NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

TPL-007-1

Project 2013-03 Geomagnetic Disturbance Mitigation

Technical Conference
May 20, 2014

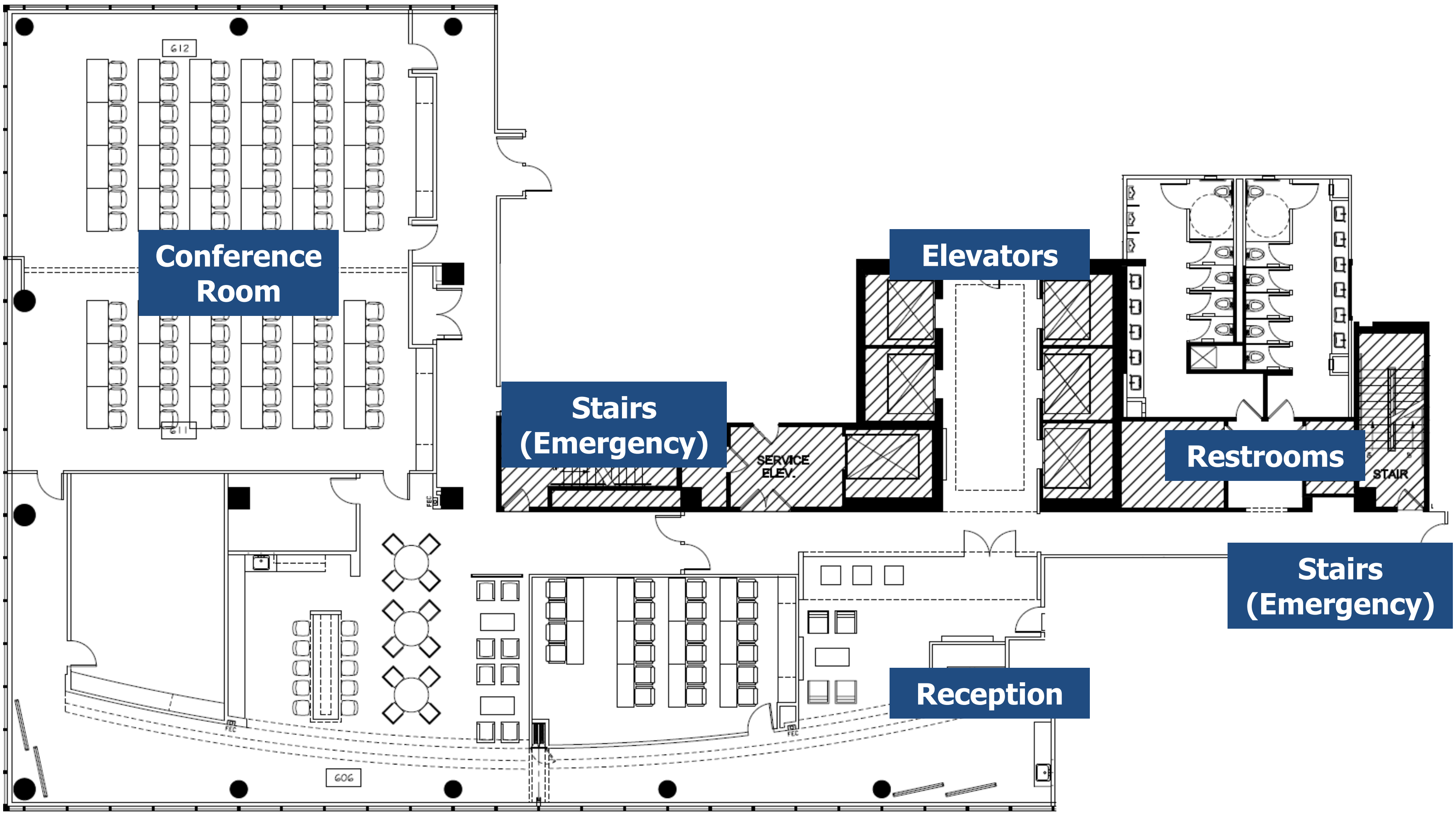
RELIABILITY | ACCOUNTABILITY




Administrative

- Internet passcode: 3htw0br3wt1s (label located on desk)
- Presentations available on the project page:
  http://www.nerc.com/pa/Stand/Pages/Geomagnetic-Disturbance-Resource.aspx

Meeting Space



NERC Antitrust Guidelines

- It is NERC's policy and practice to obey the antitrust laws 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.

Public Meeting Guidelines

- 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.

Conference Objectives

- Understand models and analysis for assessing the impact of geomagnetic disturbances (GMD) required by TPL-007-1
- Describe the benchmark GMD event and its application to GMD assessments and planning studies
- Provide an overview of transformer thermal impact assessment approaches described in the white paper
- Obtain feedback and recommendations for the Standard Drafting Team (SDT)

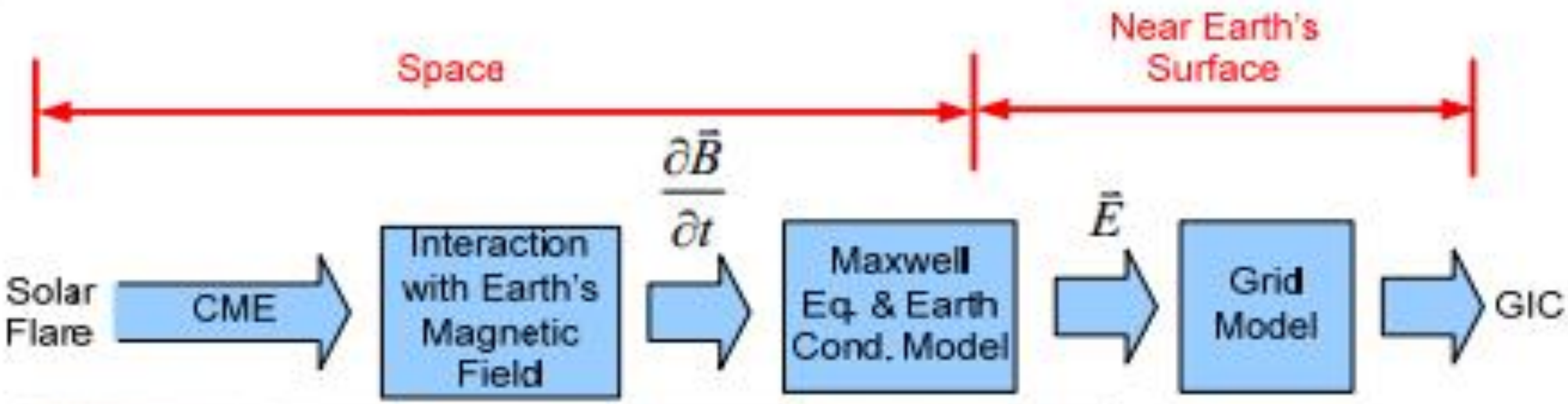
Agenda

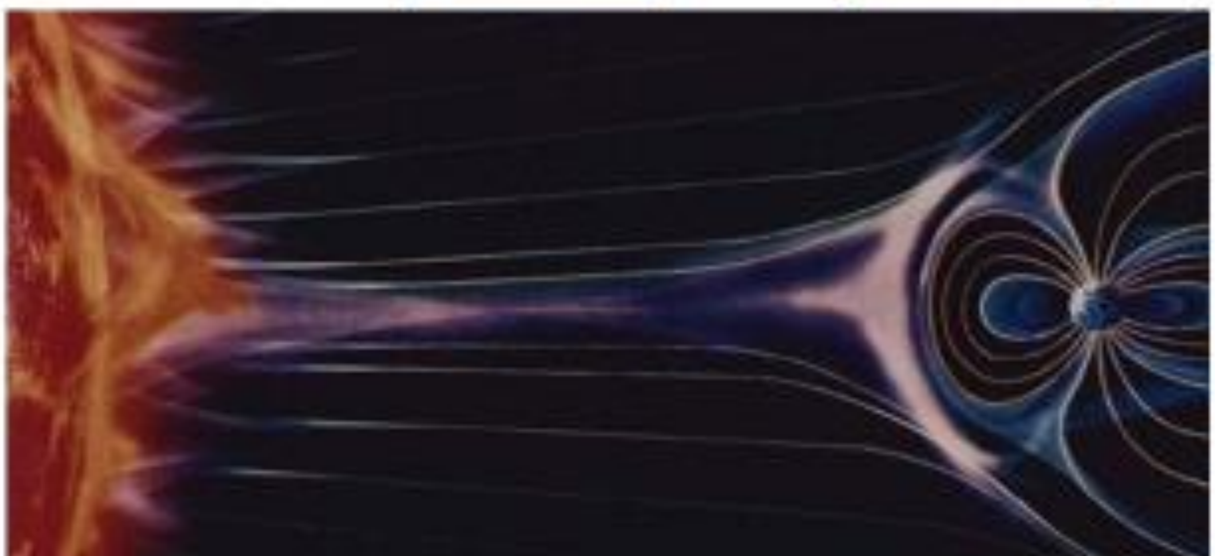
- Introductory remarks – Mark Lauby, NERC
- Background and project overview
- Topic 1: Benchmark GMD event
- Topic 2: System Models for GMD Studies
- Topic 3: GMD Vulnerability Assessment and Planning
- Recommendations for the SDT

Mark Lauby,
NERC Chief Reliability Officer

Overview – Frank Koza, PJM

GMD Issues for the Power System





<u>Geomagnetically-induced currents (GIC) can cause</u>:

- Increased reactive power consumption
- Transformer heating
- P&C misoperation

FERC Order 779

- In May 2013, FERC issued Order 779 which directs NERC to submit Reliability Standards that address the impact of GMD on the reliable operation of the Bulk-Power System
  - Stage 1 – Operating Procedures
  - Stage 2 – Detailed Assessments (Planning Studies)
- Standards project 2013-03 (GMD Mitigation) began in June 2013

143 FERC ¶ 61,147
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

18 CFR Part 40

[Docket No. RM12-22-000; Order No. 779]

Reliability Standards for Geomagnetic Disturbances

(Issued May 16, 2013)

AGENCY: Federal Energy Regulatory Commission.

ACTION: Final Rule.

SUMMARY: Under section 215 of the Federal Power Act, the Federal Energy Regulatory Commission (Commission) directs the North American Electric Reliability Corporation (NERC), the Commission-certified Electric Reliability Organization, to submit to the Commission for approval proposed Reliability Standards that address the impact of geomagnetic disturbances (GMD) on the reliable operation of the Bulk-Power System. The Commission directs NERC to implement the directive in two stages. In the first stage, NERC must submit, within six months of the effective date of this Final Rule, one or more Reliability Standards that require owners and operators of the Bulk-Power System to develop and implement operational procedures to mitigate the effects of GMDs consistent with the reliable operation of the Bulk-Power System. In the second stage, NERC must submit, within 18 months of the effective date of this Final Rule, one or more Reliability Standards that require owners and operators of the Bulk-Power System to conduct initial and on-going assessments of the potential impact of benchmark GMD

Drafting Team

Name	Registered Entity
Frank Koza (Chair)	PJM Interconnection
Randy Horton (Vice-chair)	Southern Company
Donald Atkinson	Georgia Transmission Corporation
Emanuel Bernabeu	Dominion Resource Services, Inc
Kenneth Fleischer	NextEra Energy
Luis Marti	Hydro One Networks
Antti Pulkkinen	NASA Goddard Space Flight Center
Qun Qiu	American Electric Power

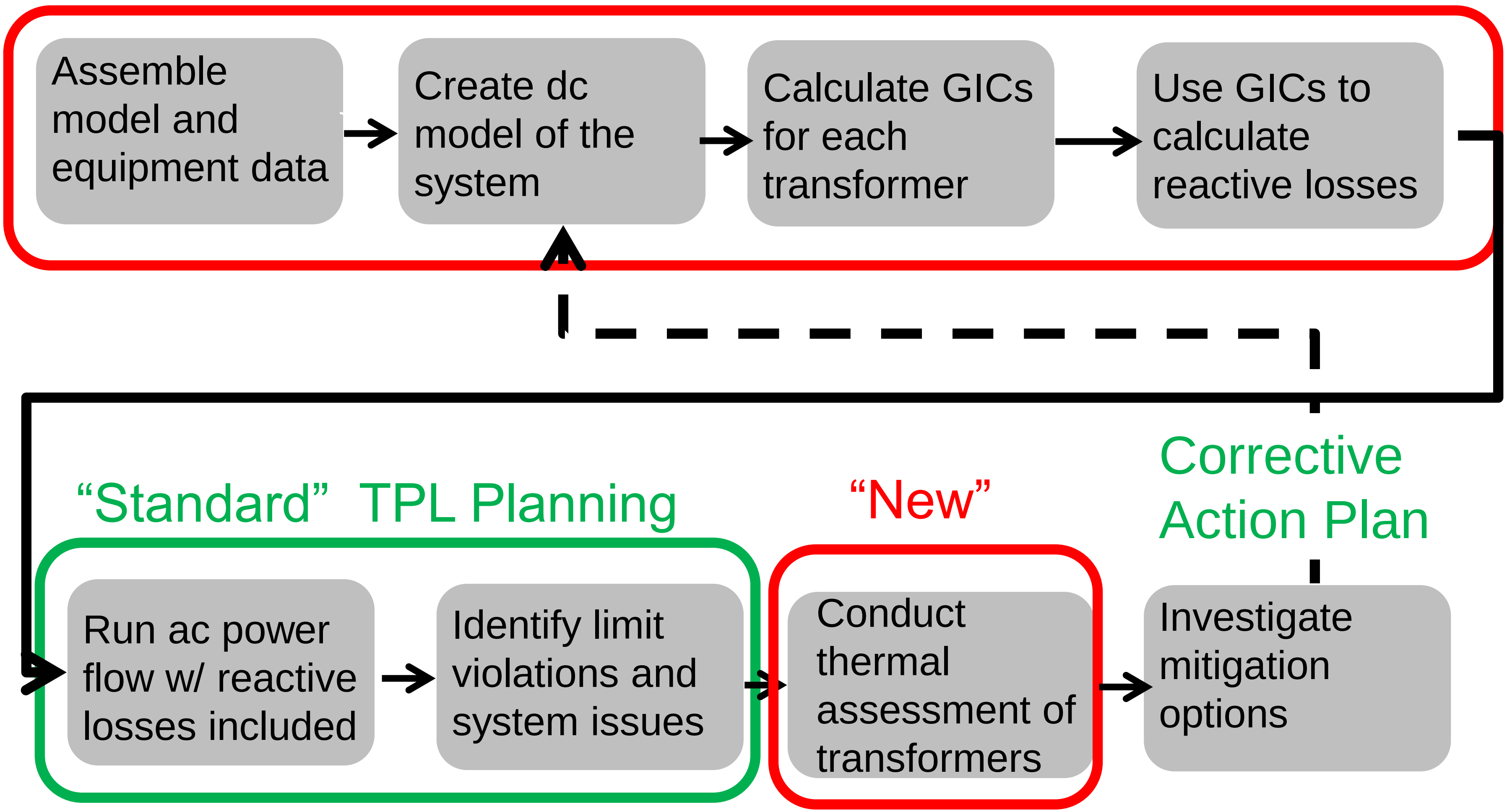
Stage 2 GMD Standard

- TPL-007-1 addresses directives requiring entities to assess impact of benchmark GMD events on systems and equipment
- Applies to Planning Coordinators, Transmission Planners, Transmission Owners and Generation Owners
  - Entities with grounded transformers connected $\geq$200 kV
- Planning entities are required to assess the risk of voltage collapse
  - Corrective Action Plans developed to address identified deficiencies
- Owners are required to assess thermal impact on transformers

Assessment Process Overview

“New” Planning Steps

GIC Calculation is now available on most power system analysis software



Initial Draft

- Drafts posted to the project page
  - TPL-007-1 Transmission System Planned Performance for Geomagnetic Disturbance Events
  - Implementation Plan
  - Benchmark GMD Event Description
  - Transformer Thermal Impact Assessment White Paper

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

NERC GMD Task Force Resources

- GMD TF Page: http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx
- Application Guide: Computing GIC in the Bulk-Power System

  http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GIC%20Application%20Guide%202013_approved.pdf
- GMD Planning Guide:

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

Schedule

- Informal comment period: April 22–May 21, 2014
- Drafting team will meet in early June to consider comments and revise drafts
- Initial comment and ballot beginning in June 2014
- NERC Board of Trustees adoption by November 2014

Today’s Discussion Topics

- Topic 1: Benchmark GMD event
- Topic 2: System Models for GMD Studies
- Topic 3: GMD Vulnerability Assessment and Planning
- Recommendations for the SDT

Benchmark GMD Event – Luis Marti, Hydro One

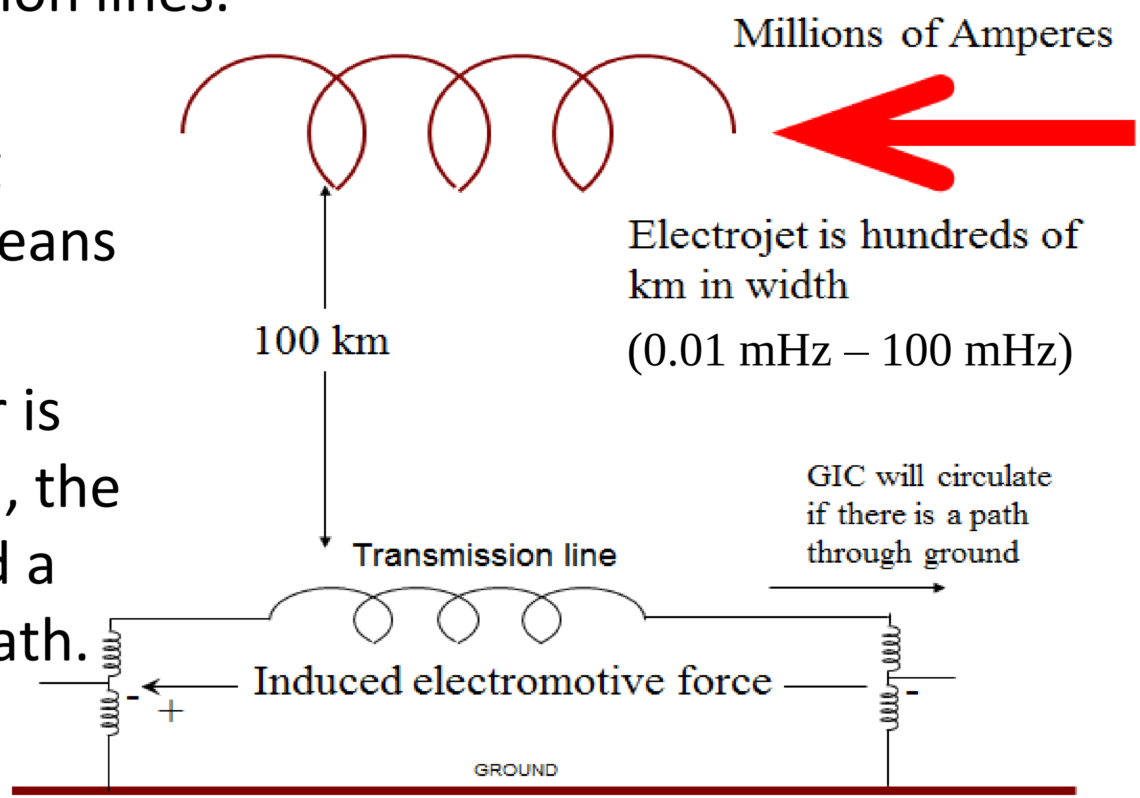
Overview

- The benchmark GMD event provides evaluation limits for assessing system performance to meet directives in Order 779
  - System performance must meet the GMD benchmark event severity after mitigation plans, if any, are in place
- Steps for calculating the geoelectric field values needed for GMD Vulnerability Assessment are contained in TPL-007-1 Attachment 1
- Description and technical justification of the benchmark event are provided in the white paper:

