of 9.27 amps at approximately 22:50 GMT might have been anticipated by a smaller negative GIC spike at approximately 9:57 GMT and a gradual rise in GIC starting at approximately 4:00 GMT.

In summary, for this sample of solar storms experienced at the Paradise site, GIC readings would not have given reasonable advance warning of sudden GIC spikes for four out of five storms.

It is the position of the Foundation for Resilient Societies that GIC readings during solar storms are similar to measurements of other naturally-occurring phenomena, such as earthquakes, floods, and hurricanes. Information on hazards to the public should be publicly disclosed. The TVA data used in this GMD warning time analysis can be downloaded at this link:

http://www.resilientsocieties.org/gicreadings.html

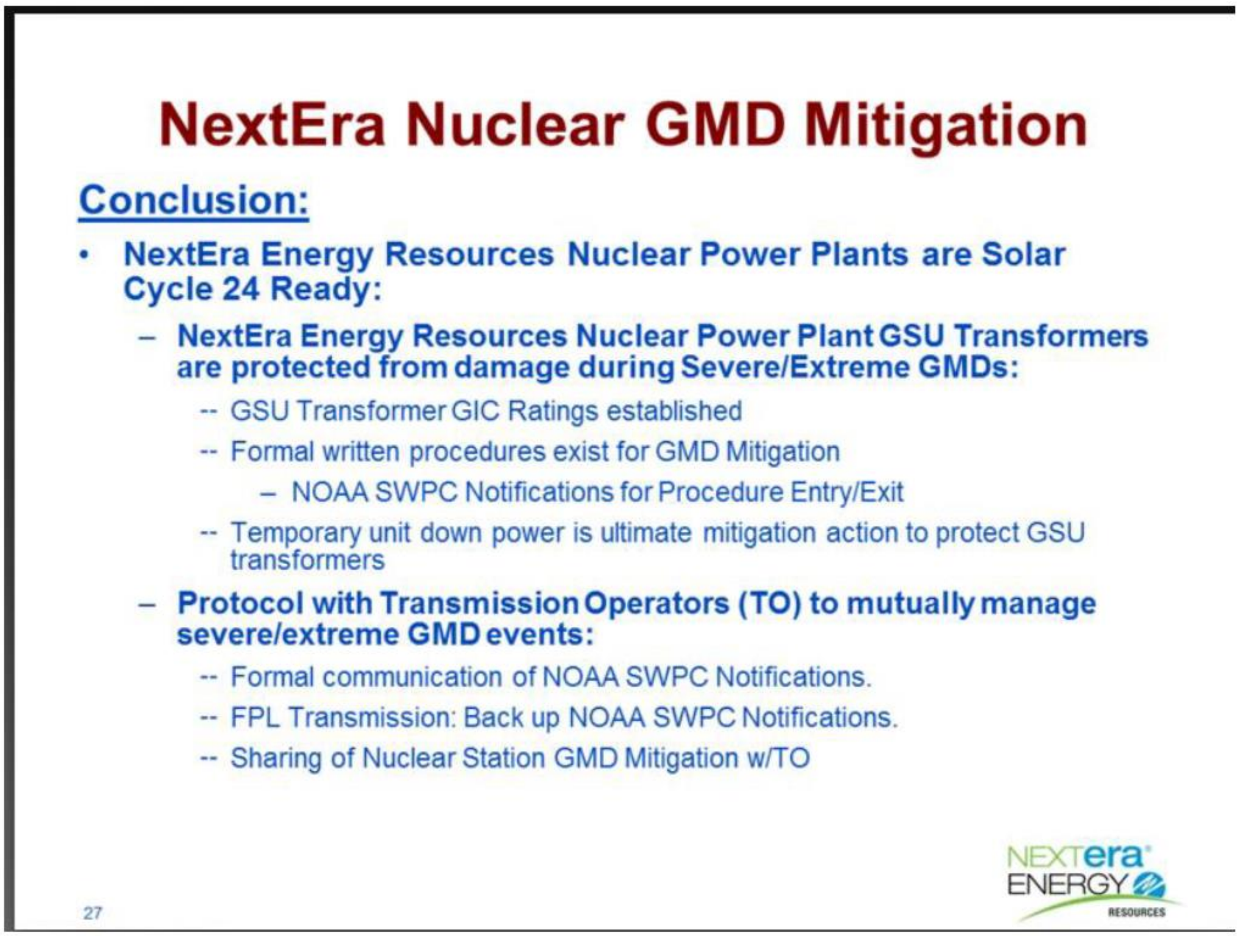
We encourage other electric utilities to make public their GIC readings.

