NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

TPL-007-1

Project 2013-03 Geomagnetic Disturbance Mitigation

Technical Conference
July 17, 2014

RELIABILITY | ACCOUNTABILITY




Administrative

- Meeting Space Safety Information
- Presentations available on the project page:

  http://www.nerc.com/pa/Stand/Pages/Geomagnetic-Disturbance-Resource.aspx

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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
- Discuss stakeholder issues

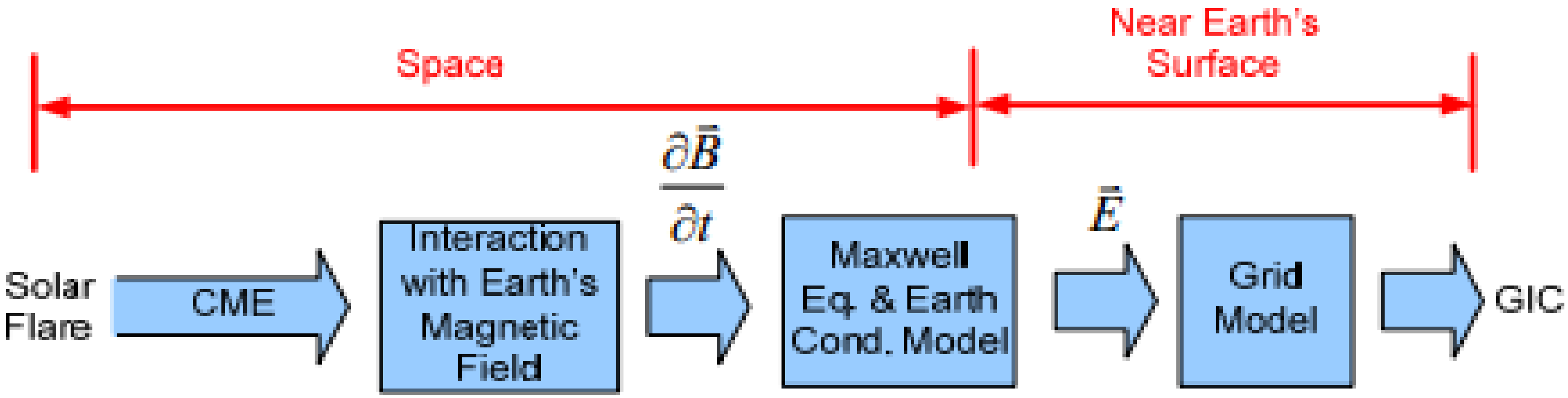
Agenda

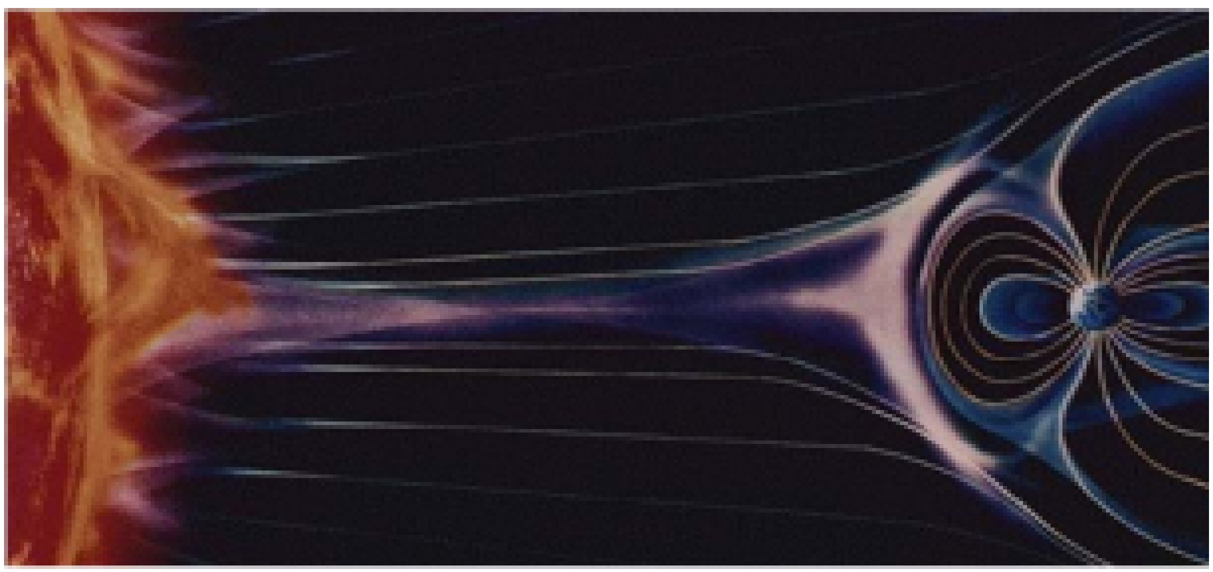
- Introduction
- Background and project overview
- Topic 1: GMD and the Power System
- Topic 2: Benchmark GMD Event Description
- Topic 3: Studies Required in a GMD Assessment
- Discussion of Draft TPL-007-1

