NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

# Geomagnetic Disturbance Planning Guide

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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.

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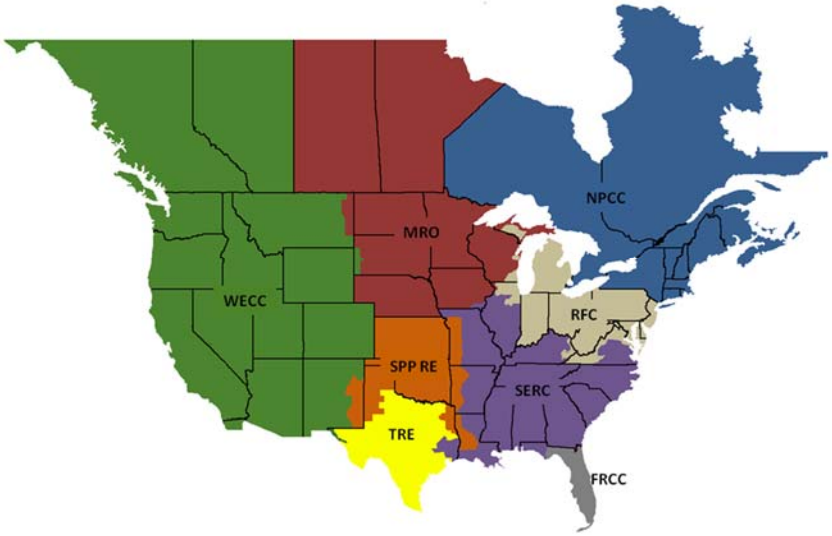
| **FRCC** | Florida Reliability Coordinating Council |
| **MRO** | Midwest Reliability Organization |
| **NPCC** | Northeast Power Coordinating Council |
| **RFC** | Reliability*First* Corporation |
| **SERC** | SERC Reliability Corporation |
| **SPP-RE** | Southwest Power Pool Regional Entity |
| **TRE**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



# Chapter 1 – Introduction

Assessments of the potential impacts associated with severe geomagnetic disturbances (GMD) do not fall within the typical study repertoire that planning engineers and system operators employ to ensure safe and reliable operation of the interconnected power system. However, many elements of a GMD study are common to standard system performance and planning studies. This guide does not describe the basic steps to carry a traditional system study, but rather highlights GMD-specific considerations as well as studies that may be outside the scope of traditional studies.

## 1.1 Organization

The Geomagnetic Disturbance Task Force has produced four documents to provide practical information and guidance in the assessment of the effects of GMD on the Bulk-Power System. While interrelated, these documents each serve a distinct purpose and can be followed on a standalone basis.

Geomagnetic Disturbance Planning Guide

This document provides guidance on how to carry out system assessment studies taking the effects of GMD into account. It describes the types of studies which should be performed, challenges in implementing each study type, and identifies the analytical tools and data resources required in each case.

Transformer Modeling Guide

This guide summarizes the transformer models that are available for GMD planning studies. These fall into two categories: magnetic models that describe transformer var absorption and harmonic generation caused by geomagnetically-induced currents (GIC) and thermal models that account for hot spot heating also caused by GIC. In the absence of detailed models or measurements carried out by transformer manufacturers, the guide summarizes "generic" values (and the inherent limitations thereof) for use in GMD studies.

Application Guide for Computing Geomagnetically-Induced Current (GIC) in the Bulk-Power System

This reference document explains the theoretical background behind calculating geomagnetically-induced currents (GIC). A summary of underlying assumptions and techniques used in modern GMD simulation tools as well as data considerations is provided.

Operating Procedure Template

This document provides guidance on the operating procedures that can be used in the management of a GMD event. The document supports the development of tailored operating procedures once studies have been conducted to assess the effects of GMD on the system.

## 1.2 Scope of the Planning Guide

This document provides guidance to planning engineers on how to incorporate and take into account the effects of GMD in system planning studies. It also describes the types of studies needed to achieve different objectives such as equipment impact assessment and performance assessment of protection and control systems during a severe GMD event. This guide is not intended to provide step-by-step instructions on how to carry out a planning study, nor does it describe tool-specific capabilities and requirements.

