NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Conference Call Agenda

Project 2013-03 (Geomagnetic Disturbance) Standard Drafting Team

April 14, 2014 | 2:00 p.m. – 4:00 p.m. ET

Dial-in: 1.866.740.1260 | Access code: 6251541 | Security code: 0414
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Administrative

1. **Introduction and administrative**
2. **Determination of quorum***
3. **NERC Antitrust Compliance Guidelines and Public Announcement***
4. **Participant conduct policy***
5. **Email list policy***
6. **Review meeting agenda**

Agenda

1. **Chair introductory remarks** - Frank Koza
2. **Review Benchmark GMD Event whitepaper* (30 min)**
3. **Review draft Transformer Assessment whitepaper* (20 min)**
4. **Review initial draft planning standard (TPL-007-1) and VRF/VSLs* (30 min)**
5. **Review initial draft Implementation Plan* (10 min)**
6. **Discuss comment form questions (10 min)**
7. **Review project schedule and future meetings**
    a. June 3-6 (Atlanta)
    b. August 19 – 22 (Toronto)
8. **Review action items**
9. **Adjourn**

*Background materials included.

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Antitrust Compliance Guidelines

I. General

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

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

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

II. Prohibited Activities

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

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

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

III. Activities That Are Permitted

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

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

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

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

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

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

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

Public Announcements

REMINDER FOR USE AT BEGINNING OF MEETINGS AND CONFERENCE CALLS THAT HAVE BEEN PUBLICLY NOTICED AND ARE OPEN TO THE PUBLIC

Conference call version:
Participants are reminded that this conference call is public. The access number was posted on the NERC website and widely distributed. Speakers on the call should keep in mind that the listening audience may include members of the press and representatives of various governmental authorities, in addition to the expected participation by industry stakeholders.

Face-to-face meeting version:
Participants are reminded that this meeting is public. Notice of the meeting was posted on the NERC website and widely distributed. Participants should keep in mind that the audience may include members of the press and representatives of various governmental authorities, in addition to the expected participation by industry stakeholders.

For face-to-face meeting, with dial-in capability:
Participants are reminded that this meeting is public. Notice of the meeting was posted on the NERC website and widely distributed. The notice included the number for dial-in participation. Participants should keep in mind that the audience may include members of the press and representatives of various governmental authorities, in addition to the expected participation by industry stakeholders.

Standards Development Process Participant Conduct Policy

I. General

To ensure that the standards development process is conducted in a responsible, timely and efficient manner, it is essential to maintain a professional and constructive work environment for all participants. Participants include, but are not limited to, members of the standard drafting team and observers.

Consistent with the NERC Rules of Procedure and the NERC Standard Processes Manual, participation in NERC's Reliability Standards development balloting and approval processes is open to all entities materially affected by NERC's Reliability Standards. In order to ensure the standards development process remains open and to facilitate the development of reliability standards in a timely manner, NERC has adopted the following Participant Conduct Policy for all participants in the standards development process.

II. Participant Conduct Policy

All participants in the standards development process must conduct themselves in a professional manner at all times. This policy includes in-person conduct and any communication, electronic or otherwise, made as a participant in the standards development process. Examples of unprofessional conduct include, but are not limited to, verbal altercations, use of abusive language, personal attacks or derogatory statements made against or directed at another participant, and frequent or patterned interruptions that disrupt the efficient conduct of a meeting or teleconference.

III. Reasonable Restrictions in Participation

If a participant does not comply with the Participant Conduct Policy, certain reasonable restrictions on participation in the standards development process may be imposed as described below.
If a NERC Standards Developer determines, by his or her own observation or by complaint of another participant, that a participant's behavior is disruptive to the orderly conduct of a meeting in progress, the NERC Standards Developer may remove the participant from a meeting. Removal by the NERC Standards Developer is limited solely to the meeting in progress and does not extend to any future meeting. Before a participant may be asked to leave the meeting, the NERC Standards Developer must first remind the participant of the obligation to conduct himself or herself in a professional manner and provide an opportunity for the participant to comply. If a participant is requested to leave a meeting by a NERC Standards Developer, the participant must cooperate fully with the request.

Similarly, if a NERC Standards Developer determines, by his or her own observation or by complaint of another participant, that a participant's behavior is disruptive to the orderly conduct of a teleconference in progress, the NERC Standards Developer may request the participant to leave the teleconference. Removal by the NERC Standards Developer is limited solely to the teleconference in progress and does not extend to any future teleconference. Before a participant may be asked to leave the teleconference, the NERC Standards Developer must first remind the participant of the obligation to conduct himself or herself in a professional manner and provide an opportunity for the participant to comply. If a participant is requested to leave a teleconference by a NERC Standards Developer, the participant must cooperate fully with the request. Alternatively, the NERC Standards Developer may choose to terminate the teleconference.

At any time, the NERC Director of Standards, or a designee, may impose a restriction on a participant from one or more future meetings or teleconferences, a restriction on the use of any NERC-administered list server or other communication list, or such other restriction as may be reasonably necessary to maintain the orderly conduct of the standards development process. Restrictions imposed by the Director of Standards, or a designee, must be approved by the NERC General Counsel, or a designee, prior to implementation to ensure that the restriction is not unreasonable. Once approved, the restriction is binding on the participant. A restricted participant may request removal of the restriction by submitting a request in writing to the Director of Standards. The restriction will be removed at the reasonable discretion of the Director of Standards or a designee.

Any participant who has concerns about NERC’s Participant Conduct Policy may contact NERC’s General Counsel.

NERC Email List Policy

NERC provides email lists, or "listservs," to NERC committees, groups, and teams to facilitate sharing information about NERC activities; including balloting, committee, working group, and drafting team work, with interested parties. All emails sent to NERC listserv addresses must be limited to topics that are directly relevant to the listserv group's assigned scope of work. NERC reserves the right to apply administrative restrictions to any listserv or its participants, without advance notice, to ensure that the resource is used in accordance with this and other NERC policies.

Prohibited activities include using NERC-provided listservs for any price-fixing, division of markets, and/or other anti-competitive behavior.[1] Recipients and participants on NERC listservs may not utilize NERC listservs for their own private purposes. This may include announcements of a personal nature, sharing of files or attachments not directly relevant to the listserv group's scope of responsibilities, and/or communication of personal views or opinions, unless those views are provided to advance the work of the listserv's group. Use of NERC's listservs is further subject to NERC's Participant Conduct Policy for the Standards Development Process.

- *Updated April 2013*

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[1] Please see NERC's Antitrust Compliance Guidelines for more information about prohibited antitrust and anti-competitive behavior or practices. This policy is available at http://www.nerc.com/commondocs.php?cd=2

Project 2013-03
Geomagnetic Disturbance Mitigation
Standard Drafting Team

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Benchmark Geomagnetic Disturbance Event Description

Project 2013-03 GMD Mitigation
Standard Drafting Team
Draft: April 14, 2014

RELIABILITY | ACCOUNTABILITY

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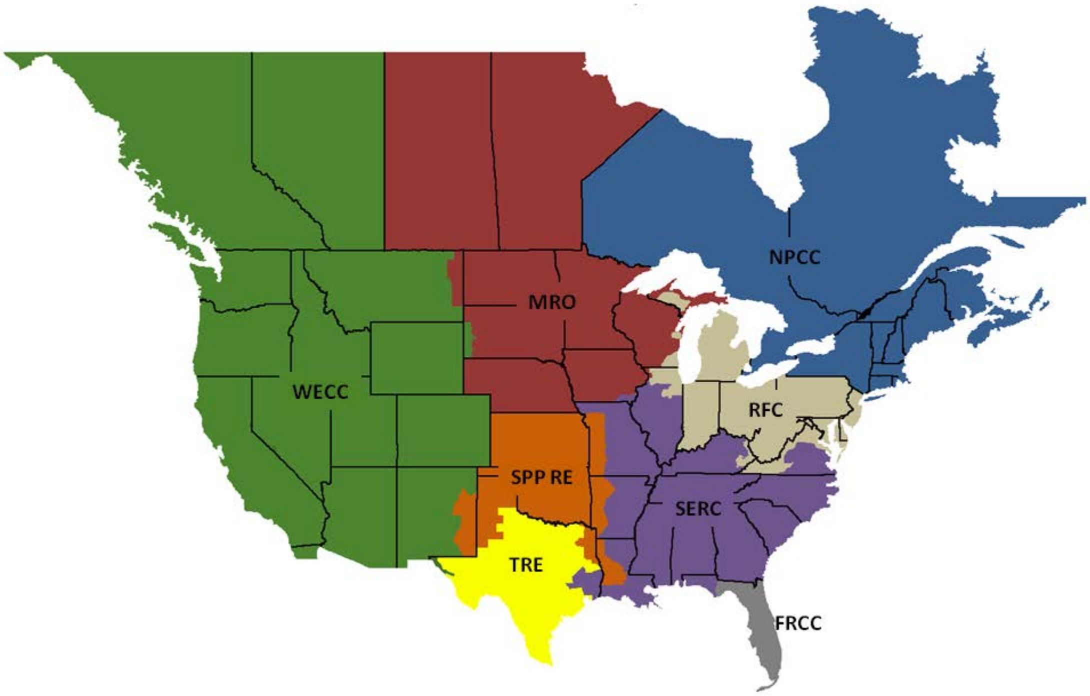
Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to ensure the reliability of the Bulk-Power System (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the electric reliability organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.

The North American BPS is divided into several assessment areas within the eight Regional Entity (RE) boundaries, as shown in the map and corresponding table below.



FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RFC	Reliability*First* Corporation
SERC	SERC Reliability Corporation
SPP-RE	Southwest Power Pool Regional Entity
TRE	Texas Reliability Entity
WECC	Western Electric Coordinating Council

Introduction

Background

The purpose of the benchmark geomagnetic disturbance (GMD) event description is to provide uniform evaluation criteria for assessing system performance during a low probability GMD event. It is to be used in conjunction with Reliability Standards that establish requirements for System modeling, vulnerability assessment, and mitigation planning. The benchmark GMD event defines the geoelectric field values used to compute GIC flows resulting from the benchmark event.

General Characteristics

The benchmark GMD event described herein takes into consideration the known characteristics of a severe GMD event and their impact on an interconnected transmission system. These characteristics include:

- Geomagnetic Latitude -- The amplitude of the induced geoelectric field for a given event is reduced as the observation point moves southward.
- Earth Conductivity – The amplitude and phase of the geoelectric field depends on the local or regional earth ground resistivity structure. Higher geoelectric field amplitudes are induced in areas of high resistivity.
- Transformer Electrical Response -- Transformers can experience half-cycle saturation when subjected to GIC. Transformers under half-cycle saturation absorb increasing amounts of reactive power (var) and inject harmonics into the system. However, half-cycle saturation does not occur instantaneously and depends on the electrical characteristics of the transformer and GIC amplitude [1]. Thus, the effects of transformer reactive power absorption and harmonic generation do not occur instantaneously and may take up to several seconds. From a practical point of view, assuming that the effects of GIC on transformer var absorption and harmonic generation are instantaneous is conservative.
- Transformer Thermal Effects (e.g. hot spot transformer heating) — Heating of the winding and other structural parts can occur in power transformers during a GMD event. However, the thermal impacts are not instantaneous and are dependent on the thermal time constants of the transformer. Thermal time constants for hot spot heating in power transformers are in the 5-20 minute range.
- Geoelectric Field Waveshape -- The geoelectric field waveshape has a strong influence on the hot spot heating of transformer windings and structural parts since thermal time constants of the transformer and time to peak of storm maxima are both on the order of minutes. The frequency content of the magnetic field (dB/dt) is a function of the waveshape, which in turn has a direct effect on the geoelectric field since the earth response to external dB/dt is frequency-dependent.
- Wide Area Geomagnetic Phenomena – The influence of GMD events is typically over a very broad area (e.g. continental scale); however, there can be pockets or very localized regions of enhanced geomagnetic activity. Since geomagnetic disturbance impacts within areas of influence of approximately 100-200 km do not have a widespread impact on the interconnected transmission system (see Appendix I), statistical methods used to assess the frequency of occurrence of a severe GMD event need to consider broad geographical regions in order to avoid bias caused by spatially localized geomagnetic phenomena.

Benchmark GMD Event Description

Severe geomagnetic disturbance events are high-impact, low-frequency (HILF) events [2]; thus, any benchmark event should consider the probability of occurrence of the event and the impact or consequences of the event. The benchmark event is composed of the following elements: (1) a reference peak geoelectric field amplitude (V/km) derived from statistical analysis of historical magnetometer data; (2) scaling factors to account for local geomagnetic latitude; (3) scaling factors to account for local earth conductivity; and (4) a reference geomagnetic field time series or waveshape to facilitate time-domain analysis GMD impact on equipment.

Reference Geoelectric Field Magnitude

The reference geoelectric field amplitude was determined through statistical analysis using the plane wave method [3]-[9], [25], geomagnetic field measurements from geomagnetic observatories in northern Europe [31] and the reference earth model shown in Table 1 [10]. For details of the statistical considerations, see Appendix I. The Quebec earth model is generally resistive and the geological structure is relatively well understood.

Table 1. Reference earth model (Quebec)

Depth (km)	Resistivity (Ω-m)
15	20,000
10	200
125	1,000
200	100
∞	3

The statistical analysis (see Appendix II) resulted in a conservative peak geoelectric field amplitude of approximately 8 V/km. For steady-state GIC and load flow analysis, the direction of the geoelectric field is assumed to be variable meaning that it can be in any direction (Eastward, Northward, or a vectorial combination thereof).

The frequency of occurrence of this benchmark GMD event is estimated to be approximately 1 in 100 years (see Appendix I). The selected frequency of occurrence is consistent with utility practices where a design basis frequency of 1 in 50 years is currently used as the storm return period for determining wind and ice loading of transmission infrastructure [11], for example.

The regional geoelectric field peak amplitude, Epeak, can be obtained from the reference value of 8 V/km using the following relationship

$$Epeak = 8 \times \alpha \times \beta \text{ (V/km)} \tag{1}$$

where α is the scaling factor to account for local geomagnetic latitude, and β is a scaling factor to account for the local earth conductivity structure (see Appendix II).

Reference Geomagnetic Waveshape

The reference geomagnetic field waveshape was selected after analyzing a number of recorded GMD events, including the reference storm of the NERC interim report of 2012 [12], measurements at the Nurmijarvi (NUR) and Memanbetsu (MMB) geomagnetic observatories for the “Halloween event” of October 29-31, 2003, and the March 1989 GMD event that caused the Hydro Quebec blackout. The geomagnetic field measurement record of the March 13-14 1989 GMD event, measured at NRCan’s Ottawa geomagnetic observatory, was selected as the reference geomagnetic field waveform because it provides generally conservative results when performing thermal analysis of power transformers (see Appendix I).

The geomagnetic latitude of the Ottawa geomagnetic observatory is 55°; therefore, the amplitude of the geomagnetic field measurement data were scaled up to the 60° reference geomagnetic latitude (see Figure 1) such that the resulting peak geoelectric field amplitude computed using the reference earth model was 8 V/km (see Figs.2 and 3). Sampling rate for the geomagnetic field waveshape is 10 seconds.

Figure 1: Benchmark geomagnetic field waveshape. Red Bn (Northward), Blue Be (Eastward).

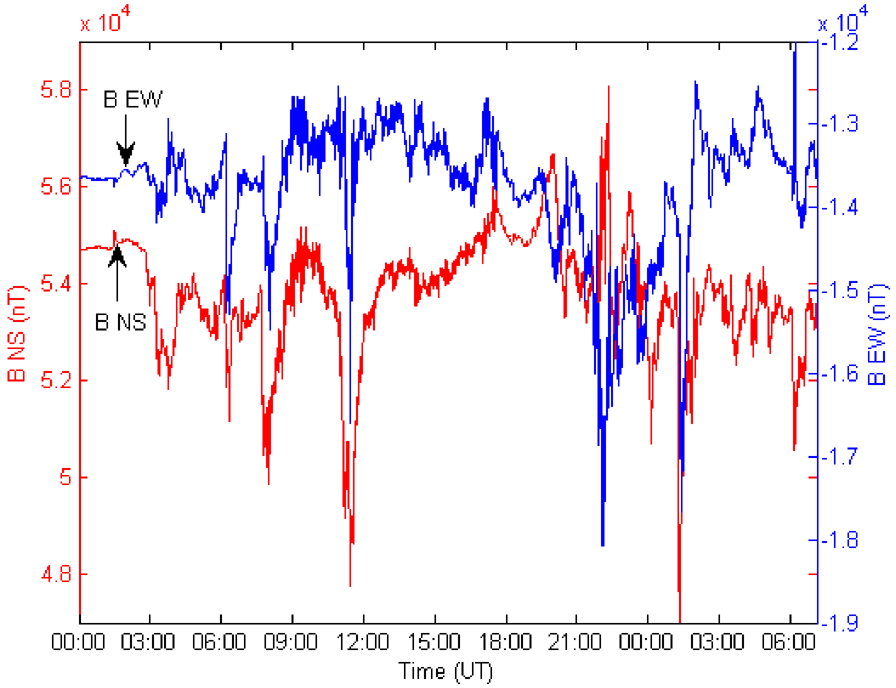


Figure. 2: Benchmark geoelectric field waveshape. E_E (Eastward).