Ken Donohoo,
Oncor Electric Delivery

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

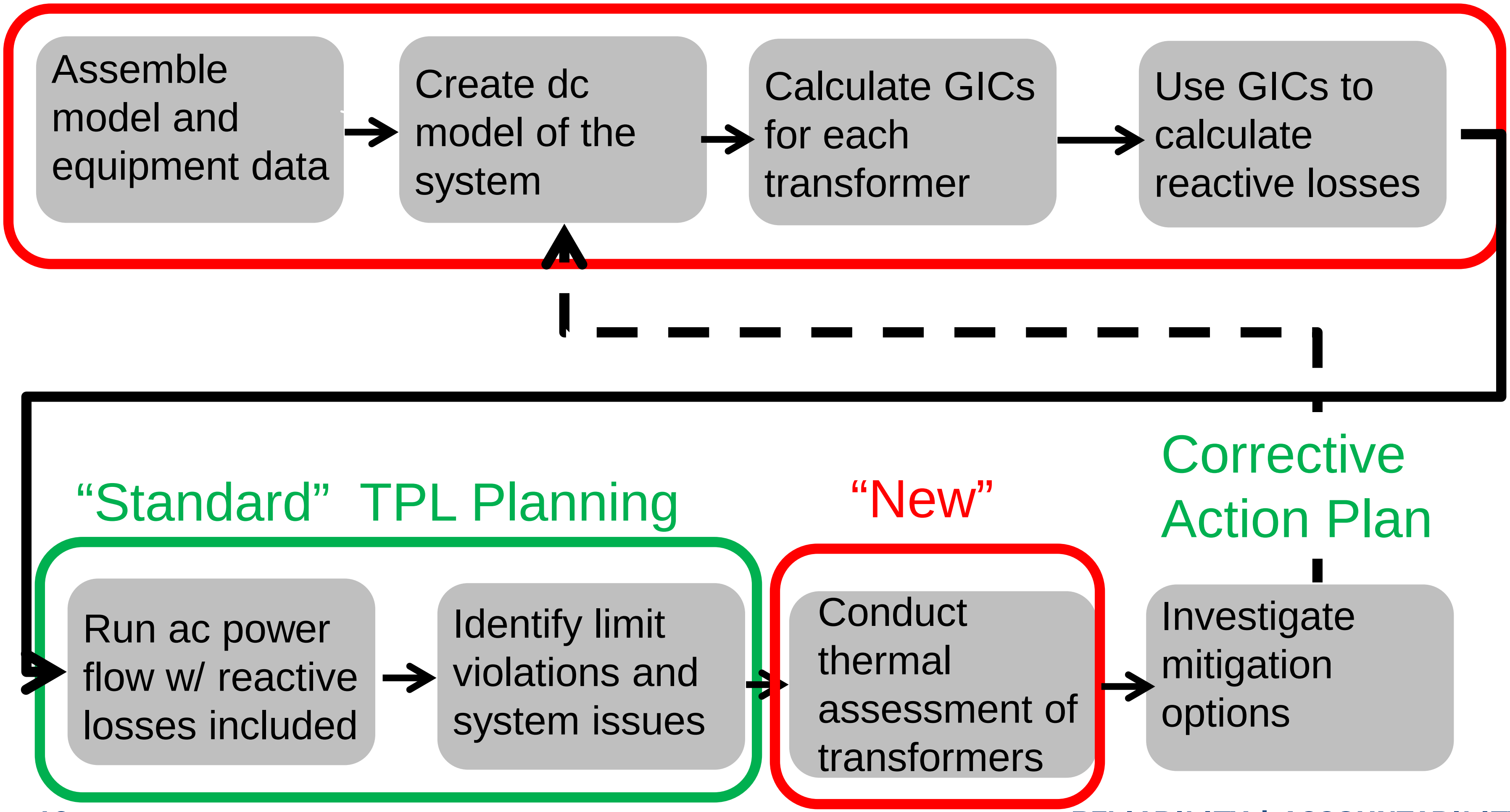
TPL-007 Summary

- Requires a **GMD Vulnerability Assessment** of the system for its ability to withstand a Benchmark GMD Event without causing a wide area blackout, voltage collapse, or damage to transformers, once every five years.
    - Applicability: Planning Coordinators, Transmission Planners
- Requires a **Transformer thermal impact assessment** to ensure that all high-side, wye grounded transformers connected at 200kV or higher will not overheat based on the Benchmark GMD Event
    - Applicability: Generator Owners, Transmission Owners

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
  - Thermal Screening Criterion (15A) White Paper
  - Draft Reliability Standard Audit Worksheet (RSAW)

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

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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

Today's Discussion Topics

- Topic 1: GMD and the Power System
- Topic 2: Benchmark GMD Event Description
- Topic 3: Studies Required in a GMD Assessment
- Discussion of Draft TPL-007-1

GMD and the Power System – Luis Marti, Hydro One

GMD and the planning engineer

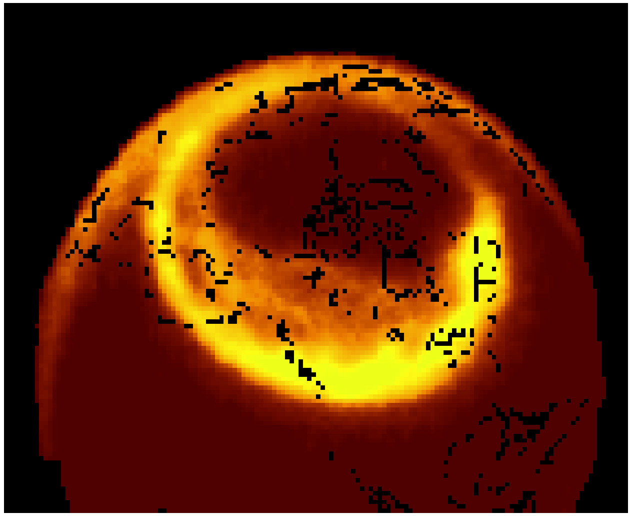
- How does a Coronal Mass Ejection (CME) interact with the power system to produce Geomagnetically Induced Currents (GIC)
- Effects of GIC on the power system
- What is needed in a GMD study

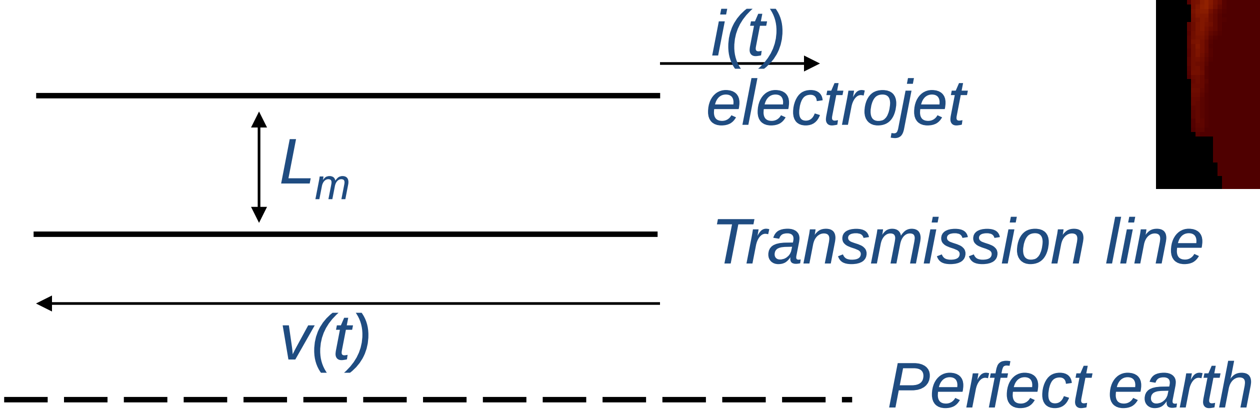
Interaction of a CME with the power system