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

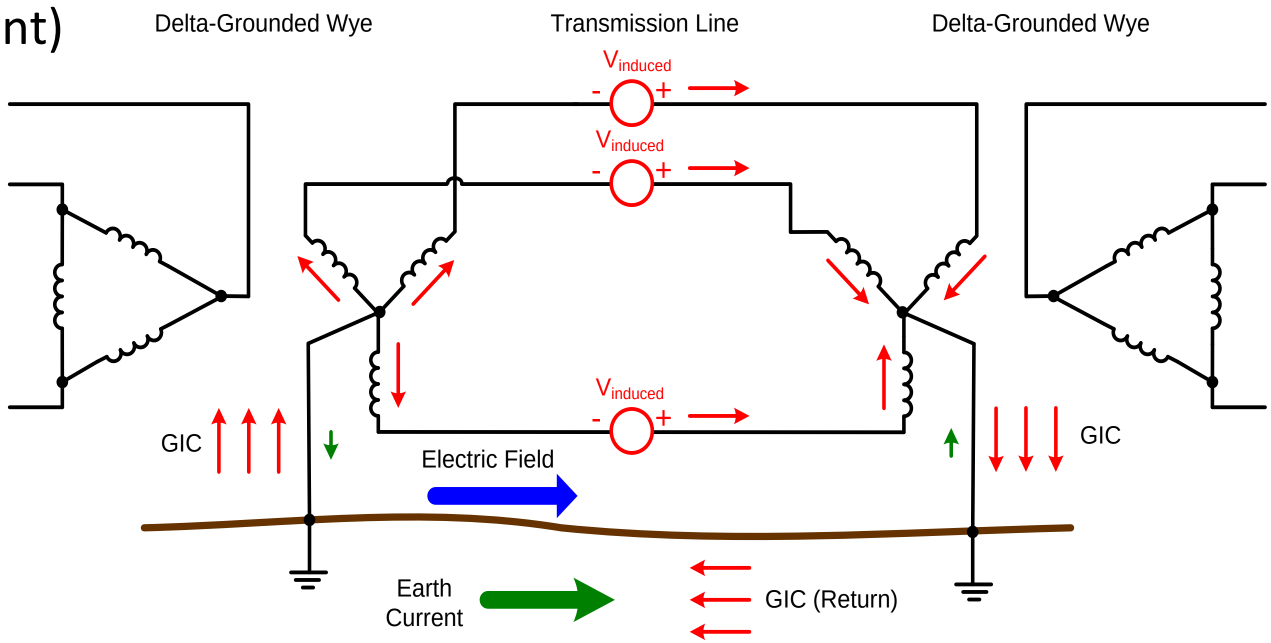
Quick GMD Refresher

- Interaction of a geomagnetic disturbance with a power network can be visualized as magnetic coupling between the electrojet and transmission lines.
- The earth resistivity determines the coupling factor (high resistivity means large coupling factor).
- After the coupling factor is taken into consideration, the earth can be considered a zero resistance return path.

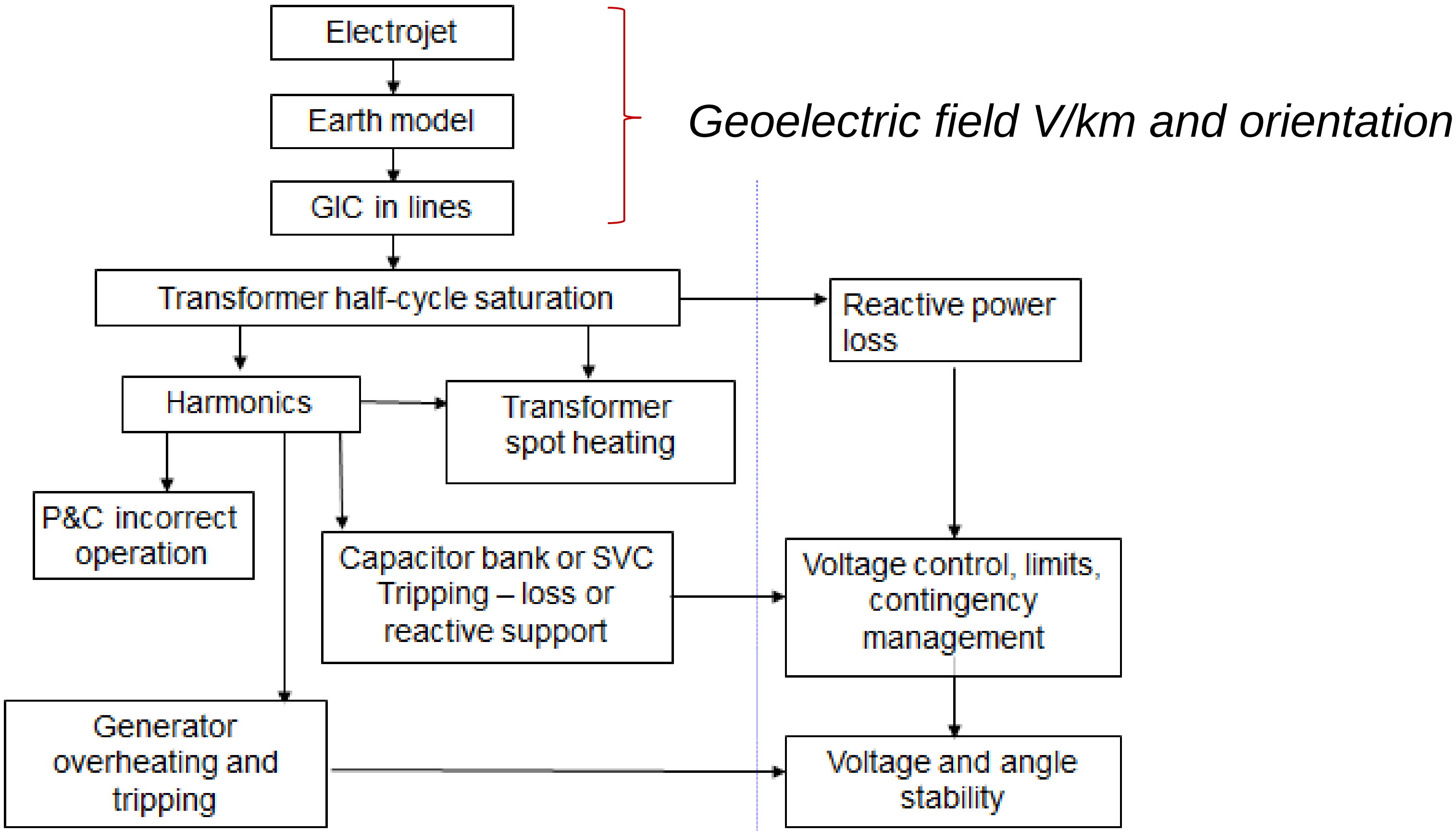


Quick GMD refresher

- The induced electromotive force is modelled as a zero sequence dc voltage source in series with the line
- Magnitude of the source depends on
  - Peak geoelectric field V/km
  - Relative orientation of transmission lines and geomagnetic field
  - Line length (to a point)



Effects of GIC in a Power System

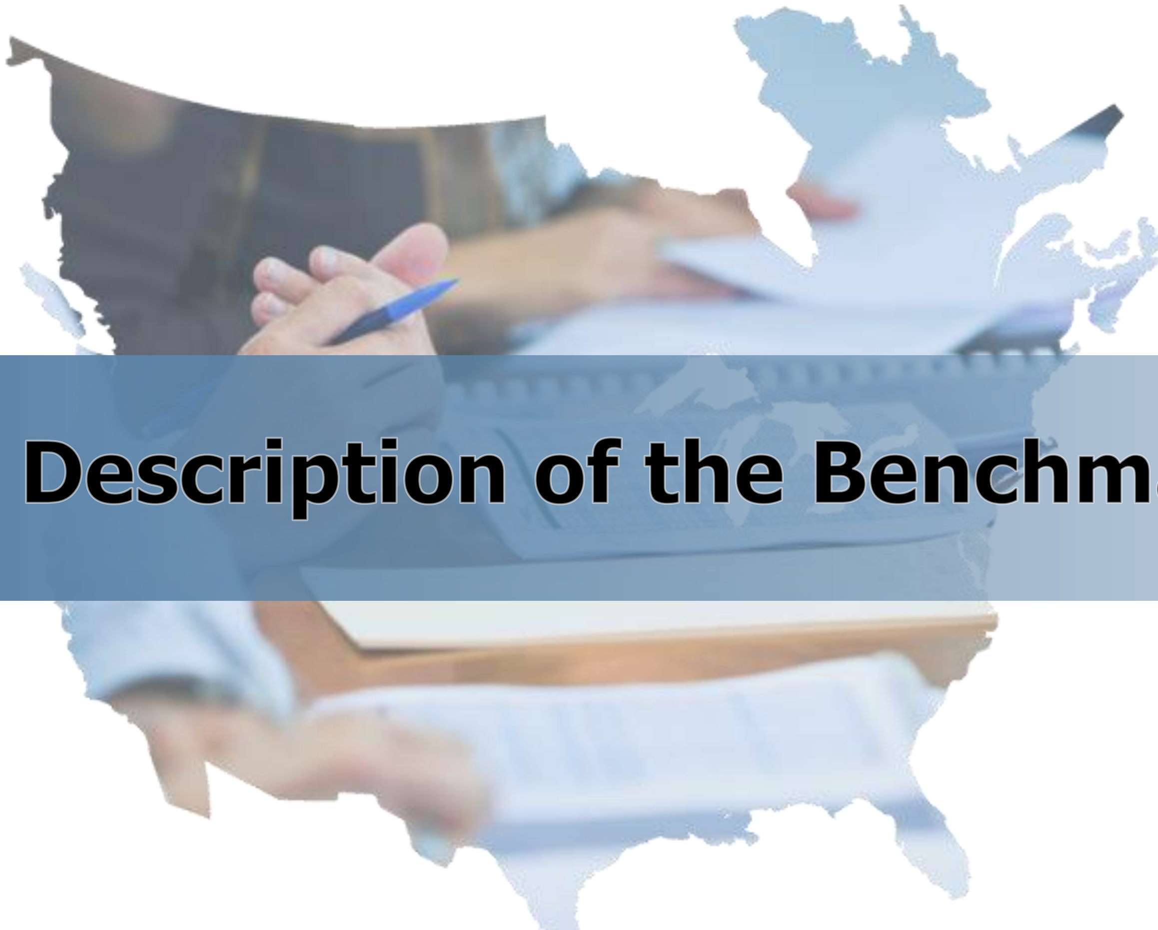


GMD Vulnerability Studies - Overview

- Calculation of GIC flows (dc model) for a given V/km
  - GIC in a transformer results in var loss (constant var source/sink)
  - Harmonics
- Load flow including the var sources/sinks obtained from the GIC Study
- P&C performance
  - Estimated harmonic currents from the GIC Study
  - Protective relay assessment
  - Control settings assessment
- Transformer thermal assessment
  - Dependent on GIC(t) – magnitude and duration dependent
  - Capability curves
  - Hot-spot thermal response

Things to Remember

- Geomagnetic field intensity changes with geomagnetic latitude
  - Amplitude decreases away from the magnetic north pole towards the equator
- Induced geoelectric field depends on earth resistivity
  - Higher resistivity means larger coupling factor and larger geoelectric field
- GIC depends on geoelectric field magnitude and relative orientation with respect to the transmission lines
  - No line orientation is immune since the orientation of the geoelectric field changes continuously during a GMD event.
  - For a given line orientation and circuit configuration there is a worst-case geoelectric field orientation
- Transformer hot-spot thermal response depends of GIC(t)



Description of the Benchmark GMD Event

Benchmark GMD Event Description

- The GMD benchmark event defines the severity of a GMD event that a system must withstand
  - Peak V/km
  - The means to calculate GIC(t)
- Reference geoelectric field amplitude (8 V/km)
  - 1-in-100 year amplitude determined statistically from geomagnetic field measurements using a resistive reference earth model (Quebec)
  - Peak dB/dt = 3,565 nT/min
  - Scaling factors account for local geomagnetic latitude and local earth resistivity
- Reference geomagnetic field waveshape
  - March 13-14 1989 GMD event selected from recorded GMD events
  - Used to calculate GIC(t) for transformer thermal assessment

Calculated Peak Geoelectric Field

$$E_{peak} = 8 \times \alpha \times \beta \text{ (in V/km)}$$

where,

E_{peak} =	Benchmark geoelectric field amplitude at System location
α =	Factor adjustment for geomagnetic latitude
β =	Factor adjustment for regional Earth conductivity model

8 V/km is the peak geoelectric field amplitude at reference location (60° N geomagnetic latitude, resistive ground model)

Why 8 V/km

- Statistical occurrence of extreme geoelectric field amplitudes is characterized considering spatial scales:
  - Same data source as NERC interim report.
  - Spatially local geoelectric field enhancements do not characterize wide area effects.
    - Localized peak 20 V/km
    - Wide area averages of 8 V/km.
- White paper includes SDT's analysis of:
  - Localized geomagnetic activity on a representative system
  - Reference storm wave shape comparison

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

Spatial Averaging

- Storm-time geoelectric fields are spatially complex which can bias statistical analysis
  - Localized e-field enhancements occur in small (~100 km) regions
- Benchmark analysis examined spatially-averaged data to address wide-area GMD effects

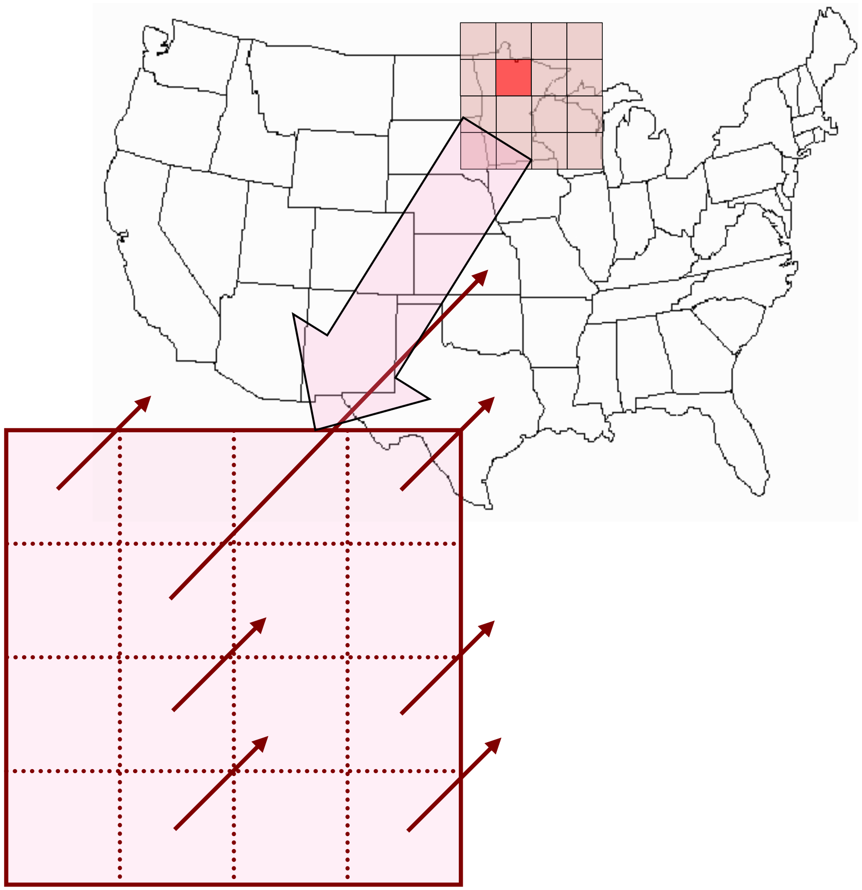
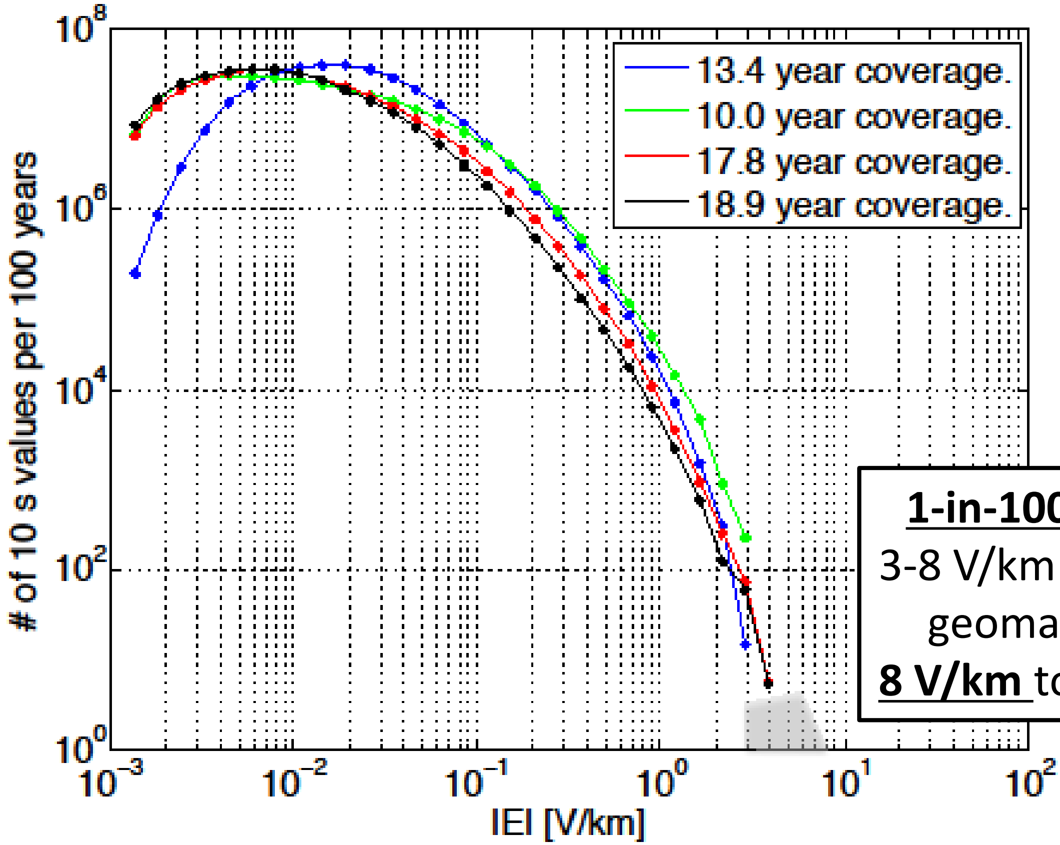