# Chapter 2 – GMD Planning Study Overview

GMD planning studies are aimed at achieving a number of objectives which can be met by following the general procedure outlined below:

1. Assess the behavior of the system in terms of voltage limits, potential voltage collapse, and cascading outages during GMD events by taking into account transformer var absorption caused by half-cycle saturation. The system must perform within applicable limits under various contingencies – such as forced outage of a shunt capacitor bank or static var compensator (SVC).
2. Assess thermal impacts on equipment. Hot spot heating of transformers due to GIC during a GMD event is a primary concern since automatic protection systems are not likely to operate on this basis. Reference temperature limits used in the thermal assessment are the short term emergency thresholds suggested in IEEE Std. C57.91 18 [1].
3. Assess the performance of protection and control (P&C) systems in terms of security and dependability.

## 2.1 GMD Event Representation

As in any other type of system study, modeling requirements and tools depend on the objectives of the study. There are four basic types of GMD-related studies (and combinations thereof).

### 2.1.1 GIC Time Domain Simulations

GIC time domain studies use time series of the geoelectric field as input data to represent the GMD event. These studies are used to assess the dynamic impact of GIC on the interconnected power system and its equipment by taking into consideration the peak values, duration, orientation and "waveshape" of the geoelectric field.

A GIC time-domain simulation solves the dc representation of the network and produces GIC flows and transformer reactive power absorption or var loss due to transformer half-cycle saturation. There are two forms of input to a time-domain study: a) a pre-defined time sequence of the geoelectric field values scaled to a given peak magnitude (V/km), or b) variation of the magnetic field at ground level as a function of time. The geoelectric field is calculated using methods such as the plane wave method (see [2]) and used to compute the induced voltage in the transmission lines, which is the driving function for the dc solution of the network at a given point in time. The modeling of the earth impedance is critical in this calculation.

On output, a time-domain simulation produces time sequences of GIC and var loss for every transformer in the network. The GIC time series can be used as input to a transformer impact simulation tool that takes into account both the magnitude and variation of GIC over time. (The NERC GMDTF Transformer Modeling Guide [3], in development at the time this guide is being prepared, will provide additional guidance).

A time sequence of var loss snapshots and corresponding power flows can be used to illustrate the progression of a storm as a function of time, but more importantly, it can be used as input for an eigenvalue-based dynamic stability assessment.

A time-domain simulation engine can also be used in real time simulation tools for control center environments [4], but such tools are not commercially available at this point in time.

The characteristics of the time sequence or "waveshape" are very important in the assessment of the thermal impact in transformers. Transformer hot spot heating is not instantaneous. It has a time constant typically in the order of minutes; therefore, it is heavily dependent on past history, rise time, magnitude and duration of GIC in the windings.

Transformer absorption of reactive power has a much smaller time constant than hot spot heating and can be viewed as quasi-instantaneous. It is, therefore, less dependent on past history and event duration, and more dependent on GIC magnitude. However, when the geoelectric field is calculated from magnetic field data (dB/dt), and the earth model is not laterally uniform, the frequency content of the dB/dt waveform can have a significant effect on the induced geoelectric field [5].

### 2.1.2 Steady-State Simulations

In steady-state studies and GIC simulations assume the magnitude and orientation of the geoelectric field to be constant. For this type of study, the GIC flow and transformer reactive power absorption calculated for the geoelectric field assumption is incorporated into the load flow model. Steady-state studies are used to determine worst-case scenarios for var reserves, voltage limits, contingencies, and the evaluation of mitigating measures for a given overall geoelectric field magnitude.

Steady-state simulations use the GIC calculation results from the solution of the dc network for an assumed time-invariant geoelectric field magnitude and orientation to determine the var loss to be used in a load flow simulation. From a system (as opposed to equipment) point of view, system studies follow traditional methods once the GIC-caused var loss has been included in the power flow system model. Studies to evaluate the effects of GIC on the system are listed below.

- <u>Voltage collapse.</u> Voltage collapse can occur when the reactive power absorption from saturating transformers is high enough to bring voltages below safe operating values – which may be further aggravated when coupled with other system contingencies such as the loss of reactive power support devices. Under such operating conditions voltage collapse can occur when the system does not have enough var resources to support current operating conditions or to recover from a valid contingency (e.g., a fault).
- <u>Operating limits.</u> Voltage and power transfer limits must be maintained for safe recovery in the case of contingencies such as line faults and major equipment trips (e.g., SVCs, generators, and shunt capacitor banks).

### 2.1.3 Transformer Impact Assessments

In this type of study the impact on the thermal behavior of a transformer is assessed using a number of criteria including time series GIC data. These studies are used to identify at-risk transformers for a given geoelectric field magnitude in order to develop mitigating measures. A detailed discussion is presented in Chapter 4.