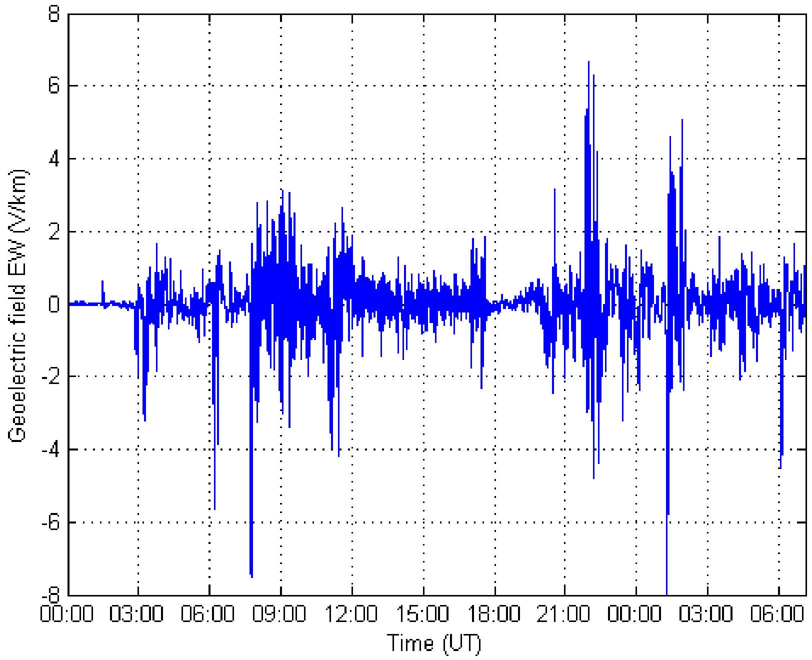
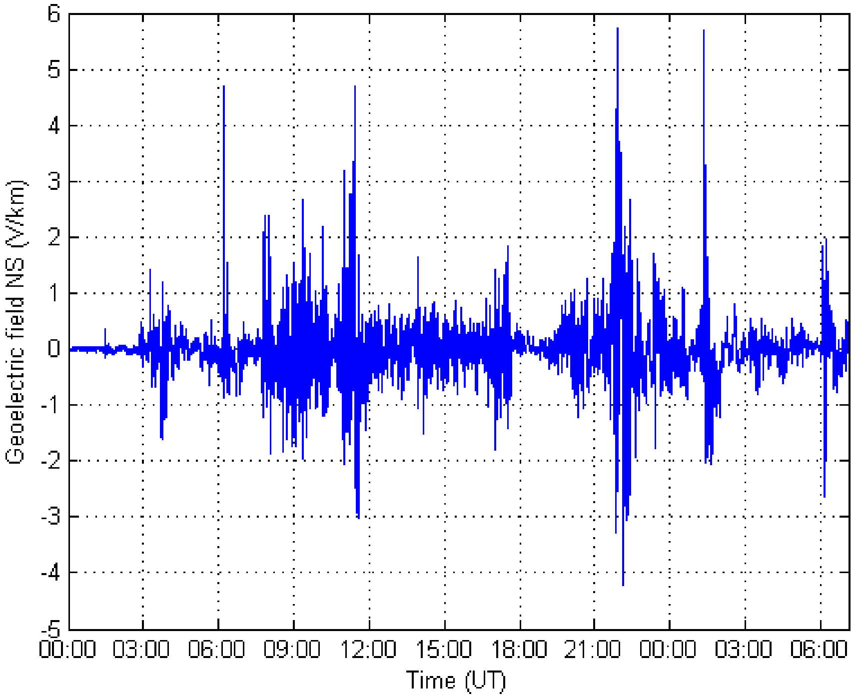


Figure. 3: Benchmark geoelectric field waveshape. E_N (Northward).



Appendix I – Technical Considerations

The following sections describe the technical justification of the assumptions that were made in the development of the benchmark event.

Statistical Considerations

Due to the lack of long-term accurate geomagnetic field observations, assigning probabilities to the occurrence of historical extreme geomagnetic storms is difficult because of the lack of high fidelity geomagnetic recordings of pre-1980s events. This is particularly true for the Carrington event for which data that allow the direct determination of the geoelectric fields experienced during the storm are not available [13].

The storm-time disturbance index Dst has often been used as a measure of storm strength even though it does not provide a direct correspondence with GIC[1]. One of the reasons for using Dst in statistical analysis is that Dst data are available pre-1980. Extreme value analysis of GMD events, including the Carrington, September 1859 and March 1989 events, has been carried out using Dst as an indicator of storm strength. In one such study [22], the (one sigma) range of 10-year occurrence probability for another March 1989 event was estimated to be between 9.4-27.8%. The range of 10-year occurrence probability for Carrington event in his analysis is 1.6-13.7%. These translate to occurrence rates of approximately 1 in 30-100 years for the March 1989 event and 1 in 70-600 years for the Carrington event. It should be noted that the error bars in such analysis are significant, but it can be concluded that the March 1989 event is, statistically speaking, likely more frequent than 1-in-100 years and the Carrington event is likely less frequent than 1-in-100 years.

The benchmark GMD event is based on a 1 in 100 year frequency of occurrence which is a conservative design basis for power systems. Also, the benchmark GMD event is not biased towards local geomagnetic field enhancements since it must address wide-area effects in the interconnected power system. Therefore, the use of Dst-based statistical considerations is not adequate in this context and only relatively modern data have been used.

The benchmark GMD event is derived from modern geomagnetic field data records and corresponding calculated geoelectric field amplitudes. Using such data allows rigorous statistical analysis of the occurrence rates of the physical parameter (i.e. rate of change in geomagnetic field, dB/dt) directly related to the geoelectric field. Geomagnetic field measurements from the IMAGE magnetometer chain for 1993-2012 have been used to study the occurrence rates of the geoelectric field amplitudes.

With the use of modern data it is possible to avoid bias caused by localized geomagnetic field enhancements. The spatial structure of high-latitude geoelectric fields can be very complex during strong geomagnetic storm events [14]-[15]. One reflection of this spatial complexity is localized geomagnetic field enhancements that result in high amplitude geoelectric fields in regions of a few hundred kilometers or less. Figure I-1[2] illustrates this spatial complexity of the storm-time geoelectric fields. In areas indicated by the bright red location, the geoelectric field can be a factor of 2-3 larger than at neighboring locations. Localized geomagnetic phenomena should not be confused with local earth structure/conductivity conductivity features that results in consistently high geoelectric

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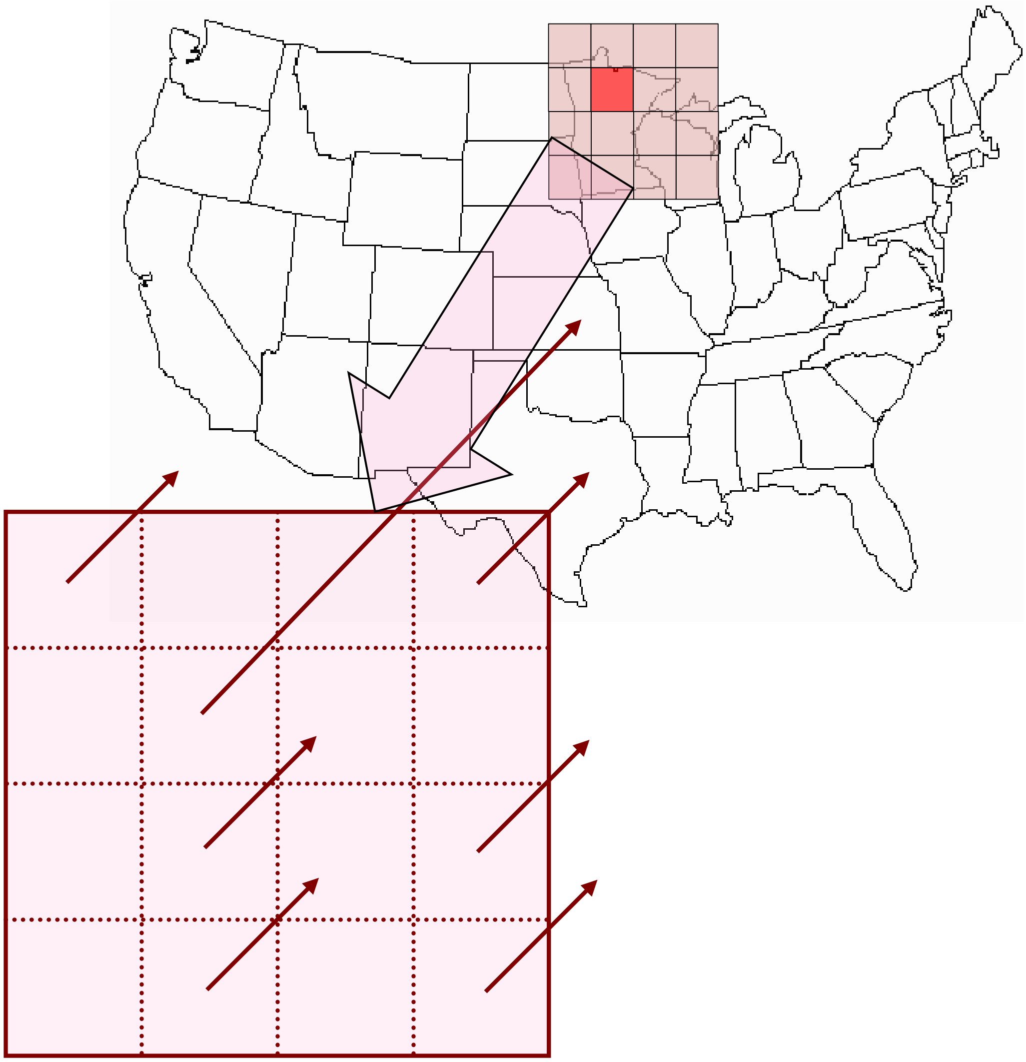
[1] Dst index quantifies the amplitude of the main phase disturbance of a magnetic storm. The index is derived from magnetic field variations recorded at four low-latitude observatories. The data is combined to provide a measure of the average main-phase magnetic storm amplitude around the world.

[2] Figure I.1 is for illustration purposes only, and is not meant to suggest that any one area is more likely to experience a localized enhanced geoelectric field.

fields (e.g., costal effects). Localized field enhancements can occur at any region exposed to auroral ionospheric electric current fluctuations.

Figure I-1: Illustration of the spatial scale between localized enhancements and larger spatial scale amplitudes of geoelectric field observed during a strong geomagnetic storm. In this illustration, the red square illustrates a spatially localized field enhancement.

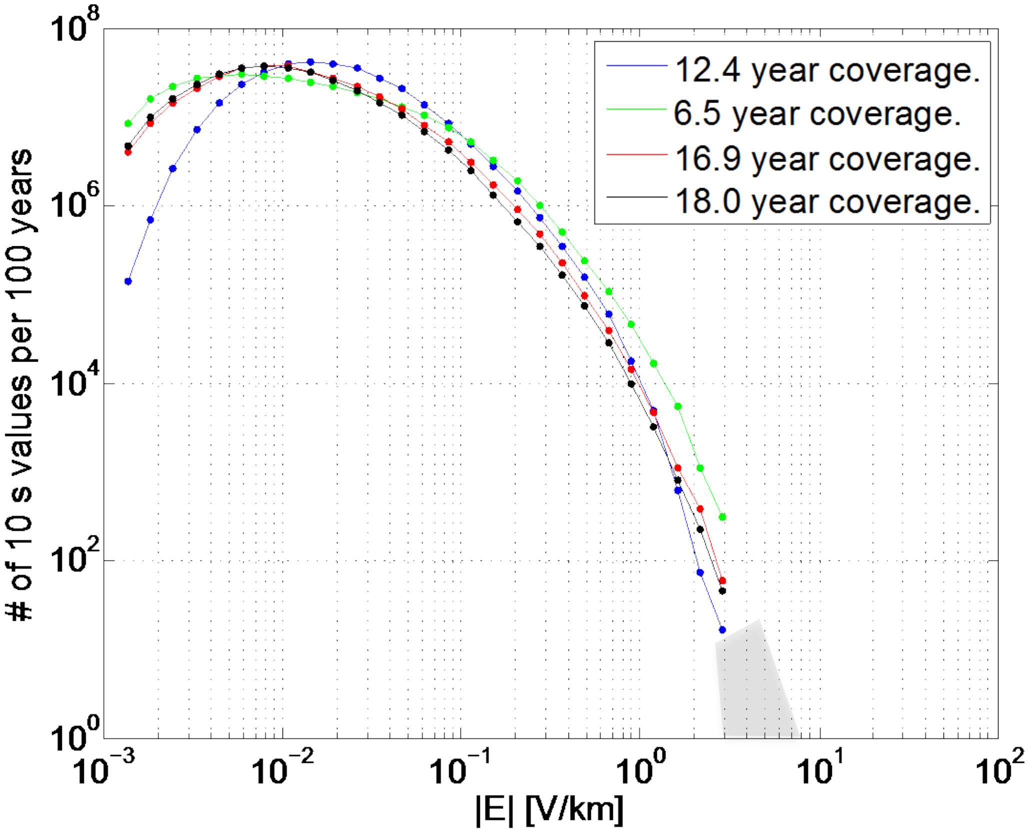


The benchmark event is designed to address wide-area effects caused by a severe GMD event, such as increased var absorption and voltage depressions. Without characterization of GMD on regional scales, statistical estimates could be weighted by local effects and suggest unduly pessimistic conditions from cascading failure and voltage collapse points of view. It is important to note that most earlier geoelectric field amplitude statistics and extreme amplitude analyses have been built for individual stations thus reflecting only localized spatial scales[16]-[19], [21]. A modified analysis is required to account for geoelectric field amplitudes at larger spatial scales. Consequently, analysis of spatially averaged geoelectric field amplitudes is presented below.

Figure I-2 shows statistical occurrence of spatially averaged high latitude geoelectric field amplitudes for the period of January 1, 1993 – December 31, 2012. The geoelectric field amplitudes were calculated using 10-s IMAGE magnetometer array observations and the Quebec ground conductivity model, which is used as a reference in the benchmark GMD event. Spatial averaging was carried out over four different station groups spanning a square area of approximately 500 km in width. For the schematic situation in Figure I-1 the averaging process would involve taking the average of the geoelectric field amplitudes over all 16 points or squares.

As can be seen from Figure I-2, the computed spatially averaged geoelectric field amplitude statistics indicate the 1-in-100 year amplitude is approximately between 3-8 V/km.

Figure I-2: Statistical occurrence of spatially averaged geoelectric field amplitudes. Four curves with dots correspond to different station groups and the gray area shows a visual extrapolation to 1-in-100 year amplitudes. The legend shows the data coverage for each station group used in computing the averaged geoelectric field amplitudes.

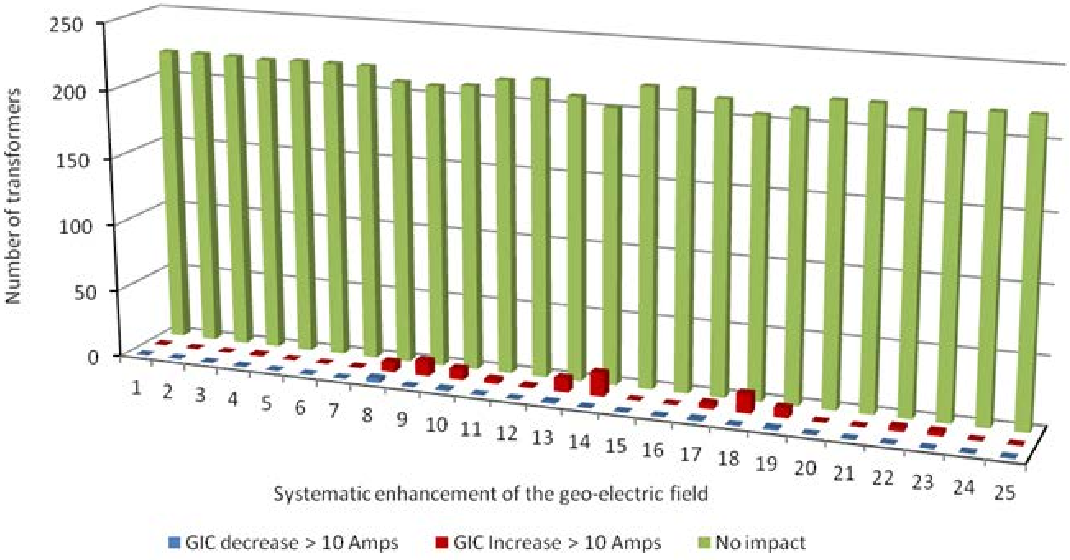


Impact of Local Geomagnetic Disturbances on GIC

The impact of local disturbances on a power network is illustrated with the following example. A 500 km by 500 km section of a North American transmission network was subdivided into 100 km by 100 km sections. The geoelectric field is assumed to be uniform within each section. The analysis is performed by scaling the geoelectric field in each section individually by an intensification factor of 2.5 and computing the corresponding GIC flows in the network, resulting in a total of 25 GIC distribution simulations. [3]In these simulations the peak geomagnetic field amplitude has been scaled according to geomagnetic latitude of the network under study.