Illustration of Localized Geoelectric Field Enhancement

Reference Geoelectric Field Amplitude



1-in-100 Year Occurrence

3-8 V/km at 60^{0} N geomagnetic latitude

8 V/km to be conservative

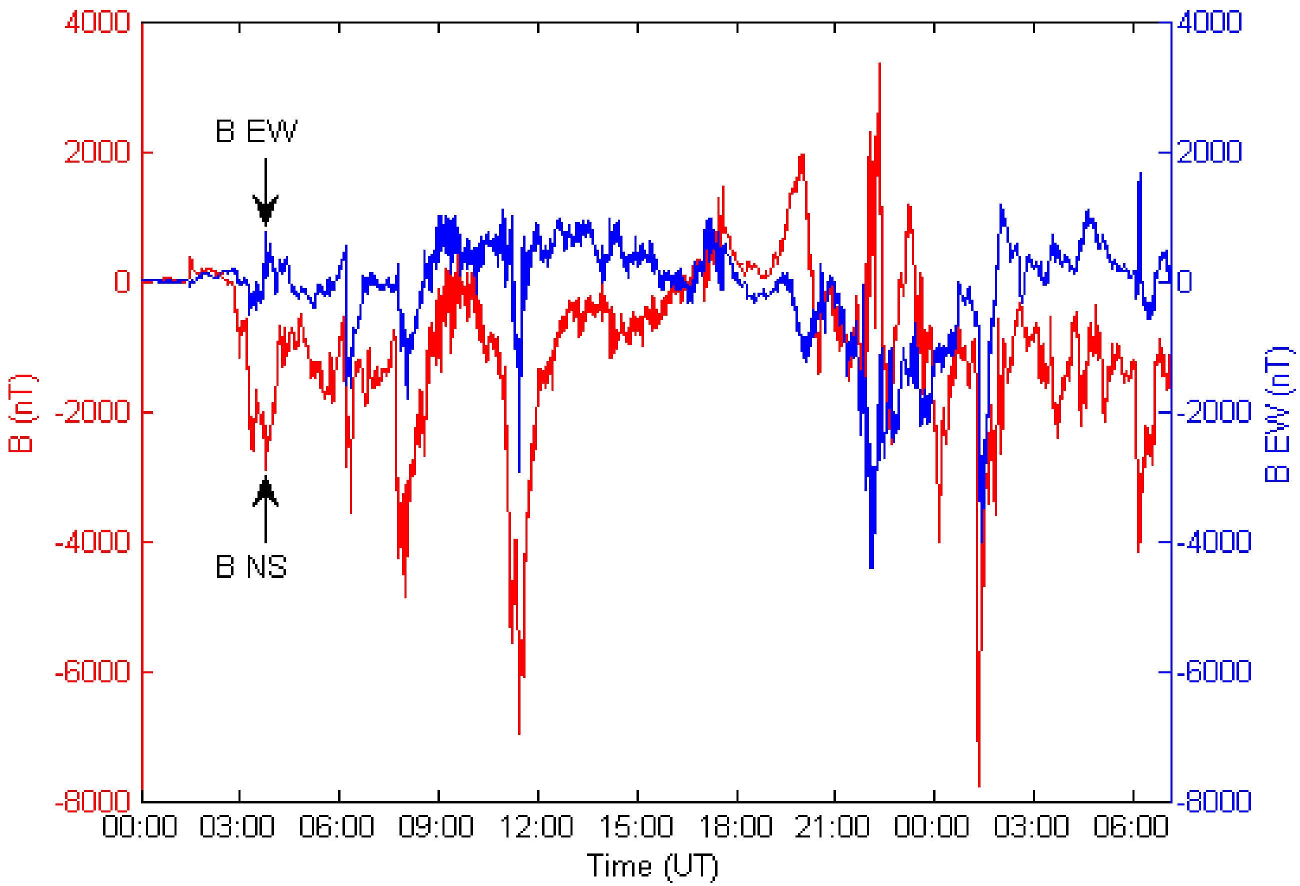
Statistical occurrence of spatially averaged high-latitude geoelectric field amplitudes from IMAGE magnetometer data (1993 – 2013)

Reference Geomagnetic Waveshape

- Needed to
  - Perform transformer thermal assessments
  - Calculate peak geoelectric fields for any earth model
- Conservative value selected after analyzing recorded GMD events
  - March 13-14, 1989 from Natural Resources Canada (NRCan) observations
  - 2003 Halloween storm (Nurmijarvi and Memanbetsu observations)
  - NERC Interim Report reference storm
- NRCan Ottawa observatory 10-second data for March 1989 event selected
  - Conservative results for transformer thermal analysis

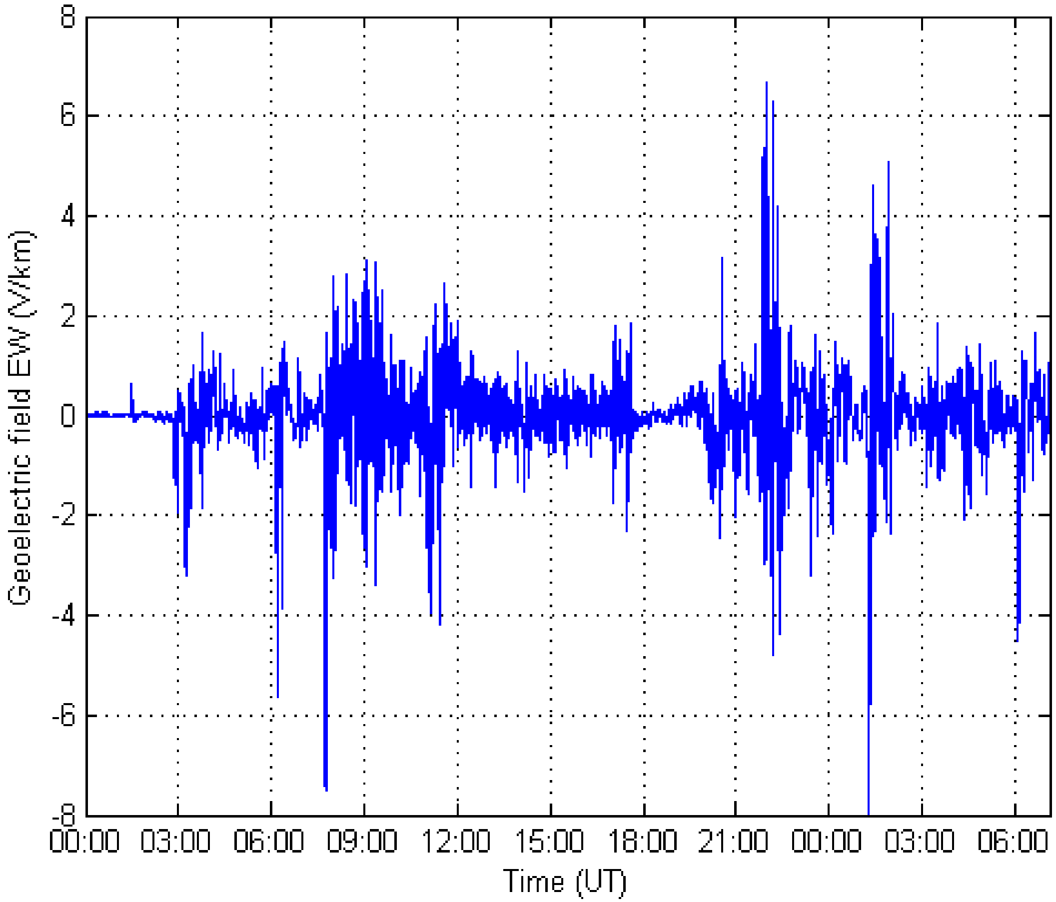
Data file available at:
http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx

Reference Geomagnetic Waveshape



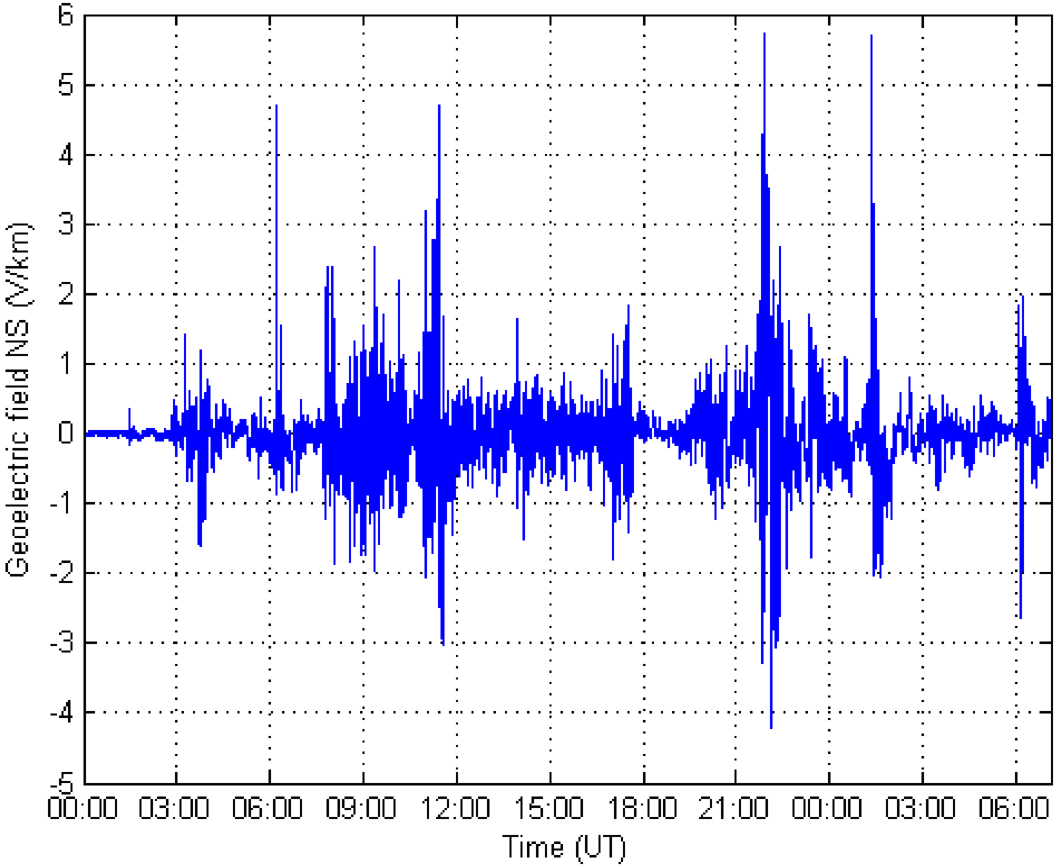
Benchmark Geomagnetic Field Waveshape. Red Bn (Northward), Blue Be (Eastward).

Reference Geoelectric Field Waveshape



Benchmark geoelectric field waveshape at 60° North. Calculated unsing the reference Quebec ground model. E_E (Eastward).

Reference Geoelectric Field Waveshape

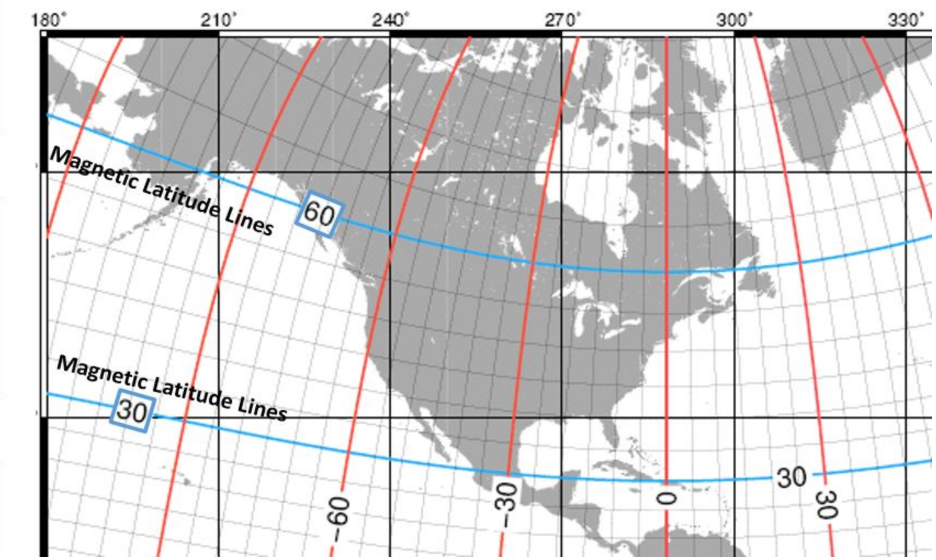


Benchmark geoelectric field waveshape at 60° North Calculated unsing the reference Quebec ground model. E_N (Northward).

Geomagnetic Latitude Scaling

- Determination of α scaling factors described in NERC GMD TF Application Guide for Computing GIC
- Table provided in TPL-007-1 Attachment 1 and Benchmark white paper

1.0 at 60° N	Juneau; Winnipeg; Churchill Falls, NL
0.3 at 50° N	New York ; St Louis; Salt Lake City
0.1 at 40° N	Jacksonville; New Orleans; Tucson



Geomagnetic Latitude Chart

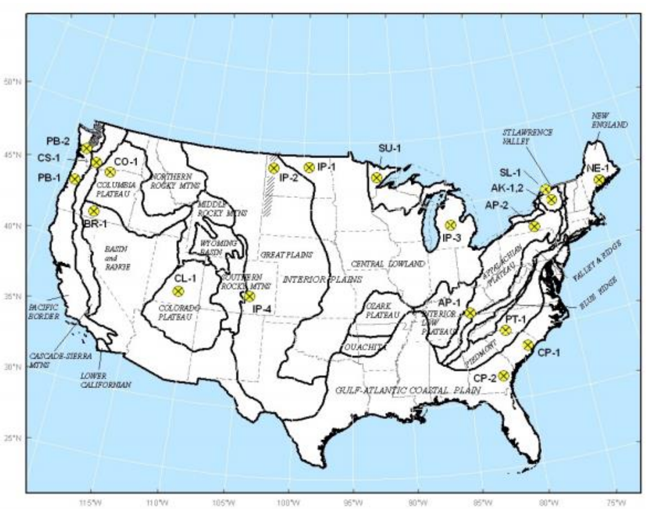
$$E_{peak} = 8 \times \alpha \times \beta \text{ (in V/km)}$$

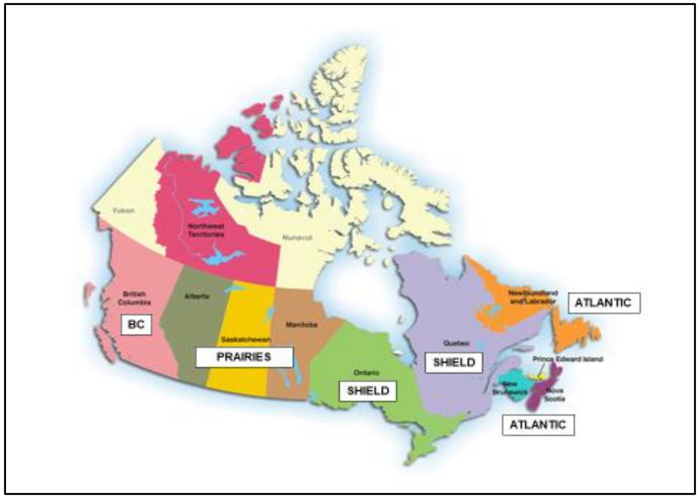
Earth Conductivity Scaling

Earth conductivity model factor (β)

0.81	Atlantic Coastal (CP-1)	0.67	British Columbia (BC)
0.27	Columbia Plateau (CO-1)	0.79	Prairies

- Table provided in TPL-007-1 Attachment 1 and Benchmark white paper
- A utility can use a technically-justified earth model and calculate its own β





Based on information from US Geological Survey (USGS) and NRCan

Examples

Example 1

- Transmission service territory that lies at a geographical latitude of 45.5° (geomagnetic latitude of 55°)
- $\alpha = 0.562$ (using formula $\alpha = 0.001 \times \exp(0.115 \times L)$)
  - Note that $0.1 < \alpha < 1.0$
- Same earth conductivity as the benchmark $\beta = 1$
- $E_{peak} = 8 \times 0.562 \times 1 = 4.5$V/km
- If territory spans more than one physiographic region (i.e. several locations 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.

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*

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Example 2

- Transmission service territory that lies at a geographical latitude of 45.5° (geomagnetic latitude of 55°)
- α = 0.562 (using formula α=0.001×exp(0.115×L))
- Earth conductivity NE1, β=0.81
- E_{peak} = 8 ×0.562 ×0.81 = 3.6V/km
- *If* the utility has a technically supported conductivity model or models and the tools to calculate the geoelectric field from the geomagnetic field then E_{peak} can be calculated directly using the reference geomagnetic field waveshape scaled by α

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*
CS1	*0.41*
IP1	*0.94*
IP2	*0.28*
IP3	*0.93*
IP4	*0.41*
NE1	*0.81*
OTT	*1.00*

Example 3

- A utility has access to tools to calculate α and β.
- For instance
  - Lat = 48.50 lon = 89.09W gives α = 0.766 (North part of the system)
  - Lat 42.42 lon = 89.13W gives α = 0.382 (South part of the system)
- North part of the system has the same earth model as the reference, therefore β = 1.0
  - $E_{peak} = 8 \times 0.766 \times 1.0 = 6.1$ V/km
- South part of the system a different earth resistivity and β = 7.65/8 = 0.9563
  - $E_{peak} = 8 \times 0.382 \times 0.9563 = 2.92$ V/km

Discussion

GIC System Models - Luis Marti, Hydro One

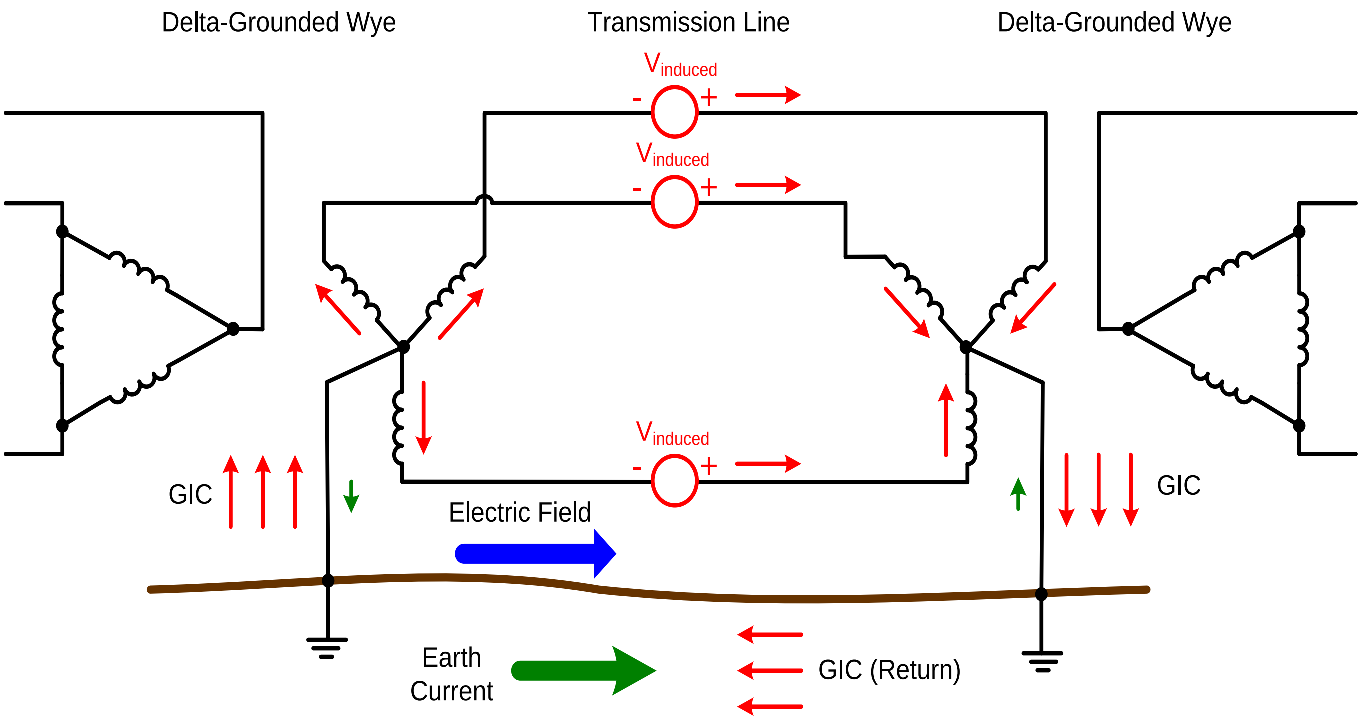
TPL-007-1 Requirement

- Requirement R1 requires each applicable Planning Coordinator (PC) and Transmission Planner (TP) to maintain ac System models and GIC System models of the planning area
- Several commercial software packages are available with GIC simulation modules
- Theory and practical details for GIC modeling are described in the Application Guide for Computing GIC in the BPS:

  http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx

GIC System Models

- **GIC Study –** The purpose is to calculate the distribution of GIC in the network. GIC frequencies range from 0.01 mHz to 100 mHz. From a power system point of view this is a dc study.