### 2.1.4 Harmonic Studies

Harmonic studies are used to assess the impact of harmonics on protection and control (P&C) systems, generators, shunt capacitor banks, and complex power electronic systems (e.g. HVDC and SVCs). These studies can identify potential vulnerabilities in protective relaying and control settings, as well as relay types (IEDs vs. electromechanical). In a typical study into P&C effects, a maximum credible total harmonic distortion (THD) and individual harmonic levels are estimated from maximum GIC flows in the least favorable geoelectric field orientation and used as the design basis for P&C studies. The relationship between GIC and harmonics generated by transformer half-cycle saturation is described in the NERC Transformer Modeling Guide [3]. This information can also be used to conduct frequency domain analysis to determine the availability of the essential shunt capacitors for var support during severe GMD events. Further discussion is presented in Chapter 4.

## 2.2 Analysis Tools

As the industry has expressed the need for GMD studies, analysis tools have become available and their capabilities have improved as the overall understanding of the GMD effects on the power system have improved. Commercially-available and open-source tools include, but are not necessarily limited to, the following:

- PowerWorld

- PSS/E
- PSLF
- OpenGIC/OpenDSS

These tools solve the dc network for a set of steady-state geoelectric field assumptions, and determine transformer var losses to be included into the power flow model (typically connected to a transformer as a constant var source). The GMD event is defined in terms of the magnitude and orientation of induced geoelectric field. The fidelity in defining the geoelectric field, however, varies between analysis tools. All tools permit a single uniform magnitude and orientation for the entire system to be defined while some also permit the geoelectric field to be specified on a circuit-by-circuit basis. Additionally, the transformer var loss may be seamlessly integrated into the power flow solution or may require user interaction.

## 2.3 State-of-the-Art and Model Confidence

Models, methods, and tools for assessment of GMD impacts are continuing to be improved and advanced. A brief summary of current assessment tools is provided with cautionary statements regarding the validation and use of such tools and models.

- <u>Earth models.</u> The US Geological Survey has produced a catalog of uniformly-layered earth models for the continental US [6]. Metatech Corporation also produced several uniformly-layered earth models for the continental US, and the parameters for four of these models are provided in Meta R-321 [7]. These models have a significant impact on the calculated geoelectric field used to compute GIC in any given transmission network and should be selected using the most up to date information available. Direct validation of the earth models is not available at this point in time. Indirect model validation will require moderate GMD events and a significant GIC monitoring infrastructure.
- <u>Reactive power loss models.</u> These models are well understood for single-phase transformers, and to a large extent, for 5-limb and shell-form type three-phase transformers. However, there is uncertainty in models of three-leg core type designs. The NERC Transformer Modeling Guide [3] provides some guidance, but transformer testing is necessary to validate modeling assumptions.
- <u>Harmonic current injections.</u> As with the reactive power loss models for the fundamental frequency, harmonic currents can be reasonably derived for single-phase transformers, 5-limb, and shell-form type transformers. However, unlike fundamental frequency relationships to GIC, harmonic current injections are much more dependent on accuracy of the transformer parameters. Further guidance is provided in [3].
- <u>Transformer hot spot thermal models</u>. Transformer manufacturers are just beginning to create dynamic hot spot heating models which can be applied to system planning studies. The NERC Transformer Modeling Guide [3] provides some guidance, but transformer testing is necessary to validate manufacturer models.
- <u>dc network model.</u> The dc network consists of circuit resistances, transformer winding resistances, and station grounding resistances (see [2]). In principle, the model is straightforward, and has a high level of confidence so long as transmission line and transformer resistances are known. Resistance values derived from power flow models can contain considerable errors. Effective station grounding resistance (ground grid resistance including the effects of grounded shield wires and/or multi-grounded distribution neutrals) is a key parameter in the dc model. If not known from measurements or sophisticated simulation methods, it is very difficult to assign credible default values.

## 2.4 Initial Screening

The first step in a GMD planning study is to determine the level of detail and complexity needed. Utility planners should consider carrying out detailed (as opposed to screening) studies in cases where there has been history of system or equipment issues during moderate GMD events such as the March 13, 1989 and October 31, 2003 solar storms. Issues to examine are:

- Capacitor bank tripping,
- Tripping of FACTS devices such as SVC and HVDC,
- Voltage dips/fluctuations of 1% or more that are clearly attributable to the GMD event,
- Generator tripping, and
- Unexpected post-event accumulation of dissolved gasses in transformers.