Conflicting Goals of GMD Operating Procedures and GSU Transformer Protection

GMD Operating Procedures for regional balancing authorities typically specify system posturing, including increase of reactive power and operating reserves. An example would be the operator actions specified in the ISO-New England GMD Operating Procedures (yellow highlighting added):

> **Step 1.9 Determine if any actions will be taken.**
>
> **Instructions**
>
> While determining what actions to take the Operations Shift Supervisor may consult LCCs; neighboring RC/BA; GMD monitoring sites; Manager, Control Room Operations; or the Director, Operations to help with evaluating the situation.
>
> The following are possible actions that could be taken:
>
> a. Discontinue maintenance work and restore out of service high voltage transmission lines. Avoid taking long lines out of service
> b. Maintain system voltages within acceptable operating range to protect against voltage swings
> c. Review the availability of the Chester SVC and capacitor banks to respond to voltage deterioration if necessary
> d. Adjust the loading on Phase II, the Cross Sound Cable and Highgate HVdc ties to be within the 40% to 90% range of nominal rating of each pole
> e. Reduce the loading on Inter-RCA/BAA ties and on other internal critical transmission lines and interfaces to 90%, or less, of their security limits
> f. Do not lower TMSR below 50%, spinning units online will provide more reactive reserves. If geomagnetic activity is severe enough consider increasing TMSR forcing more units with reactive reserves online.
> g. Consider posturing Generators operating at their Eco Max to provide room for reserves and reactive capacity in accordance with CROP.25001 Posturing.
> h. Dispatch generation to manage system voltage, tie line loading and to distribute operating reserve
> i. Bring equipment capable of synchronous condenser operation on line to provide reactive power reserve
> j. In conjunction with personnel at those locations where GMD measurements are to be taken, ensure the monitoring equipment is in service
> k. Closely monitor RTCA Voltage contingencies and consider the impact of tripping large shunt and series capacitor banks and static VAR compensators.
> l. If conditions are severe enough, consult with LCCs and consider reclosing tripped capacitor banks and SVCs ASAP that are likely tripped by erroneous relay action and not damage.

An implicit goal of the ISO-New England GMD Operating Procedures is to prevent load shedding and cascading blackout by increasing generation. At the same time, generation operators within New England with vulnerable GSU transformers plan to avoid equipment damage by reducing generation. An example would be NextEra Energy, operator of the Seabrook, New Hampshire nuclear power plant. The Seabrook plant is contained within the ISO-New England control area. A slide from the NextEra presentation at the April 16, 2013 Space Weather Workshop summarizes their "GMD Mitigation" procedures:



Note that NextEra specifically states "Temporary unit down power is the ultimate mitigation action to protect GSU transformers." The GMD mitigation procedures of NextEra are not unique; an investigation by the NRC revealed that PSEG, operator of the Salem 1, Salem 2, and

Hope Creek nuclear plants in New Jersey has also employed downrating of GSU transformers during solar storms.[9]

It is operationally implausible for regional balancing authorities to dispatch generation to provide real and reactive power reserves at the same time that generation operators are downrating GSU transformers, especially within very short warning times of 10 minutes or less provided by satellite-based forecasts and GIC readings. Such imprudent and unrealistic Operating Procedures are a recipe for control room chaos, uncontrolled load shedding, and cascading blackout.

The areas of the United States most exposed to GMD—the Northeast and Pacific Northwest—also have baseload power supplied by nuclear power plants. These plants depend on a reliable bulk power system for safe operation. If nuclear plants experience loss of outside power in the chaos of a severe GMD event, emergency reactor shutdowns are required by NRC regulation. If backup diesel generators do not reliably function, reactor core heating and spent fuel boiling can occur, as the events at the Fukushima Daiichi nuclear plants amply showed. Geomagnetic disturbance is not a just a threat to Bulk-Power System reliability, but also a threat to nuclear safety.

[9] See pages 15-16 of "Commonsense Appeal to the FERC Commissioners for Action on a Regulatory Standard for Solar Storm Protection" filed on FERC docket AD12-13-000 by the Foundation for Resilient Societies.

SUMMARY CONCLUSIONS

Real-world experience at Central Maine Power shows that Operating Procedures do not reliably prevent equipment tripping. Any FERC Order for GMD protection should include mitigation of harmonics produced by transformer half-cycle saturation, especially when harmonic currents can cause tripping of susceptible equipment such as SVCs and capacitor banks. SVC tripping due to harmonics was the immediate cause of the March 1989 Hydro-Quebec Blackout that cascaded in only 93 seconds.

The specific example of a transformer failure at Seabrook possibly caused by GIC-induced vibration—now augmented with disclosure of significant “growling" of the Seabrook and Point Beach transformers during GMD events—shows that transformer vibration cannot be discounted as a potential GMD failure mode. Any FERC Order for GMD protection should include appropriate investigation of transformer vibration as a potential failure mode and partial power reduction as a mitigation measure.