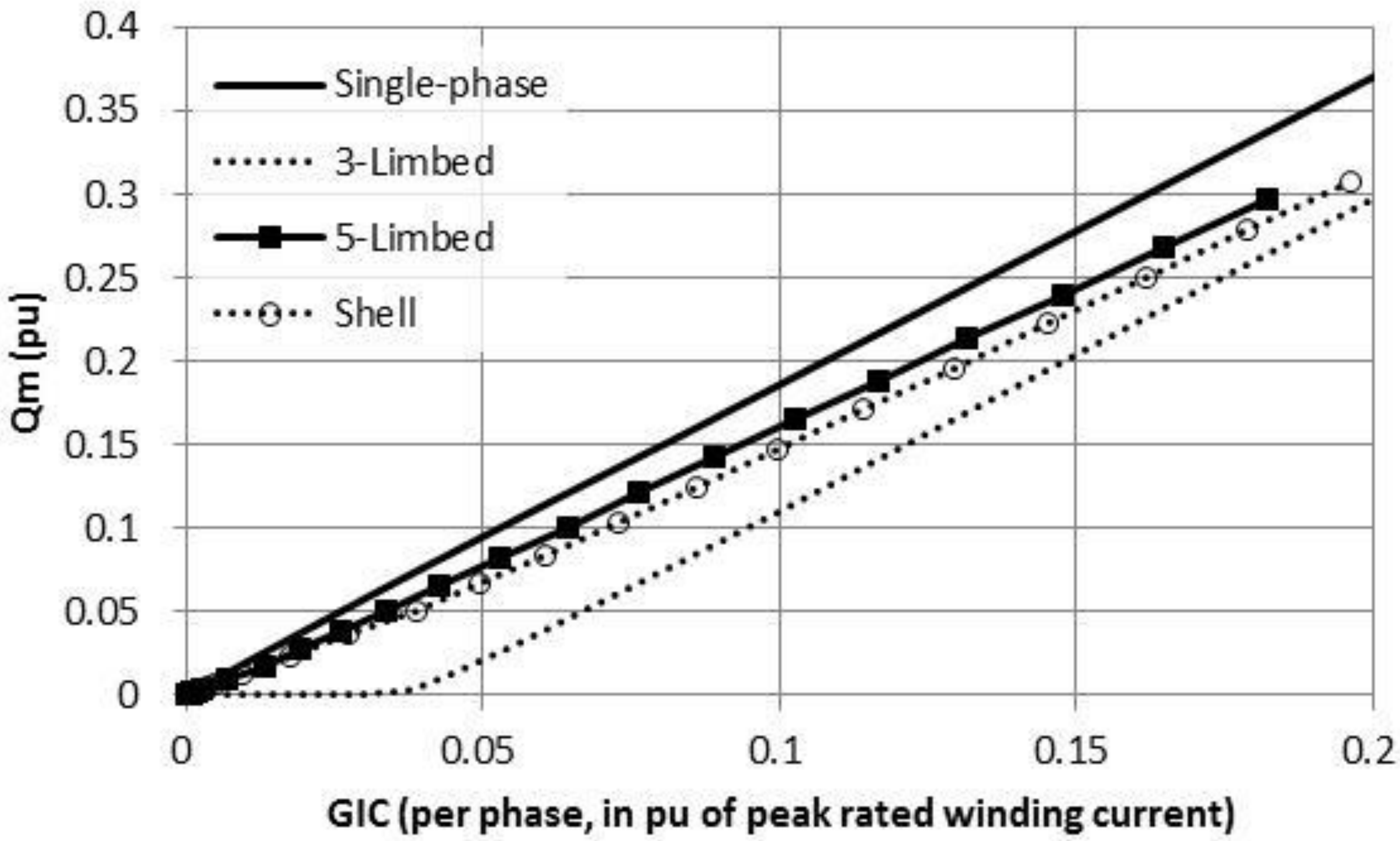
Modeling/Data Needs

- GIC studies require models and data that are not typically included in (load flow) transmission planning models
  - Transmission lines are represented as a resistance in series with a voltage source. The magnitude of the voltage source depends on:
    - Length and orientation of the transmission line with respect to the direction of the geoelectric field (note that GPS coordinates of substation locations must be mapped to buses included in the dc model)
    - Peak amplitude of the geoelectric field, which is defined by the benchmark GMD event
  - Transformers are represented by their winding resistances (mutual coupling between windings is ignored because of the low frequencies involved)
  - The effective grounding of a station is also modelled as a resistance

Modeling/Data Needs

- Electrical transformer models
  - Curves that relate effective GIC in a transformer to reactive power absorption in the transformer due to half-cycle saturation
  - Curves that relate effective GIC to harmonics generated by half-cycle saturation
  - Different curves for different transformer core construction
    - 1-phase core-type
    - 3-phase 5-limb
    - 3-phase shell
    - 3-phase 3-limb
  - Software vendor defaults or user-supplied

Example of GIC – var curves



Data Sources

- Station GPS coordinates. This determines the relative orientation of the transmission circuits and the geoelectric field.
- Transmission line dc resistance
- Transformer winding dc resistance from test sheet, not from load flow model
- Station grounding equivalent resistance, including the effect of shield wires
- Peak amplitude of the geoelectric field defined by the benchmark GMD event. This peak amplitude depends on geographical latitude (α factor) and local deep earth resistivity (β factor)

Results of a GIC Study

- The GIC or dc study produces the following results for a given geoelectric field orientation, or the maximum GIC for the worst possible geoelectric field orientation:
  - Distribution of GIC in every transformer in the system
  - 60 Hz reactive power absorption in every transformer.
- The dc model should represent projected System conditions which may include adjustments to System posture that occur at the onset of a GMD event
  - Recalling maintenance outages, etc.
- Because the orientation of the geoelectric field is constantly changing, the steady-state GIC analysis should consider various geoelectric field orientations (e.g. 15-30 deg. Increments).
  - Several commercially available software packages have this capability

Technical Resources for GIC Modeling

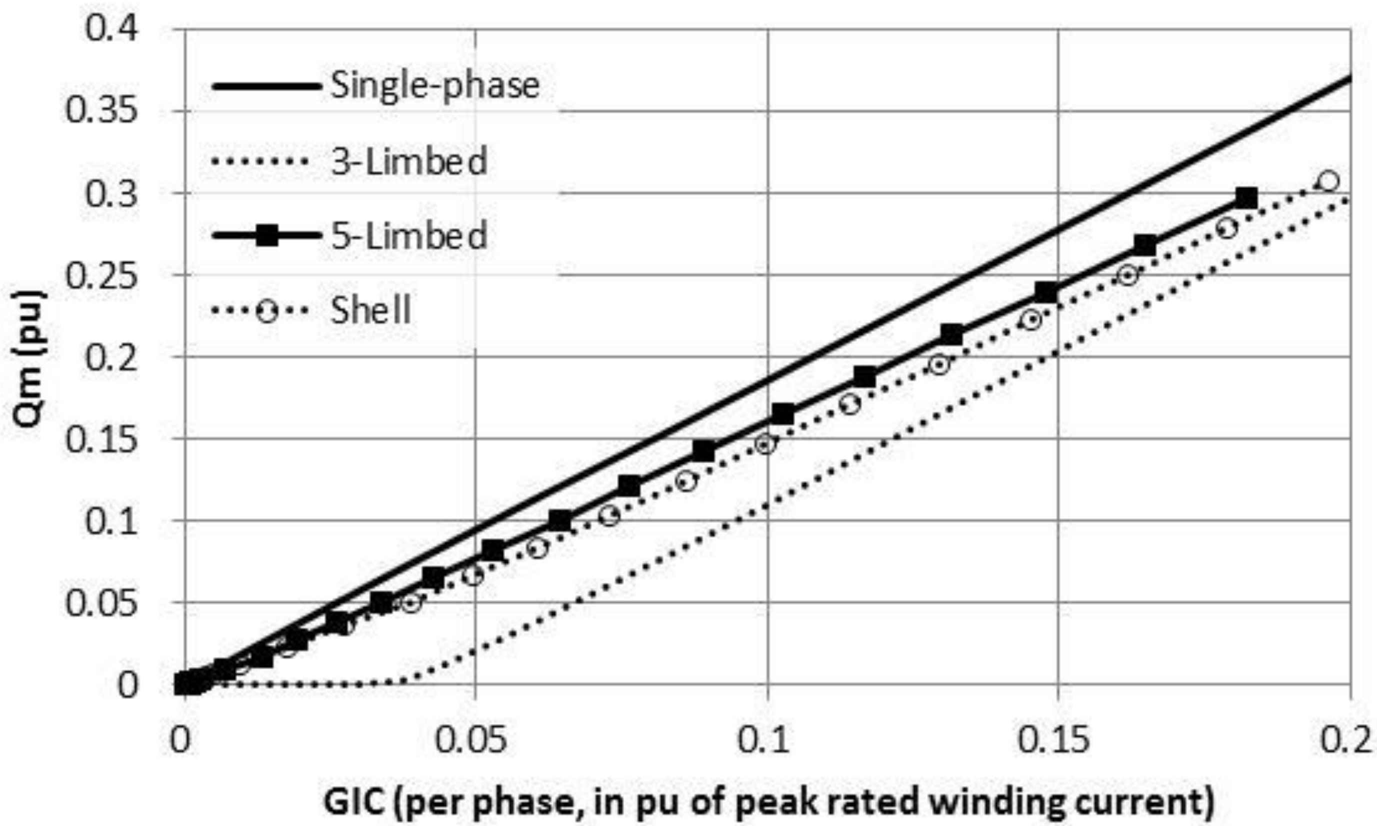
- Technical resources on the GMD TF Project page
  http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx
  - GIC Application Guide (PC approved December 2013)
  - GMD Planning Guide (PC approved December 2013)
  - 2012 GMD Report
- Technical resources are also available for free at www.epri.com.
  - Contact Rich Lordan (EPRI) at rilordan@epri.com for additional information and listing of available information

Steady-state Power Flow Analysis – Randy Horton, Southern Company

TPL-007-1 Requirements

- Requirement R2 specifies conditions for the GMD Vulnerability Assessment steady state analysis
- Planning event details and performance criteria are contained in Table 1
- Commercial software packages are available with features to support GIC and power flow analysis with varying degrees of integration
  - Siemens PSS®E
  - GE PSLF
  - PowerWorld
- When performing power flow analysis including the effects of GIC it is important to understand the relationship between GIC and transformer var losses due to half-cycle saturation

Example of GIC – var curves



A conservative approach is to model the losses as a constant current load connected to the terminals of the transformer

Planning Details

- Once the GIC flows have been determined, a steady-state power flow analysis is conducted to evaluate the effects of the additional reactive power absorption of transformers due to half-cycle saturation
  - System peak Load and Off-peak load is examined
  - Analysis should account for posturing that is executable in response to space weather forecasts
- Analysis must include removal of Reactive Power compensation devices and other Transmission Facilities that may be deemed to be impacted by GIC (e.g., Protection System operation or misoperation)

Performance Criteria

- The objective of the GMD Vulnerability Assessment is to prevent instability, uncontrolled separation, Cascading, and uncontrolled Islanding of the System during a GMD event.
- System performance evaluation is based on:
  - System steady-state voltage and power flow limits established by the Transmission Planner and Planning Coordinator
  - Cascading and uncontrolled islanding shall not occur
- Flexibility is given to allow the use of limits exclusive to GMD events
- Load Rejection shall not be used as the primary method of achieving required performance

Discussion

GMD Planning and Traditional System Planning – Randy Horton Southern Company

Differences from Traditional Transmission Planning

- TPL-007-1 is being developed to address specific directives in Order 779 within a transmission planning framework
    - TPL-001 provides an approved model that is adaptable
    - Technical guidelines for GMD Planning were developed from a transmission assessment and planning approach
- In drafting TPL-007-1, specific requirements in TPL-001 were adapted to account for GMD-related factors:
    - Severe GMD event is considered a High-Impact, Low-Frequency event
    - Available tools, models, and methods are maturing
- Traditional assessment of multiple contingencies is not required in TPL-007-1 because GIC is assumed to be a common-mode stress across the network

Contingencies

- Contingencies studied in TPL-007 are related to the GMD event
  - Loss of all Reactive Power compensation devices and other Transmission Facilities with Protection and Control Systems that may trip from harmonics or be affected by harmonic overcurrents

Performance Criteria

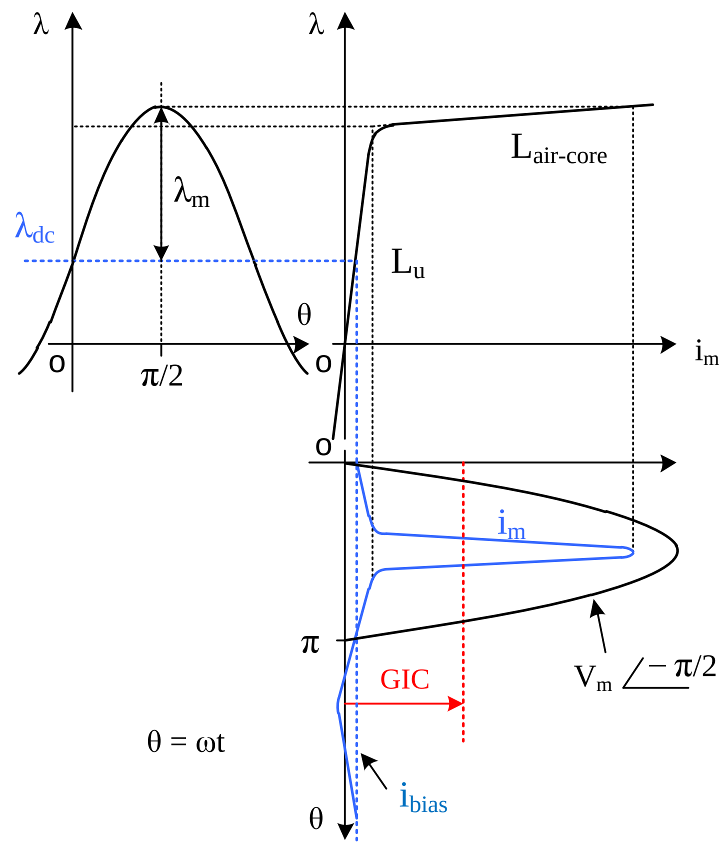
- The objective of the GMD Vulnerability Assessment is to prevent instability, uncontrolled separation, Cascading, and uncontrolled Islanding of the System during a GMD event.
- Load Rejection is permitted in planning analysis
  - Load Rejection shall not be used as the primary method of achieving required performance

Discussion

Thermal Effects of GIC on Transformers – Luis Marti, Hydro One

Half Cycle Saturation

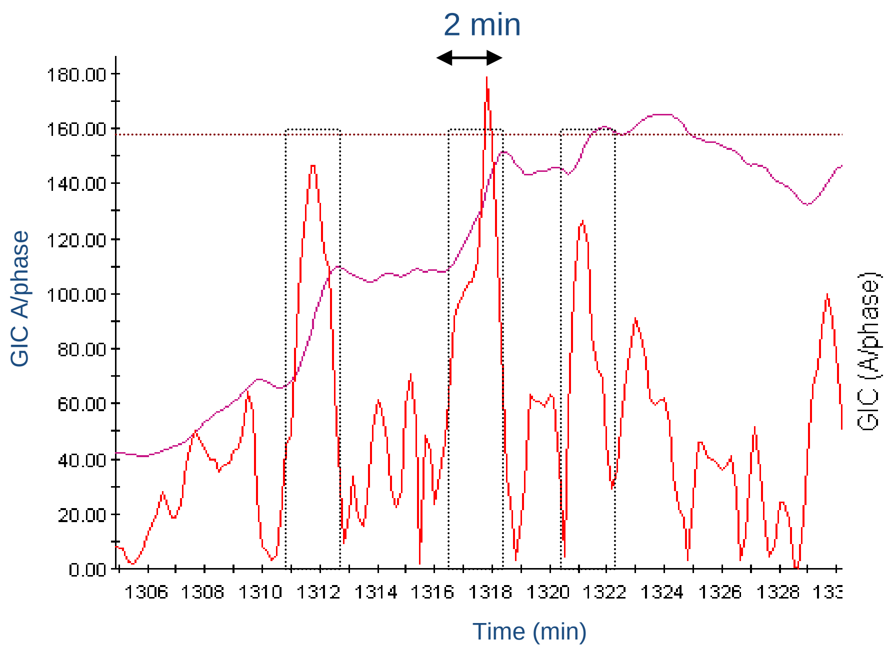
- GIC produces a dc offset of the ac sinusoidal flux within the transformer resulting in:
  - Harmonics
  - Increase in reactive power absorption
  - Hot-spot heating of windings due to stray flux
  - Hot-spot heating of non-current carrying parts due to stray flux
    - Fitch-plate, tie-plate, tank walls
  - Increase in vibration and noise

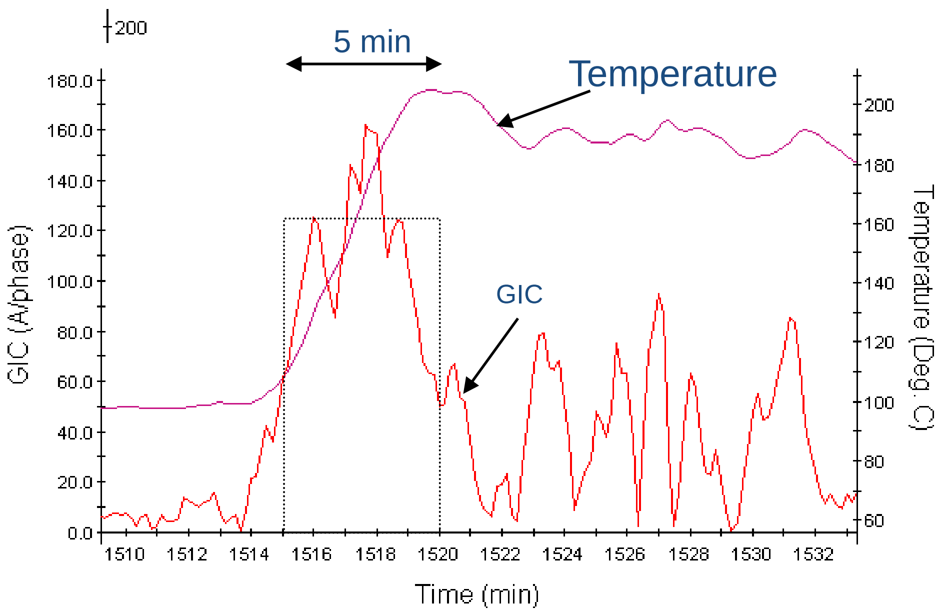


Thermal Effects

- Hot-spot heating is dependent upon
  - Transformer thermal time constant (on the order of 2 to 20 minutes)
    - Time constant is approximately the time to reach 60 percent of final value
  - GIC peak amplitude and duration
  - GIC waveshape
  - Loading (constant temperature in the context of hot-spot heating)
  - Ambient temperature
  - Transformer cooling mode
- There is no unique test GIC current waveshape. Every transformer sees a different GIC(t)