If the examination of historical event logs does not indicate any of the above issues, power flow analysis that takes into account the effects of GIC (i.e., transformer var absorption) should be used to determine whether more detailed studies are warranted. Systems with operating voltages at or below 200 kV, and without past issues, may not require additional detailed studies to be performed given the minimal GIC expected on this portion of the interconnected power system [8]. A procedure for performing an initial screening analysis is as follows:

1. Determine the design-basis geoelectric field peak magnitude (V/km) for the appropriate geographical area of the system. Guidance in this determination can be obtained from the NERC GIC Application Guide [2].
2. Compute GIC flows using a dc model of the system. Estimate transformer var loss to be used in power flow.
3. Perform power flow analysis using system load levels and stressed system conditions using generic models for transformer reactive power absorption. Loss of reactive power sources such as shunt capacitor banks and SVCs (on protection) should be considered as valid contingencies associated with the GMD event. A conservative approach is to assume that all transformers are single-phase; however, in some cases this approach will be overly conservative. If voltage fluctuations do not exceed 3% and operational limits are met, then more detailed power flow studies are probably not necessary.
4. Verify that the thermal impact on transformers is below applicable thresholds as described in Chapter 4.

If the power flow simulations show voltage fluctuations above 3% under normal criteria contingencies or if thermal limits associated with generic transformer capability curves are approached, then it is necessary to carry out more detailed studies as further described in Chapters 3 and 4. Note that the 3% voltage fluctuation screening criteria provides margin to account for the quality of input data obtained from load flow models. It is not an operational parameter.

# Chapter 3 – System Impact Assessment

In the case of a GMD event, system impact studies are very similar to standard system planning or outage management studies. The main differences are:

- Reactive power absorption in transformers must be modeled to ascertain if voltage limits are met.
- System interconnections must be taken into consideration with more detail to account for reactive power losses in neighboring networks. Reasonable approximations can be obtained by modeling two or more key buses into the neighboring network.
- There are additional contingencies to be considered when performing equipment impact considerations.

The guidelines presented here are not intended to provide direction to the planning engineer on how to carry out system studies, but rather to provide awareness on what additional considerations should be taken into account to plan for a GMD event.

## 3.1 Reliability Criteria

The scientific understanding of credible storms and their impact on the interconnected power system is evolving. Consequently, several schools of thought exist for determining the design-basis event on which to base impact assessment:

1. The interconnected power system should withstand the most severe event based on both a) frequency of occurrence – and b) local geographical and geological features. Unfortunately, statistical extrapolations must be performed using limited data; thus, the error bars can be quite large for low probability events. The most widely mentioned frequency of occurrence is 1 in 100 years; however, the resulting storm severity can vary significantly depending on model data and assumptions. Studies that predict such severe impact on the system have not been duplicated independently.
2. The system will be designed and operated to withstand the most severe event (for given geomagnetic latitude and earth resistivity characteristics) as determined on the basis of a balance between costs and impact. Since the system and equipment impact is localized, a severe GMD would cause little if any permanent equipment damage with a managed load and generation rejection approach.
3. Do not assume that there is a fixed design basis event. Increase the geoelectric field intensity until reactive power losses force substantial load and generation rejection. Use this value with the appropriate margin as the maximum GMD event to assess transformer impact.

For the purposes of this guide, it will be assumed that the system planner has determined a design basis value that it takes into account geography, geomagnetic latitude and earth resistivity as further described in the NERC GMDTF GIC Application Guide [2].

## 3.2 System Model

The dc equivalent system model is thoroughly discussed in the NERC GIC Application Guide [2]. Some of the high level considerations are:

- Modeling only those portions of the network which are 230 kV and above has been suggested [11]. In some systems it may be appropriate to model the network below 230 kV. Which voltage levels to include in the model depends on the types of connections and location of the transformer stations. A more complete discussion of the rationale behind the selection of the minimum voltage level for a GMD study can be found in [8]
- The extent to which the ac system is modeled should be consistent with existing practices. If interconnections are represented in the model by equivalent networks, then sensitivity studies should be

carried out to validate the equivalent representation. These sensitivity studies should be based on an explicit model which includes at least two key buses into the neighboring system. A delta-connected load station would not be considered a key bus, whereas a generation station or a station with autotransformers would be considered a key station. A more detailed discussion of the accuracy of different approaches to define equivalent networks is found in [2].