- The (Auroral/Boreal) electrojet can be visualized as a conductor 100 km or so above the earth carrying slowly-varying currents in excess of 1,000,000 A
- A CME increases the size and magnitude of the currents
- Oversimplification:

$$V(t) = L_m \frac{di(t)}{dt}$$

Assuming L_m constant



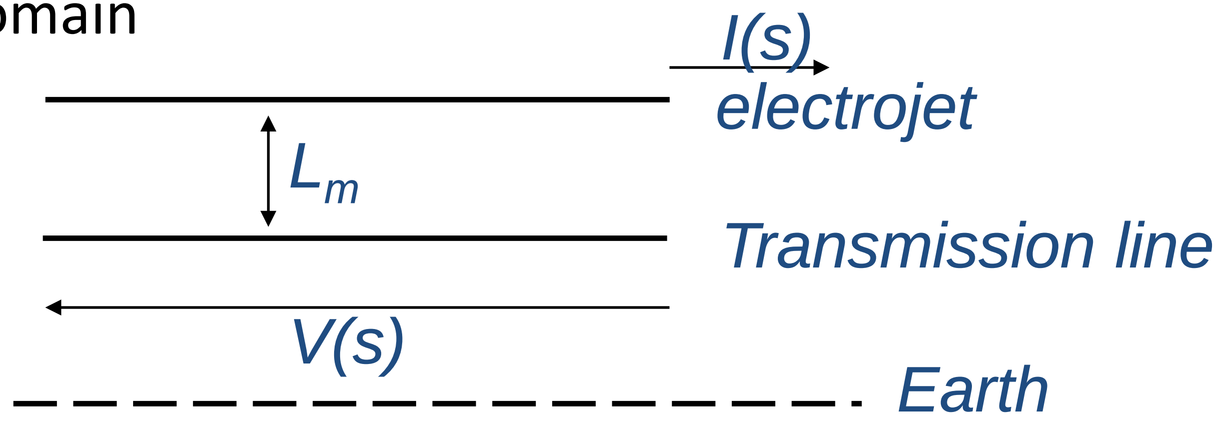


Interaction of a CME with the power system

- In the frequency domain

$$V(t) = L_m \frac{di(t)}{dt}$$

- Becomes



$$V(s) = L_m s \cdot I(s)$$

$$V(\omega) = j\omega \cdot L_m \cdot I(\omega)$$

- If earth is not an infinite perfectly conducting plane, then Lm is frequency dependent (Carson earth return terms)

$$V(\omega) = j\omega \cdot L_m(\omega) \cdot I(\omega)$$

$$E(\omega)=\frac{Z(\omega)}{j\omega\cdot\mu_o}\cdot j\omega\cdot B(\omega)=C(\omega)\cdot G(\omega)$$