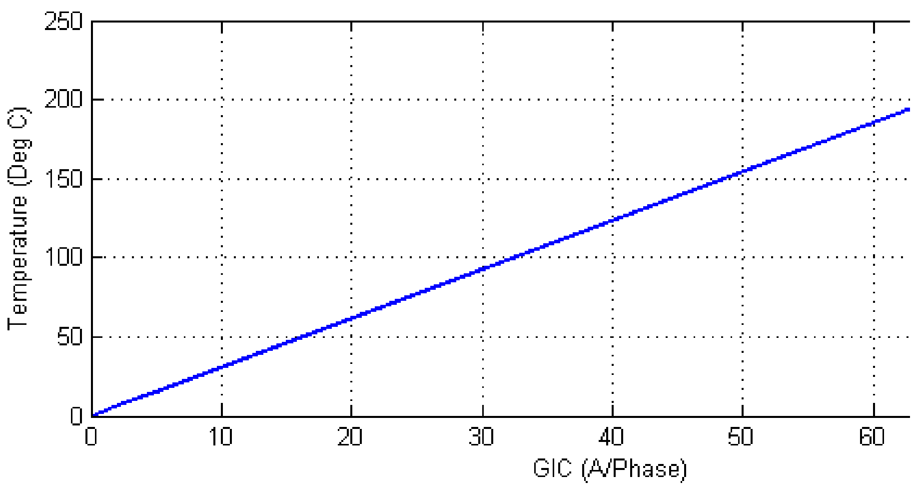
Same event, same transformer type, different locations in the system

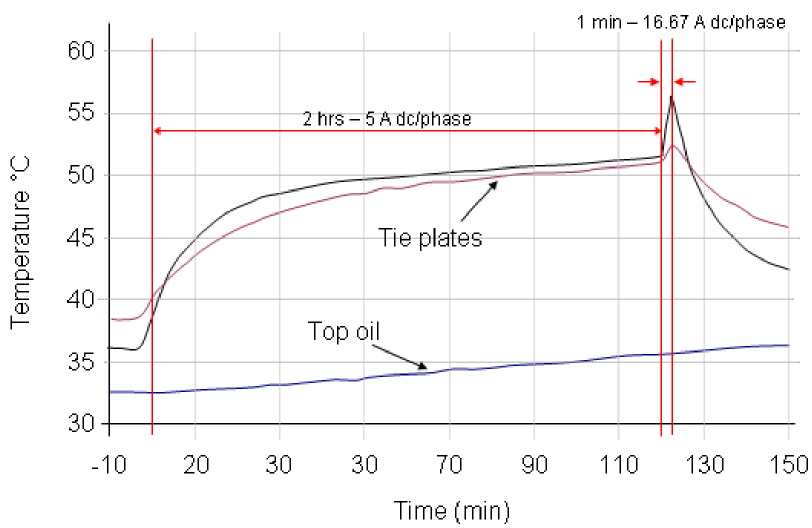




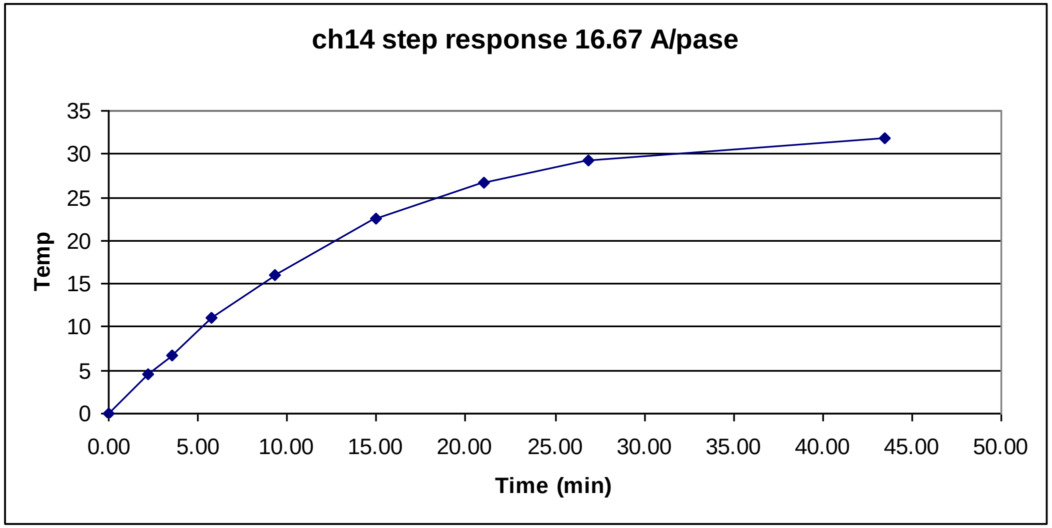
Thermal Response

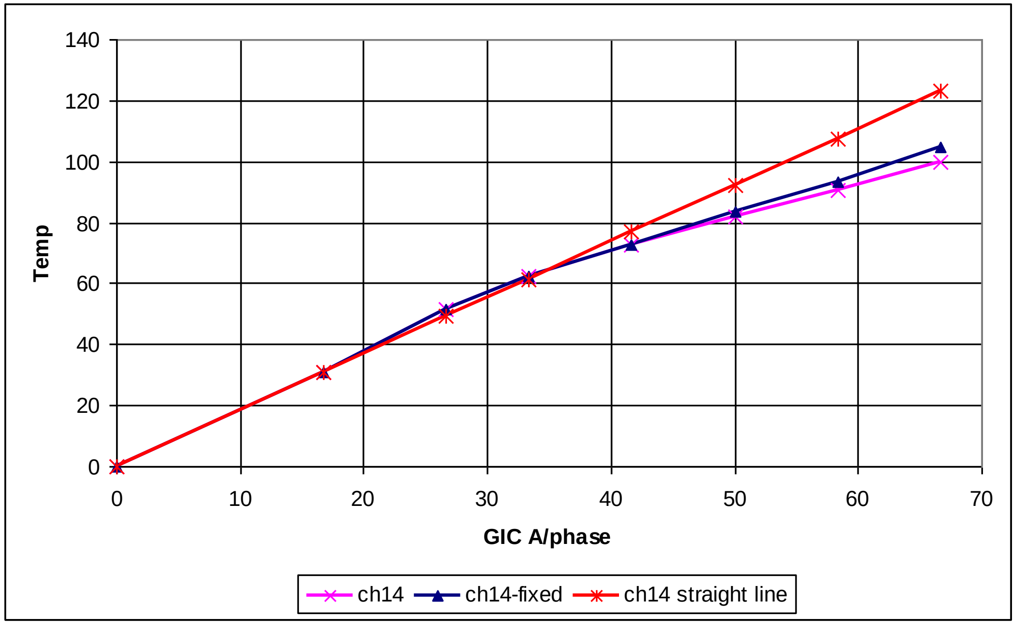
- If the transformer hot-spot thermal step response is known (temperature increase to a dc step), the temperature increase due to an arbitrary GIC(t) can be calculated
- Thermal step response can be measured (in properly instrumented transformers), or calculated by the manufacturer





Sample Measured Thermal Response





Hot-spots

- Excessive winding hot-spot temperatures can cause loss of life of cellulosic insulation
- Excessive tank or other internal metallic part temperatures can result in gassing. Gas bubbles can cause dielectric breakdown

Thermal Effects

- Adverse effects due to hot-spot heating also depend on age, condition, and type of Transformer
- Technically sound sources of temperature thresholds include
  - Manufacturer-provided information
  - Limits for safe transformer operation such as those found in IEEE Standard C57.91-2011 for hot-spot heating during short-term emergency loading

Excerpt from maximum temperature limits suggested in IEEE C57-91 2011.

	Normal life expectancy loading	Planned loading beyond nameplate rating	Long-time emergency loading	Short-time emergency loading
Insulated conductor hottest-spot temperature °C	120	130	140	180
Other metallic hot-spot temperature (in contact and not in contact with insulation), °C	140	150	160	200
Top-oil temperature °C	105	110	110	110

Transformer Thermal Assessment – Luis Marti, Hydro One

TPL-007-1 Requirements

- Requirement R7 requires Transmission Owner (TO) and Generator Owner (GO) to assess thermal impact of GIC flow from the benchmark GMD event in applicable transformers
- Maximum effective GIC in each transformer is needed input from the GIC Study

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

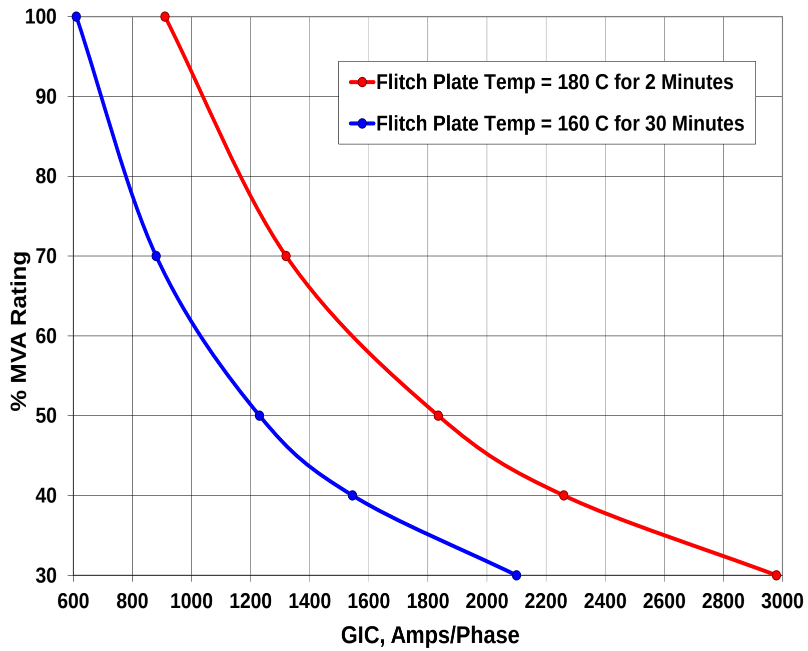
  - I_H is the dc current in the high voltage winding;
  - I_N is the neutral dc current;
  - V_H is the rms rated voltage at HV terminals;
  - V_X is the rms rated voltage at the LV terminals.
- From this GIC Study maximum $I_{dc,eq}$, GIC(t) is calculated as input for the thermal assessment process.

TPL-007-1 Requirements

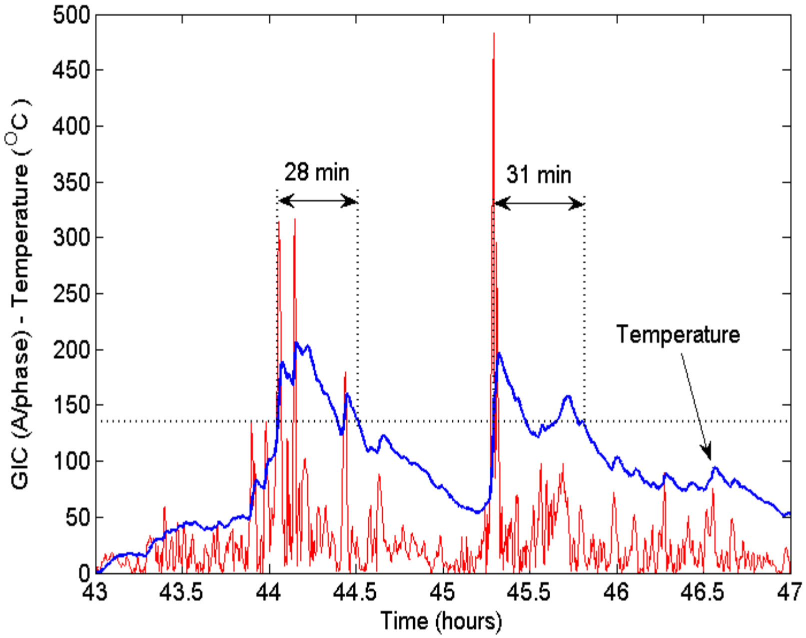
- Assessment must include suggested actions and supporting analysis which are provided to the TP and PC to mitigate identified issues (Requirement R8)
- White paper describes approaches using manufacturer capability curves or thermal response modeling

Transformer Thermal Assessment

- Assessment approaches:



Transformer manufacturer capability curves



Thermal response simulation

Considerations in a Transformer Thermal Assessment

- In the absence of manufacturer-specific information, use the temperature limits for safe transformer operation suggested in the IEEE Standard C57.91-2011 standard, for hot-spot heating during short-term emergency operation.
- The C57.91 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.
- 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.

Considerations in a Transformer Thermal Assessment

- The worst case temperature rise for winding and metallic part (e.g., tie plate) hot-spot 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).
- The are differences in the hot-spot thermal response of every transformer. Unless the characteristics of a transformer are known, it is prudent to use conservative models as screening tools and then go into more detail if thermal limits are encroached.

Considerations in a Transformer Thermal Assessment

- Temperature increases due to ambient temperature and transformer loading: for planning purposes, maximum ambient and loading temperature should be used unless there is a technically justified reason to do otherwise

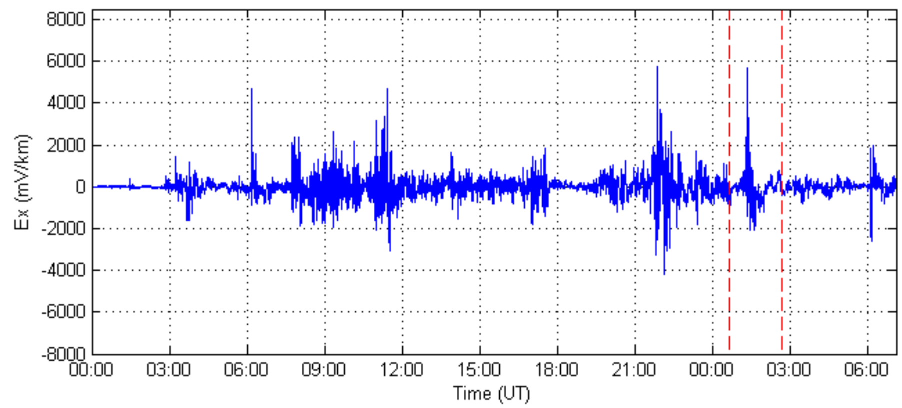
NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

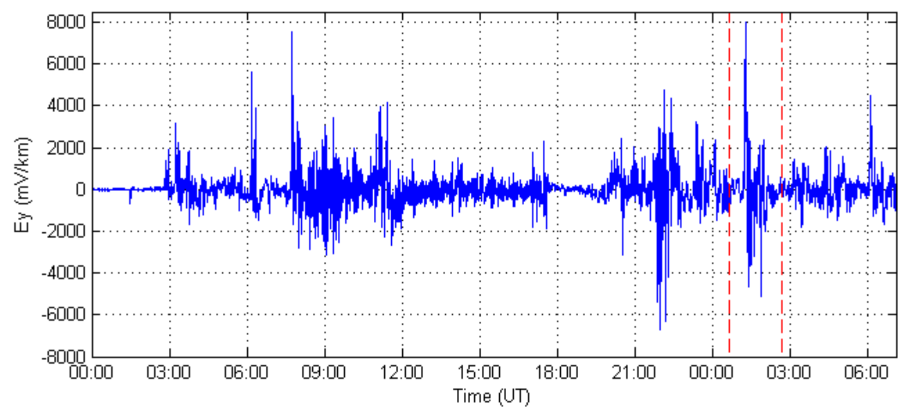
Steps in a Transformer Thermal Assessment

- Assessment steps for a given transformer
  - Obtain transformer GIC from GIC Study for eastward and northward geoelectric fields (1 V/km)
  - Calculate GIC(t) from the reference geomagnetic time series (scaled according to geomagnetic latitude and earth resistivity)
  - Assess if temperature limits are encroached with the resulting GIC(t)

Calculation of GIC(t)

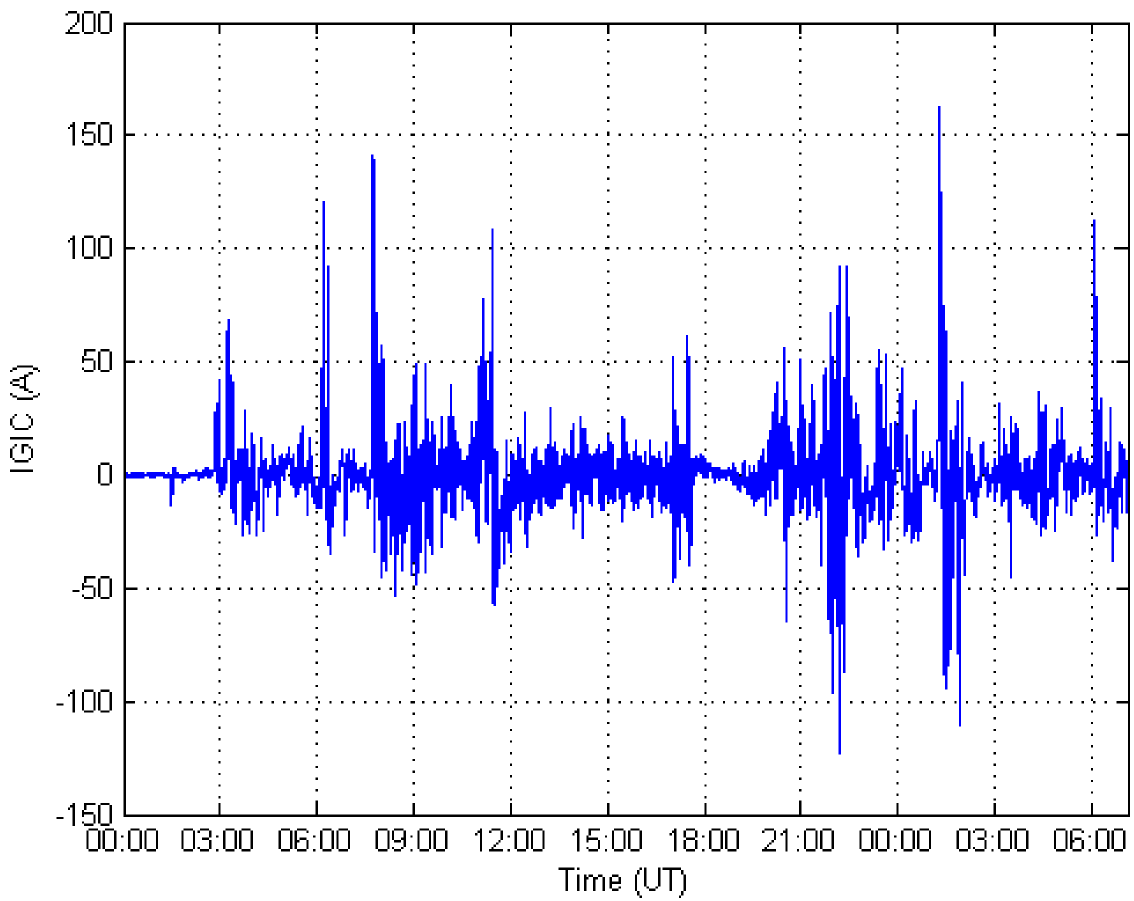
- Calculate component GIC values due to eastward and northward geoelectric fields for each transformer (GIC_E and GIC_N) for 1 V/km
- Scale each component GIC value according to using the scaled geoelectric field time series





$$GIC(t) = E_E(t) \cdot GIC_E + E_N(t) \cdot GIC_N \text{ (A/Phase)}$$

GIC(t)