Real-world data shows GIC readings do not reliably give advance warning of sudden GIC spikes. Nor can a satellite in the Lagrange 1 Orbital Position, such as the ACE satellite, reliably give advance warning of greater than 10 minutes for exceptionally severe and fast-moving solar storms. Any FERC Order for GMD protection should prohibit Operating Procedures containing "triggers" for operator action that rely on unrealistic, non-actionable warning times from GIC monitors and satellite-based space weather forecasts.

It is logically inconsistent for regional balancing authorities to dispatch reserve generation at the same time that generation operators are taking their own actions to downrate GSU transformers. Any FERC Order for GMD protection should prohibit Operating Procedures of regional balancing authorities that fundamentally conflict with the GMD mitigation procedures of generation operators.

The Supplemental Comments of April 29, 2013 submitted by John G. Kappenman of Storm Analysis Consultants, Inc. use models to assert that, even if there were to be sufficient advance warning of solar storms, partial power reduction as specified in some Operating Procedures is an unworkable remedy. According to the Kappenman comment, downrating of electric generation, while a sure cause of lost revenue, would not significantly reduce transformer half-cycle saturation. As a result, harmonic production and equipment tripping, transformer overheating and vibration, reactive power consumption, and other hazards to Bulk-Power System reliability would persist. These models should be confirmed by further analytic and empirical study.

At this time, there is no practical Operating Procedure substitute for hardware to automatically block GIC from entering the Bulk-Power System, including hardware to block GIC from entering transformer neutrals. Idaho National Laboratory tested a neutral blocking device in late 2012. Test results will be publicized in a forthcoming paper, "Power Grid Protection against Geomagnetic Disturbances (GMD)" to be presented at the "2013 IEEE Power & Energy Society General Meeting." The paper discloses a critical result of the Idaho National Laboratory test; namely, that the neutral blocking system effectively blocked the injected DC current and as a result transformer vibrations and the generation of harmonics were eliminated.[10] In contrast, GMD Operating Procedures cannot claim to eliminate transformer vibrations and generation of harmonics. A brochure from the vendor ABB also indicates that the tested neutral blocking system will prevent generation of harmonics.[11] In contrast, Operating Procedures will only attempt to bolster reactive power reserves, manage transformer heating, and execute contingency plans to compensate for critical equipment tripped out due to harmonics—and are remotely feasible only for storms without rapid GIC spikes.

[10] F. R. Faxvog, et al., "Power Grid Protection against Geomagnetic Disturbances(GMD)," at page 6, forthcoming (July 2013), IEEE Power & Energy Society, Vancouver, BC, Canada, July 21-25, 2013.

[11] ABB's "Technical Data on SolidGround," ABB Brochure SG-22-2GNM110098 at page 3 (2013) indicates that in "GIC mode" the protective equipment "effectively blocks geomagnetic induced currents" which prevents both "transformer half wave saturation" and "generation of harmonics on power lines."

The experience of Central Maine Power shows that GMD Operating procedures are deficient during even moderate storms, such as the August 24, 2005 storm where the Chester SVC, providing reactive power support to 2,700 MW of transmitted power, tripped out. Unresolved issues with GMD Operating Procedures, including ineffective mitigation of harmonic production and transformer vibration, would likely make Operating Procedures spectacularly ineffective during severe solar storms.

The FERC Commissioners should not permit use of technically deficient GMD Operating Procedures that will not protect Bulk-Power System reliability, but instead provide a false sense of security to a trusting public. The FERC Commissioners should continue to require automatic blocking of geomagnetically induced currents from entering the Bulk-Power System, as proposed in the current NOPR, because automatic blocking is the only comprehensive and effective GMD mitigation measure.

Respectfully submitted by:

Thomas S. Popik, Chairman, and

William R. Harris, Secretary, for the

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Appendix 1

CENTRAL MAINE POWER COMPANY
SMD ACTIVITY ARCHIVE
August 1991 to Present Date

(Chester SVC SUNBURST equipment in service since March of 91)