Figure I-3 shows the number of transformers that experience a GIC increase greater than 10 Amps (in red), those that experienced a reduction in GIC of more than 10 Amps (in blue), and those that remain essentially the same (in green). It can be observed that there is a small set of transformers that are affected by the local amplification of the geo-electric field but that the impact on the GIC distribution of the entire network due to a local intensification of the geoelectric field in a "local peak" is minor. Therefore, it can be concluded that the effect of local disturbances on the larger transmission system is relatively minor and do not warrant further consideration in network analysis.

Figure I-3: Number of transformers that see a 10 A/phase change in GIC due to local geoelectric field intensification.



Impact of Waveshape on Transformer Hot-spot Heating

Thermal effects (e.g. hot spot transformer heating) in power transformers are not instantaneous. Thermal time constants associated with hot spot heating in power transformers are in the 5-20 minute range; therefore, the waveshape of the geomagnetic and geoelectric field has a strong impact on transformer hot spot heating of windings and metallic parts since thermal time constants are of the same order of magnitude as the time-to-peak

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[3] An intensification factor of 2.5 would make a general 8 V/km peak geoelectric field in the entire network show a 20 V/km intensified geoelectric field in one of the twenty five 100 km by 100 km sections.

of storm maxima. The waveshape of the March 13-14 1989 GMD event measured at the Ottawa geomagnetic observatory was found to be a conservative choice when compared with other events of the last 20 years, such as the reference storm of the NERC interim report of 2012 [12], measurements at the Nurmijarvi (NUR) and Memanbetsu (MMB) geomagnetic observatories for the "Halloween event" of October 29-31, 2003

To illustrate, the results of a thermal analysis performed on a relatively large test network with a diverse mix of circuit lengths and orientations is provided in Figures I-4 and I-5.

Figure I-4: Calculated peak metallic hot spot temperature for all transformers in a test system with a temperature increase of more than 20°C. for different GMD events scaled to the same peak geoelectric field.

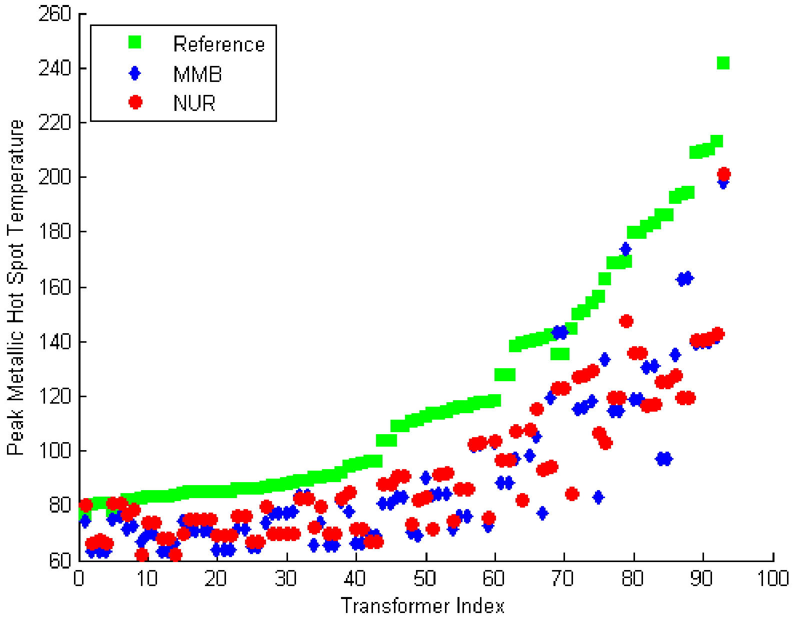
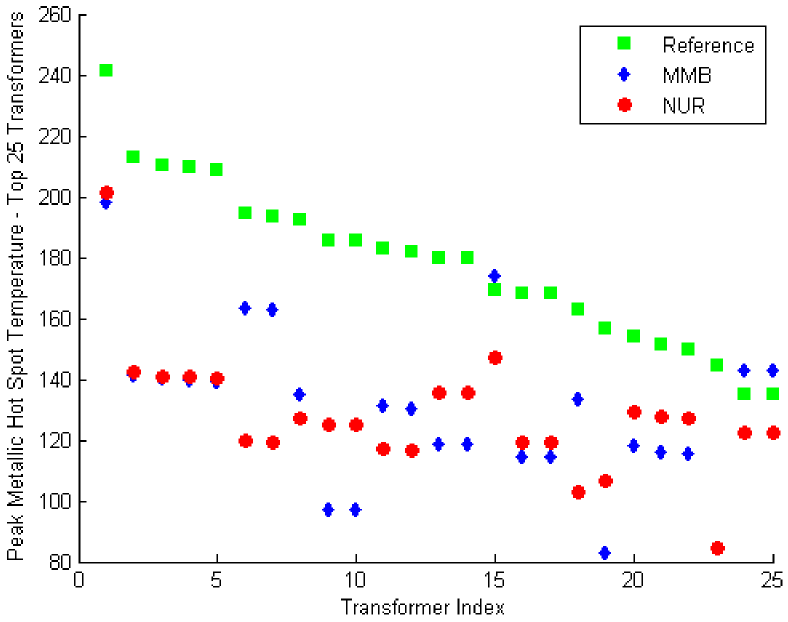


Figure I-5: Calculated peak metallic hot spot temperature for the top 25 transformers in a test system for different GMD events scaled to the same peak geoelectric field.



Appendix II – Scaling the Benchmark GMD Event

The intensity of a GMD event depends on geographical considerations such as geomagnetic latitude[4] and local earth conductivity[5] [3]. Scaling factors for geomagnetic latitude take in consideration that the intensity of a GMD event varies according to latitude-based geographical location. Scaling factors for earth conductivity take into account that the induced geoelectric field depends on earth conductivity, and that different parts of the continent have different earth conductivity and deep earth structure.

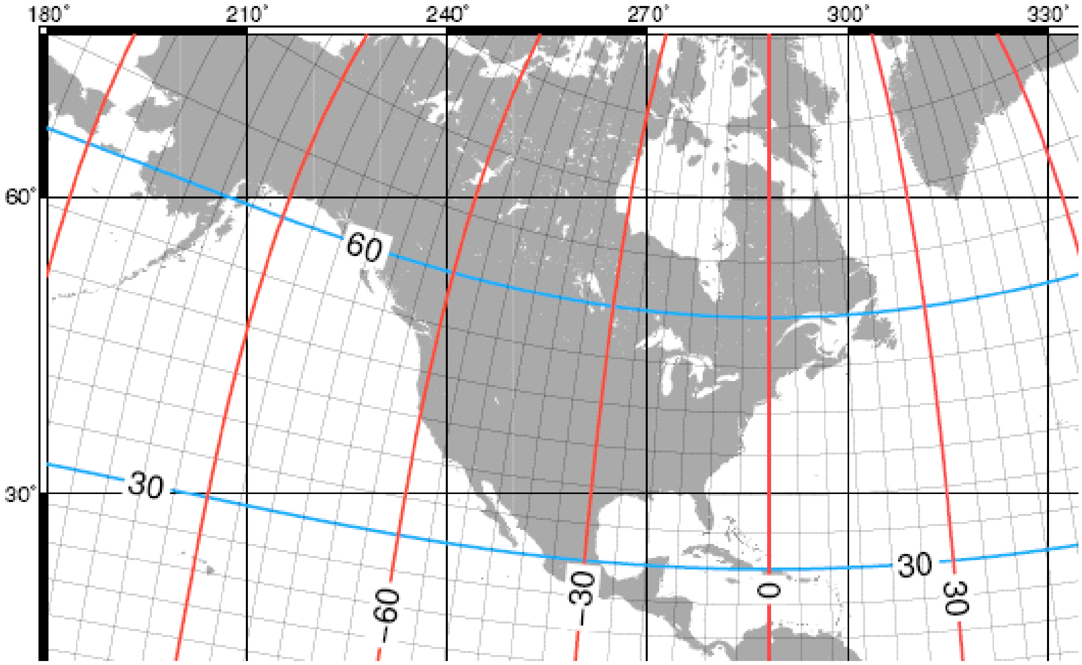
Scaling the Geomagnetic Field

The benchmark GMD event is defined for geomagnetic latitude of 60° and it must be scaled to account for regional differences based on geomagnetic latitude. To allow usage of the reference geomagnetic field waveshape in other locations, Table II-1 provides a scaling factor correlating peak geoelectric field to geomagnetic latitude as described in Figure II-1 [3]. This scaling factor α has been obtained from a large number of global geomagnetic field observations of all major geomagnetic storms since the late 1980s [13], [20], [32] and can be approximated with the empirical expression in (II.1)

$$\alpha = 0.001 \cdot e^{(0.115 \cdot L)} \qquad \text{(II.1)}$$

where L is the geomagnetic latitude in degrees

Figure II-1: Geographic and geomagnetic latitudes in North America.



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[4] Geomagnetic latitude is analogous to geographic latitude, except that bearing is with respect to the magnetic poles, as opposed to the geographic poles. Geomagnetic phenomena are often best organized as a function of geomagnetic coordinates.

[5] Local earth conductivity refers to the electrical characteristics to depths of hundreds of km down to the earth's mantle. In general terms, lower ground conductivity results in higher geoelectric field amplitudes.

Table II-1 Geomagnetic field scaling factors according to geomagnetic latitude

Geomagnetic Latitude (Degrees)	Scaling Factor1 (α)
≤ 40	0.10
45	0.2
50	0.3
55	0.6
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

Scaling the Geoelectric Field

The benchmark GMD event is defined for the reference Quebec earth model provided in Table 1. This earth model has been used in many peer-reviewed technical articles and has been subject to considerable validation efforts [10]. The peak geoelectric field depends on the geomagnetic field waveshape and the local earth conductivity. Ideally, the peak geoelectric field, E_{peak}, is obtained by calculating the geoelectric field from the scaled geomagnetic waveshape using the plane wave method and taking the maximum value of the resulting waveforms

$$\begin{aligned} E_N &= (z(t)/\mu_o) * B_E(t) \\ E_E &= -(z(t)/\mu_o) * B_N(t) \\ E_{peak} &= \max\{|E_E(t), E_N(t)|\} \end{aligned} \qquad \text{(II-1)}$$

where,

* denotes convolution in the time domain,

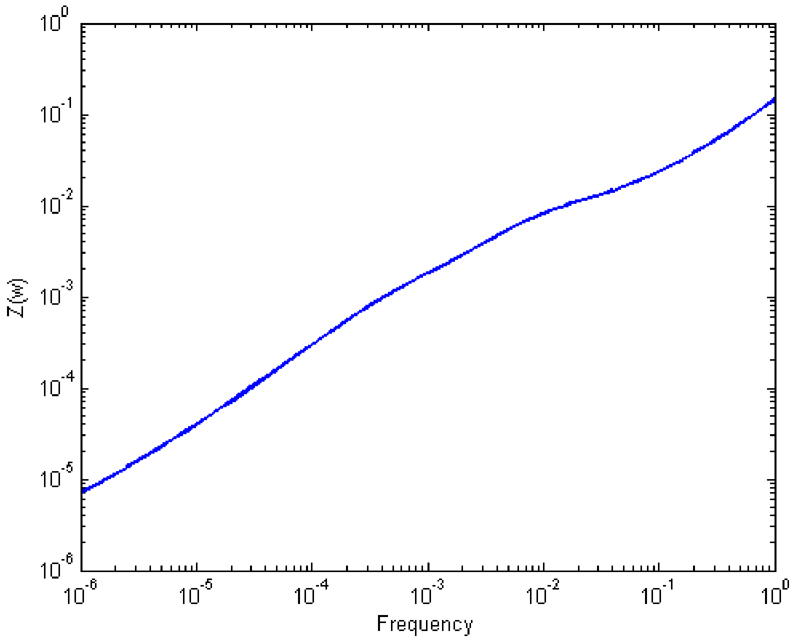
z(t) is the earth surface impedance calculated from the laterally uniform or 1D earth model,

$B_E(t)$, $B_N(t)$ are the scaled Eastward and Northward geomagnetic field waveshapes,

$E_E(t)$, $E_N(t)|$ are the vectorial magnitude of the calculated Eastward and Northward geoelectric field $E_E(t)$ and $E_N(t)$.

As noted previously, the response of the earth to B(t) (and dB/dt) is frequency dependent. Figure II-2 shows the magnitude of Z(ω) for the reference earth model.

Figure II-2: Magnitude of the earth surface impedance for the reference earth model.



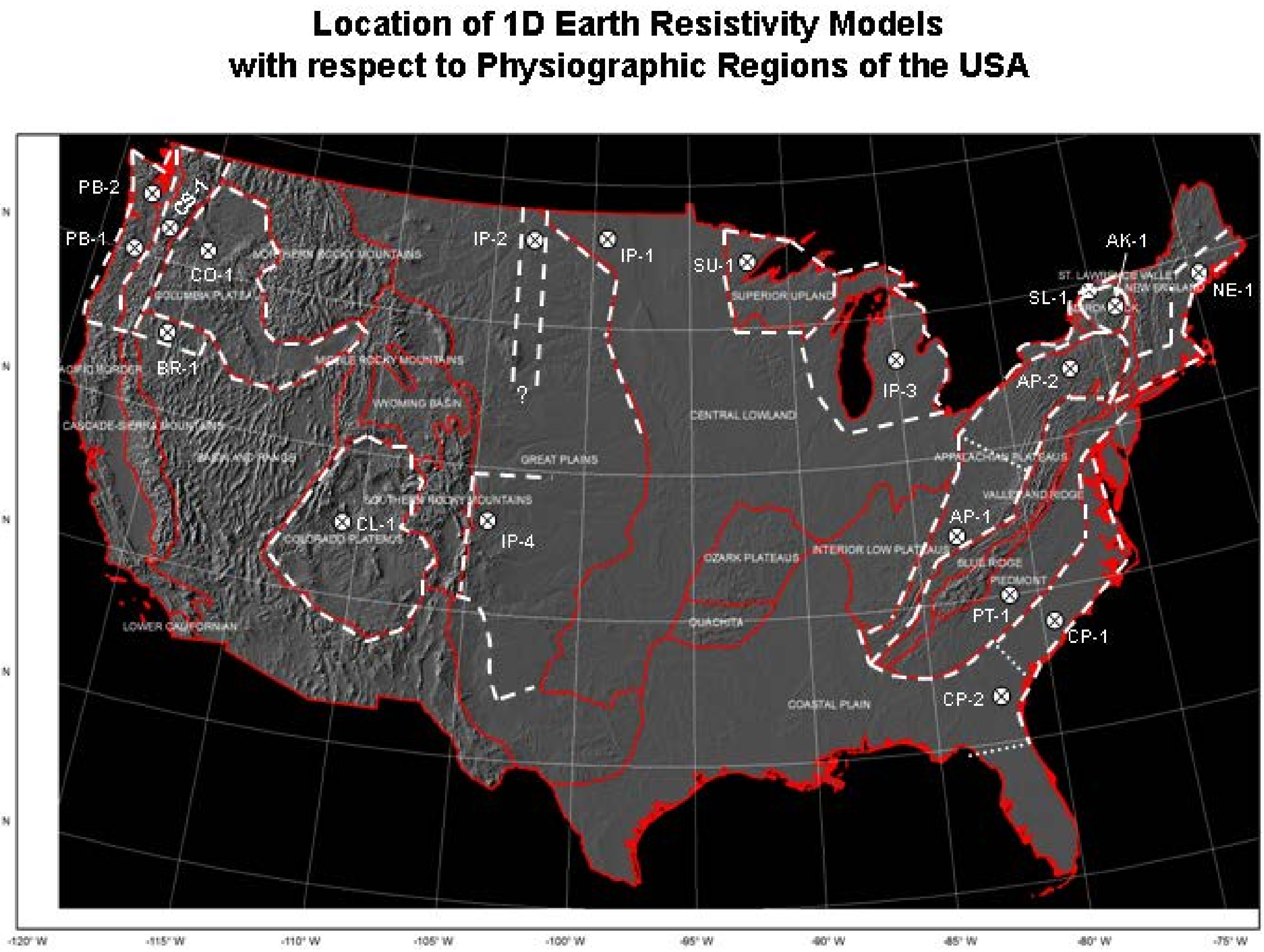
If a utility does not have the capability of calculating the waveshape or time series for the geoelectric field, an earth conductivity scaling factor β can be obtained from Table II-2. Using α and β, the peak geoelectric field E_{peak} for a specific service territory can be obtained shown in Figure II-3 using (II-2)

$$Epeak = 8 \times \alpha \times \beta \text{ (V/km)} \tag{II-2}$$

It should be noted that (II-2) is an approximation based on the following assumptions:

- The earth models used to calculate Table II-2 for the United States were obtained using best known USGS data and are not necessarily validated using field measurements.
- The models used to calculate Table II-2 for Canada were obtained from NRCan and reflect the average structure for large regions. When models are developed for sub-regions these will all be different (to a greater or lesser degree) from the average model. For instance, detailed models for Ontario have been developed by NRCan and comprise of 7 major sub-regions.
- The conductivity scaling factor β is calculated as the quotient of the local geoelectric field peak amplitude in a physiographic region with respect to the reference peak amplitude value of 8 V/km. Both geoelectric field peaks amplitudes are calculated using the reference geomagnetic field time series. If a different geomagnetic field time series were used, the calculated scaling factors β would be different that the values in Table II-2 because the frequency content of storm maxima is, in principle, different for every storm. However, the reference time series produces generally more conservative values of β when compared to the time series of reference storm of the NERC interim report of 2012 [12], measurements at the Nurmijarvi (NUR) and Memanbetsu (MMB) geomagnetic observatories for the "Halloween event" of October 29-31, 2003, and other recordings of the March 1989 event at high latitudes (Meanook observatory, Canada). The average variation between minimum and maximum β is approximately 12%. Figure II-4 illustrates the values of β calculated using the 10-second geomagnetic field recordings for these geomagnetic field time series.
- If a utility has technically-sound earth models for its service territory of sub-regions thereof, then the use of such earth models is preferable to estimate E_{peak}.