- The dc network model should be consistent in size and scope with the ac model with the following exceptions.
    - The dc model does not include shunt capacitor banks.
    - The dc model does not need to include stations with ungrounded transformers. Ungrounded or surge arrester-grounded transformers could be represented as a high resistance branch, but this can lead to numerical instability of the model [2].
    - Equivalent circuits in the ac model are generally not directly translatable into dc equivalents. Guidance on dc network equivalent circuits is provided in the NERC GIC Application Guide [2].
    - Interconnections to lower kV portions of the system, not explicitly represented in the dc network, may need to be represented by an equivalent model.

Guidance on modeling transformer var losses as a function of GIC flows within power flow models is provided in [3].

## 3.3 System Impact Assessment Studies

For a given geoelectric field magnitude and direction, determine GIC flows and associated transformer var loss. From this point determine if voltage criteria and operating limits are met using power flow analysis that takes into account the GIC-caused var losses. Standard methodology to assess operating limits and contingencies should be used.

Points to consider when performing system impact studies are provided below.

- Several general orientations of the geoelectric field should be considered. The number of orientations to consider should be determined on a system basis; however, dividing the number of potential geoelectric field orientations into 30° increments has been successfully used [4].
- The assumption that the East-West geoelectric field orientation is the worst case is not justifiable from the point of view of var loss because its effects are quasi-instantaneous, and the orientation of the geoelectric field changes continuously during a GMD event.
- Reactive power margins (see [8] and [10]) can be identified in different parts of the system for different geoelectric field orientations [11].
    - A single geoelectric field orientation is unlikely to be the worst case for all zones. Thus, the geoelectric field orientation which results in the largest increase to total system reactive power losses in the system is not a sufficient indicator of the worst case.
    - A conservative approach is to divide the system in zones on the basis of var margins, and assume var margins for the worst geoelectric field orientation for each zone.
- The GIC flows must be determined for each change in system configuration, whether due to contingencies or potential mitigation strategy, during the course of the evaluations.
- Loss of reactive power sources such as shunt capacitor banks and SVCs (on protection) should be considered as valid contingencies.

# Chapter 4 – Equipment Impact Assessment

A significant concern regarding the effects of a GMD event is the possibility of damage of major equipment – especially damage to costly and long replacement lead time equipment such as generators, SVCs, and HV/EHV transformers. From a technical point of view, each type of equipment needs different considerations on the basis of impact and whether or not existing automatic protection is sufficient to prevent long term effects.

## 4.1 Transformer Thermal Impact Screening Process

The effects of half-cycle saturation on HV and EHV transformers, namely localized "hot spot" heating, are relatively well understood qualitatively, but rather difficult to quantify. A transformer GMD impact assessment requires thresholds that must take into consideration GIC magnitude and duration, as well as transformer physical characteristics such as design and condition (age, gas content, and moisture in the oil). A simple threshold on the basis of GIC current alone cannot take into account such factors and would be difficult to justify as a screening threshold. The NERC GMDTF phase 1 report [12] provides the following guidance in this respect:

- Use the temperature limits for safe transformer operation suggested in the IEEE Std. C57.91 standard for hot spot overheating during short-term emergency operation. The standard does not suggest that exceeding these limits will result in transformer failure, but rather undue 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 potential transformer damage, these thresholds can be considered conservative.
- To be consistent with IEEE Std. C57.91 suggested limits, 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).
- Take into consideration temperature increases due to ambient temperature and transformer loading. For planning purposes, maximum ambient temperature and loading temperature to a full heat run should be used.
- Take into consideration the "waveshape" of the reference GMD event in terms of peak magnitude, duration and frequency of the geoelectric field, and the fact that winding and metallic part hot spot heating have different thermal time constants with respect to GIC. In other words, the hot spot temperature rise will be different if the GIC currents are sustained for 2 or 10 minutes at a given GIC peak magnitude.
- Take into consideration the "effective" current in transformers and in autotransformers, reflecting the different GIC ampere-turns in the common and the series windings (see [2]). The effective current is expressed on a "per phase" basis and can be very different from the neutral currents obtained from GIC neutral measurement devices.

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

1. Transformer manufacturer GIC capability curves. These curves relate permissible peak GIC (obtained by the user from a steady state calculation) and loading for a specific transformer; example manufacture capability curves are plotted in Figure 1. Presentation details vary between manufacturers and limited information is provided concerning 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. While they are simple to use, manufacturers maintain that in the near term, such capability curves have to be developed for every transformer design and vintage in the absence of transformer standards defining thermal duty due to GIC.