Storm Rating (Top 10)	Event Date	Chester SVC Transformer DC Neutral (A)	Storm Severity	Comments
1	**3/13/89**	**N/A**	**Severe**	**Hydro Quebec Blackout – All Orrington caps trip; Yarm 4 and MY gen vars went over +300 MVAR each; Orrington caps would not close back in**
	6/5/91	42.9	Major	Impacts to CMP unknown/not documented
	6/17/91	31.7	Major	Impacts to CMP unknown/not documented
	7/9/91	20.7	Moderate	Impacts to CMP unknown/not documented
	7/13/91	27.4	Moderate	Impacts to CMP unknown/not documented
	10/1/91	27.7	Moderate	Impacts to CMP unknown/not documented
	10/29/91	45	Major	Impacts to CMP unknown/not documented
	11/8/91	47	Major	Impacts to CMP unknown/not documented
	2/3/92	47.5	Major	Impacts to CMP unknown/not documented
	2/8-27/92	51.2	Major	Impacts to CMP unknown/not documented
	5/10/92	50	Major	Impacts to CMP unknown/not documented
	4/5/93	19.9	Moderate	Impacts to CMP unknown/not documented
	9/13/93	26.2	Moderate	Impacts to CMP unknown/not documented
	2/21/94	31	Major	Impacts to CMP unknown/not documented
	4/17/94	18	Moderate	Impacts to CMP unknown/not documented
	5/2/94	33.5	Major	Impacts to CMP unknown/not documented
	8/23/92	33.8	Major	Impacts to CMP unknown/not documented
	2/21/94	31	Major	Impacts to CMP unknown/not documented
	5/1/94	33.5	Major	Impacts to CMP unknown/not documented
	9/8/94	42	Major	Impacts to CMP unknown/not documented
4	**5/4/98**	**74.3**	**Severe**	**2 caps tripped at Orrington; Orrington Bus @ 328kV**
8	**10/22/99**	**61.3**	**Severe**	**NKI**
	1/28/00	-12	Minor	NKI
	2/12/00	-12	Minor	NKI
3	**4/6/00**	**81.7**	**Severe**	**SVC filter banks trip; distribution customers UPS's not functioning properly in North Coastal areas**
	5/24/00	52	Major	NKI
2	**7/15/00**	**-76**	**Severe**	**MS2 declared by ISO; Orrington KC3 trip; 7kV swing on 345kv system; many Auto xfmr LTC operations**
10	8/11/00	42.8	Major	**Surowiec KC2 trip - no apparent reason other than due to GIC**
9	9/17/00	-59.5	Major	NKI
	10/5/00	-28.4	Moderate	NKI
	12/00	N/A	N/A	Entire month of December saw constant minimal activity; nothing greater than 5A neutral peak and 4.1 6th harm peak but activity was present entire month

CENTRAL MAINE POWER COMPANY
SMD ACTIVITY ARCHIVE
August 1991 to Present Date

Chester SVC SUNBURST equipment in service since March of 91)

Storm Rating (Top 10)	Date	Chester SVC Transformer DC Neutral (A)	Storm Severity	Comments
6	**3/30/01**	**76.2**	**Severe**	**MIS G1 trip but think it was due to faulty control board – no other evidence for trip**
	4/11/01	-30.9	Major	NKI
	6/13/01	32.6	Major	May be an anomaly – one time spike with very little activity before or after spike
	6/21/01	173.4 ???	**Severe**	May be an anomaly – one time spike with very little activity before or after spike
	6/25/01	<5		Spike of 6th harm and very little neutral current flowing
	9/30/01	19.3	Moderate	NKI
	10/21/01	-21.5	Moderate	NKI
7	**11/5/01**	**63.6**	**Severe**	NKI
5	**11/24/01**	**89.9**	**Severe**	**Chester SVC filter banks trip**
	4/17-18/02	-15.0	Moderate	NKI
	4/19-20/02	21.1	Moderate	NKI
	9/4/02	17.0	Moderate	NKI
	5/29-30/03	60.6	**Severe**	NKI; 5/29/03; Kp of 8
	10/24 to 11/5/03	-98.0	**Severe**	NKI; 10/29/03 Very large GIC flow but no impacts seen by CMP
	7/24-27/04	52.5	Major	NKI; 7/27/04
	11/7-10/04	-88.0	**Severe**	NKI; 11/9/04
	1/17-22/05	52.2	Major	NKI; 1/21/05
	5/15/05	83.1	**Severe**	NKI
	8/24/05	96.9	**Severe**	Chester SVC Filter banks tripped
	9/11/05	33.4	Major	NKI
	12/14-15/06	37.5	Major	NKI; 12/14/06
	1/11-13/08	12.1	Minor	NKI; 1/11/08 Associated with Kp of 6
	1/17-19/08	39.9	Major	NKI; 1/18/08 Associated with Kp of 6
	3/25-28/08	8.6	Minor	NKI; 3/27/08 Associated with Kp of 6
	4/20 to 5/1/08	14.9	Minor	NKI; 4/20/08 Associated with Kp of 6
	3/31/09	10.5	Minor	
	6/24-25/09	7.1	Minor	NKI; 6/25/09 Associated with Kp of 6
	4/5-7/10	18.6	Moderate	NKI; 4/5/10 Associated with Kp of 6
	6/4/11	5.0	Minor	NKI
	6/5-8/11	9.6	Minor	NKI; 6/8/11 Associated with Kp of 6
	8/5-6/11	11.1	Minor	NKI; 8/5/11 Associated with Kp of 7
	9/9/11	3.7	Minor	NKI; Associated with Kp of 6
	9/26-27/11	24.7	Moderate	NKI; 9/26/11 Associated with Kp of 7
	10/24-25/11	22.1	Moderate	NKI; 10/24/12 Associated with Kp of 6