Figure II-3: Physiographic regions of North America.



Physiographic Regions of Canada (Placeholder Map)

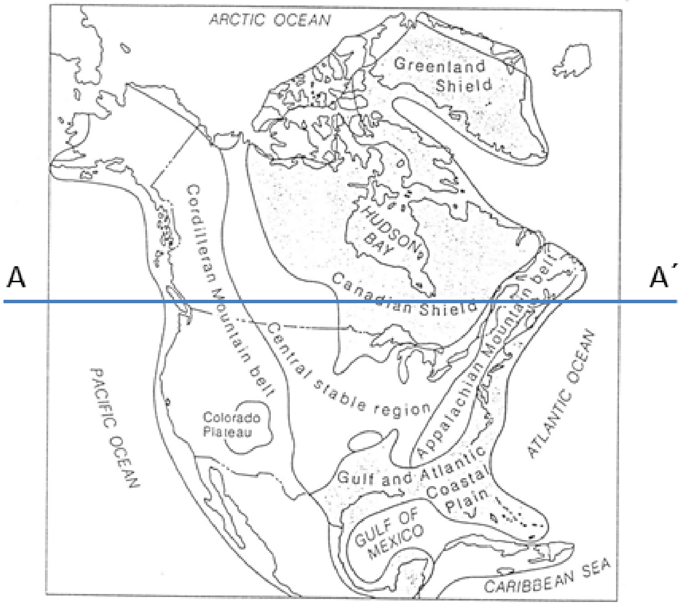
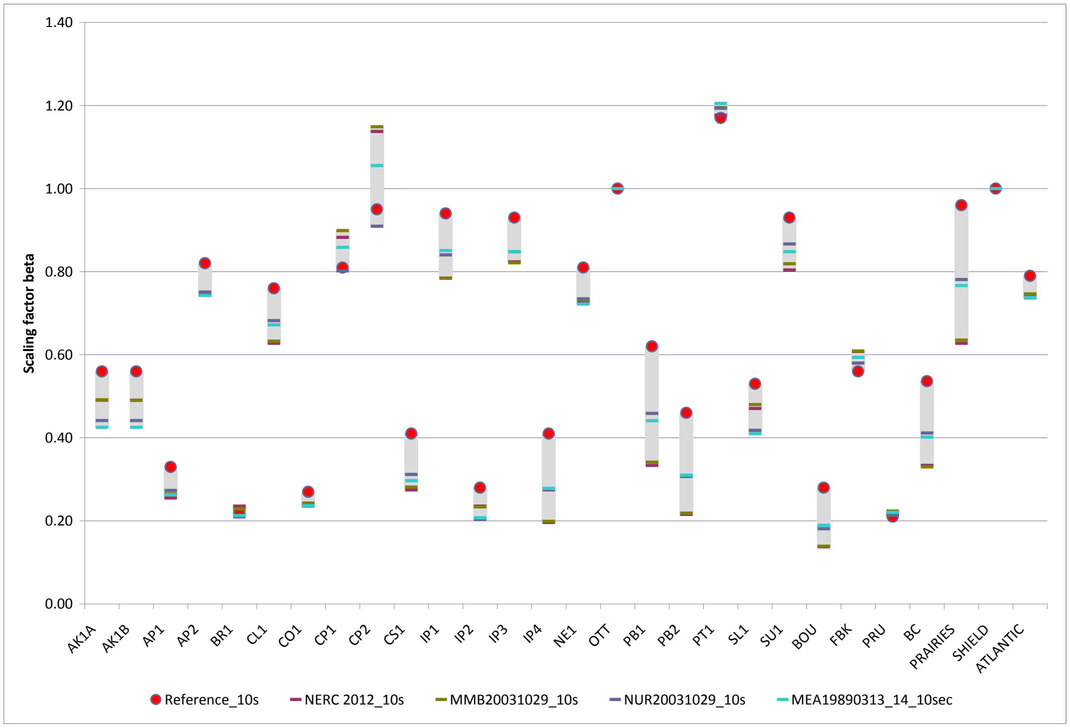


Table II-1
Geoelectric field scaling factors according to earth model

USGS Earth model	**Scaling Factor (β)**
AK1A	0.56
AK1B	.0.56
AP1	0.33
AP2	0.82
BR1	0.22
CL1	0.76
CO1	0.27
CP1	0.81
CP2	0.95
CS1	0.41
IP1	0.94
IP2	0.28
IP3	0.93
IP4	0.41
NE1	0.81
OTT	1.00
PB1	0.62
PB2	0.46
PT1	1.17
SL1	0.53
SU1	0.93
BOU	0.28
FBK	0.56
PRU	0.21
BC	0.67
PRAIRIES	0.96
SHIELD	1.0
ATLANTIC	0.79

Figure II-4: Beta factors calculated for different GMD events. Red circles corresponds to the values in Table II-1



Example Calculations

Example 1

Consider a transmission service territory that lies at a geographical latitude of 45.5°, which translates to a geomagnetic latitude of 55°. The scaling factor α from Table II.1 is 0.562; therefore, the benchmark waveshape and the peak geoelectric field will be scaled accordingly. If the service territory has the same earth conductivity as the benchmark then β=1, and the peak geoelectric field will be

$$\alpha = 0.562$$

$$\beta = 1$$

$$Epeak = 8 \times 0.562 \times 1 = 4.5 \text{ V/km}$$

If the service territory spans more than one physiographic region (i.e. several locations within the serive territory have a different earth model) then the largest α can be used across the entire service territory for conservative results. Alternatively, the network can be split into multiple subnetworks, and the corresponding geoelectric field amplitude can be applied to each subnetwork.

Example 2

Consider a service territory that lies at a geographical latitude of 45.5° which translates to a geomagnetic latitude of 55°. The scaling factor α from Table II.1 is 0.562; therefore, the benchmark waveshape and the peak geoelectric field will be scaled accordingly.

The service territory has lower conductivity that the reference benchmark conductivity, and according to the conductivity factor β from Table II.2. Then:

Conductivity factor β=1.17

$$\alpha = 0.562$$

$$\beta = 1.17$$

$$Epeak = 8 \times 0.562 \times 1.17 = 5.3 \text{ V/km}$$

References

[1] L. Bolduc, A. Gaudreau, A. Dutil, “Saturation Time of Transformers Under dc Excitation”, Electric Power Systems Research, 56 (2000), pp. 95-102

[2] *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System*, A Jointly-Commissioned Summary Report of the North American Reliability Corporation and the U.S. Department of Energy’s November 2009 Workshop.

[3] NERC GIC Application Guide

[4] Kuan Zheng, Risto Pirjola, David Boteler, Lian-guang Liu, “Geoelectric Fields Due to Small-Scale and Large-Scale Source Currents”, *IEEE Transactions on Power Delivery*, Vol. 28, No. 1, January 2013, pp. 442-449.

[5] David Boteler, “Geomagnetically Induced Currents: Present Knowledge and Future Research”, *IEEE Transactions on Power Delivery*, Vol. 9, No. 1, January 1994, pp. 50-58.

[6] David Boteler, “Modeling Geomagnetically Induced Currents Produced by Realistic and Uniform Electric Fields”, *IEEE Transactions on Power Delivery*, Vol. 13, No. 4, January 1998, pp. 1303-1308.

[7] J. L. Gilbert, W. A. Radasky, E. B. Savage, “A Technique for Calculating the Currents Induced by Geomagnetic Storms on Large High Voltage Power Grids”, Electromagnetic Compatibility (EMC), 2012 IEEE International Symposium on.

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

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

[10] Boteler, D. H., and R. J. Pirjola, The complex-image method for calculating the magnetic and electric fields produced at the surface of the Earth by the auroral electrojet, Geophys. J. Int., 132(1), 31—40, 1998

[11] ANSI Standard C2, *National Electric Safety Code*, 2012, ISBN 978-0-7381-6588-2

[12] NERC 2012 Report

[13] Pulkkinen, A., E. Bernabeu, J. Eichner, C. Beggan and A. Thomson, Generation of 100-year geomagnetically induced current scenarios, *Space Weather*, Vol. 10, S04003, doi:10.1029/2011SW000750, 2012.

[14] Pulkkinen, A., A. Thomson, E. Clarke, and A. Mckay, April 2000 geomagnetic storm: ionospheric drivers of large geomagnetically induced currents, Annales Geophysicae, 21, 709-717, 2003.

[15] Pulkkinen, A., S. Lindahl, A. Viljanen, and R. Pirjola, Geomagnetic storm of 29–31 October 2003: Geomagnetically induced currents and their relation to problems in the Swedish high-voltage power transmission system, Space Weather, 3, S08C03, doi:10.1029/2004SW000123, 2005.

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

[17] Langlois, P., L. Bolduc, and M. C. Chouteau, Probability of occurrence of geomagnetic storms based on a study of the distribution of the electric field amplitudes measured in Abitibi, Québec, in 1993–1994, J. Geomagn. Geoelectr., 48, 1033–1041, 1996.

[18] Boteler, D. H., Assessment of geomagnetic hazard to power systems in Canada, Nat. Hazards, 23, 101–120, 2001.

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

[20] Ngwira, C., A. Pulkkinen, F. Wilder, and G. Crowley, Extended study of extreme geoelectric field event scenarios for geomagnetically induced current applications, Space Weather, Vol. 11, 121–131, doi:10.1002/swe.20021, 2013.

[21] Campbell, W. C., Observation of electric currents in the Alaska oil pipeline resulting from auroral electrojet current sources, Geophys. J. R. Astron. Soc., 61, 437–449, 1980.

[22] Love, J., Credible occurrence probabilities for extreme geophysical events: Earthquakes, volcanic eruptions, magnetic storms, Geophysical Research Letters, Vol. 39, L10301, doi:10.1029/2012GL051431, 2012.

[23] Pulkkinen, A., A. Thomson, E. Clarke, and A. Mckay, April 2000 geomagnetic storm: ionospheric drivers of large geomagnetically induced currents, Annales Geophysicae, 21, 709-717, 2003.

[24] Boteler, D. H., and R. J. Pirjola, The complex-image method for calculating the magnetic and electric fields produced at the surface of the Earth by the auroral electrojet, Geophys. J. Int., 132(1), 31—40, 1998.

[25] Boteler, D. H., Assessment of geomagnetic hazard to power systems in Canada, Nat. Hazards, 23, 101–120, 2001.

[26] Cagniard, L., Basic theory of the magneto-telluric method of geophysical prospecting, Geophysics, 18(3), 605, 1953.

[27] Campbell, W. C., Observation of electric currents in the Alaska oil pipeline resulting from auroral electrojet current sources, Geophys. J. R. Astron. Soc., 61, 437–449, 1980.

[28] Langlois, P., L. Bolduc, and M. C. Chouteau, Probability of occurrence of geomagnetic storms based on a study of the distribution of the electric field amplitudes measured in Abitibi, Québec, in 1993–1994, J. Geomagn. Geoelectr., 48, 1033–1041, 1996.

[29] Pulkkinen, A., A. Thomson, E. Clarke, and A. Mckay, April 2000 geomagnetic storm: ionospheric drivers of large geomagnetically induced currents, Annales Geophysicae, 21, 709-717, 2003.

[30] Pulkkinen, A., S. Lindahl, A. Viljanen, and R. Pirjola, Geomagnetic storm of 29–31 October 2003: Geomagnetically induced currents and their relation to problems in the Swedish high-voltage power transmission system, Space Weather, 3, S08C03, doi:10.1029/2004SW000123, 2005.

[31] [http://space.fmi.fi/image/]

NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Transformer Thermal Impact Assessment (Draft)

Project 2013-03 (Geomagnetic Disturbance Mitigation)

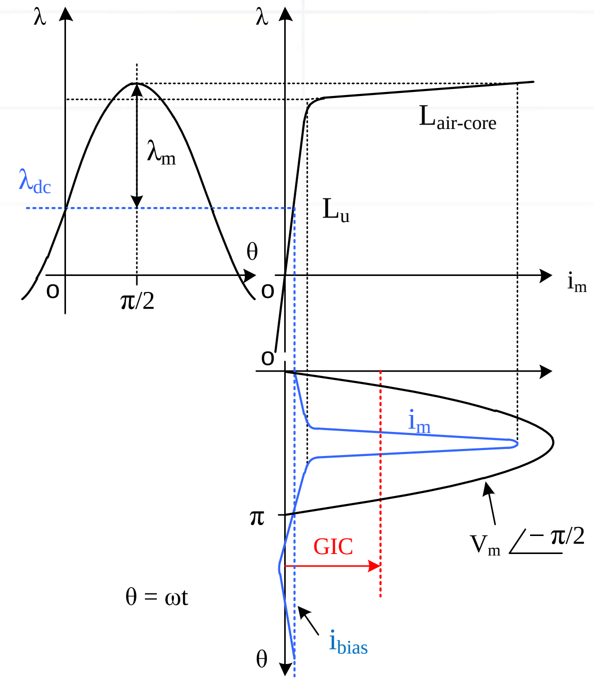
TPL-007-1 Transmission System Planned Performance during Geomagnetic Disturbances

Background

Large power transformers connected to the EHV transmission system can experience both winding and structural part hot spot heating as a result of GMD events. TPL-007 will require owners of such transformers to conduct thermal analyses of their transformers to determine if the transformers will be able to withstand the thermal transient effects associated with the Benchmark GMD event. This paper discusses methodologies that can be employed to conduct such analyses, including example calculations.

The primary impact of GMDs on large power transformers is a result of the quasi-dc current that flows through wye-grounded transformer windings. This geomagnetically induced current (GIC), results in an offset of the ac sinusoidal flux resulting in asymmetric or half-cycle saturation (see Figure1).

Figure 1: **Mapping magnetization current to flux through core excitation characteristics**



Half-cycle saturation results in a number of known effects:

- Hot spot heating of transformer windings due to stray flux;
- Hot spot heating of non-current carrying transformer metallic members due to stray flux;
- Harmonics;
- Increase in reactive power absorption; and
- Increase in vibration and noise level.

This paper focuses on hot spot heating of transformer windings and non current-carrying metallic parts. Effects such the generation of harmonics, increase in reactive power absorption, vibration and noise are not within the scope of this document.

Technical Considerations

The effects of half-cycle saturation on HV and EHV transformers, namely localized “hot spot” heating, are relatively well understood, but are difficult to quantify. A transformer GMD impact assessment must consider GIC amplitude, duration, and transformer physical characteristics such as design and condition (e.g., age, gas content, and moisture in the oil). A single threshold value of GIC cannot be justified as a “pass or fail” screening criterion where “fail” means that the transformer will suffer damage. A single threshold value of GIC only makes sense in the context where “fail” means that a more detailed study is required and that “pass” means that GIC in a particular transformer is so low that a detailed study is unnecessary. Such threshold would have to be technically justifiable and sufficiently low to be considered a conservative value within the scope of the benchmark[A1].

The following considerations should be taken into account when assessing the thermal susceptibility of a transformer to half-cycle saturation:

- In the absence of manufacturer specific information, use the temperature limits for safe transformer operation such as those suggested in the IEEE Std. C57.91-2011 standard [1] for hot spot heating during short-term emergency operation. This standard does not suggest that exceeding these limits will result in transformer failure, but rather that it will result in additional aging of cellulose in the paper-oil insulation, and the potential for the generation of gas bubbles in the bulk oil. Thus, from the point of view of evaluating possible transformer damage due to increased hot spot heating, these thresholds can be considered conservative for a transformer in good operational condition.

- The worst case temperature rise for winding and metallic part (e.g., tie plate) heating should be estimated taking into consideration the construction characteristics of the transformer as they pertain to dc flux offset in the core (e.g., single-phase, shell, 5 and 3-leg three-phase construction).

- Bulk oil temperature due to ambient temperature and transformer loading must be added to the incremental temperature rise caused by hot spot heating. For planning purposes, maximum ambient and loading temperature should be used unless there is a technically justified reason to do otherwise.