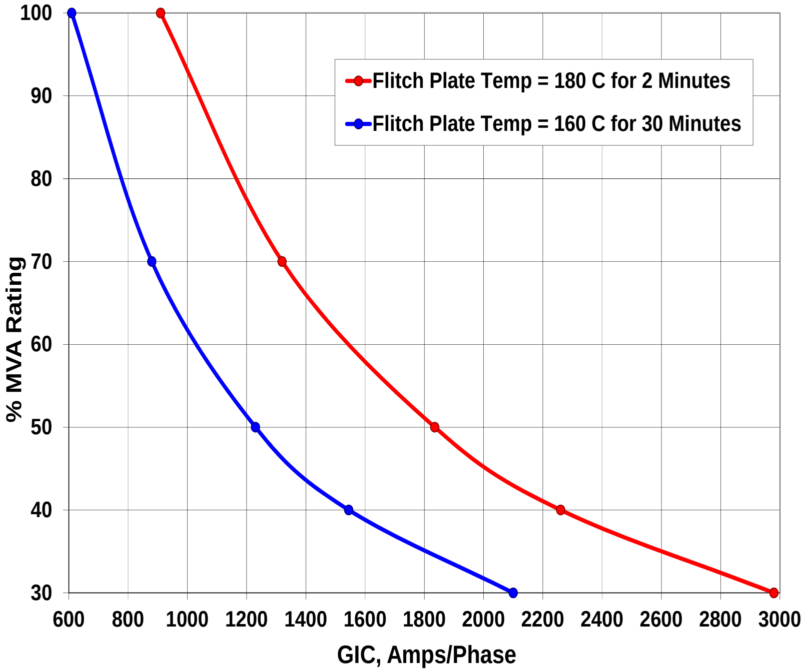


**Fig. 1:** Sample GIC manufacturer capability curve of a large single-phase transformer design using the Flitch plate temperature criteria [13].

2. <u>Generic GIC capability curves</u>, such as the ones in the NERC Transformer Modeling Guide [3]. These curves assumed a pre-defined GIC waveshape (e.g. the GMDTF reference storm or the March 1989 storm) and the hot spot temperatures are estimated with thermal transfer functions [14]. The hot spot thermal transfer functions used are based on what is believed to be conservative measurements and assumptions. The effect of transformer construction is taken into consideration using the generic magnetic models produced by the NERC GMD Task Force phase 2 project. Thresholds are based on IEEE Std. C57.91 emergency loading hot spot limits. At this point in time, limited comparisons with manufacturer's GIC capability curves are available. Initial comparisons with a limited number of transformers suggest that the generic capability curves are conservative, meaning, a lower peak GIC causes higher hot spot heating (see Fig. 2).

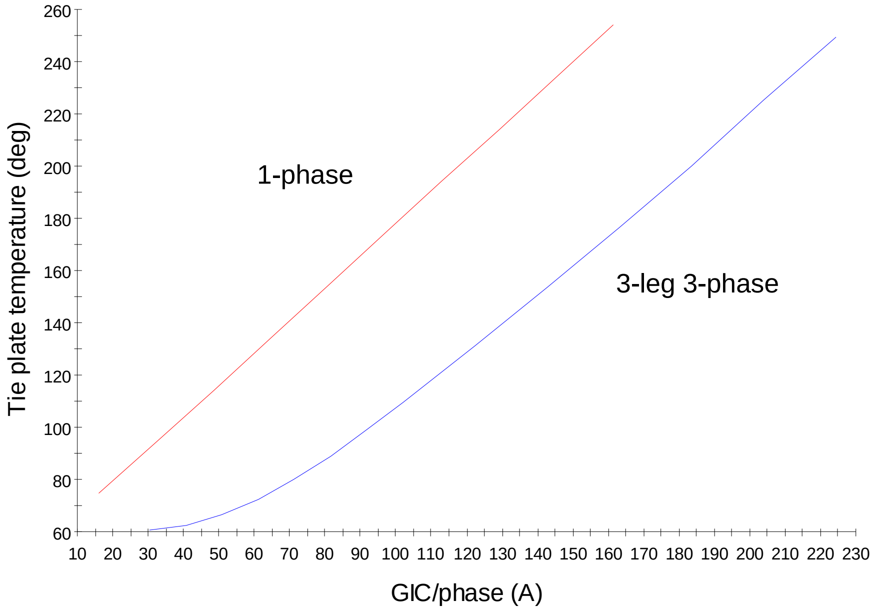


**Fig. 2:** Sample capability curve derived from the March 1989 GMD event time series. Tie plate temperature at full load. GIC/phase corresponds to the peak GIC for the time series.