CENTRAL MAINE POWER COMPANY
SMD ACTIVITY ARCHIVE
August 1991 to Present Date

Chester SVC SUNBURST equipment in service since March of 91)

Storm Rating (Top 10)	Date	Chester SVC Transformer DC Neutral (A)	Event Severity	Comments
	1/24-25/12	7.3	Minor	NKI; 1/25/12 Associated with Kp of 6
	3/7-9/12	13.6	Minor	NKI; 3/9/12 Associated with Kp of 7
	3/12-15/12	5.7	Minor	NKI; 3/12/12 Associated with Kp of 6
	4/23-24/12	6.1	Minor	NKI; 4/23/12 Associated with Kp of 7
	6/16-18/12	20	Moderate	NKI; 6/16/12 Associated with Kp of 6
	7/13-16/12	5.4	Minor	NKI; 7/15/12 Associated with Kp of 6
	9/5/12	3.8		NKI; Associated with Kp of 6
	9/30 to 10/1/12	7.1	Minor	NKI; 10/1/12 Associated with Kp of 7
	10/8-11/12	12.6	Minor	NKI; 10/11/12 Associated with Kp of 6
	10/11/12	12.6	Minor	NKI; Associated with Kp of 6
	10/13/12	2.8		NKI; Associated with Kp of 6
	11/16/12	37.9	Major	NKI; Associated with Kp of 6
	11/14/12	6.3	Minor	NKI; Associated with Kp of 6

- Event Severity class based on Chester SVC SUNBURST 2000 GIC Recording standards/criteria
  - Storm ratings are based on magnitude of both the transformer neutral and 6th harmonic currents as well as the effect the storm had on CMP's system
- N/A – Chester SVC recording instrumentation not installed at this time or data not available
- NKI – No Known Impacts to grid

Appendix 2

Geomagnetic Disturbance Mitigation for Nuclear Generator Main Power Transformers

Kenneth R. Fleischer, P.E.

April 16, 2013

NextEra Nuclear GMD Mitigation

Background (Cont'd):

- **October 29, 2003 Solar Storm:**
  - Seabrook records 80A GIC on GSU Transformer
    - -- Note: Seabrook was returning from outage and Holding at 30% Power for Reactor Physics
  - Point Beach Unit 1 down powers (Unit 2 in Refueling Outage)
    - -- K-Index 9 issued from WE PSS to Point Beach Control Room
    - -- Peak GIC was 48A DC (varying between 9A and 48A)
      - "Significant Growling" reported in Operations Logs
    - -- Transmission Company opened one of the transmission lines reducing GIC to about 4A (GSU noise reduced)
    - -- GIC rises again to 68A DC
    - -- PBNP U1 reduced power between 70% - 84% for 54 hours.
      - 10/29/2003 @ 03:13 to 10/31/2003 @ 09:00.

NextEra Nuclear GMD Mitigation

Background (Cont'd):

Nuclear Solar Cycle 24 Readiness: Spring 2010

- GMD Assessments of Seabrook, Point Beach, Duane Arnold
- Seabrook historical evidence of elevated GSU neutral current readings during past storms (kept weekly records).
  - -- Also reported "growling" during solar storms
- Point Beach had GIC monitors on both GSU transformers
  - -- Only feed was to the former WEPCo Transmission Office
    - No local feed to the Point Beach Station Nuclear Control Room
  - -- Useful during days when Point Beach was regulated
  - -- Also reported "growling" during solar storms
- DAEC no historical information, was confirmed off-line during both March & Sept 1989 storms, so no Ops Logs records.

NEXTera ENERGY RESOURCES

NextEra Nuclear GMD Mitigation

Monitoring & Validation Period:

- **During majority of 2011 period, installed DC Hall Effect split-ring transducer during NOAA K-Index 6 WARNINGS.**
- **Seabrook and Point Beach confirmed GIC "Hot Spots"**
- **DAEC barely registered past 3A DC during Solar Cycle 24**
- **Seabrook has reached greater than 40A DC multiple times**
- **Point Beach reached 55.8A DC during the October 24 & 25, 2011 Solar Storm:**
  - Note: With one of the PBNP units in a refueling outage GIC on the remaining unit was double past GIC readings (Note: Kewaunee was on-line).
  - No down power required.
- **Over time, GMD procedures were improved (Lessons Learned) and NOAA K-Index Entry temporarily moved from K-7 to K-6**