- The time series or “waveshape” of the reference GMD event in terms of peak amplitude, duration and frequency of the geoelectric field has an important effect on hot spot heating. Winding and metallic part hot spot heating have different thermal time constants and their temperature rise will be different if the GIC currents are sustained for 2 or 10 minutes for a given GIC peak amplitude.
- The “effective” GIC in autotransformers (reflecting the different GIC ampere-turns in the common and the series windings) must be used in the assessment. The effective current $I_{dc,eq}$ in an autotransformer is defined by [4]

$$I_{dc,eq} = I_H + (I_N / 3 - I_H) V_X / V_H \tag{1}$$

where,

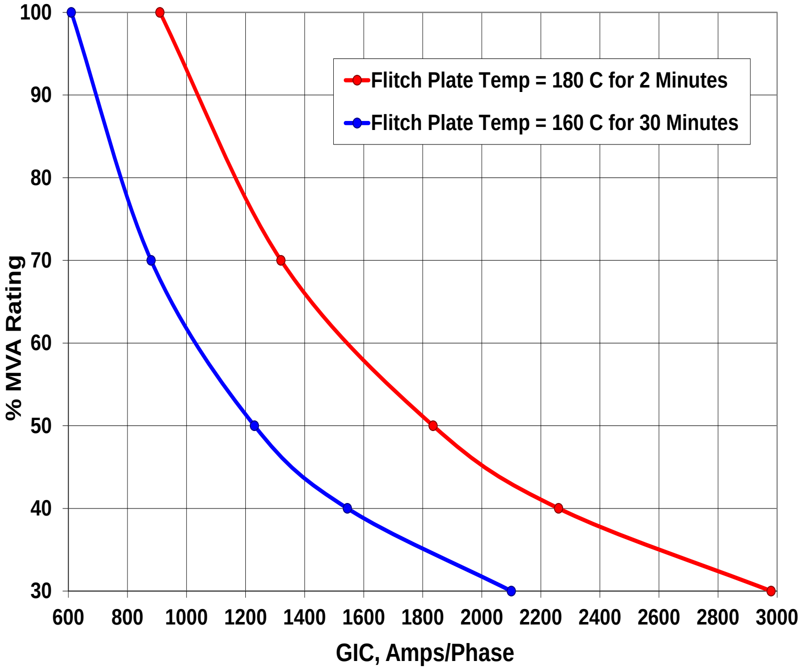
I_H is the dc current in the high voltage winding;
I_N is the neutral dc current;
V_H is the rms rated voltage at HV terminals;
V_X is the rms rated voltage at the LV terminals.

Transformer Thermal Impact Assessment Process

There are two different ways to carry out a detailed thermal impact screening:

1. Transformer manufacturer GIC capability curves. These curves relate permissible peak GIC (obtained by the user from a steady-state GIC calculation) and loading for a specific transformer. An example of manufacturer capability curves is provided in Figure 2. Presentation details vary between manufacturers and limited information is available regarding the assumptions used to generate these curves, in particular the assumed waveshape or duration of the effective GIC. Some manufacturers assume that the “waveshape” of the GIC in the transformer windings is a square pulse of 2, 10, or 30 minutes in duration. In the case of the transformer capability curve shown in Figure 2 [2], a square pulse of 900 A/phase with a duration of 2 minutes would reach a temperature of 180 °C at full load. While GIC capability curves are relatively simple to use, a fair amount of engineering judgment is necessary to ascertain what portion of a GIC waveshape is equivalent to, for instance, a 2 minute pulse. Also, manufacturers generally maintain that in the absence of transformer standards defining thermal duty due to GIC, such capability curves have to be developed for every transformer design and vintage.

Figure 2: Sample GIC manufacturer capability curve of a large single-phase transformer design using the Flitch plate temperature criteria [2].



2. Thermal response simulation[1]. The input to this type of simulation is the time series or waveshape of effective GIC flowing through a transformer (taking into account the actual configuration of the system) and the output of the simulation is the hot spot temperature (winding or metallic part) time sequence for a given transformer. An example of GIC input and hotspot temperature time series values from [3] are shown in Figure 3. The hot spot thermal transfer functions can be obtained from measurements or calculations provided by transformer manufacturers. Default values can be used (e.g. those provided in [3]) when specific data are not available. Hot spot temperature thresholds shown in Figure 3 are consistent with IEEE Std. C57.91 emergency loading hot spot limits. Emergency loading time limit is usually 30 minutes.

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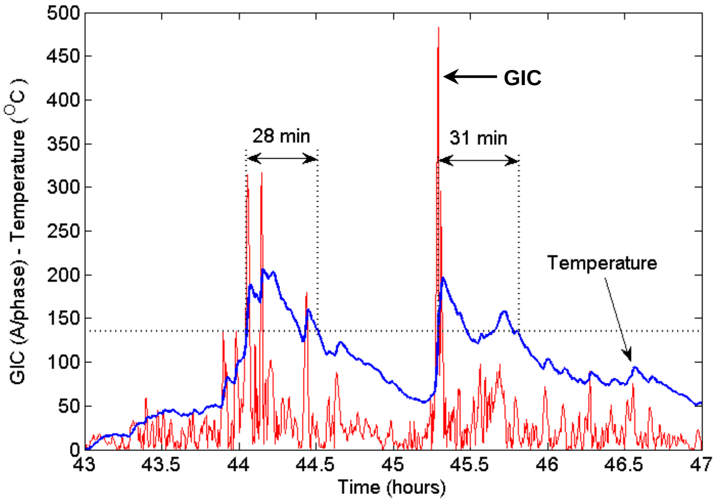
[1] Technical details of this methodology can be found in [3].

Figure 3: Sample tie plate temperature calculation. Blue trace is incremental temperature and red trace is the magnitude of the GIC/phase [3]



It is important to reiterate that the characteristics of the time sequence or "waveshape" are very important in the assessment of the thermal impact of GIC on transformers. Transformer hot spot heating is not instantaneous. The thermal time constants of transformer windings and metallic parts are typically on the order of minutes (metallic part) to tens of minutes (winding); therefore, hot spot temperatures are heavily dependent on: GIC history and rise time, amplitude and duration of GIC in the transformer windings, bulk oil temperature due to loading, ambient temperature and cooling mode.

Calculation of the GIC waveshape for a transformer

The following procedure can be used to generate time series GIC data, i.e. GIC(t), using a software program capable of computing GIC in the steady-state. The steps are as follows:

1. Calculate contribution of GIC due to eastward and northward geoelectric fields for the transformer under consideration
2. Scale the GIC contribution according to the reference geoelectric field time series to produce the GIC time series for the transformer under consideration.

1. Most available GIC–capable software packages can calculate GIC in steady-state in a transformer assuming a uniform Eastward geoelectric field of 1 V/km (GIC_E) while the Northward geoelectric field is zero. Similarly, GIC_N can be obtained when a uniform Northward geoelectric field of 1 V/km while the Eastward geoelectric field is zero. GIC_E and GIC_N are the normalized GIC contributions for the transformer under consideration.

2. If the earth conductivity is assumed to be uniform (or laterally uniform) in the transmission system of interest, then the transformer GIC (in A/phase/V/km) for any value of E_E (t) and E_N(t) can be calculated using (2) [4].

$$GIC(t) = \left|E(t)\right| \cdot \left\{GIC_E \sin(\varphi(t)) + GIC_N \cos(\varphi(t))\right\} \tag{2}$$

where

$$\left|E(t)\right| = \sqrt{E_N^2(t) + E_E^2(t)} \tag{3}$$

$$\varphi(t) = \tan^{-1}\left(\frac{E_E(t)}{E_N(t)}\right) \tag{4}$$

GIC_N is the effective GIC due to a Northward geoelectric field of 1 V/km and GIC_E is the effective GIC due to an Eastward geoelectric field of 1 V/km.

The geoelectric field time series E_N(t) and E_E(t) is obtained, for instance, from the reference geomagnetic field time series [5] after the appropriate geomagnetic latitude factor α is applied[2]. Applying (2) to each point in E_N(t) and E_E(t) results in GIC(t).

GIC(t) Calculation Example

Let us assume that from the steady-state solution, the effective GIC in this transformer is GIC_E = -6A/phase if E_N=0, E_E=1 V/km and GIC_N = 9.6A/phase if E_N=1 V/km, E_E=0. Let us also assume the geomagnetic field time series corresponds to a geomagnetic latitude where α = 1 and that the earth conductivity corresponds to the reference earth model in [5]. The resulting geoelectric field time series is shown in Figure 4. Therefore,

$$GIC(t) = \sqrt{E_N^2(t) + E_E^2(t)} \cdot \left\{GIC_E \sin\varphi(t) + GIC_N \cos\varphi(t)\right\}$$

$$GIC(t) = \sqrt{E_N^2(t) + E_E^2(t)} \cdot \left\{-16 \cdot \sin\theta(t) + 9.6 \cdot \cos\theta(t)\right\}$$

The resulting GIC waveshape GIC(t) is shown in Figs. 5 and 6 and can subsequently be used for thermal analysis.

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[2] The geomagnetic factor α is described in [4] and is used to scale the geomagnetic field according to geomagnetic latitude. The lower the geomagnetic latitude (closer to the equator) the lower the amplitude of the geomagnetic field.

It should be emphasized that even for the same reference event, the GIC(t) waveshape in every transformer will be different, depending on the location within the system and the number and orientation of the circuits connecting to the transformer station. Assuming a single generic GIC(t) waveshape to test all transformers is incorrect.

Figure 4: Calculated geoelectric field $E_N(t)$ and $E_E(t)$ assuming $\alpha=1$ and $\beta=1$ (reference earth model). Zoom area for subsequent graphs is highlighted.

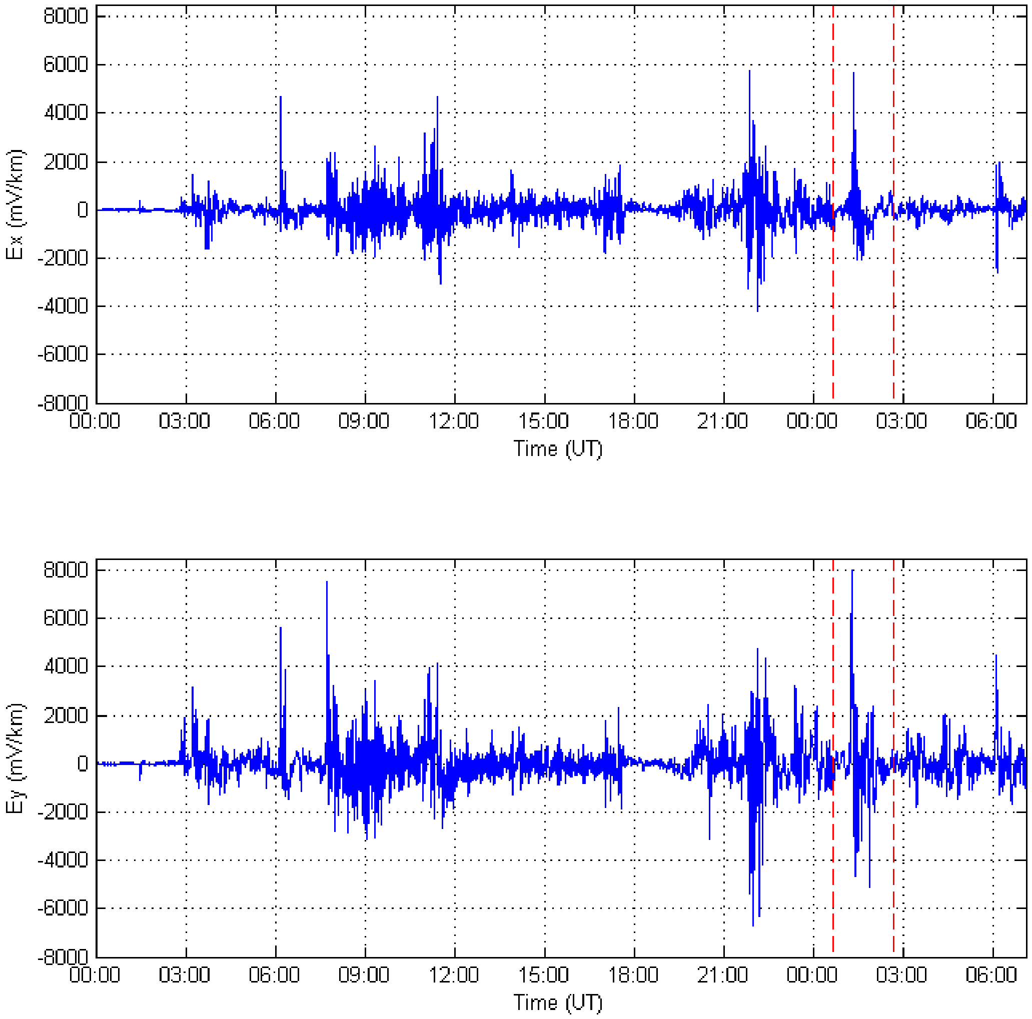


Figure 5: Calculated GIC(t) assuming α=1 and β=1 (reference earth model)

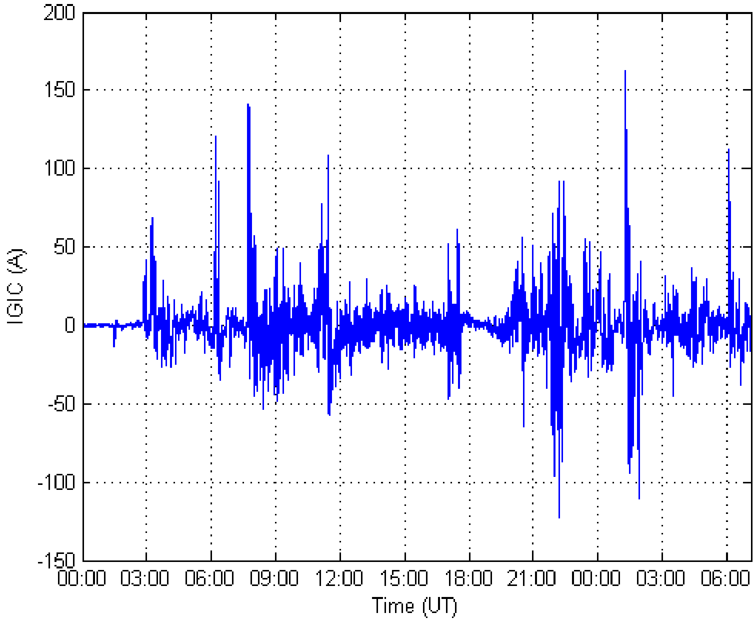
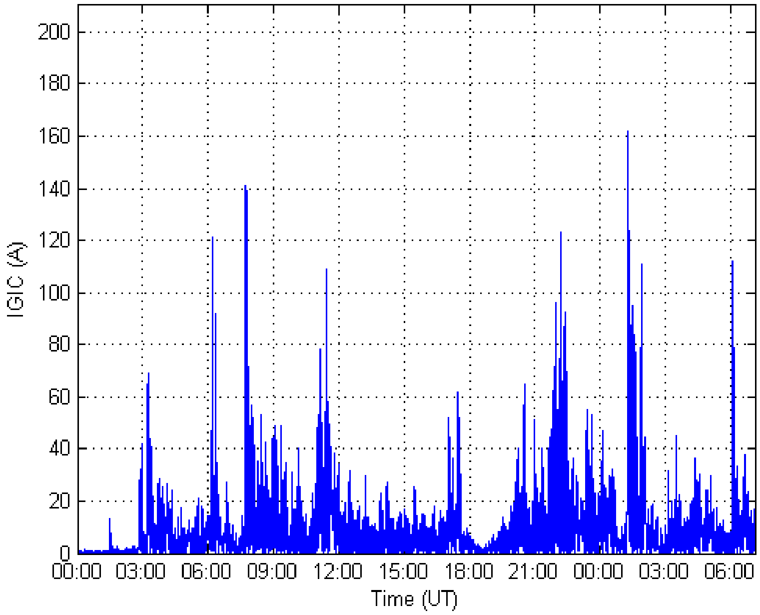


Figure 6: Calculated magnitude of GIC(t) assuming α=1 and β=1 (reference earth model)



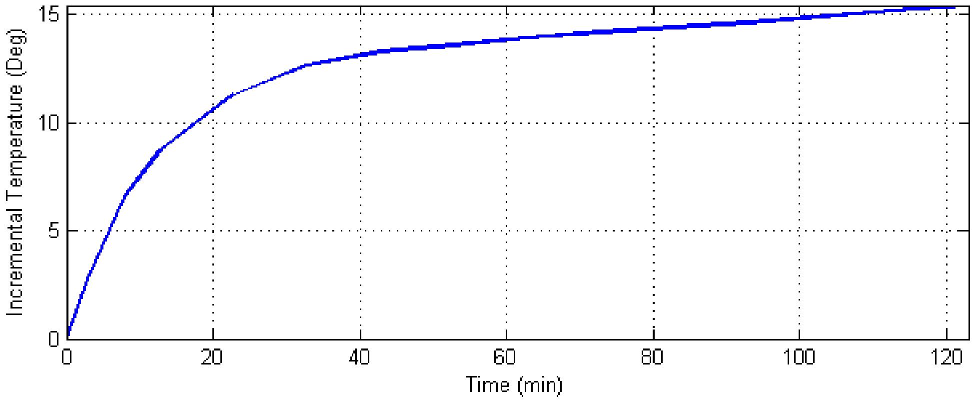
Transformer Thermal Assessment Examples

There are two basic ways to carry out a transformer thermal analysis once the GIC time series GIC(t) is known for a given transformer: 1) using manufacturer's capability curves, and 2) calculating the thermal response as a function of time.