3. Thermal response simulation. Details of this implementation can be found in [14]; however, the input is the effective time series GIC flowing through a transformer (taking into account the actual configuration of the system) and the output is the hot spot temperature time sequence for each transformer [3]. Example GIC input and hotspot temperature time series values are shown in Figure 2. The hot spot thermal transfer functions can be obtained from measurements or calculations provided by transformer manufacturers or defaults, such as the ones shown in the NERC Transformer Modeling Guide, can be used instead. Hot spot temperature thresholds are based on IEEE Std. C57.91 emergency loading hot spot limits.

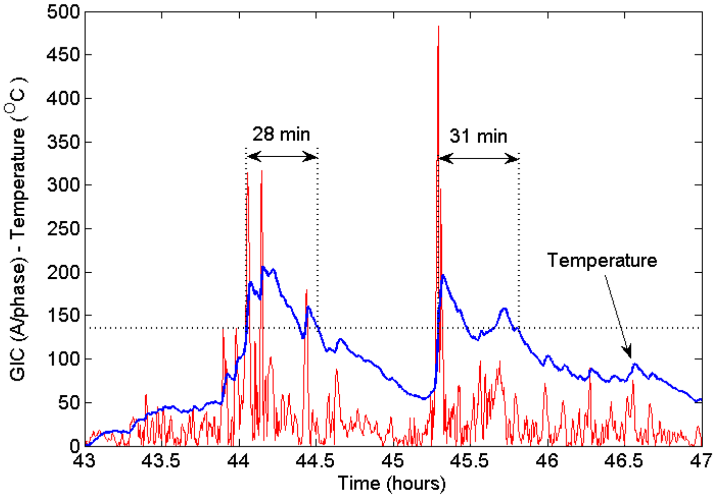


**Fig. 2:** Sample tie plate temperature calculation. Blue trace is incremental temperature and red trace is the magnitude of the GIC/phase [14].

It is important to reiterate that the characteristics of the time sequence or "waveshape" are very important in the assessment of the thermal impact in transformers. Transformer hot spot heating is not instantaneous. The thermal time constant of transformer windings and metallic parts is typically of the order of minutes; therefore, hot spot temperatures are heavily dependent on loading, history, rise time, magnitude and duration of GIC in the windings.

## 4.2 Generator, Capacitor Bank, SVC, and Protective Relaying Impacts

System harmonic analyses are necessary to investigate harmonic-related system impacts of GMD. Low-order harmonic current injections can travel considerable distances through the transmission system. Thus, at any location in the system the harmonic currents and voltages may represent the aggregated contribution of multiple GIC-saturated transformers. As such, harmonic withstand capabilities of any given system component should not be solely evaluated against the harmonic injections of a particular transformer (e.g. the harmonic currents flowing into a generator are not solely due to saturation of the GSU transformer). Harmonic injection models are provided in the NERC Transformer Modeling Guide [3].

SVCs may trip if excessive harmonic current and voltage distortion cause intentional protective relay operation, excessive interactions with the SVC control system, or due to protection misoperation (false tripping) due to vulnerabilities of the protection system.

If the protective relaying of a shunt capacitor bank is such that it cannot detect harmonic overcurrents (e.g. microprocessor based relaying schemes as explained in the NERC GMDTF phase 1 report ) it may be prudent to carry out simulations to have a sense of the GIC level for which a specific shunt capacitor bank may trip or fail. System resonant behavior plays a large role in establishing capacitor bank harmonic current duty. Resonances are often related to specific system conditions, so it may be necessary to study a large range of possible system configurations, including a wide range of permutations of capacitor bank status, in order to identify worst-case harmonic current stress.

Harmonic currents flowing into a generator cause a magnetic field that rotates relative to the generator's rotor. The oscillating magnetic field, as seen by the rotor, causes additional heating of the rotor. This is similar to the effect of negative-sequence fundamental currents on generators, except that harmonic currents do not need to be negative sequence to cause this heating. Ideally, generator protection would remove the unit from service before damage could result [15]. However, according to [16], protective relaying may not act before there is undue over-heating caused by harmonics. Most modern generator protection relays specifically ignore non-fundamental current components.

## 4.3 Harmonic Impact Studies

The industry has limited availability of appropriate software tools to perform the harmonic analysis. General purpose electromagnetic transients programs can be used, via their frequency domain initial conditions solution capability. However, building network models that provide reasonable representation of harmonic characteristics, particularly damping, across a broad frequency range requires considerable modeling effort and expert knowledge. Use of simplistic models would result in highly unpredictable results.