NEXTera ENERGY RESOURCES

NextEra Nuclear GMD Mitigation

Solar Storm of July 15, 2012:

- **Highest NOAA ALERT: K-Index of 6**
- **Seabrook:**
  - Highest GIC peak: 40A DC
  - Three GIC peaks of 30A DC
  - First Down power from 85%* to 78%
  - Second Down power from 78% to 63%
  - Duration: 40 hours (long elevated GIC event)
    -- 7/14/2012 at 14:10 (EDT) to 7/16/2012 at 06:46 (EDT)
- **Point Beach:**
  - GIC not as significant in Wisconsin; however, storm registered
  - Both Units peaked approximately 3.5A DC

*Seabrook was derated to 85% power due to an unrelated issue with the main generator.

NEXTera ENERGY RESOURCES

NextEra Nuclear GMD Mitigation

Solar Storm of October 24 & 25, 2011:

- **Highest NOAA ALERT: K-Index of 6**
- **Point Beach:**
  - Point Beach Unit 2 GIC data peaked at 55.8A on October 24, 2011 at 8:27 PM (Central)
  - Point Beach Unit 1 was off-line for refueling outage
  - Kewaunee (5 miles north) was on-line
- **Significant GIC event duration was approximately 22 minutes (short duration)**
- **Seabrook:**
  - **No GIC data available as Seabrook was off-line in an outage**

NEXTera ENERGY RESOURCES

NextEra Nuclear GMD Mitigation

Conclusion:

- NextEra Energy Resources Nuclear Power Plants are Solar Cycle 24 Ready:
  - NextEra Energy Resources Nuclear Power Plant GSU Transformers are protected from damage during Severe/Extreme GMDs:
    - -- GSU Transformer GIC Ratings established
    - -- Formal written procedures exist for GMD Mitigation
      - NOAA SWPC Notifications for Procedure Entry/Exit
    - -- Temporary unit down power is ultimate mitigation action to protect GSU transformers
  - Protocol with Transmission Operators (TO) to mutually manage severe/extreme GMD events:
    - -- Formal communication of NOAA SWPC Notifications.
    - -- FPL Transmission: Back up NOAA SWPC Notifications.
    - -- Sharing of Nuclear Station GMD Mitigation w/TO

NEXTera ENERGY RESOURCES

Appendix 3

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Voluntary Survey

Geomagnetic Disturbance Task Force
Transformer Modeling

Voluntary Survey of Transmission Owners and Generator Owners: April 19 – May 17, 2013

Now Available

The Geomagnetic Disturbance Task Force Equipment Model Development and Validation team seeks voluntary participants for a transformer modeling project being coordinated under task 1.4 of the Phase 2 Project Plan. The survey will identify entities that agree to coordinate with equipment manufacturers of transformers entering service or who have instrumented transformers already in service to obtain magnetic and thermal models and participate in validation measurements. The test specification follows. This effort will contribute to development of tools for owners and operators to conduct Planning Assessments of the BES in the presence of geomagnetically-induced current (GIC).

GIC can potentially cause half-cycle saturation in transformers. This can lead to winding and structural element hot spots, which in turn may degrade the mechanical strength of winding insulation. However, if construction and design details of a transformer are known, it is possible to estimate the amount of winding and structural elements heating by mathematical modeling. Taking part in this survey will improve the tools available to the participating entities and the industry to plan and operate the power system in the presence of GIC.

Instructions

A voluntary survey is open through 8 p.m. Eastern on **Friday, May 17, 2013**. Please use this electronic form to provide responses to listed questions. If you experience any difficulties in using the electronic form, please contact Wendy Muller at wendy.muller@nerc.net.

Next Steps

The Geomagnetic Disturbance Task Force Equipment Model Development and Validation team will review survey responses and coordinate with selected participants for validation testing. Testing is planned to begin in 2013. Periodic updates on this project are presented at GMD Task Force meetings, webinars, and conference calls and at Planning Committee meetings.

Background

As described in the approved GMD Task Force Phase 2 Project plan, The GMDTF will review, and verify where applicable, the work products of NERC and other industry and scientific organizations in support of two key areas:

- Tools for assessing vulnerabilities
- Best practices in operations

More information is available by clicking here for the GMD Task Force project page.

RELIABILITY | ACCOUNTABILITY

NERC

For more information or assistance, please contact Mark Olson, NERC Staff, at mark.olson@nerc.net or at 404-446-9760.

North American Electric Reliability Corporation
3353 Peachtree Rd, NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

Survey Questions

1. Do you have any transformers (230 kV and above) that will go into service in 2013?

2. If the answer to 1 is yes, would you be willing to engage the manufacturer to
    a. Produce thermal and magnetic models for the transformers (specification in Appendix I)?
    b. Produce measurements to validate the modeling (specification in Appendix II)?