Example 1: Using a thermal response tool

The thermal step response of the transformer can be obtained for both winding and metallic part hot spots from: (a) measurements; (b) manufacturer's calculations; or (c) generic published values. Figure 7 shows the measured metallic hot spot thermal response from [3] that will be used in this example. Figure 8 shows the estimated incremental temperature rise (asymptotic response) of the hot spot to long duration GIC steps[3]. The asymptotic response in Figure 8 is extrapolated linearly from relatively low magnitude dc measurements. This is a conservative approximation but not necessarily an unreasonable one for illustration purposes. In the Fingrid transformer tests reported in 2002 [6], the measured maximum value of the asymptotic response of the inside of the yoke clamp (highest hot spot temperature) is 15% lower than the value obtained using linear extrapolation. The linear extrapolation result in a calculated temperature peak 9% higher than the measured asymptotic behavior when the GIC(t) time series in Figure 6 is used.

Figure 7: Thermal step response to a 5 A/phase dc step [3]. Metallic hot spot heating.



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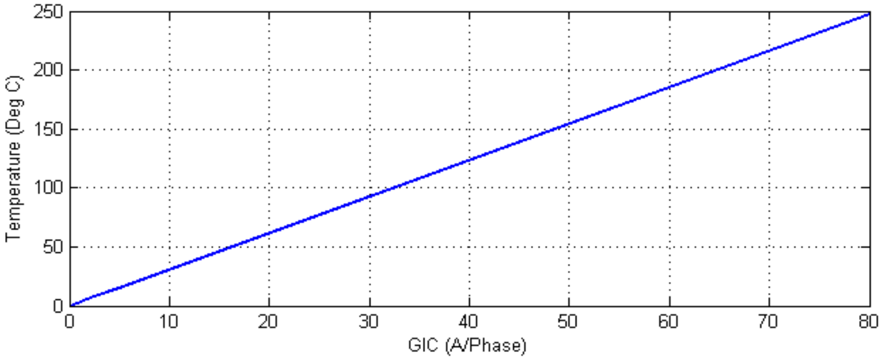
[3] The heating of the bulk oil due to the hot spot temperature increase is not included in the asymptotic response because the time constant of bulk oil heating is at least an order of magnitude larger than the time constants of hot spot heating.

Figure 8: Asymptotic thermal step response [3]. Metallic hot spot heating.



In order to obtain the thermal response of the transformer to a GIC waveshape such as the one in Figure 6, a thermal response model is required. To create a thermal response model, the measured or manufacturer-calculated transformer thermal step responses (winding and metallic part) for various GIC levels are required. The GIC(t) time series or waveshape is then applied to the thermal model to obtain the incremental temperature rise as a function of time θ(t) for the GIC(t) waveshape. The total temperature is calculated by adding the oil temperature, for example, at full load.

Figure 9 shows the calculated GIC(t) and the corresponding hot spot temperature time series θ(t) . Figure 10 shows a close-up of the peak transformer temperatures calculated in this example.

Figure 9: Magnitude of GIC(t) and metallic hot spot temperature θ(t) assuming full load oil temperature of 75.3°C (30°C ambient).

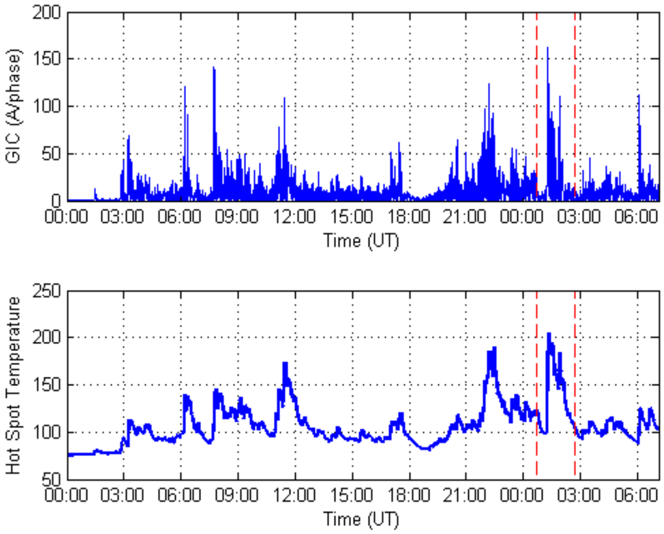
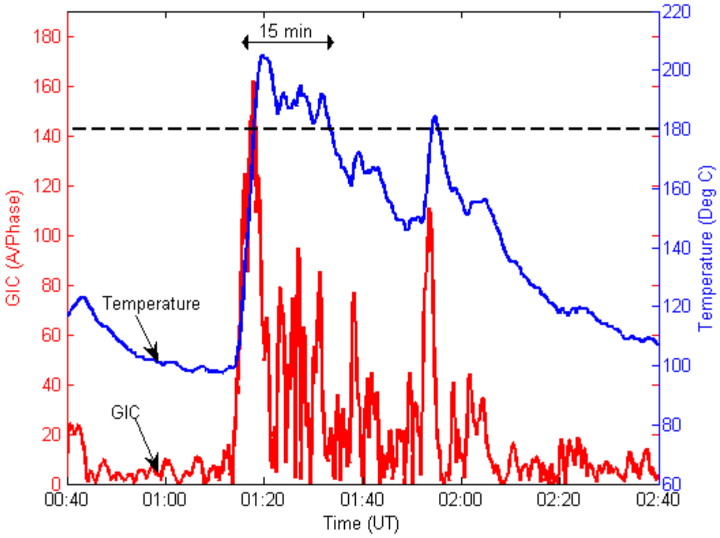


Figure 10: Close-up. Metallic hot spot temperature θ(t) assuming a full load (blue trace). Red trace is GIC(t).

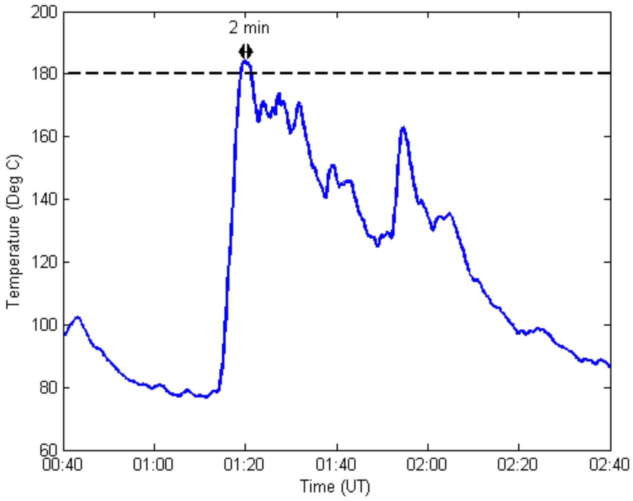


In this example the IEEE Std. C57.91 emergency loading hot spot threshold of 200°C for metallic hot spot heating is exceeded for 3 minutes (as opposed to 30 minutes for emergency overloading). Peak temperature is 204°C. The IEEE standard is silent as to whether the temperature can be higher than 200°C for less than 30 minutes. Manufacturers can provide guidance on individual transformer capability.

It is not unusual to use a lower temperature threshold to account for calculation and data margins as well transformer condition. Figure 10 shows that 180°C will be exceeded for 15 minutes.

At 70% loading, the initial temperature is 54.5 °C rather than 75.3 °C and the hot spot temperature peak is 183°C. In this case the 180 °C threshold is exceeded for 2 minutes (see Figure 11).

Figure 11: Close-up. Metallic hot spot temperature assuming a 70% load (oil temperature of 54.5°C).



Example 2: Using a manufacturer's capability curves

The capability curves used in this example are shown in Figure 12. To be consistent with the previous example, these particular capability curves have been reconstructed from the thermal step response shown in Figures 8 and 9, and the simplified loading curve shown in Figure 14 (calculated using formulae from IEEE Std. C57.91).

Figure 12: Capability curve of a transformer based on the thermal response shown in Figures 8 and 9

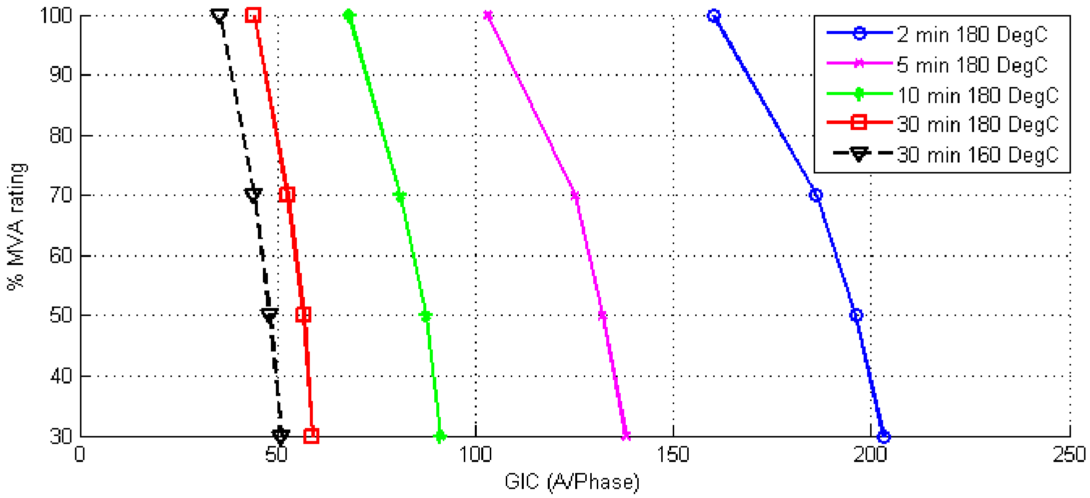
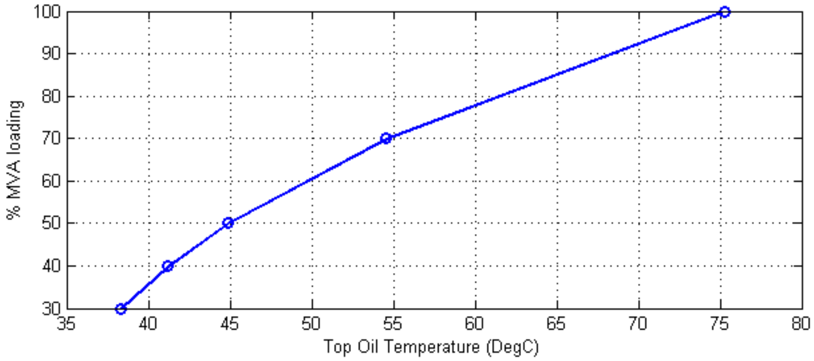


Figure 13: Simplified loading curve assuming 30°C ambient temperature.



The basic notion behind the use of capability curves is to compare the calculated GIC in a transformer with the limits at different GIC pulse widths. A narrow GIC pulse has a higher limit than a longer duration or wider one. If the calculated GIC and assumed pulse width falls below the appropriate pulse width curve then the transformer is within its capability.

To use these curves it is necessary to estimate an equivalent square pulse that matches the waveshape of GIC(t), generally at a GIC(t) peak. Figure 14 shows a close-up of the GIC near its highest peak superimposed to a 160 A/phase, 2 minute pulse at 100% loading from Figure 12. Since a narrow 2-minute pulse is not representative of GIC(t) in this case, a 5 minute pulse with an amplitude of 103 A/phase at 100% loading has been superimposed on Figure 15. It should be noted that a 160 A/phase, 2 minute pulse is equivalent to a 103A/phase 5 minute pulse from the point of view of transformer capability. Deciding what GIC pulse is equivalent to the portion of GIC(t) under consideration is a matter of engineering judgment.

Figure 14: Close-up of GIC(t) and a 2 minute GIC pulse at full load.

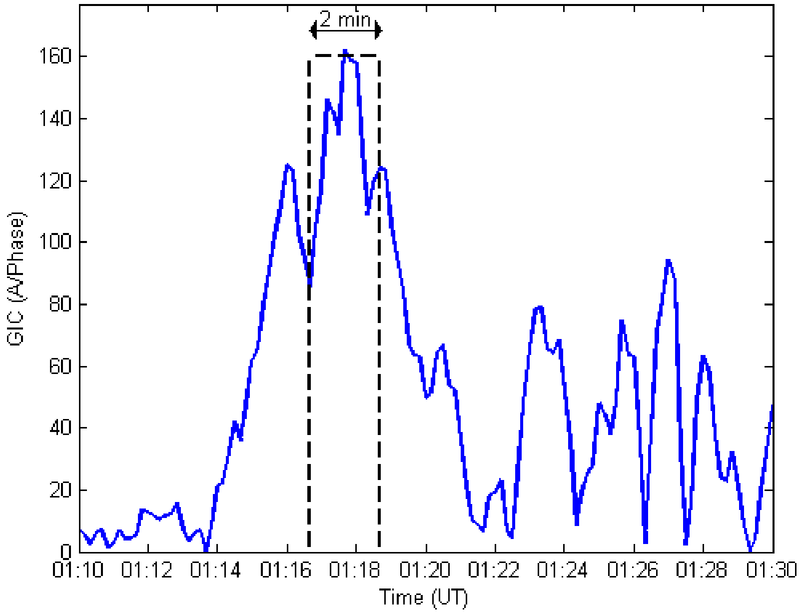
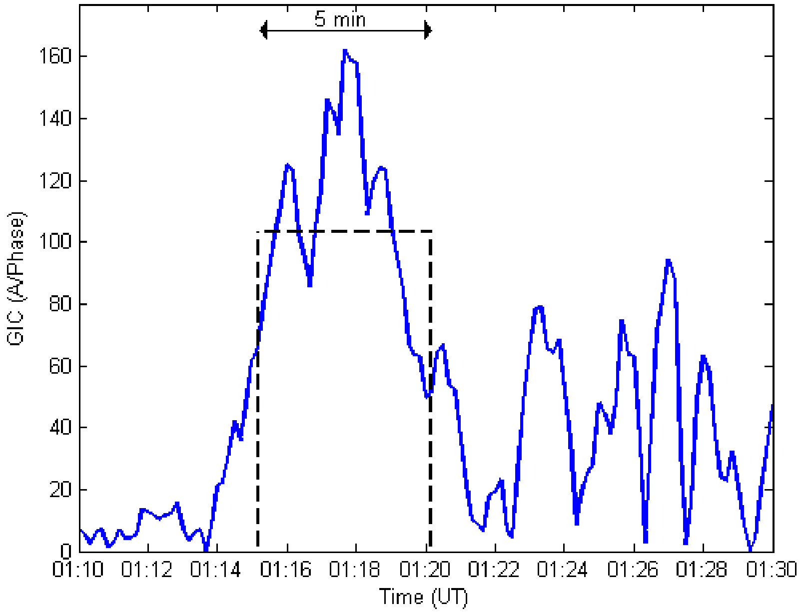


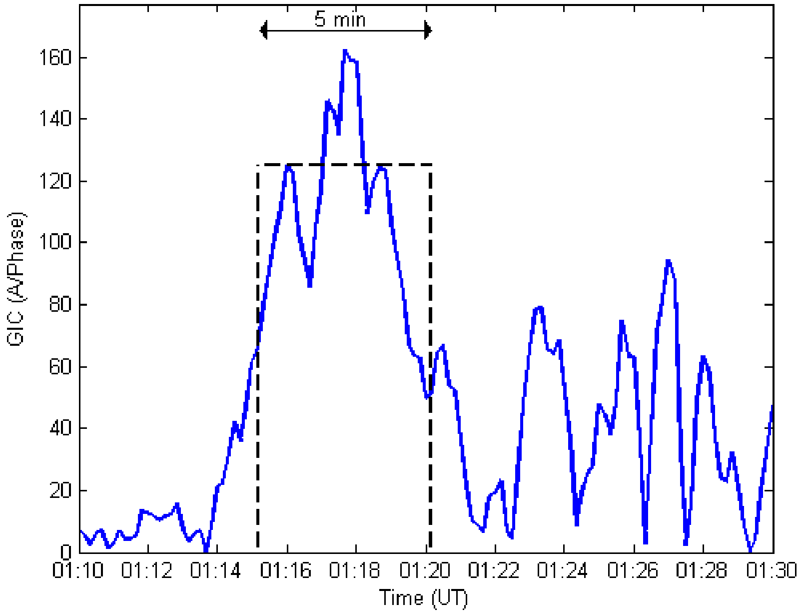
Figure 15: Close-up of GIC(t) and a 5 minute GIC pulse at full load.



When using a capability curve it should be understood that the curve is derived assuming that there is no hot spot heating due to prior GIC at the time the GIC pulse occurs (only an initial temperature due to loading). Therefore, in addition to estimating the equivalent pulse that matches GIC(t), allowances have to be made in terms of prior hot spot heating. From these considerations it is apparent that the capability curves would be exceeded at full load with a 180 °C threshold .

At 70% loading, the two and five minute pulses from Figure 12 would have amplitudes of 186 and 125 A/phase, respectively. The 5 minute pulse is illustrated in Figure 16. In this case, it is not easy to assess if the GIC(t) is within the capability curve for 70% loading. In general, capability curves are easier to use when GIC(t) is substantially above or clearly below the GIC thresholds for a given pulse duration.