Interaction of a CME with the power system

$$V(\omega)=L_m(\omega)\cdot j\omega\cdot I(\omega)$$

- According to the plane wave method of evaluating geoelectric fields

$$E(\omega)=\frac{Z(\omega)}{j\omega\cdot\mu_o}\cdot j\omega\cdot B(\omega)$$

Earth impedance function

Geomagnetic field at ground level

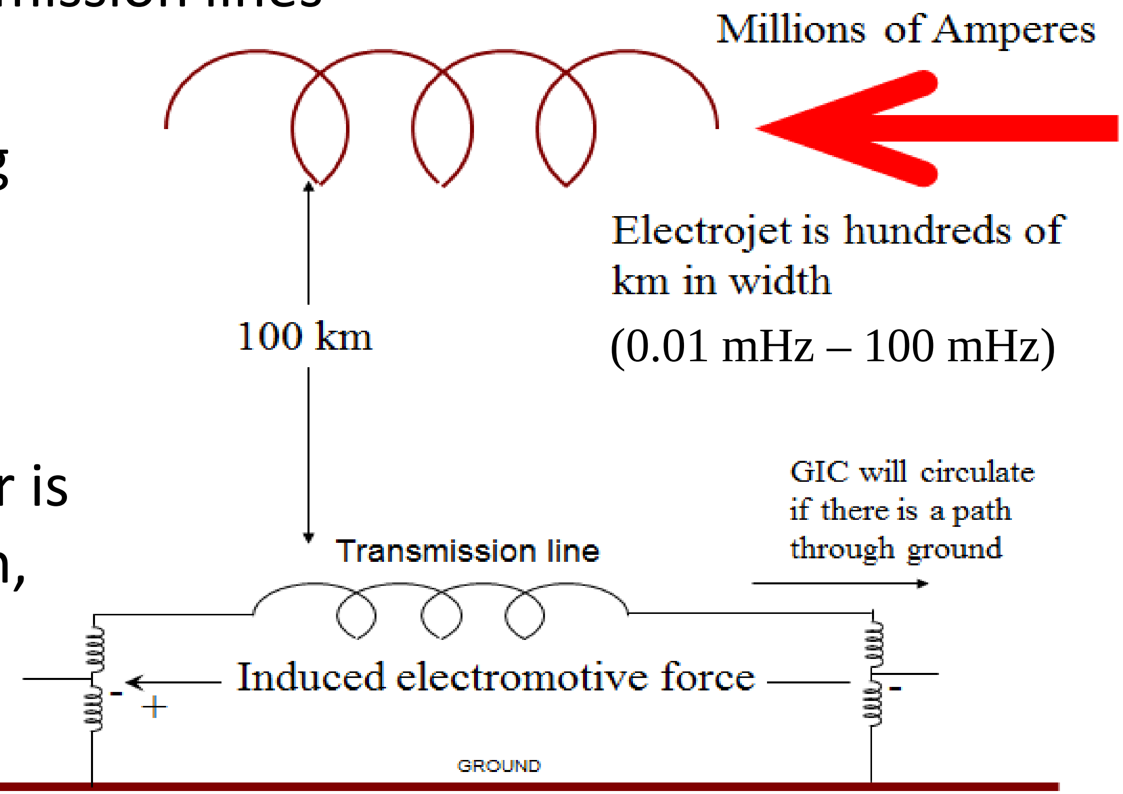
- In the time domain

$$E(t)=G(t)*\frac{dB(t)}{dt}$$

Induced geoelectric field

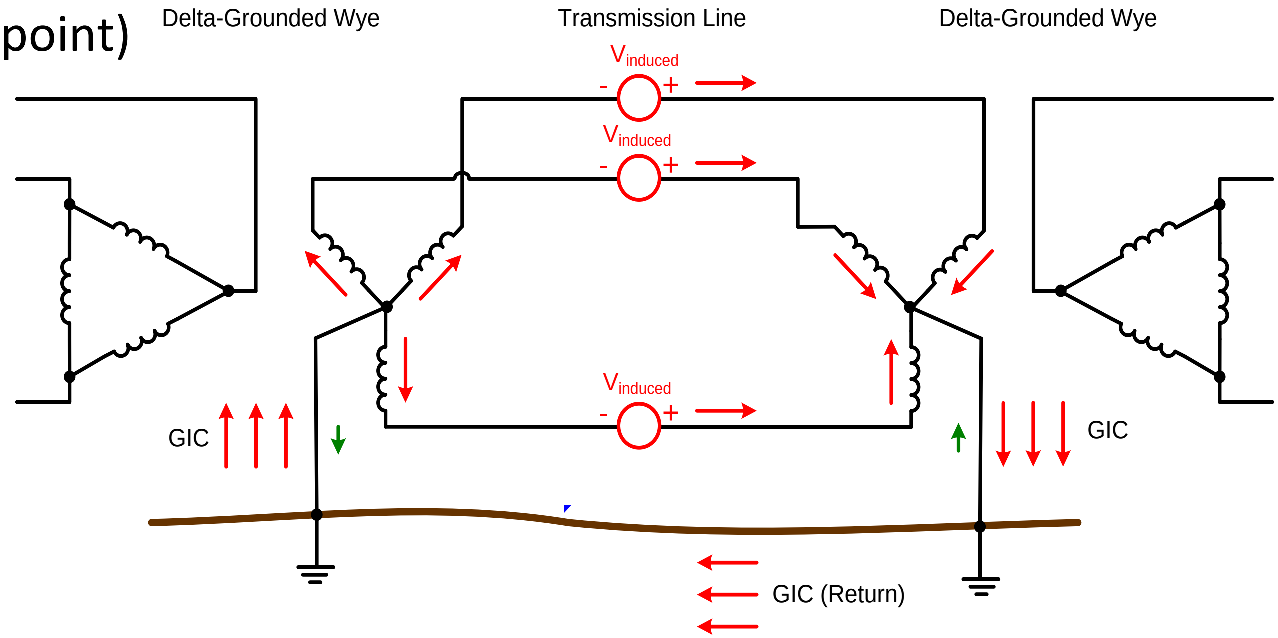
Another way to look at it

- 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.