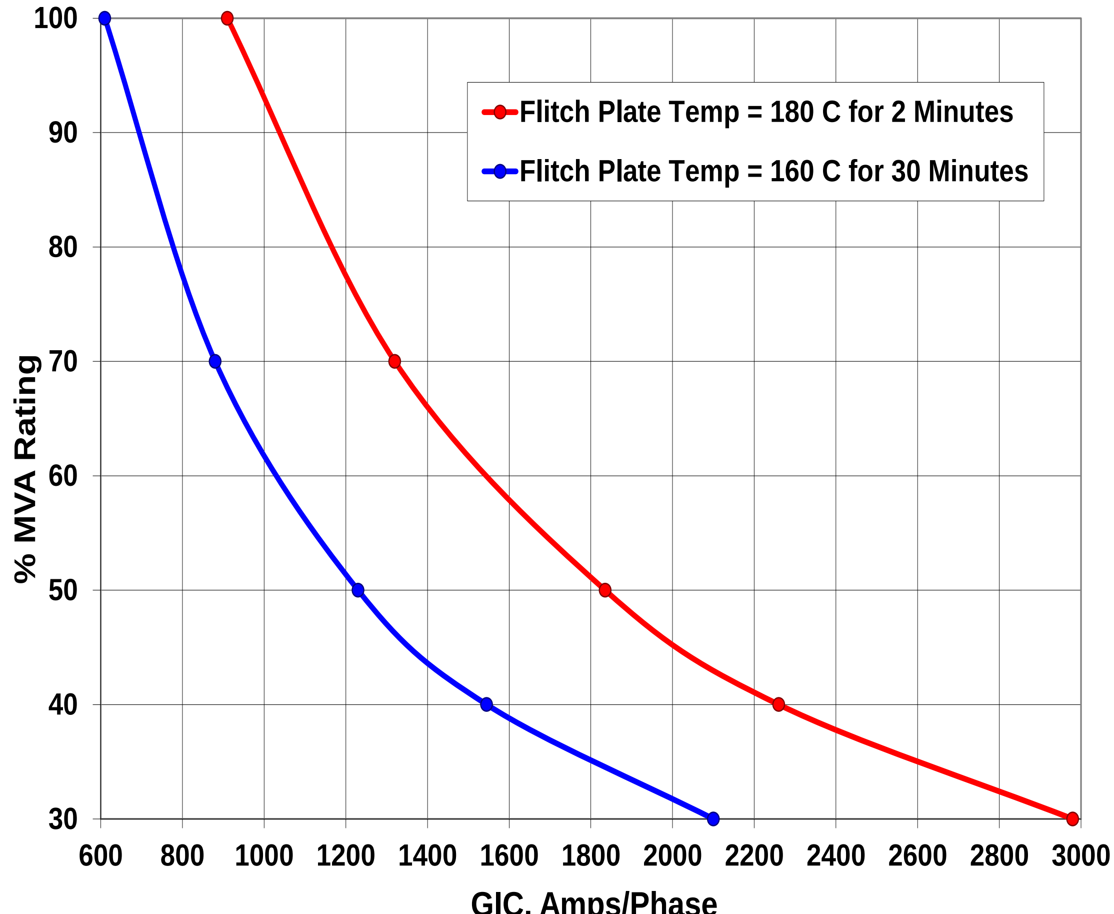


Calculated GIC(t) Assuming α=1 and β=1 (Reference Earth Model)

Assessment of Limit Encroaching

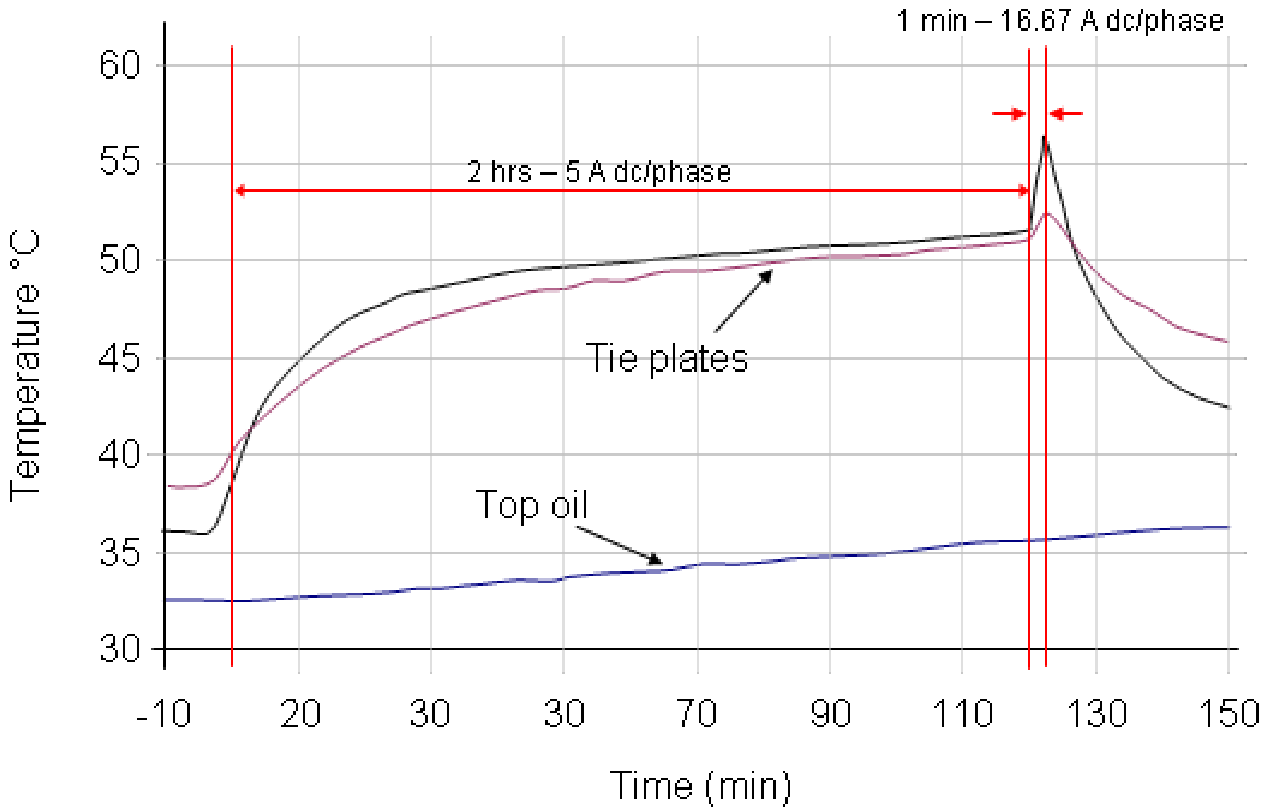
- Each transformer will see a different GIC(t)
- Assess if each transformer will be affected by GIC(t)
  - Winding hot-spot
  - Metallic part hot-spot
- Adjust thresholds according to age and condition
- Three ways to do this
  - Peak GIC(t) is so low compared to the transformer’s GIC capability that a detailed assessment is unnecessary. Technical justification required.
  - Manufacturer-provided GIC capability curves relating permissible peak GIC pulses of a given duration and loading for a specific transformer
  - Transformer thermal response simulation of hot-spot temperature to GIC time-series data

Example GIC Capability Curve



Sample GIC manufacturer capability curve of a large single-phase transformer design using the Flitch plate temperature criteria. (Girgis and Vedante, IEEE PES Meeting 2013)

Example Thermal Step Response



Sample of measured GIC thermal step response (Marti et al, IEEE Transactions on Power Delivery, 2013

Sample Thermal Assessment

Example to Illustrate the Methodology

- Transformer thermal behavior obtained from published literature
  - Combination of limited testing and conservative extrapolation
- It is not intended to be viewed as representative of any one transformer
- The GIC values used are not intended to be indicative of any one system in particular
  - They were selected so that the hot-spot temperatures approach the limits suggested in IEEE Standard C57.91
  - They illustrate that for the same GMD event, different transformers see different GIC(t) waveshapes

Assessment Steps

- Obtain GIC for a given transformer from GIC Study
  - When the Eastward geoelectric filed is zero and the Northward geoelectric field is 1.0
  - When the Eastward geoelectric filed is 1.0 and the Northward geoelectric field is zero
- Calculate GIC(t) using the properly-scaled benchmark geoelectric field time series
- Assess the transformer capability with either:
  - Compare GIC(t) with the capability curve
  - Calculate the thermal response to GIC(t) and compare against IEEE Standard C57.91 suggested hot-spot temperature limits for short term emergency loading

Calculation of GIC(t)

- There a number of equivalent ways to calculate GIC(t)

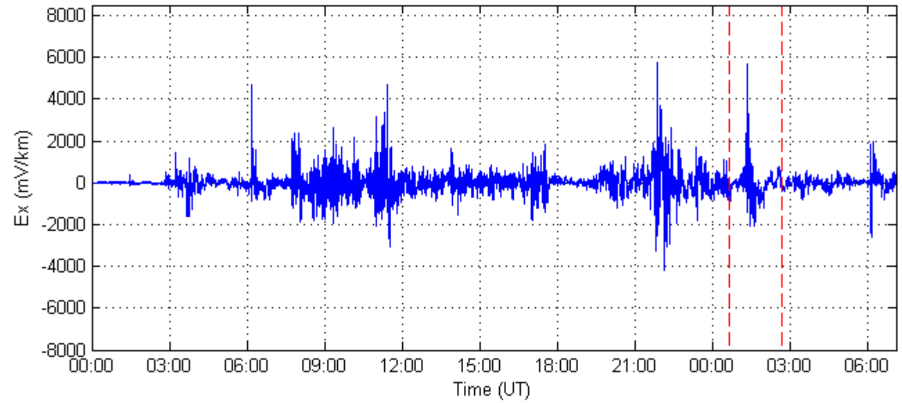
$$GIC(t) = E_E(t) \cdot GIC_E + E_N(t) \cdot GIC_N$$

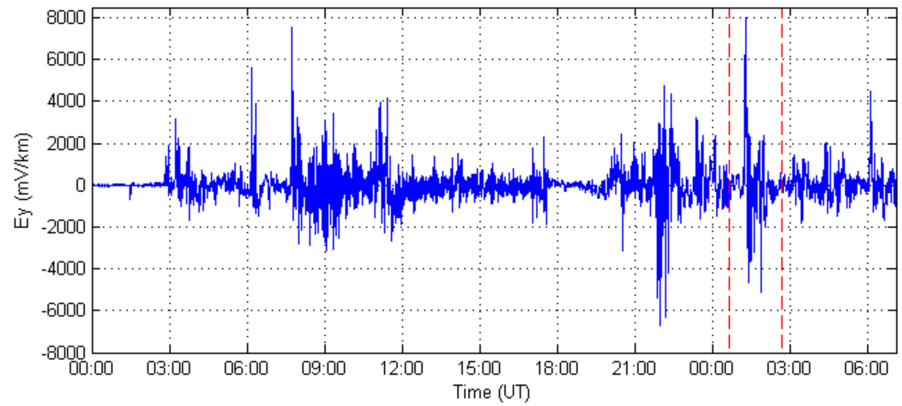
1. From GIC Study obtain GIC_N and GIC_E when V/km = E_{peak}
   - Normalize $E_E(t)$ and $E_N(t)$ for the reference geoelectric field time series to obtain a peak magnitude peak of 1 V/km
2. From GIC Study obtain GIC_N and GIC_E when E_N = 1 V/km and E_E = 1 V/km
   - Normalize $E_E(t)$ and $E_N(t)$ for the reference geoelectric field time series to obtain a peak magnitude peak of E_{peak}
3. Use software tools that produce GIC(t) directly

- Care must be taken not to double-count α and β scaling

Calculation of GIC(t)

- Calculate component GIC values due to eastward and northward geoelectric fields for each transformer (GIC_E and GIC_N) for 1 V/km
- Scale each component GIC value according to using the scaled geoelectric field time series

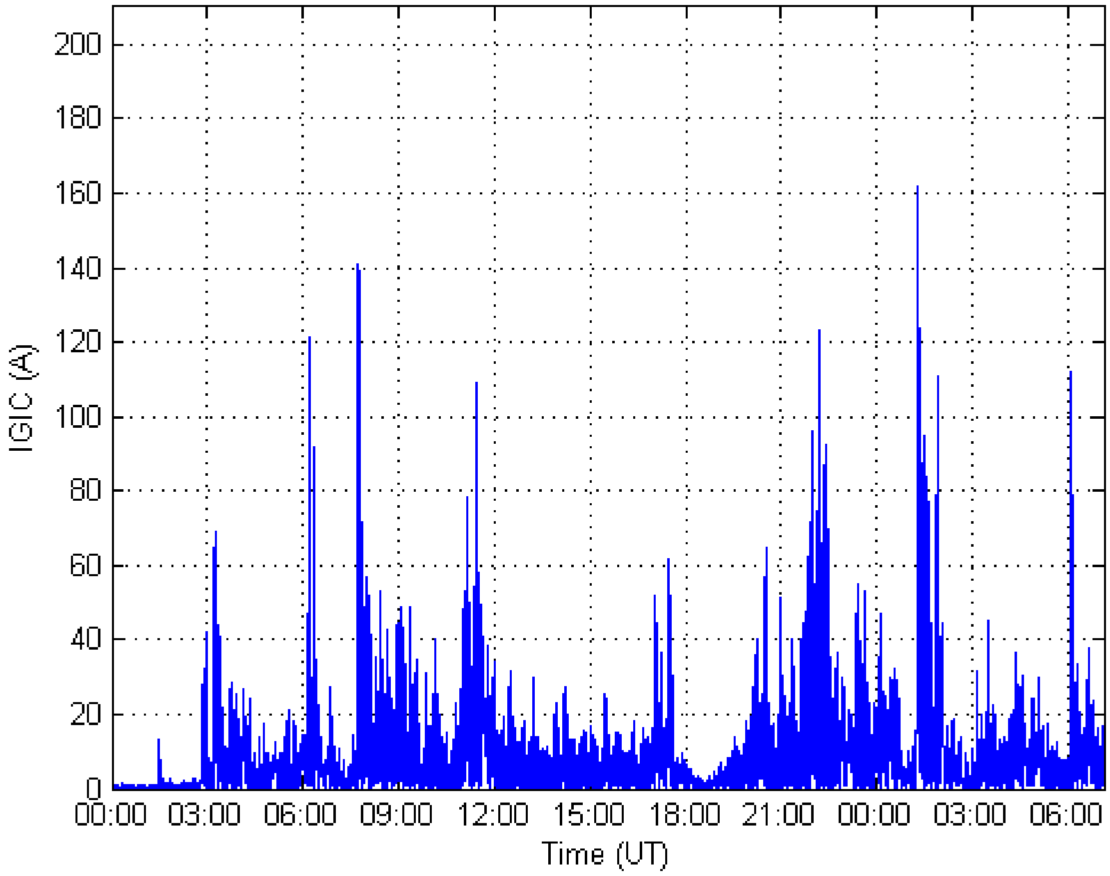




$$GIC(t) = E_E(t) \cdot GIC_E + E_N(t) \cdot GIC_N$$ (A/Phase)

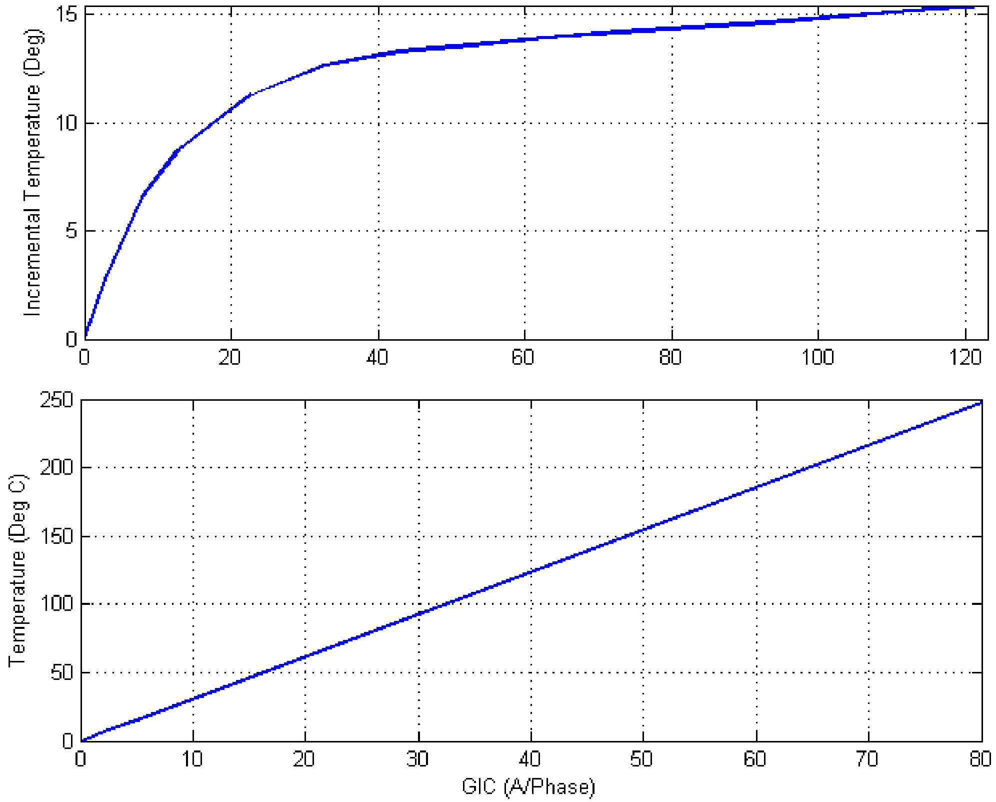
Calculation of GIC(t)

- It is easier to work with the absolute value of GIC(t)



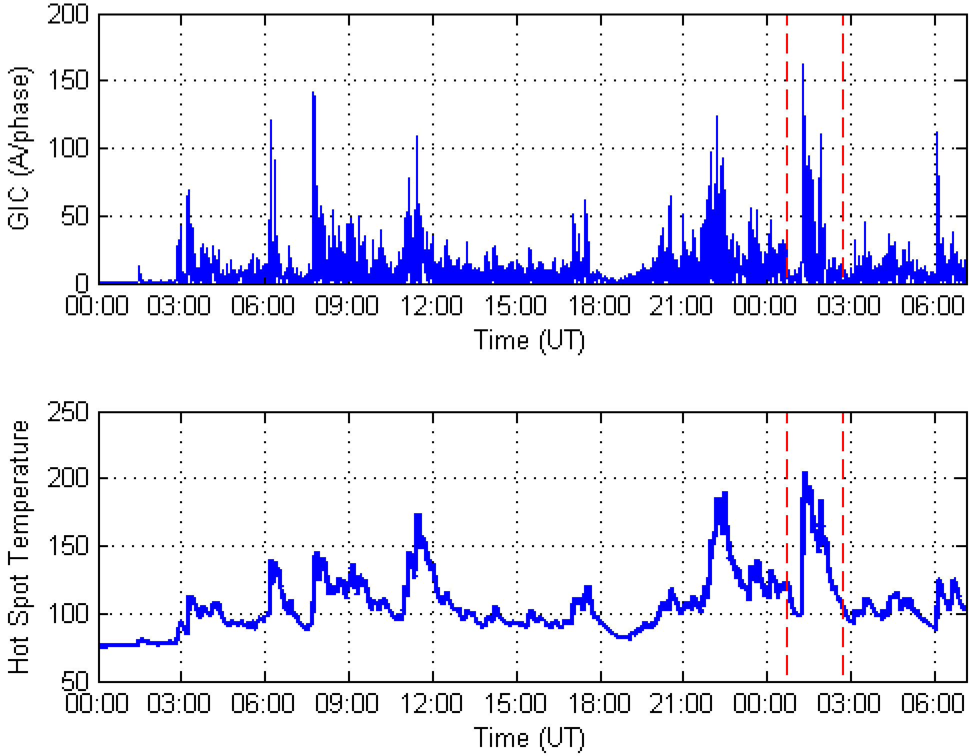
Assessing Capability Using Thermal Response Tools