Figure 16: Close-up of GIC(t) and a 5 minute GIC pulse assuming 70% load.



References

[1] "IEEE Guide for loading mineral-oil-immersed transformers and step-voltage regulators," IEEE Std C57.91-2011 (Revision of IEEE Std C57.91-1995).

[2] Girgis, R.; Vedante, K., "Methodology for evaluating the impact of GIC and GIC capability of power transformer designs", IEEE PES 2013 General Meeting Proceedings, Vancouver, Canada.

[3] Marti, L., Rezaei-Zare, A., Narang, A. , "Simulation of Transformer Hotspot Heating due to Geomagnetically Induced Currents," IEEE Transactions on Power Delivery, , vol.28, no.1, pp.320-327, Jan. 2013.

[4] GMD application guide, NERC

[5] White paper on the definition of the GMD benchmark

[6] Matti Lahtinen, Jarmo Elovaara, "GIC occurrences and GIC test for 400 kV system transformer", IEEE Transactions on Power Delivery, Vol. 17, No. 2, April 2002.

Standard Development Timeline

This section is maintained by the drafting team during the development of the standard and will be removed when the standard becomes effective.

Development Steps Completed

1. The Standards Committee accepted the Standard Authorization Request (SAR) submitted by the Geomagnetic Disturbance Task Force (GMD TF) and approved Project 2013-03 (Geomagnetic Disturbance Mitigation) on June 5, 2013.
2. The SAR was posted for informal comment from June 26, 2013 through August 12, 2013.

Description of Current Draft

This draft is the first posting of the proposed standard. It is posted for a 30-day informal comment.

Anticipated Actions	Anticipated Date
45-day Formal Comment Period with Initial Ballot	2Q14
45-day Formal Comment Period with Additional Ballot	3Q14
Final ballot	4Q14
BOT adoption	November 2014

Effective Dates

The definition shall become effective on the first day of the first calendar quarter after the date that this standard is approved by an applicable governmental authority or as otherwise provided for in a jurisdiction where approval by an applicable governmental authority is required for a standard to go into effect. Where approval by an applicable governmental authority is not required, the definition shall become effective on the first day of the first calendar quarter after the date this standard is adopted by the NERC Board of Trustees or as otherwise provided for in that jurisdiction.

The Requirements shall become effective as described in the Implementation Plan beginning on the first day of the first calendar quarter that is 12 months after the date that this standard is approved by an applicable governmental authority or as otherwise provided for in a jurisdiction where approval by an applicable governmental authority is required for a standard to go into effect. Where approval by an applicable governmental authority is not required, the Requirements shall become effective on the first day of the first calendar quarter that is 12 months after the date this standard is adopted by the NERC Board of Trustees or as otherwise provided for in that jurisdiction.

Compliance shall be implemented over a 4-year period as described in the Implementation Plan.

Version History

Version	Date	Action	Change Tracking
1	TBD	Project 2013-03 (Phase 2)	new standard

Definitions of Terms Used in Standard

This section includes all newly defined or revised terms used in the proposed standard. Terms already defined in the Reliability Standards Glossary of Terms are not repeated here. New or revised definitions listed below become approved when the proposed standard is approved. When the standard becomes effective, these defined terms will be removed from the individual standard and added to the Glossary.

Geomagnetic Disturbance Vulnerability Assessment or GMD Vulnerability Assessment: Documented evaluation of potential susceptibility to voltage collapse, Cascading, or localized damage of equipment due to geomagnetic disturbances.

A. Introduction

1. **Title: Transmission System Planned Performance for Geomagnetic Disturbance Events**

2. **Number:** TPL-007-1

3. **Purpose:** Establish requirements for Transmission system planned performance during geomagnetic disturbance (GMD) events within the Near-Term Transmission Planning Horizon.

4. **Applicability:**

   4.1. Functional Entities:

   4.1.1 Planning Coordinator with a Planning Coordinator area that includes a power transformer with a high side, wye-grounded winding connected at 200 kV or higher

   4.1.2 Transmission Planner with a Transmission Planning area that includes a power transformer with a high side, wye-grounded connected at 200 kV or higher

   4.1.3 Transmission Owner who owns a power transformer(s) with a high side, wye-grounded winding connected at 200 kV or higher

   4.1.4 Generation Owner who owns a power transformer(s) with a high side, wye-grounded winding connected at 200 kV or higher

5. **Background:**

   During a GMD event, geomagnetically-induced currents (GIC) may cause transformer hot-spot heating or damage, loss of Reactive Power sources, increased Reactive Power demand, and Misoperation, the combination of which may result in voltage collapse and blackout.

B. Requirements and Measures

R1. Each Planning Coordinator and Transmission Planner shall maintain ac System models and geomagnetically-induced current (GIC) System models within its respective area for performing the studies needed to complete its GMD Vulnerability Assessment. The models shall use data consistent with that provided in accordance with the MOD standards, supplemented by other sources as needed, including items represented in the Corrective Action Plan, and shall represent projected System conditions. This establishes Category P8 as the normal System condition for GMD planning in Table 1. The System models shall include: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

   1.1. Existing Facilities

   1.2. Known outage(s) of generation or Transmission Facility(ies) with a duration of at least six months.

1.3. New planned Facilities and changes to existing Facilities

1.4. Real and reactive Load forecasts

1.5. Known commitments for Firm Transmission Service and Interchange

1.6. Resources (supply or demand side) required for Load

M1. Each Planning Coordinator and Transmission Planner shall have evidence in either electronic or hard copy format that it is maintaining ac System models and geomagnetically-induced current (GIC) System models within its respective area, using data consistent with MOD standards including items represented in the Corrective Action Plan, representing projected System conditions, and that the models represent the required information in accordance with Requirement R1.

Rationale for Requirement R1:

A GMD Vulnerability Assessment requires a dc GIC System model to calculate GIC flow which is used to determine Transformer Reactive Power absorption and Transformer thermal response. Details for developing the GIC System model are provided in the GIC Application Guide developed by the NERC GMD Task Force and available at: http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GIC%20Application%20Guide%202013_approved.pdf

The ac System model is used in conducting steady-state power flow analysis that accounts for the Reactive Power absorption of transformers due to GIC in the System.

The projected System condition for GMD planning may include adjustments to posture the System that are executable in response to space weather information. These adjustments could include recalling maintenance outages, for example.

R2. Each Planning Coordinator and Transmission Planner shall complete a GMD Vulnerability Assessment of the Near Term Transmission Planning Horizon for its respective area once every 60 months. This GMD Vulnerability Assessment shall use studies, document assumptions, and document summarized results of the steady state analysis. *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

2.1. Studies shall include the following conditions:

2.1.1. System peak Load for one year within the Near-term Transmission Planning Horizon.

2.1.2. System Off-Peak Load for one year within the Near-term Transmission Planning Horizon.

2.2 Studies shall be conducted based on the benchmark GMD event described in Appendix 1to determine whether the system meets the performance requirements in Table 1.

M2. Each Planning Coordinator and Transmission Planner shall have dated evidence such as electronic or hard copies of its GMD Vulnerability Assessment meeting all of the requirements in Requirement R2.

Rationale for Requirement R2:

GMD Vulnerability Assessment includes steady-state power flow analysis and supporting studies that account for the effects of GIC. Performance criteria is specified in Table 1.

System peak Load and Off-peak Load must be examined in the analysis.

The GMD Planning Guide developed by the NERC GMD Task Force provides technical information on GMD-specific considerations for planning studies. It is available at:

http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GMD%20Planning%20Guide_approved.pdf

R3. Each Planning Coordinator and Transmission Planner that determines through the GMD Vulnerability Assessment conducted in Requirement R2 that its System does not meet the performance requirements of Table 1 shall develop a Corrective Action Plan addressing how the performance requirements will be met. The Corrective Action Plan shall: *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

3.1. List System deficiencies and the associated actions needed to achieve required System performance. Examples of such actions include:

- Installation, modification, retirement, or removal of Transmission and generation Facilities and any associated equipment.
- Installation, modification, or removal of Protection Systems or Special Protection Systems.
- Use of Operating Procedures specifying how long they will be needed as part of the Corrective Action Plan.
- Use of Demand-Side Management, new technologies, or other initiatives.

3.2. Be reviewed in subsequent GMD Vulnerability Assessments for continued validity and implementation status of identified System Facilities and Operating Procedures.

M3. Each Planning Coordinator and Transmission Planner shall have evidence such as electronic or hard copies of its Corrective Action Plan as specified in Requirement R3.

R4. Each Planning Coordinator and Transmission Planner shall have criteria for acceptable System steady state voltage limits for its System during the GMD conditions described in Appendix 1. *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

M4. Each Planning Coordinator and Transmission Planner shall have evidence such as electronic or hard copies of the criteria for acceptable System steady state voltage limits for its System in accordance with Requirement R4.

Rationale for Requirement R4:

System steady state voltage limits for GMD Vulnerability Assessment may by different from the limits used in the TPL-001 Planning Assessment. The planner must adhere to established limits that ensure the planned System achieves the performance requirements in Table 1.

R5. Each Planning Coordinator, in conjunction with each of its Transmission Planners, shall determine and identify each entity's individual and joint responsibilities for performing the required studies for the GMD Vulnerability Assessment. *[Violation Risk Factor: Low] [Time Horizon: Long-term Planning]*

M5. Each Planning Coordinator, in conjunction with each of its Transmission Planners, shall provide dated documentation on roles and responsibilities, such as meeting minutes, agreements, and e-mail correspondence that identifies that agreement has been reached on individual and joint responsibilities for performing the required studies and Assessments in accordance with Requirement R5.

R6. Each Planning Coordinator and Transmission Planner shall distribute its GMD Vulnerability Assessment and Corrective Action Plan, if any, to adjacent Planning Coordinators, adjacent Transmission Planners, and Transmission Owners and Generator Owners in its respective planning area as specified in the Applicability Section 4.1.3 and 4.1.4 within 90 calendar days of completion, and to any functional entity that has a reliability related need and submits a written request for the information within 30 days of such a request. *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

6.1 If a recipient of the GMD Vulnerability Assessment results provides documented comments on the results, the respective Planning Coordinator or Transmission Planner shall provide a documented response to that recipient within 90 calendar days of receipt of those comments.

M6. Each Planning Coordinator and Transmission Planner shall provide evidence, such as email notices, or postal receipts showing recipient and date, that it has distributed its GMD Vulnerability Assessment and Corrective Action Plan, if any, to adjacent Planning Coordinators and adjacent Transmission Planners within 90 days of completion, and to any functional entity who has indicated a reliability need within 30 days of a written request and that the Planning Coordinator or Transmission Planner has provided a documented response to comments received on GMD Vulnerability Assessment results within 90 calendar days of receipt of those comments in accordance with Requirement R5.

Rationale for Requirement R6:

Distribution of GMD Vulnerability Assessments and Corrective Action Plans provides a means for sharing relevant information with other entities responsible for planning reliability. Results of GIC studies and planned mitigation measures may affect neighboring systems and should be taken into account by planners. Additionally, this GIC information is essential for determining the thermal impact of GIC on transformers in the planning area and must be provided to entities responsible for performing the thermal impact assessment.

R7. Each Transmission Owner and Generator Owner shall conduct an assessment of thermal impact for all of its solely and jointly owned power transformers with grounded wye windings connected at 200 kV or higher. The assessment shall: *[Violation Risk Factor: High] [Time Horizon: Long-term Planning]*

7.1. Be based on the geomagnetically-induced current (GIC) flow determined in the steady-state analysis conducted in Requirement R2

7.2. Document assumptions used in the analysis

7.3. Describe suggested actions to mitigate the impact of geomagnetically-induced currents, if any.

M7. Each Transmission Owner and Generator Owner shall have evidence such as electronic or hard copies of its assessment of thermal impact for all of its solely and jointly owned power transformers with grounded wye windings connected at 200 kV or higher as specified in Requirement R7.

Rationale for Requirement R7:

The thermal impact assessment may be based on manufacturer-provided GIC capability curves, thermal response simulation, or other technically justified means. A process for conducting the assessment is presented in the whitepaper posted on the project page.

http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx

R8. Each Transmission Owner and Generator Owner shall provide its assessment of thermal impact specified in Requirement R7 for all of its solely and jointly owned power transformers with grounded wye windings connected at 200 kV or higher within 90 days of completion to the Planning Coordinator and Transmission Planner with responsibility for the area in which the associated power transformer is located. *[Violation Risk Factor: Medium]* *[Time Horizon: Long-term Planning]*

M8. Each Transmission Owner and Generator Owner shall have dated evidence such as postal receipts or email confirmation that it has provided a copy of its assessment of thermal impact for all of its solely and jointly owned power transformers with grounded wye windings connected at 200 kV or higher as specified in Requirement R7 to the Planning Coordinator and Transmission Planner with responsibility for the area in which the associated power Transformer is located within the timeframe prescribed in Requirement R8.

Table 1 –Steady State Planning Events

Steady State:

a. The System shall remain stable. Cascading and uncontrolled islanding shall not occur.
b. Consequential Load Loss as well as generation loss is acceptable as a consequence of P8 planning event.
c. Planned System adjustments such as Transmission configuration changes and re-dispatch of generation are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings.
d. System steady state voltages shall be within acceptable limits as established by the Planning Coordinator and the Transmission Planner.

Category	Initial Condition	Event	Interruption of Firm Transmission Service Allowed	Non-Consequential Load Loss Allowed
P8 GMD Event with Outages	1. System as may be postured in response to space weather information[1], and then 2. GMD event[2]	Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation during the GMD event	Yes[3]	Yes[3]

Table 1 – Steady State Performance Footnotes

1. The System condition for GMD planning may include adjustments to posture the System that are executable in response to space weather information.
2. The GMD conditions for planning event P8 are described in Appendix 1 (Benchmark GMD Event).
3. The objective of the GMD Vulnerability Assessment is to prevent instability, uncontrolled separation, or Cascading failures of the System during a GMD event. Non-Consequential Load Loss and/or curtailment of Firm Transmission Service may be needed to meet BES performance requirements during studied GMD conditions but should only be used as a last resort and not as the primary method of achieving required performance. GMD Operating Procedures should be based on predetermined triggers from studied GMD conditions so that any Non-Consequential Load Loss or curtailment of Firm Transmission Service is minimized and controlled.

Appendix 1

Calculating Geoelectric Fields for the Benchmark GMD Event

The benchmark GMD event defines the geoelectric field values used to compute GIC flows that are needed to conduct a GMD Vulnerability Assessment. It is composed of the following elements: (1) a reference peak geoelectric field amplitude of 8 V/km derived from statistical analysis of historical magnetometer data; (2) scaling factors to account for local geomagnetic latitude; and (3) scaling factors to account for local earth conductivity; and (4) a reference geomagnetic field time series or waveshape. The benchmark GMD event description is available on the Project 2013-03 Geomagnetic Disturbance Mitigation project page:
http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx

The regional geoelectric field peak amplitude to be used in GMD Vulnerability Assessment, E_{peak}, can be obtained from the reference geoelectric field value of 8 V/km using the following relationship

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

where α is the scaling factor to account for local geomagnetic latitude, and β is a scaling factor to account for the local earth conductivity structure.