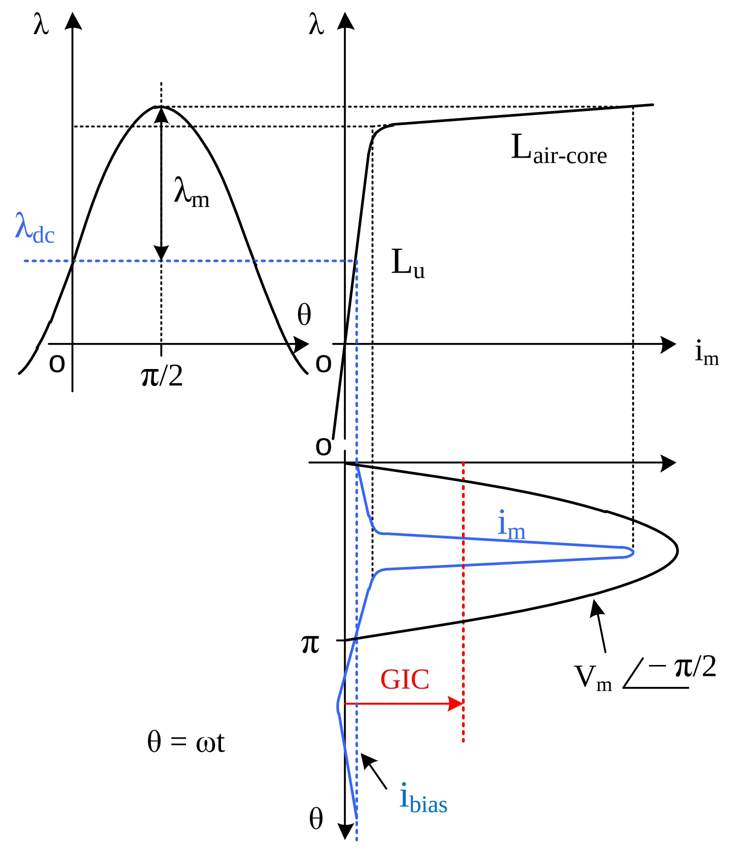
GIC and the power system

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

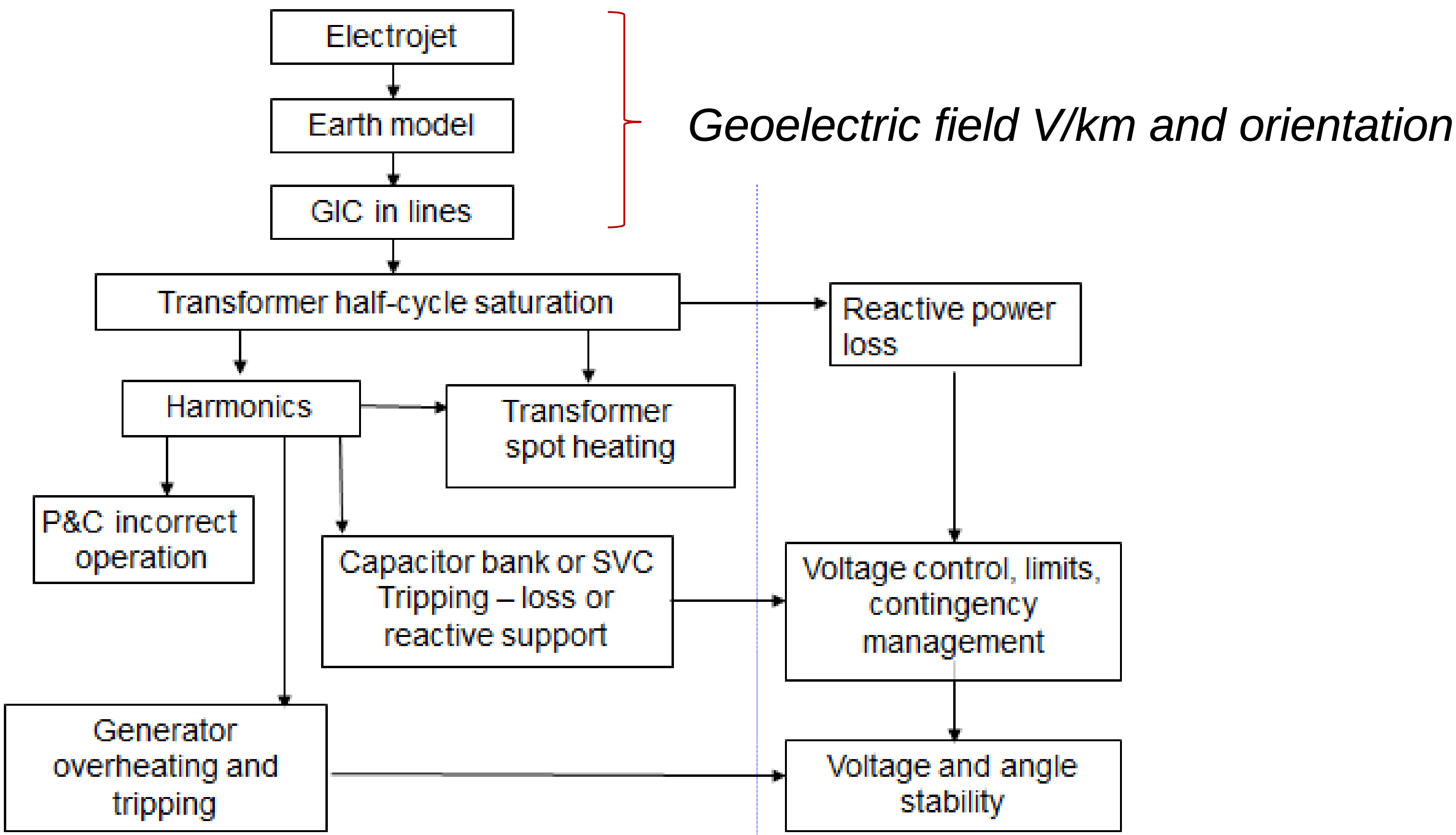


GIC and Half Cycle Saturation

- 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, clamps, tank walls
  - Increase in vibration and noise