- Identify the thermal step response for winding and metallic part hot-spots



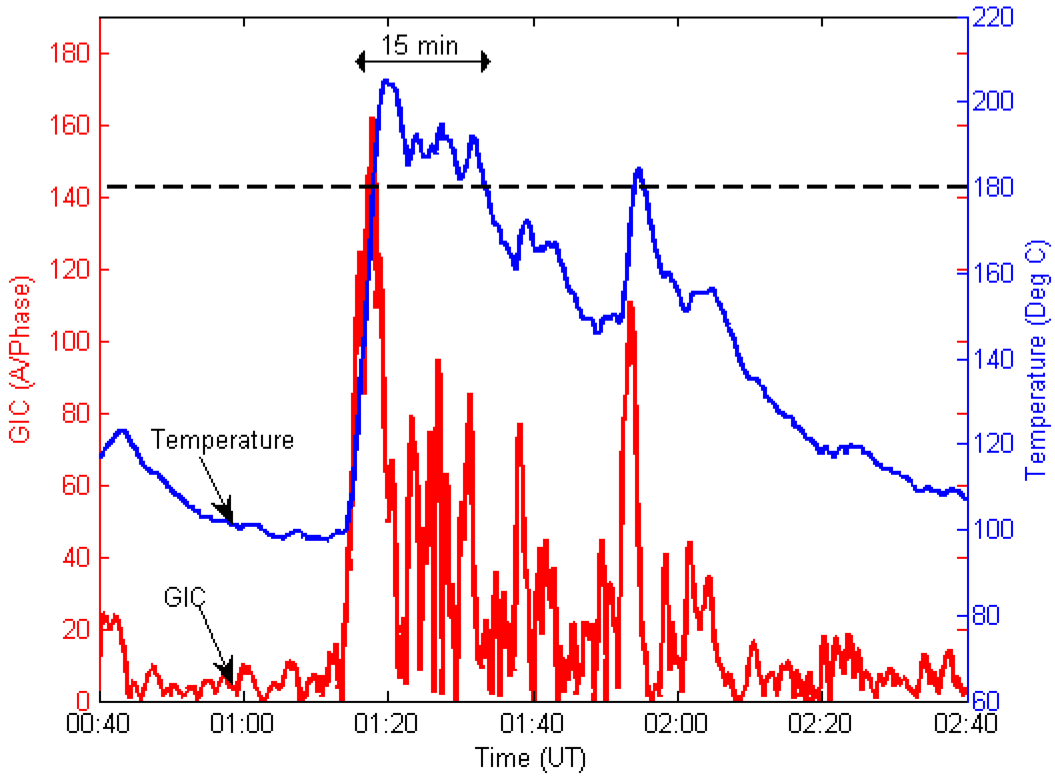
Using Thermal Response Tools

- Obtain the thermal response to GIC(t) with a thermal analysis tool



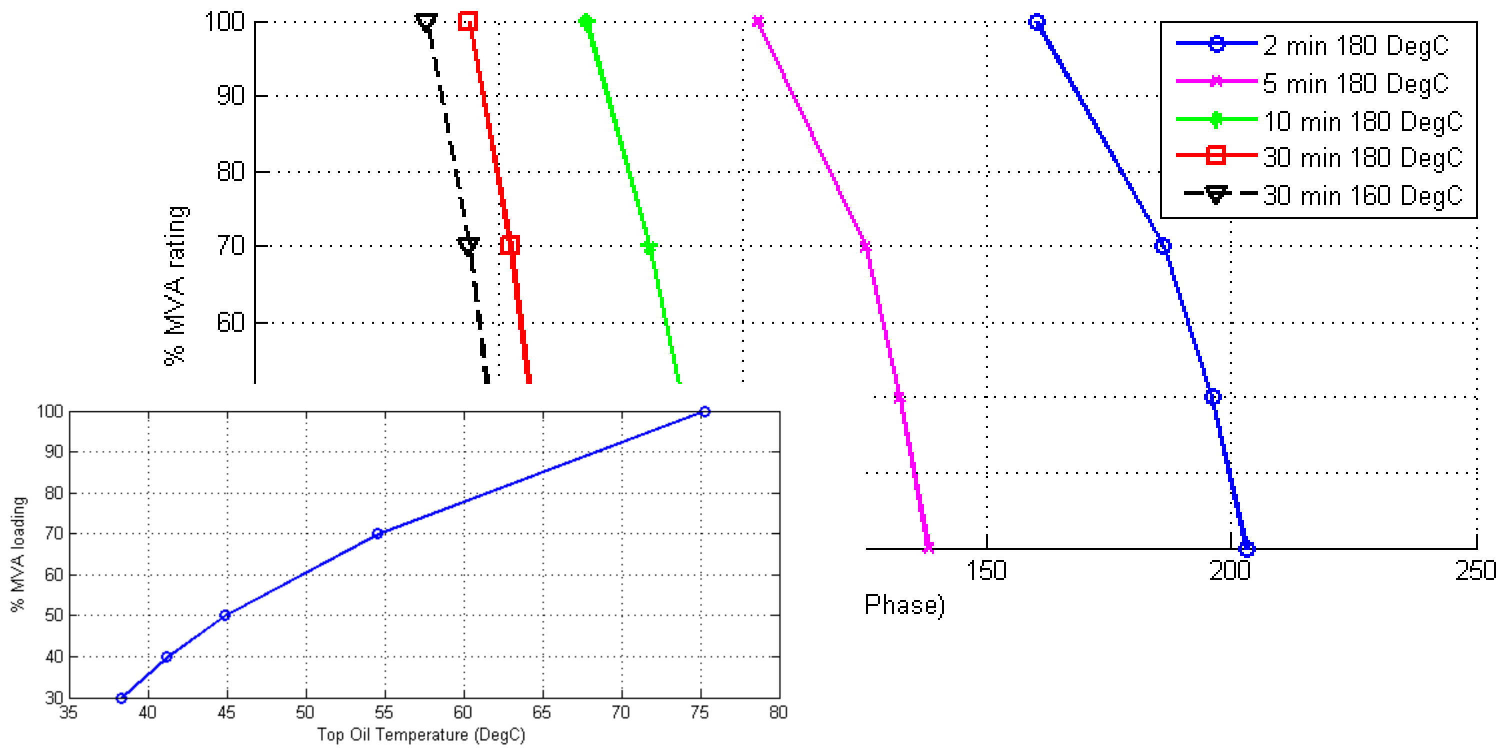
Using Thermal Response Tools

- Verify that it meets criteria



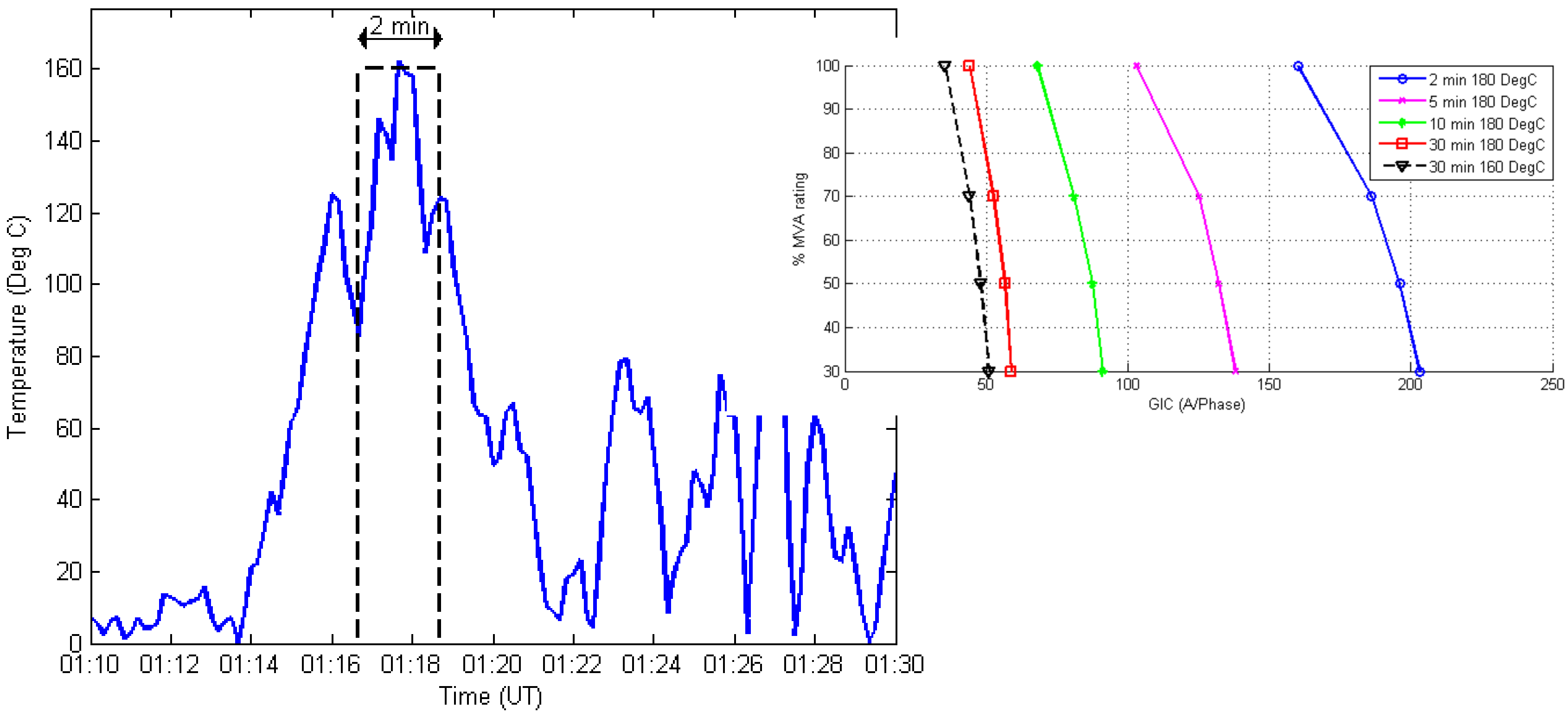
Assessing Capability Using Capability Curves

- Identify the correct capability curve from manufacturer
- For the purposes of this example the capability curve was constructed with the thermal step response and simplified loading curve
- All modelling assumptions are therefore identical. Only the methodology is different



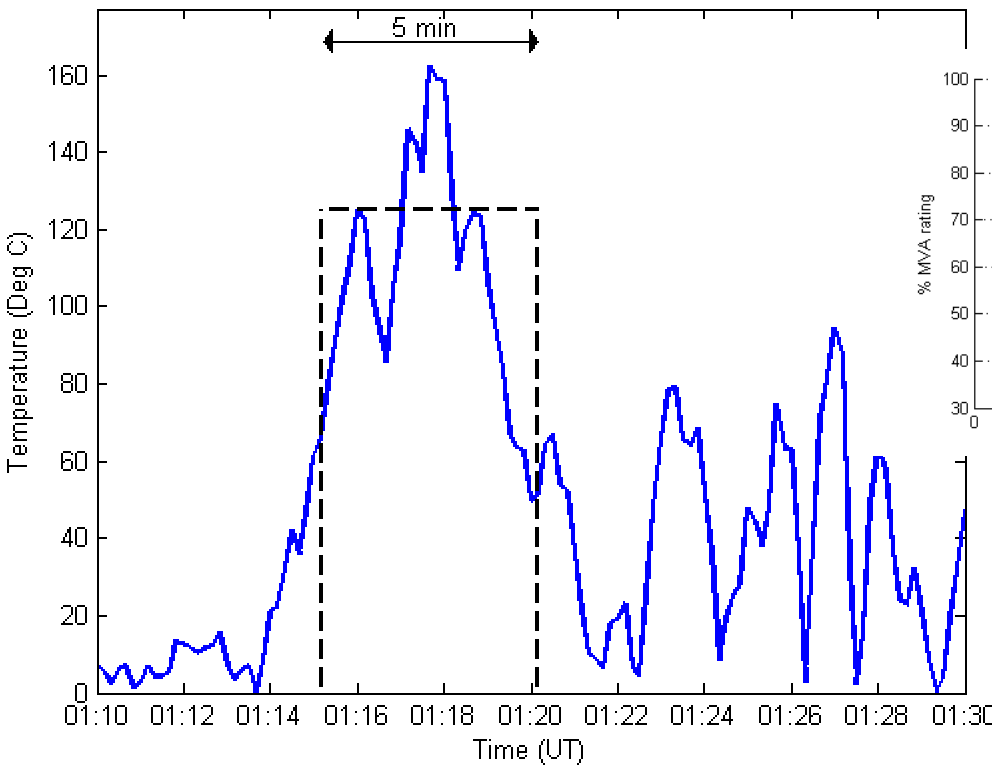
Using Capability Curves

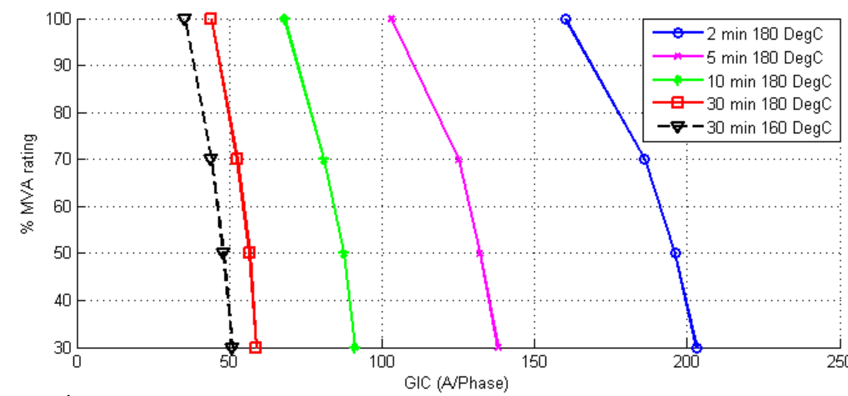
- Identify if the relevant part of GIC(t) matches the pulse widths provided in the curve



Using Capability Curves

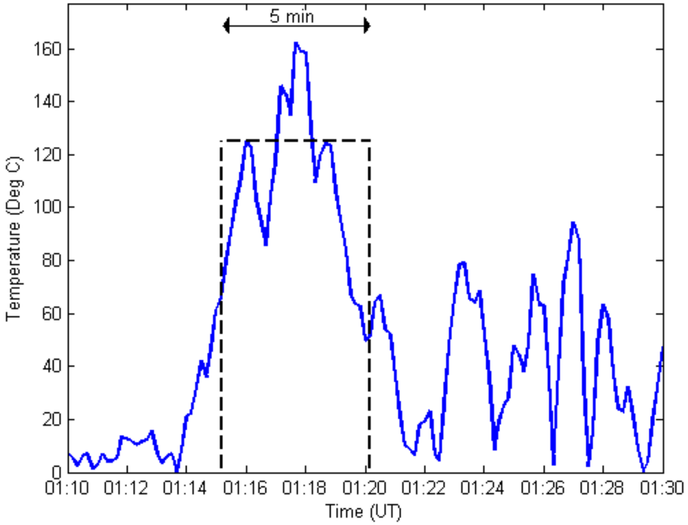
- Identify if the relevant part of GIC(t) matches the pulse widths provided in the curve





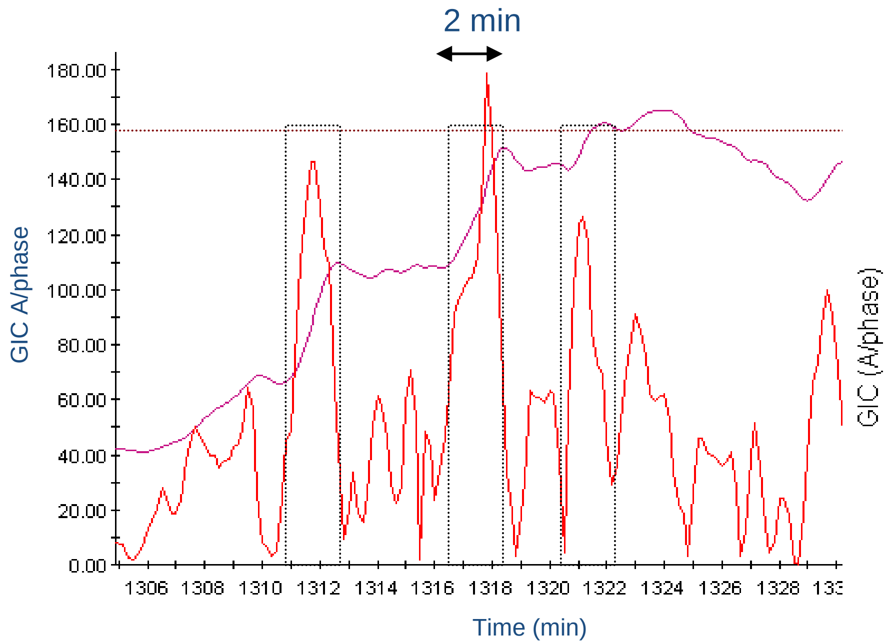
Using Capability Curves

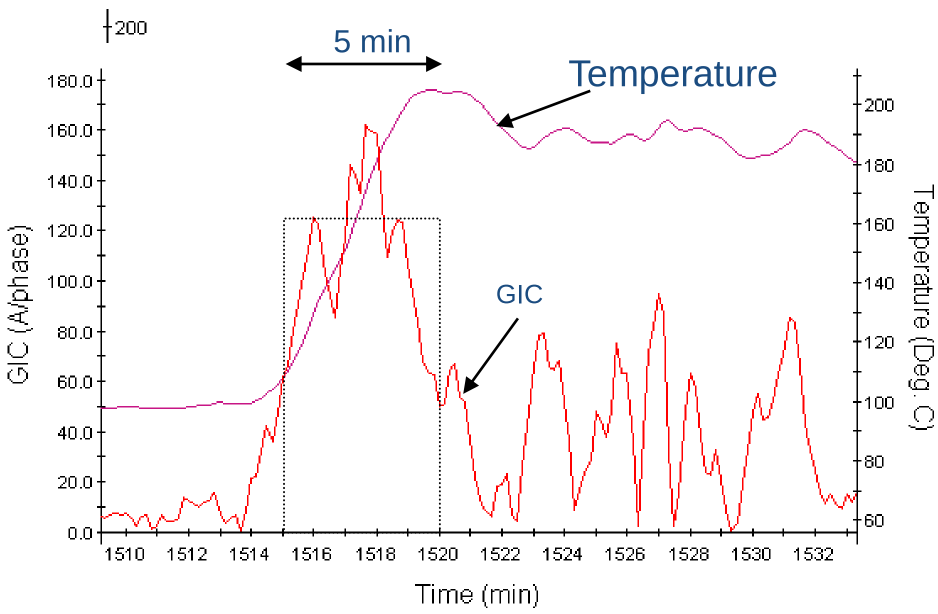
- Use engineering judgment or ask your friendly neighborhood manufacturer when the capability is marginal
- In this example, capability is close to thresholds and pencils would probably have to be sharpened for a more detailed assessment



Using Capability Curves

- Remember that not all “signatures” are created equal and that it is prudent to consider heating by previous GIC “pulses”