There are a few dedicated harmonic analysis programs available to the industry, which perform their analysis in the frequency domain and apply reasonable rules for defining frequency-dependent characteristics of system components. Some of these are limited to a single harmonic source, thus requiring the user to perform superposition of the phasor harmonic components externally. Others model only line-mode propagation characteristics, and are not configured to model ground mode behavior.

The desired modeling tool should have the following characteristics:

- Model multiple harmonic current sources with defined phase angles and magnitudes.
- Perform analysis for both line and ground modes. Alternatively, should perform phase domain analysis.
- Provide appropriate frequency-dependent representation of system component impedances. The ideal tool should be able to take input data from common fundamental-frequency databases, and convert to proper frequency-dependent representation using rules in the absence of better data, with a minimum of user intervention.
- Provide voltage and currents for any bus or branch in the system for the superimposed injections, with results shown in phase and sequence component form for individual harmonics, and resolved into the time domain to provide the peak voltage for the superposition of harmonic components.

Harmonic analysis results can be compared to the withstand capabilities of various equipment to determine if tripping, failure to trip when appropriate, or material damage is a possibility. Unfortunately, this tolerance level is poorly defined for most equipment, with the possible exception of capacitors. IEEE Standard 18 provides ample information on the withstand limit of capacitor units [17]. However, the sensitivity of capacitor bank protection systems is not as well defined. Harmonic impact on generators is dependent on the sequence component of the harmonic current flowing into the generator, as the harmonics need to be resolved into the rotor reference frame to determine the equivalent rotor frequency and the resulting rotor heating potential.

# Chapter 5 – Evaluation of Mitigation Measures and GIC Monitoring

Depending on the modeled effects in the system, mitigating measures can take one of the following forms:

- Reassignment of var resources,
- System reconfiguration, normally by bringing key circuits in and out of service,
- Load rejection,
- Using GIC reduction devices (GRDs) on SVC transformers to ensure they can provide reactive support during any event, and
- Using GIC reduction devices to maintain transformer currents below an arbitrary threshold (independent of GIC "waveshape") or to ensure that key transformers remain in service during any event.

It should be noted that a GRD on a GSU (Generator Step Up) transformer would not prevent a generator from tripping on unbalance or negative sequence protection. Usage of GRDs should always be conditional to the results of system suitability studies (protection impact and failure modes) as well as functional requirements including those provided in [12]. Additionally, the application of GRDs must consider the failure of a GRD as a valid contingency.

The studies required for the evaluation of mitigation measures are essentially the same ones used to assess impact. The only difference is that mitigation measures introduce system configuration changes which must be evaluated with the same guidelines described in Chapters 3 and 4.

## 5.1 Integration of Equipment Impact and System Impact Studies

System impact studies are aimed at maintaining the safe and reliable operation of the power system; whereas, equipment impact studies are aimed at maintaining the integrity of major assets. As mitigating measures introduce system configuration changes that affect both, an iterative process is required. The integration of system and equipment impact studies can be approached either in a top-down or bottom-up fashion.
The top-down approach includes the following procedural steps:

1. Carry out system impact studies assuming the maximum design-basis geoelectric field.
2. Evaluate mitigating measures (if any) to maintain limits.
3. Carry out equipment impact assessment using the ultimate system configuration, including contingencies. If equipment considerations require additional mitigating measures that entail system re-configuration, repeat the system studies and iterate.

The procedures comprising the bottom-up approach are:

1. Carry out system impact studies increasing the geoelectric field up to the point where mitigation measures to maintain limits are necessary. Define this as the threshold configuration and GIC level.
2. Carry out equipment impact assessment using the threshold configuration, including contingencies. If equipment considerations require mitigating measures, reduce the magnitude of the geoelectric field to the point where there are no equipment issues.
3. If the threshold scenario is lower than the design basis scenario, increase the geoelectric field to defined staged mitigating measures iterating between system and equipment impact studies.

The advantage of the bottom-up approach is that it results in staged mitigating measures. This would be consistent with a strategy that combines operating measures with other mitigation strategies, such as system re-configuration and possibly a limited number of GRDs. The advantage of the top-down approach is that the system is expected to withstand the design basis event without having to worry about intermediate mitigating actions.

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# Appendix I – NERC GMD Task Force Leadership Roster

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