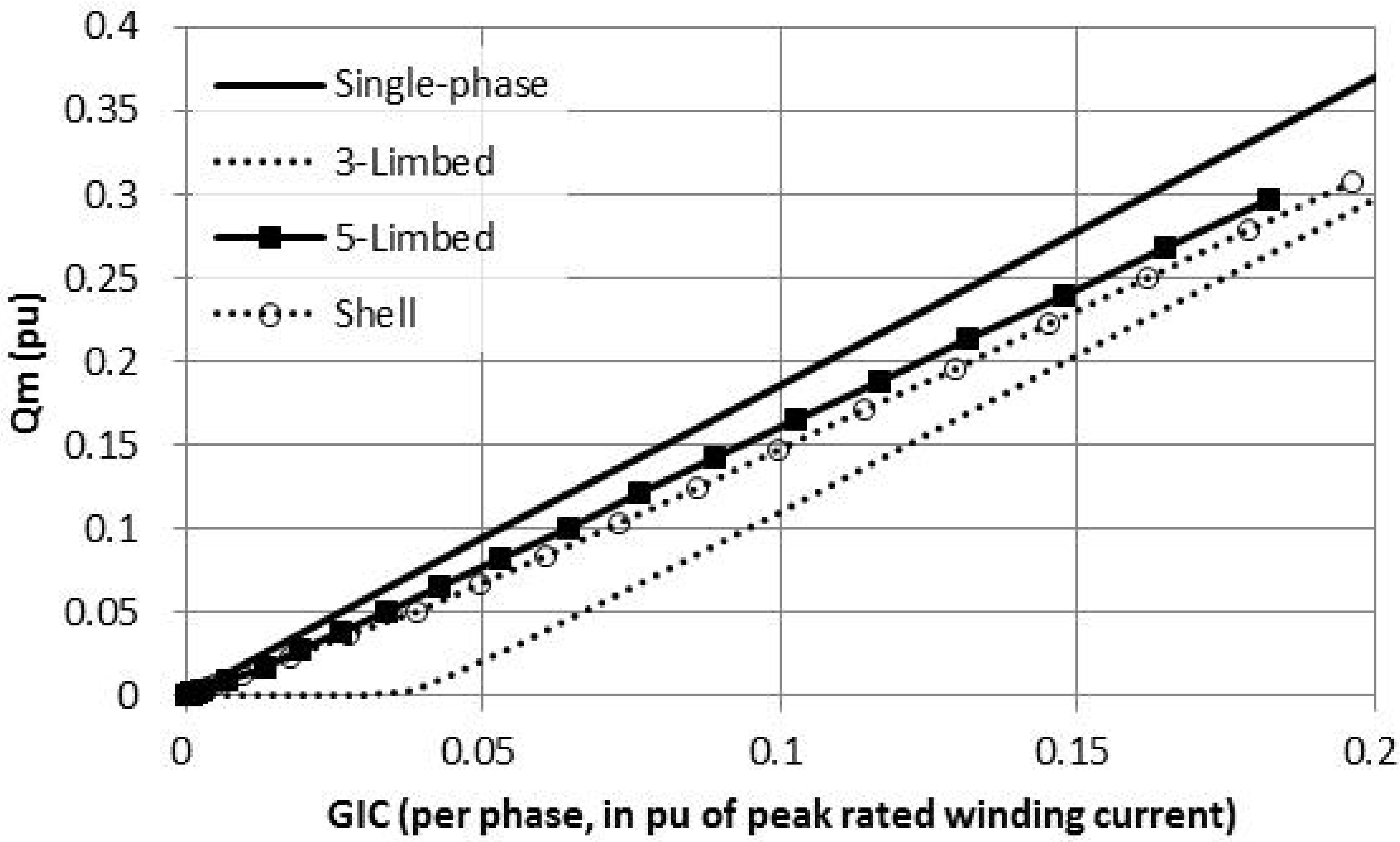
Effects of GIC in a power system



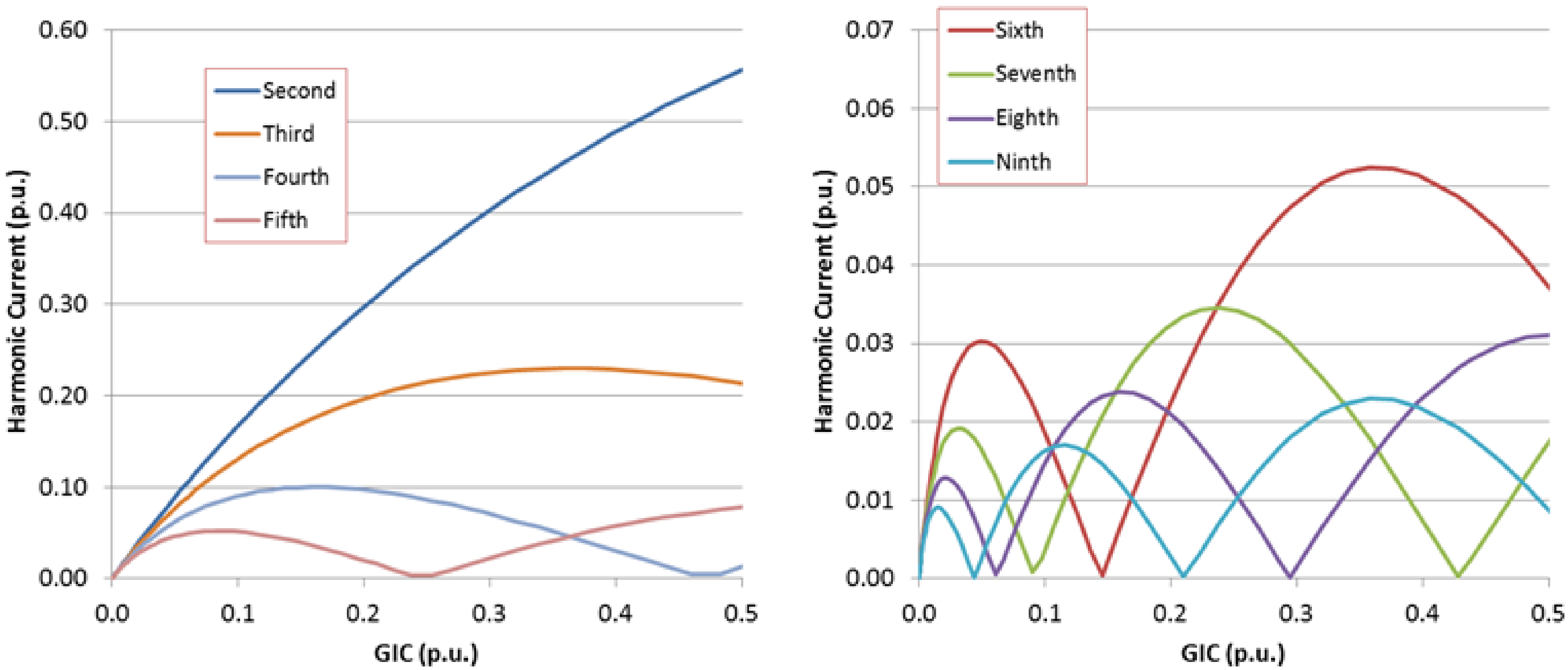
What is needed for a GMD vulnerability study

- Geoelectric field (from benchmark event – adjusted by earth model(s) and geomagnetic latitude)
- The dc model of the network for wye-grounded transformers with HV > 200 kV)
- Reactive power loss for load flow (var loss vs. GIC)
- Load flow system model (which includes var losses)
- GIC(t) based on the benchmark GMD event to assess transformer thermal behavior (calculated from the dc model)
- Transformer hot spot thermal step response