3. Do you have in-service transformers with internal fiber optic sensors placed to capture winding and metallic hot spot temperatures?

4. If the answer to 3 is yes, then

    a. Do these units have analytical thermal and magnetic models as defined in Appendix I?
    b. Do they have GIC monitors?
    c. Is var loss monitored?
    d. Are harmonics monitored (e.g., using differential protection IEDs)?

5. If the answer to 4 (a-d) is no, would you consider adding instrumentation and/or engaging the manufacturer to produce thermal and magnetic models?

6. Does your entity require funding support to participate in this survey?

Appendix I – Transformer model specification

In order to understand the effect of geo-magnetically induced currents on the performance of power transformers, designs should be subjected to analysis under quasi dc loading and when possible the transformer(s) shall be tested to verify the results of the analytical modeling.

The analysis shall identify the critical transformer internal hot spots resulting from the injection of the dc currents into the HV winding neutral while the transformer is energized and establish the relationship between dc current loading and the resulting hot spot temperature rise as a function of time, which will govern the transformer hot spot thermal behavior in the case of GIC exposure.

For the purpose of testing the transformer shall be equipped with fiber optic sensing.

I.1 Background Information

Injection of dc currents into transformer windings is known to cause asymmetrical half cycle saturation of the core to an extent dependent on the dc current level as well as core construction and nominal flux density. This results in a distorted, relative to the norm, leakage flux distribution internally to the transformer causing increased heating and therefore temperatures rise beyond design limits.

Excessive temperatures have a potential to accelerate cellulose insulation aging as well as produce undesirable gassing in oil, degrading dielectric properties of the dielectric circuit.

To assess the duty subjected on particular transformers when exposed to GIC events while in service, [Utility] requests vendors to perform analytical studies and full scale tests at the dc current injection levels as described below.

I.2 Performance Analysis Requirement

Conduct analytical studies using appropriate methodologies and tools. The following conditions shall be modeled:

1.2.1 With the transformer operating at no-load, impress a step increase in dc current of 10A/phase onto the HV winding neutral and determine hot spot temperature rise internal to the winding and other metallic components. Produce plots and tables (as electronic files) showing the change in temperature, as a function of time, for the winding hot spot temperatures and for all other internal components (i.e. core, tie-plates, clamps, magnetic shields and tank).

1.2.2 After reaching the temperature steady state value for each step of the impressed dc current, step the magnitude of the dc current back to zero (0) Amps and produce plots showing the resulting drop in temperature as a function of time reaching again a steady-state value. A sample of a plot is attached for information in Appendix 3.

The analysis shall be carried on until a steady-state temperature is reached (unless the hot spot temperature reaches the short term overloading hot spot limits specified in IEEE C57.91) or to the point when the temperature reached is such that the validity of the analytical algorithm becomes grossly suspect in which event further analysis need not to be continued.

1.2.3 Repeat the above calculations for per-phase step currents of 20A, 30A, 50A, 100A and 200A.

1.2.4 Repeat all the above stated calculations (clauses 3.1 & 3.2) when the transformer is rated at 100% load, 50% load and 25%load.

2. Deliverables Required

2.1 Report summarizing results of analysis and modeling

- Overview of work carried out
- Generic description of analytical methodology, software and modeling approach
- Identification of physical locations of internal hot spots and a comparison to the hot spots related to overload condition
- Graphs showing the calculated values of temperature versus time for all critical components analyzed as well as electronic files of numerical values
- Core magnetization characteristics, summary of flux density and exciting currents for all the cases analyzed as graphical plots as well digital values in electronic format
- Conclusions and recommendations

Appendix II - Test Requirements

1. General Test Requirements

The transformer under test (one unit) shall be equipped with a set of fiber optic sensors and a data acquisition unit to measure local hot spot temperatures under the condition of simultaneously applied ac excitation and dc injected current into the HV neutral.

The dc injected currents shall be applied in the range of 10-30 amps per phase in 10 amp increments (total of six measurements for step increase and step decrease measurements), followed by 50 A, 100 A and 200 A if practically possible. The ac excitation shall be at rated voltage.

The positioning of the fiber sensors shall be determined based on the results of calculations and analysis performed by the vendor and sensor locations shall be decided prior to the commencement of manufacture.

Dissolved gas analysis –DGA shall be taken following each GIC test (before and after the test) and analyzed by a third part laboratory (Morgan Schaffer). Reference criteria for the transformer thermal tests shall be for reference only and determined in consultation with the vendor following the completion of analysis.

GIC test shall be terminated immediately in case the temperature of the transformer components exceed limits stated in clause 4.4 of this specification.

The tests shall follow the routine thermal and dielectric tests.