Discussion

Mitigation Planning – Randy Horton Southern Company

TPL-007-1 Requirements

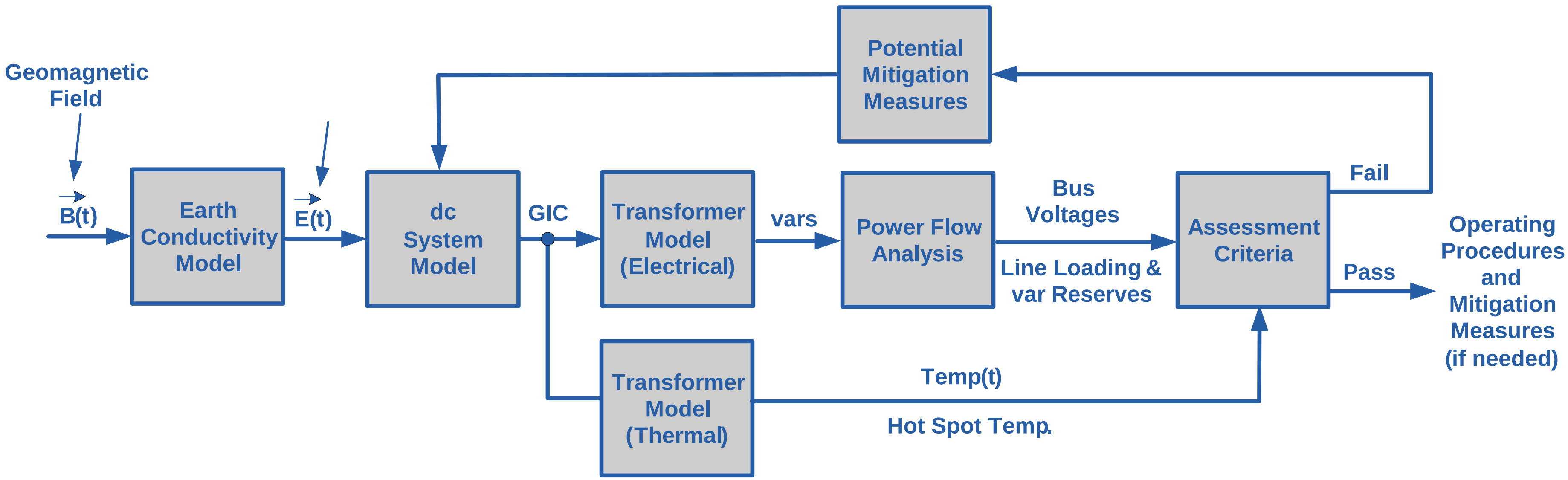
- Requirement R3 requires PCs and TPs to develop a Corrective Action Plan when results of the GMD Vulnerability Assessment indicate performance requirements of Table 1 are not met

Mitigation Strategies

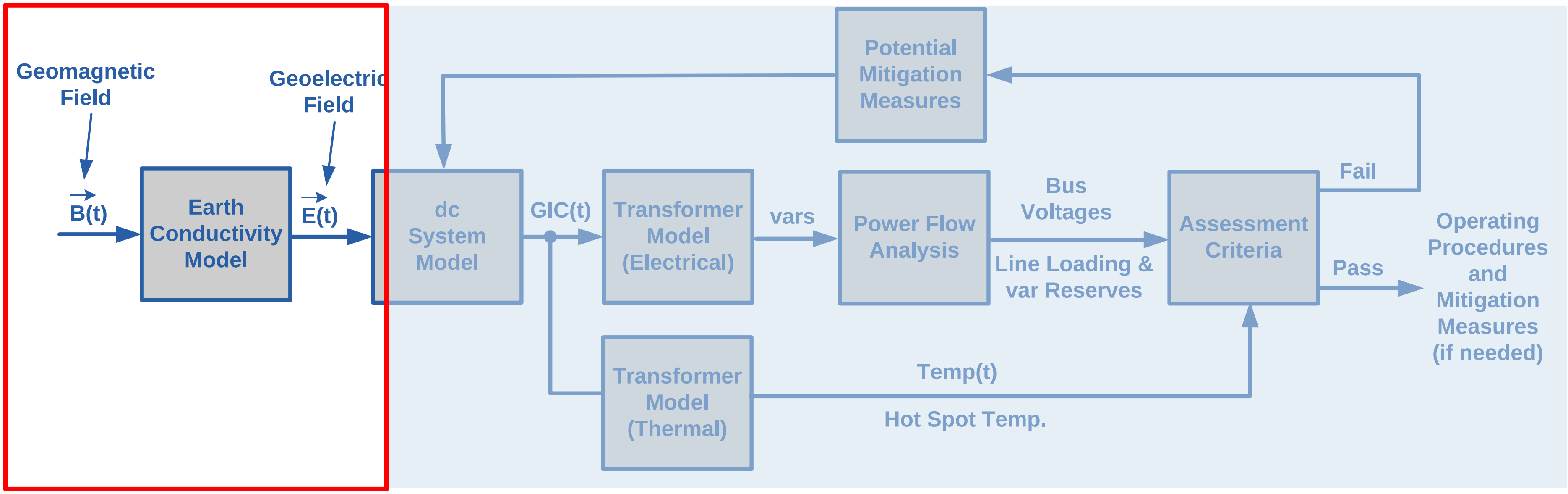
- Mitigation options include:
  - Operating Procedures (if supported by system study)
  - GIC reduction or blocking devices
  - Protection upgrades
  - Equipment replacement
- Mitigating measures will introduce changes to GIC flow in the System and can have unintended consequences
  - Planners may need to take an iterative approach
  - Additional technical studies (insulation coordination, system protection, resonance, etc.) may be required depending on the type of mitigation that is employed
- Technical considerations are available in Chapter 5 of the GMD Planning Guide and in the 2012 GMD Report

GMD Vulnerability Assessment Process Summary

Integrated View of the Assessment Process

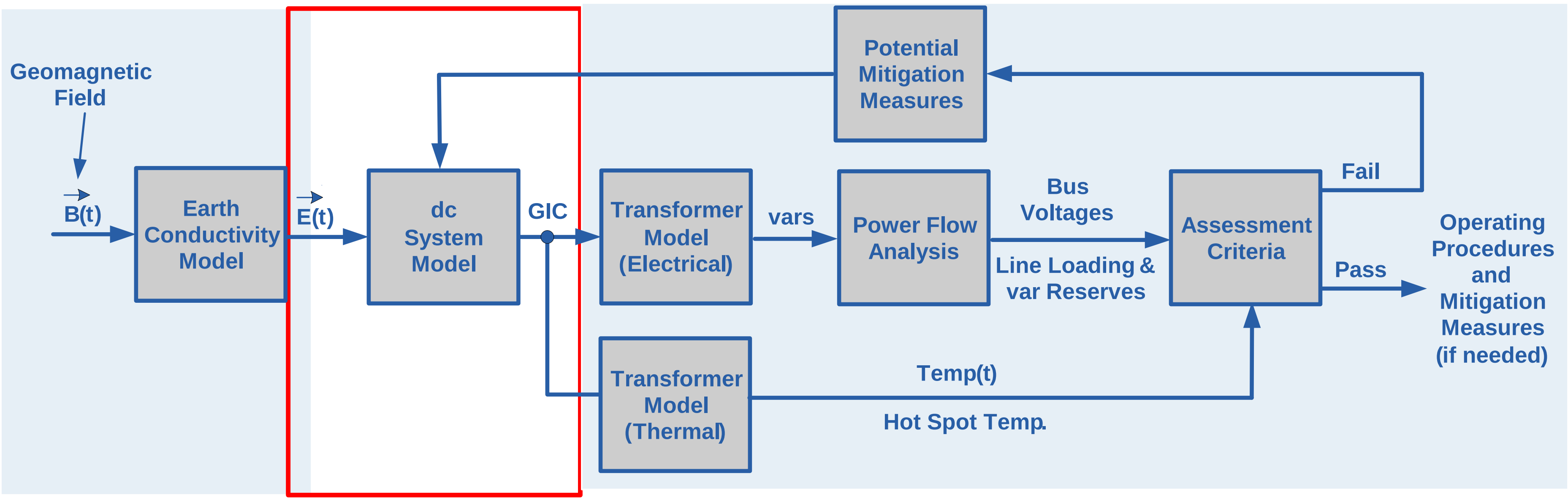


Benchmark GMD Event



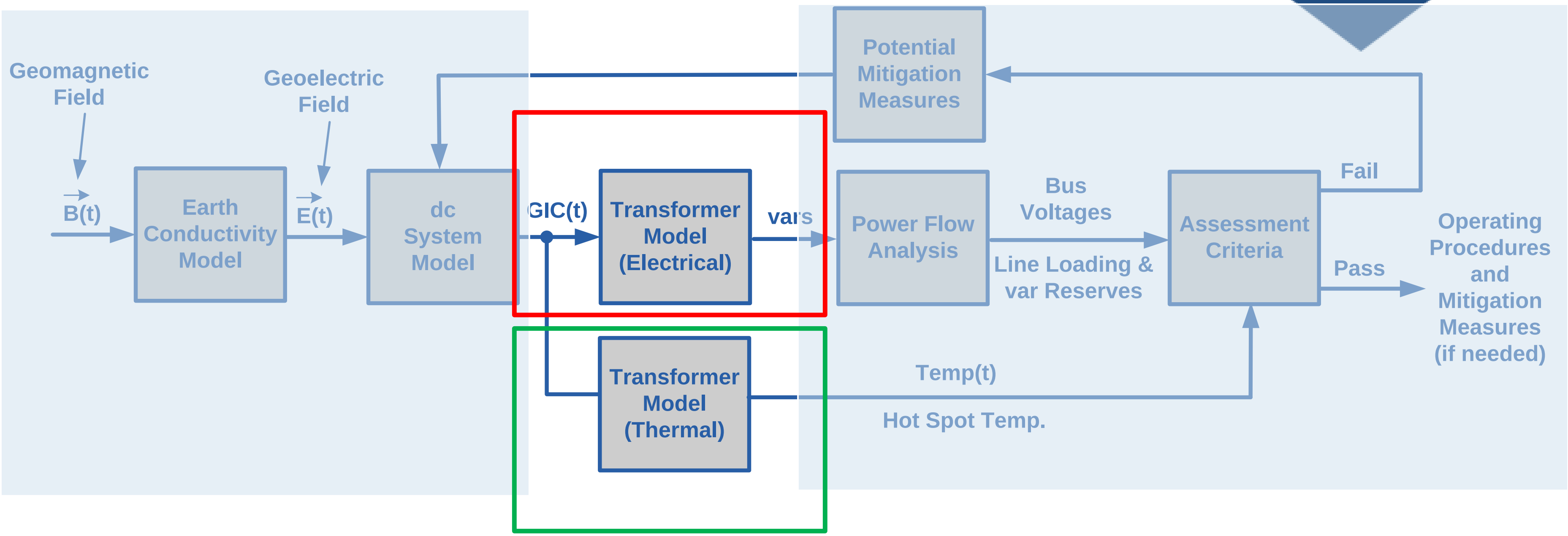
- The Benchmark GMD Event defines the geoelectric field amplitude(s) used to compute GIC flows in the GMD Vulnerability Assessment
  - Both peak geoelectric field amplitude and wave-shape are needed

dc Model and GIC Study



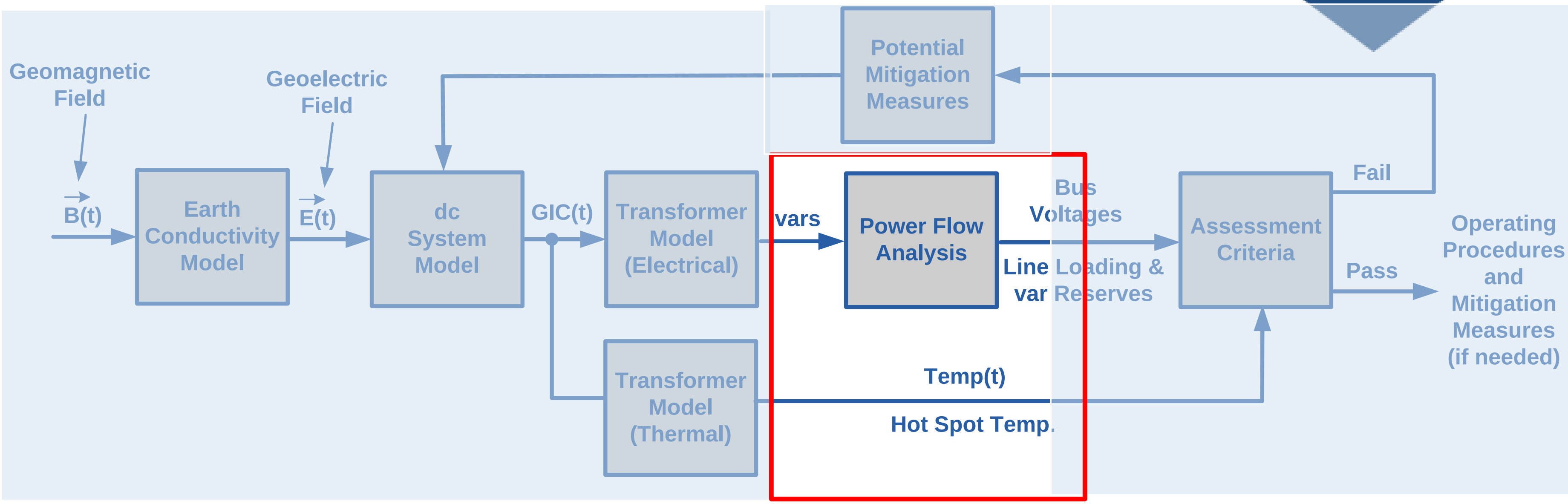
- Planners develop a dc model for portions of the system that include a power transformer with a wye-grounded winding with terminal voltage greater than 200 kV

Transformer Models



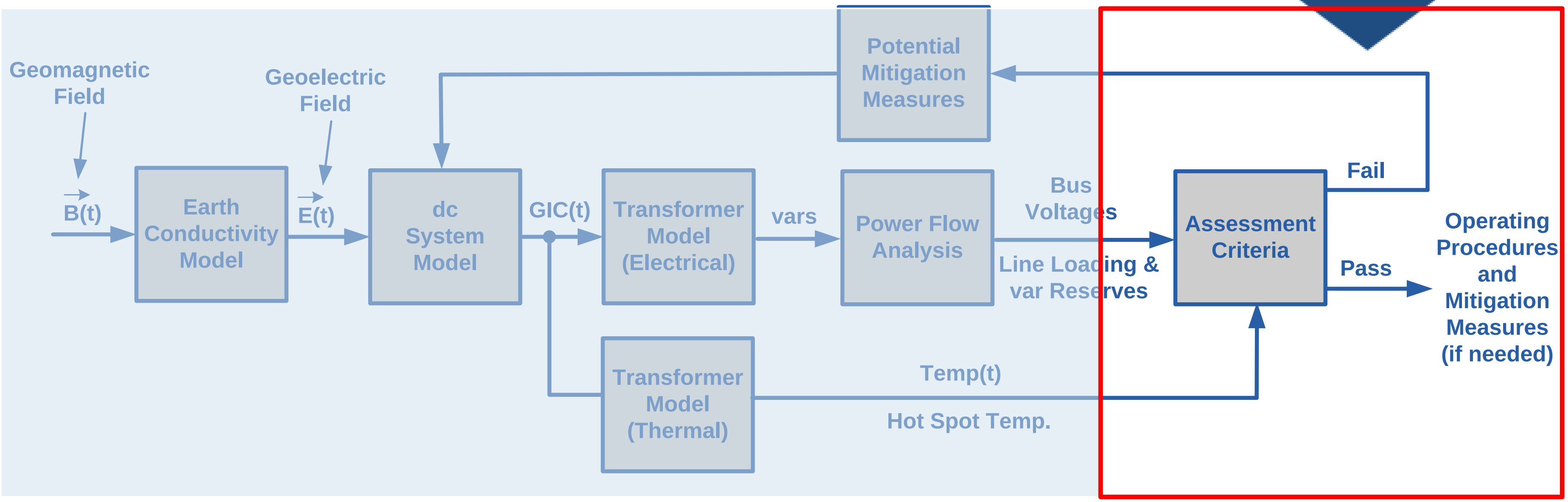
- Planners will need models for transformer Reactive Power absorption vs. effective GIC
- Owners will assess thermal impact using thermal response modeling or manufacturer capability curves

Steady-State Analysis



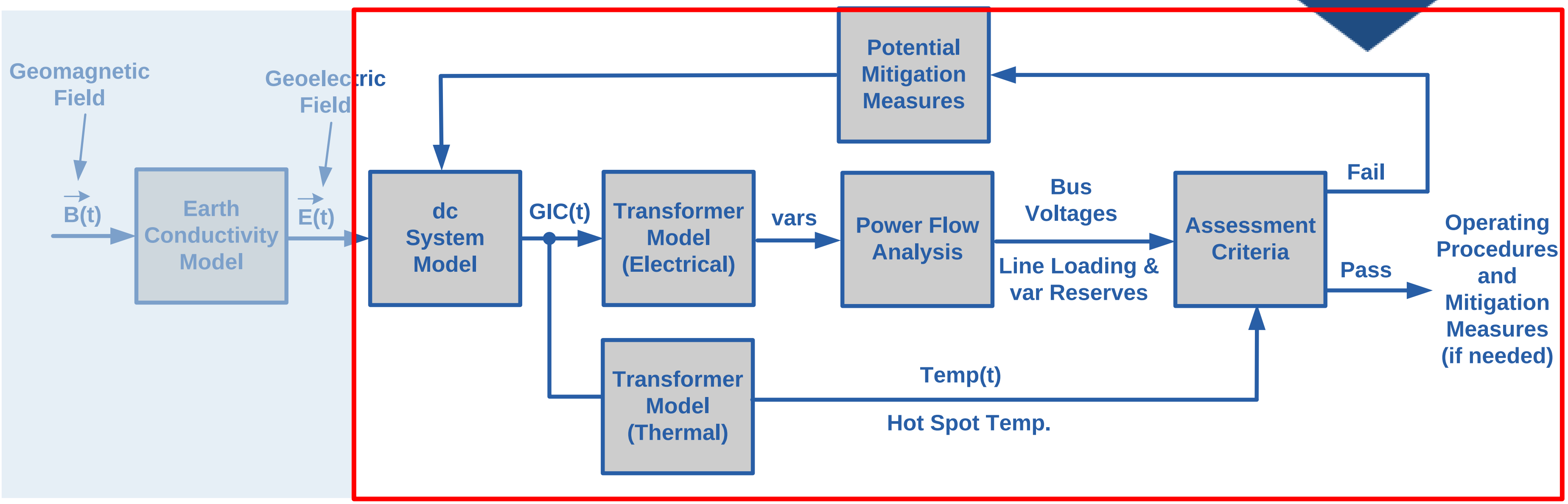
- A steady-state power flow analysis is conducted that accounts for the additional reactive power absorption of transformers due to the flow of GIC in the system
  - System peak Load and Off-peak load should be examined
  - Reactive Power compensation devices that may be impacted by GIC should be removed (e.g., capacitor banks or SVCs that may trip due to harmonics)

Assessment Criteria



- The objective of the GMD Vulnerability Assessment is to prevent instability, uncontrolled separation, or Cascading failure of the System during a GMD event
- System performance is evaluated based on
  - System steady-state voltage limits established by the Transmission Planner and Planning Coordinator
  - Cascading and uncontrolled islanding shall not occur

Mitigation



- Mitigating measures will introduce changes to GIC flow in the System
  - An iterative approach may be appropriate in some cases

Discussion and Recommendations

Topics from Informal Comments

- Implementation plan timelines
- Coordination between TP and PC

Summary and Wrap-up