Scaling the Geomagnetic Field

The benchmark GMD event is defined for geomagnetic latitude of 60° and it must be scaled to account for regional differences based on geomagnetic latitude. Table A1 provides a scaling factor correlating peak geoelectric field to geomagnetic latitude. Alternatively, the scaling factor α can be computed with the empirical expression

$$\alpha = 0.001 \cdot e^{(0.115 \cdot L)}$$

where L is the geomagnetic latitude in degrees

Table A1 Geomagnetic Field Scaling Factors According to Geomagnetic Latitude

Geomagnetic Latitude (Degrees)	Scaling Factor1 (α)
≤ 40	0.10
45	0.2
50	0.3
55	0.6
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

Scaling the Geoelectric Field

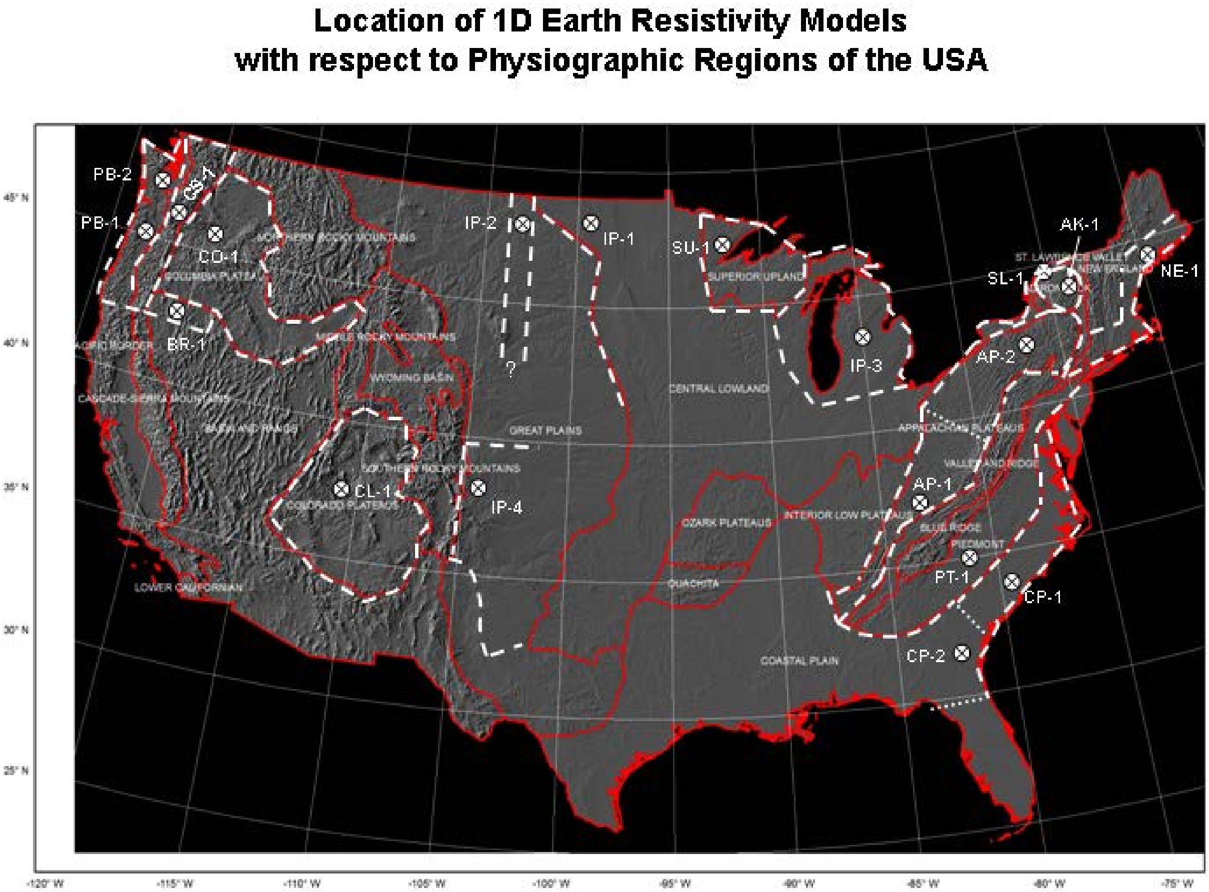
The benchmark GMD event is defined for the reference Quebec earth model described in Table A3. The peak geoelectric field, E_{peak}, to be used in a GMD Vulnerability Assessment may be obtained by either

- Calculating the geoelectric field for the ground conductivity in the planning area and the reference geomagnetic field time series scaled according to geomagnetic latitude, using a procedure such as the plane wave method described in the NERC GMD Task Force GIC Application Guide; or
- Using the earth conductivity scaling factor β from Table A2 that correlates to the ground conductivity map in Figure A1 or Figure A2. Along with the scaling factor α, β is applied to the reference geolectric field using the following equation to obtain the regional geoelectric field peak amplitude E_{peak} to be used in GMD Vulnerability Assessment.

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

The earth models used to calculate Table A2 for the United States were obtained using best known USGS data. The models used to calculate Table A2 for Canada were obtained from NRCan and reflect the average structure for large regions. NRCan also has developed some models for sub-regions which should be used when available. Because all models in Table A2 are approximations, a planner can substitute a technically justified earth model for its planning area when available.

Figure A1. Physiographic Regions of the Continental United States.



Additional map detail is available at the U.S. Geological Survey (http://geomag.usgs.gov/)

Figure A2. Physiographic Regions of Canada (PLACEHOLDER)

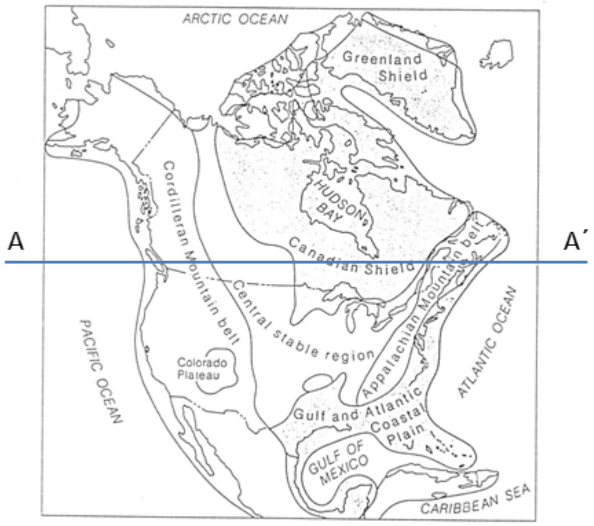


Table A2. Geoelectric Field Scaling Factors

USGS Earth model	Scaling Factor (β)
AK1A	0.56
AK1B	.0.56
AP1	0.33
AP2	0.82
BR1	0.22
CL1	0.76
CO1	0.27
CP1	0.81
CP2	0.95
CS1	0.41
IP1	0.94
IP2	0.28
IP3	0.93
IP4	0.41
NE1	0.81
OTT	1.00
PB1	0.62
PB2	0.46
PT1	1.17
SL1	0.53
SU1	0.93
BOU	0.28
FBK	0.56
PRU	0.21
BC	0.67
PRAIRIES	0.96
SHIELD	1.0
ATLANTIC	0.79

Table A3. Reference earth model (Quebec)

Depth (km)	Resistivity (Ω-m)
15	20,000
10	200
125	1,000
200	100
∞	3

1. Compliance Monitoring Process

1.1. Compliance Enforcement Authority

As defined in the NERC Rules of Procedure, “Compliance Enforcement Authority” means NERC or the Regional Entity in their respective roles of monitoring and enforcing compliance with the NERC Reliability Standards

1.2. Evidence Retention

The following evidence retention periods identify the period of time an entity is required to retain specific evidence to demonstrate compliance. For instances where the evidence retention period specified below is shorter than the time since the last audit, the CEA may ask an entity to provide other evidence to show that it was compliant for the full time period since the last audit.

The Planning Coordinator, Transmission Planner, Transmission Owner, and Generator Owner shall keep data or evidence to show compliance as identified below unless directed by its Compliance Enforcement Authority to retain specific evidence for a longer period of time as part of an investigation:

The responsible entities shall retain documentation as evidence for three years.

If a Planning Coordinator, Transmission Planner, Transmission Owner, or Generator Owner is found non-compliant, it shall keep information related to the non-compliance until mitigation is complete and approved or for the time specified above, whichever is longer.

The Compliance Enforcement Authority shall keep the last audit records and all requested and submitted subsequent audit records.

1.3. Compliance Monitoring and Assessment Processes:

Compliance Audits

Self-Certifications

Spot Checking

Compliance Violation Investigations

Self-Reporting

Complaints Text

1.4. Additional Compliance Information

None

Table of Compliance Elements

R #	Time Horizon	VRF	Violation Severity Levels			
			Lower VSL	Moderate VSL	High VSL	Severe VSL
R1	Long-term Planning	Medium	The responsible entity's ac System model and geomagnetically-induced current (GIC) model failed to include one of the elements in Requirement R1, Parts 1.1 through 1.6.	The responsible entity's ac System model and geomagnetically-induced current (GIC) model failed to include two of the elements in Requirement R1, Parts 1.1 through 1.6.	The responsible entity's ac System model and geomagnetically-induced current (GIC) model failed to include three of the elements in Requirement R1, Parts 1.1 through 1.6.	The responsible entity's ac System model and geomagnetically-induced current (GIC) model failed to include four or more of the elements in Requirement R1, Parts 1.1 through 1.6. OR The responsible entity's ac System model and geomagnetically-induced current (GIC) model did not represent projected System conditions as described in Requirement R1. OR The responsible entity's ac System model and geomagnetically-induced current (GIC) model did not use data consistent with the MOD standards including items represented in the Corrective Action Plan.

R2	Long-term Planning	High	N/A	N/A	The responsible entity's completed GMD Vulnerability Assessment failed to include one of the following Parts of Requirement R2: Part 2.1 or 2.2. OR The responsible entity completed a GMD Vulnerability Assessment but it was more than 60 calendar months and less than or equal to 72 calendar months since the last GMD Vulnerability Assessment	The responsible entity's completed GMD Vulnerability Assessment failed to include two of the following Parts of Requirement R2: Part 2.1 or 2.2. OR The responsible entity completed a GMD Vulnerability Assessment but it was more than 72 calendar months since the last GMD Vulnerability Assessment OR The responsible entity does not have a completed GMD Vulnerability Assessment
R3	Long-term Planning	Medium	N/A	N/A	The responsible entity's Corrective Action Plan failed to comply with one of the elements in Requirement R3 parts 3.1 and 3.2	The responsible entity's Corrective Action Plan failed to comply with two of the elements in Requirement R3 parts 3.1 and 3.2 OR The responsible entity did not have a Corrective Action Plan as required by Requirement R3.

R4	Long-term Planning	Medium	N/A	N/A	N/A	The responsible entity does not have criteria for acceptable System steady state voltage limits for its System during the GMD conditions as required.
R5	Long-term Planning	Low	N/A	N/A	N/A	The Planning Coordinator, in conjunction with each of its Transmission Planners, failed to determine and identify individual or joint responsibilities for performing required studies.
R6	Long-term Planning	Medium	The responsible entity distributed its GMD Vulnerability Assessment and Corrective Action Plan, if any, to adjacent Planning Coordinators, adjacent Transmission Planners, and Transmission Owners and Generator Owners in its respective planning area as specified in the Applicability Section 4.1.3 and 4.1.4 but it was more than 90 days but less than or equal to 120 days following completion.	The responsible entity distributed its GMD Vulnerability Assessment and Corrective Action Plan, if any, to adjacent Planning Coordinators, adjacent Transmission Planners, and Transmission Owners and Generator Owners in its respective planning area as specified in the Applicability Section 4.1.3 and 4.1.4 but it was more than 120 days but less than or equal to 130 days following its completion.	The responsible entity distributed its GMD Vulnerability Assessment and Corrective Action Plan, if any, to adjacent Planning Coordinators, adjacent Transmission Planners, and Transmission Owners and Generator Owners in its respective planning area as specified in the Applicability Section 4.1.3 and 4.1.4 but it was more than 130 days but less than or equal to 140 days following its completion.	The responsible entity distributed its GMD Vulnerability Assessment and Corrective Action Plan, if any, to adjacent Planning Coordinators, adjacent Transmission Planners, and Transmission Owners and Generator Owners in its respective planning area as specified in the Applicability Section 4.1.3 and 4.1.4 but it was more than 140 days following its completion. OR

			OR, The responsible entity distributed its GMD Vulnerability Assessment and Corrective Action Plan, if any, to functional entities having a reliability related need who requested the results in writing but it was more than 30 days but less than or equal to 40 days following the request.	OR, The responsible entity distributed its GMD Vulnerability Assessment and Corrective Action Plan, if any, to functional entities having a reliability related need who requested the results in writing but it was more than 40 days but less than or equal to 50 days following the request.	OR, The responsible entity distributed its GMD Vulnerability Assessment and Corrective Action Plan, if any, to functional entities having a reliability related need who requested the results in writing but it was more than 50 days but less than or equal to 60 days following the request.	The responsible entity did not distribute its GMD Vulnerability Assessment and Corrective Action Plan, if any, to adjacent Planning Coordinators, adjacent Transmission Planners, and Transmission Owners and Generator Owners in its respective planning area as specified in the Applicability Section 4.1.3 and 4.1.4 . OR The responsible entity distributed its GMD Vulnerability Assessment and Corrective Action Plan, if any, to functional entities having a reliability related need who requested the results in writing but it was more than 60 days following the request. OR The responsible entity did not distribute its GMD Vulnerability Assessment and Corrective Action Plan, if any, to functional entities having a

						reliability related need who requested the results in writing.
R7	Long-term Planning	High	The responsible entity failed to conduct an assessment of thermal impact for 5% or less of its solely owned and jointly owned power transformers with grounded wye windings rated 200 kV or higher.	The responsible entity failed to include one of the required elements as listed in Requirement R7 parts 7.1 through 7.3 OR The responsible entity failed to conduct an assessment of thermal impact for more than 5% up to (and including) 10% of its solely owned and jointly owned power transformers with grounded wye windings rated 200 kV or higher.	The responsible entity failed to include two or more of the required elements as listed in Requirement R7 parts 7.1 through 7.3 OR The responsible entity failed to conduct an assessment of thermal impact for more than 10% up to (and including) 15% of its solely owned and jointly owned power transformers with grounded wye windings rated 200 kV or higher.	The responsible entity failed to conduct an assessment of thermal impact for more than15% of its solely owned and jointly owned power transformers with grounded wye windings rated 200 kV or higher.
R8	Long-term Planning	Medium	The responsible entity provided a copy of its assessment of thermal impact to the Planning Coordinator and Transmission Planner but it was more than 90 days but less than or equal to 120 days following its completion.	The responsible entity provided a copy of its assessment of thermal impact to the Planning Coordinator and Transmission Planner but it was more than 120 days but less than or equal to 130 days following its completion.	The responsible entity provided a copy of its assessment of thermal impact to the Planning Coordinator and Transmission Planner but it was more than 130 days but less than or equal to 140 days following its completion.	The responsible entity provided a copy of its assessment of thermal impact to the Planning Coordinator and Transmission Planner but it was more than 140 days following its completion. OR The responsible entity did not provide a copy of its thermal vulnerability assessment to the Planning Coordinator

						and Transmission Planner.

C. Regional Variances

None.

D. Interpretations

None.

E. Associated Documents

None.

Guidelines and Technical Basis

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Implementation Plan

Project 2013-03 Geomagnetic Disturbance Mitigation

Implementation Plan for TPL-007-1 – Transmission System Planned Performance During Geomagnetic Disturbances

Approvals Required

TPL-007-1 – Transmission System Planned Performance During Geomagnetic Disturbances

Prerequisite Approvals

None

Retirements

None

Revisions to Glossary Terms

There is a new definition in the proposed standard, which shall become effective when TPL-007-1 is approved by the applicable governmental authority:

Geomagnetic Disturbance Vulnerability Assessment or GMD Vulnerability Assessment: Documented evaluation of potential susceptibility to voltage collapse, Cascading, or localized damage of equipment due to geomagnetic disturbances.

Applicable Entities

Planning Coordinator with a Planning Coordinator area that includes a power transformer with a high side wye-grounded winding with terminal voltage greater than 200 kV

Transmission Planner with a Transmission Planning area that includes a power transformer with a high side wye-grounded winding with terminal voltage greater than 200 kV

Transmission Owner who owns a power transformer(s) with a high side, wye-grounded winding connected at 200 kV or greater

Generation Owner who owns a power transformer(s) with a high side, wye-grounded winding connected at 200 kV or greater

Conforming Changes to Other Standards

None

Effective Dates

Compliance with TPL-007-1 shall be implemented over a 4-year period as follows. Phased implementation provides:

- Necessary time for entities to develop the required models.

- Proper sequencing of assessments. The assessment of thermal impact on transformers is dependent upon geomagnetically-induced current (GIC) flow calculations that are determined in the Steady-state analysis.
- Necessary time for development of viable Corrective Action Plans, which may require entities to develop, perform, and or validate new and/or modified studies, assessments, procedures, etc., to meet the TPL-007-1 requirements. Some mitigation measures may have significant budget, siting, or construction planning requirements.

Requirements R1 and R5 shall become effective on the first day of the first calendar quarter that is 12 months after the date that this standard is approved by an applicable governmental authority or as otherwise provided for in a jurisdiction where approval by an applicable governmental authority is required for a standard to go into effect. Where approval by an applicable governmental authority is not required, Requirements R1 and R5 shall become effective on the first day of the first calendar quarter that is 12 months after the date this standard is adopted by the NERC Board of Trustees or as otherwise provided for in that jurisdiction.

Requirement R2, Requirement R4, and Requirement R6 shall become effective on the first day of the first calendar quarter that is 24 months after the date that this standard is approved by an applicable governmental authority or as otherwise provided for in a jurisdiction where approval by an applicable governmental authority is required for a standard to go into effect. Where approval by an applicable governmental authority is not required, Requirement R2, Requirement R4, and Requirement R6, shall become effective on the first day of the first calendar quarter that is 24 months after the date this standard is adopted by the NERC Board of Trustees or as otherwise provided for in that jurisdiction.

Requirement R7 and R8 shall become effective on the first day of the first calendar quarter that is 36 months after the date that this standard is approved by an applicable governmental authority or as otherwise provided for in a jurisdiction where approval by an applicable governmental authority is required for a standard to go into effect. Where approval by an applicable governmental authority is not required, Requirements R7 and R8 shall become effective on the first day of the first calendar quarter that is 36 months after the date this standard is adopted by the NERC Board of Trustees or as otherwise provided for in that jurisdiction.

Requirement R3 shall become effective on the first day of the first calendar quarter that is 48 months after the date that this standard is approved by an applicable governmental authority or as otherwise provided for in a jurisdiction where approval by an applicable governmental authority is required for a standard to go into effect. Where approval by an applicable governmental authority is not required, Requirement R3 shall become effective on the first day of the first calendar quarter that is 48 months after the date this standard is adopted by the NERC Board of Trustees or as otherwise provided for in that jurisdiction.