2 Test Connections

2.1 The GIC test shall be performed with two transformers of the same type and design configured in a "back to back" connection to avoid injecting dc current into upstream ac excitation source. The HV terminals shall be connected together and the rated voltage and excitation current applied to the parallel connected LV terminals.

A dc current shall be injected into the grounded HV neutral of one transformer and circulated through the HV winding of the two transformers and back out the HV neutral (to ground) of the 2nd transformer.

The vendor shall provide a schematic diagram of the externally connected transformers under test.

2.2 Test Sequence and Duration

Following the completion of all dielectric tests, the transformer shall be set up for the GIC tests.

The first set of tests shall be conducted with rated excitation voltage applied and step increase in dc injection of 10 A per phase. Once the temperature reached the steady state value, the current shall be stepped back to 0 A while continuing to record temperatures until they again reach steady-state values. The above procedure shall be repeated for step currents of 20 A, 30 A, 50 A, 100 A and 200 A per phase (whatever is practically possible).

Test duration of the initial injection of 10 A step increase shall last till a steady state temperature value is reached, after which time the current will be stepped back to 0 A while continuing to record temperatures at all measurement points until they reach a steady state value. If the transformer is equipped with pumps, they shall be running during the GIC tests.

2.3 Test Measurements

During the test the following transformer characteristics shall be recorded and measured for each increment of injected dc current:

- Applied ac voltage
- Injected dc current
- Exciting per/phase winding current
- No load losses
- Exciting current harmonics (% and order to at least 11th harmonic) and total harmonic distortion
- Measured hot spot temperature rise of the internal transformer components (tie-plates, clamps, windings, core)
- Perform thermo-vision scanning of the transformer tank (walls and cover)
- Top & bottom transformer oil temperature
- Ambient temperature
- Measure transformer sound level at no-load (100% voltage) and a dc injection of 30A/phase (for information only)
- Record 3-phase active and reactive power consumption

Following the completion of all measurements, the hot spot temperatures shall be translated to take account of additional temperature rise under nameplate loading condition (oil temperature) along with explanation of the basis for doing so.

2.4 Test Criteria

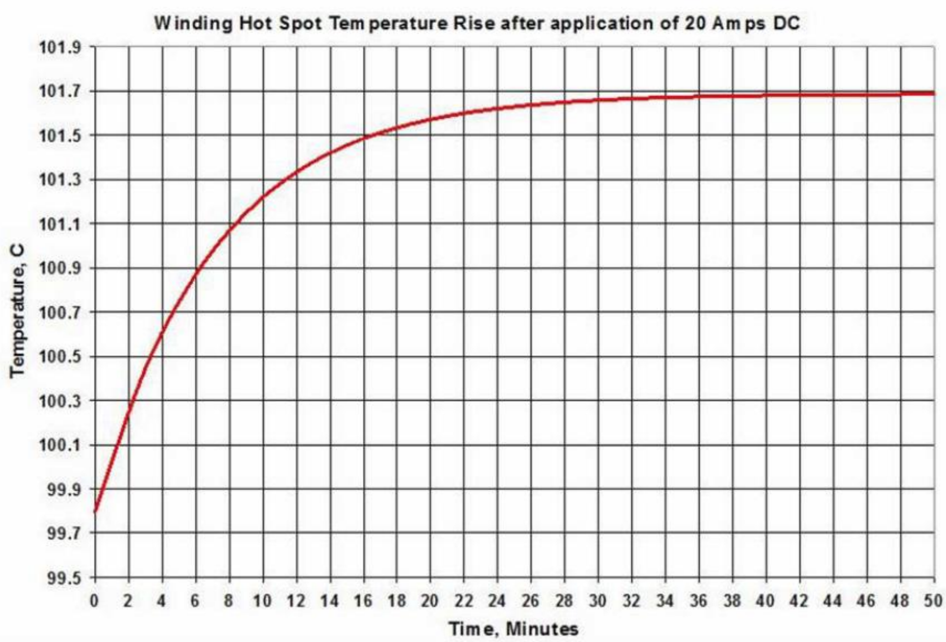
The hot spot criteria for winding hot spot and internal to the transformer metal components shall be referenced to the criteria stated for the transformer temperature limits for short time overload in IEEE C57.91:

- Windings - 180◦C
- Metal components adjacent to cellulose insulation - 180◦C
- Metal components not adjacent to cellulose insulation - 200◦C

3. Test Report

- Graphs and tabulated results (as electronic files) as per clause 4.0
- Pictures with identified locations of the fiber sensors
- Results of DGA for each case
- Conclusions

Appendix 3


Winding Hot Spot Temperature Rise after application of 20 Amps DC
Temperature, C
101.9
101.7
101.5
101.3
101.1
100.9
100.7
100.5
100.3
100.1
99.9
99.7
99.5
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
Time, Minutes