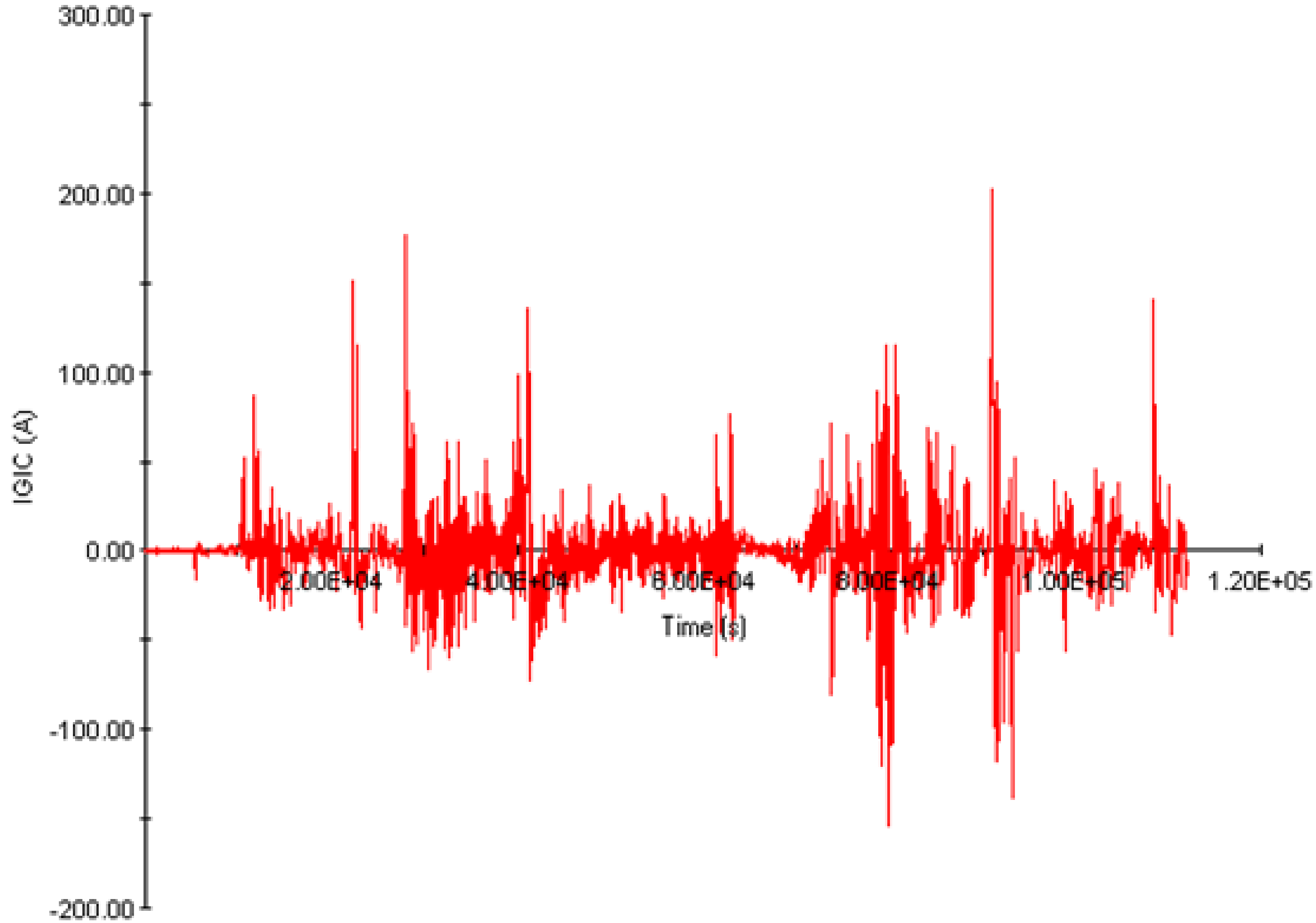
Example of GIC – var curves



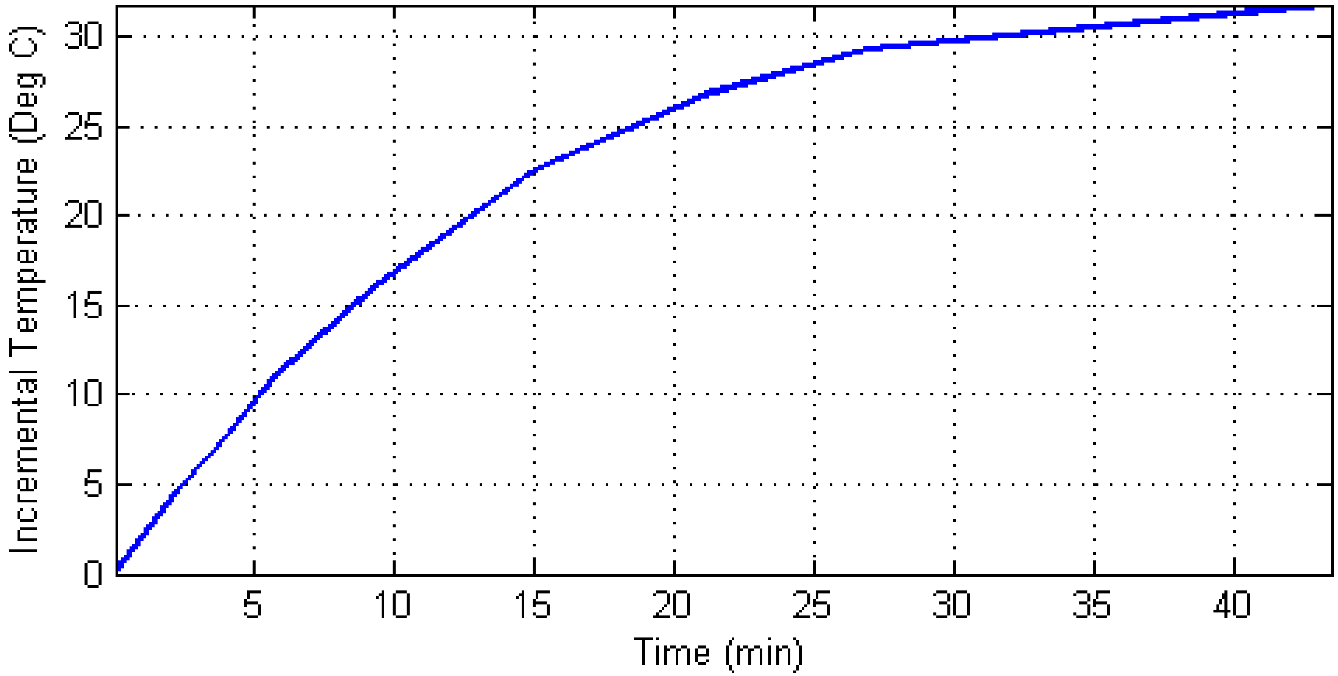
Example of GIC – harmonic curves



Example of GIC(t)

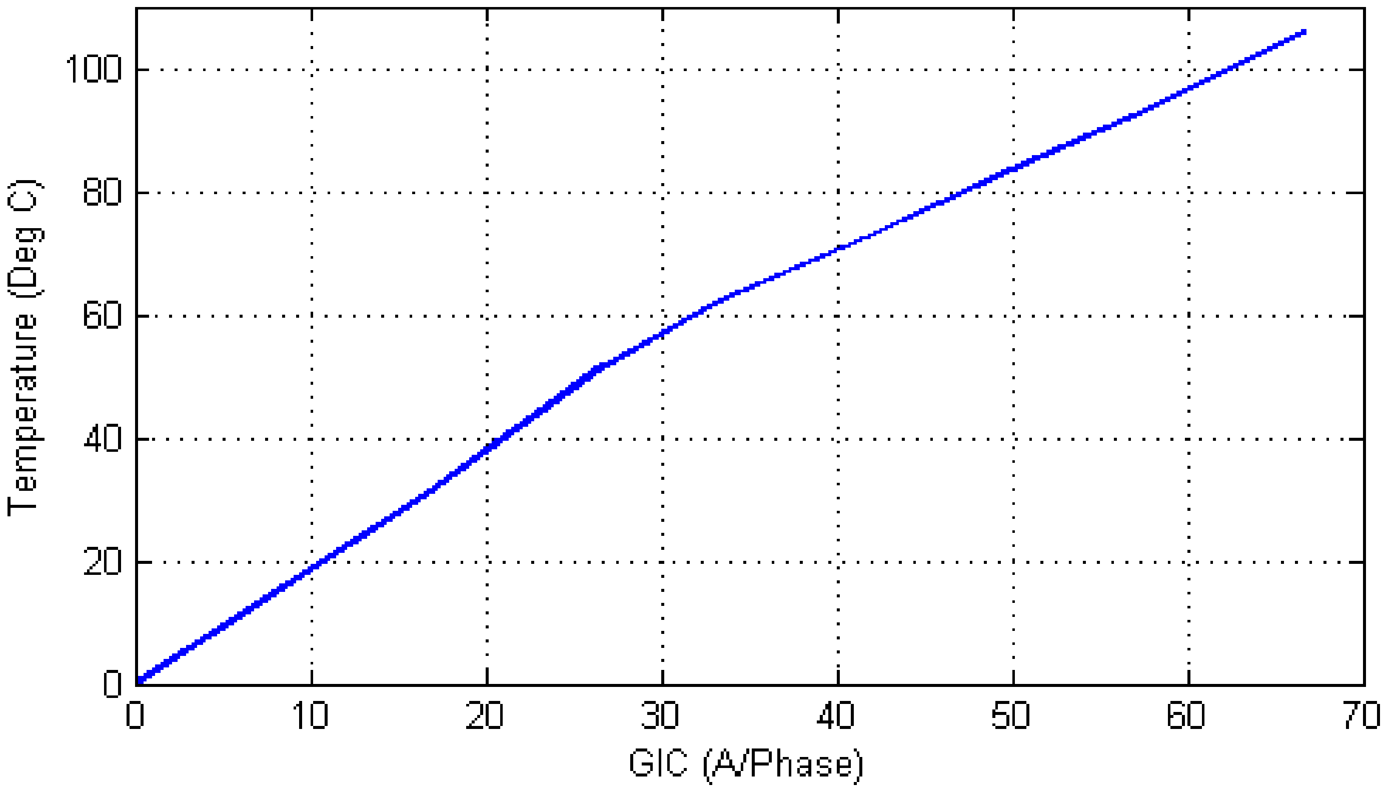


Example of thermal step response



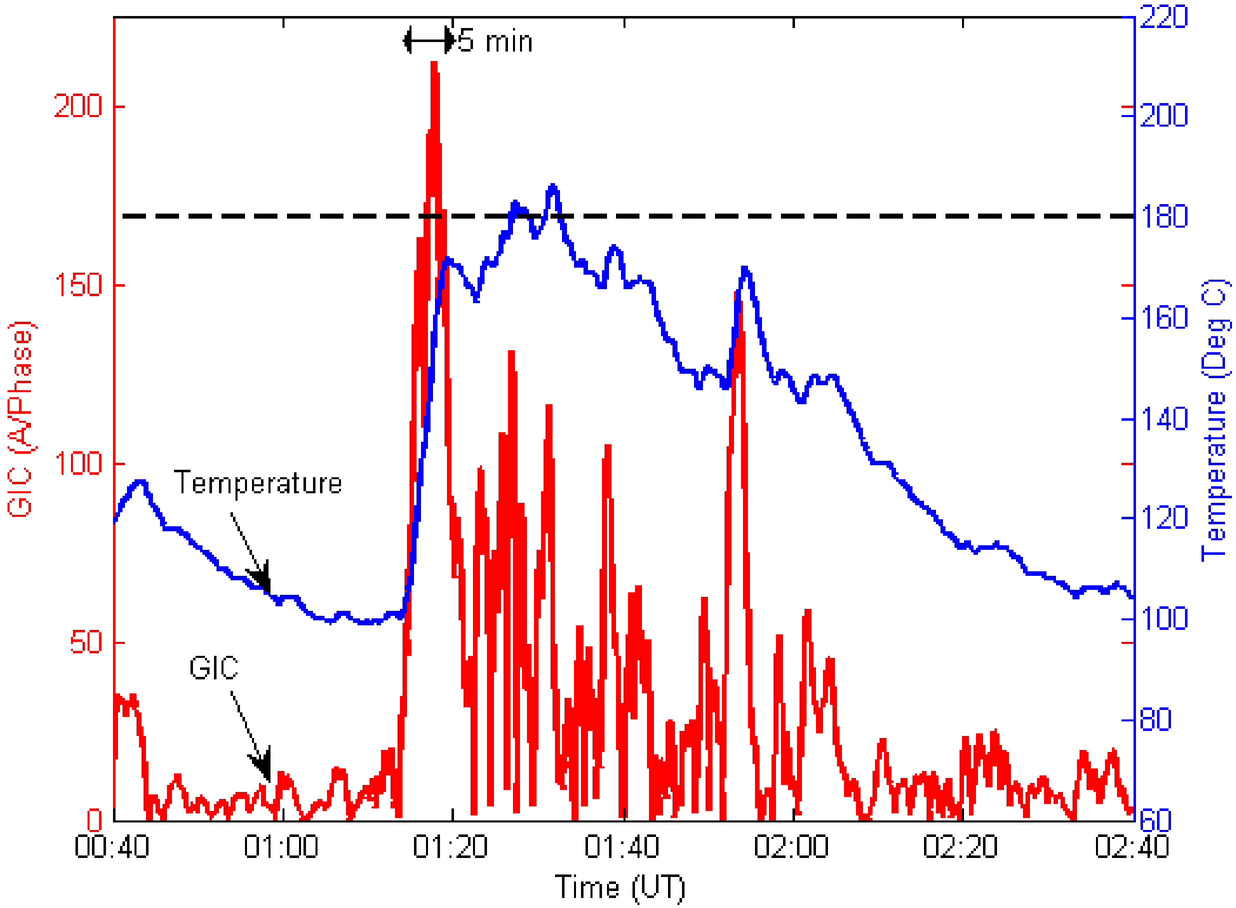
Measured thermal step response to a 16.67 A/phase dc Step
Metallic hot spot heating

Example of asymptotic thermal response



Measured asymptotic thermal step response.
Metallic hot spot heating

Example of hot spot thermal response to GIC(t)



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

Things to remember

- Transformer hot spot thermal response depends on GIC(t)
- Every transformer in the system sees a different maximum GIC(t)
- GIC(t) is easy to calculate. Three pieces of information are needed
  - GIC_E for E_EW = 1 and E_NS = 0 from GIC study
  - GIC_N for E_EW = 0 and E_NS = 1 from GIC study
  - $E_{EW}(t)$ and $E_{NS}(t)$ from the benchmark

$$GIC(t) = \alpha \times \beta \times \{GIC_E \cdot E\_EW(t) + GIC_N \cdot E\_NS(t)\}$$

- Will show a sample calculation later

Benchmark GMD Event Description – Randy Horton, Southern Company

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 at a 10s sampling rate dB/dt = 3,565 nT/min or 594 nT/10s
  - 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

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

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

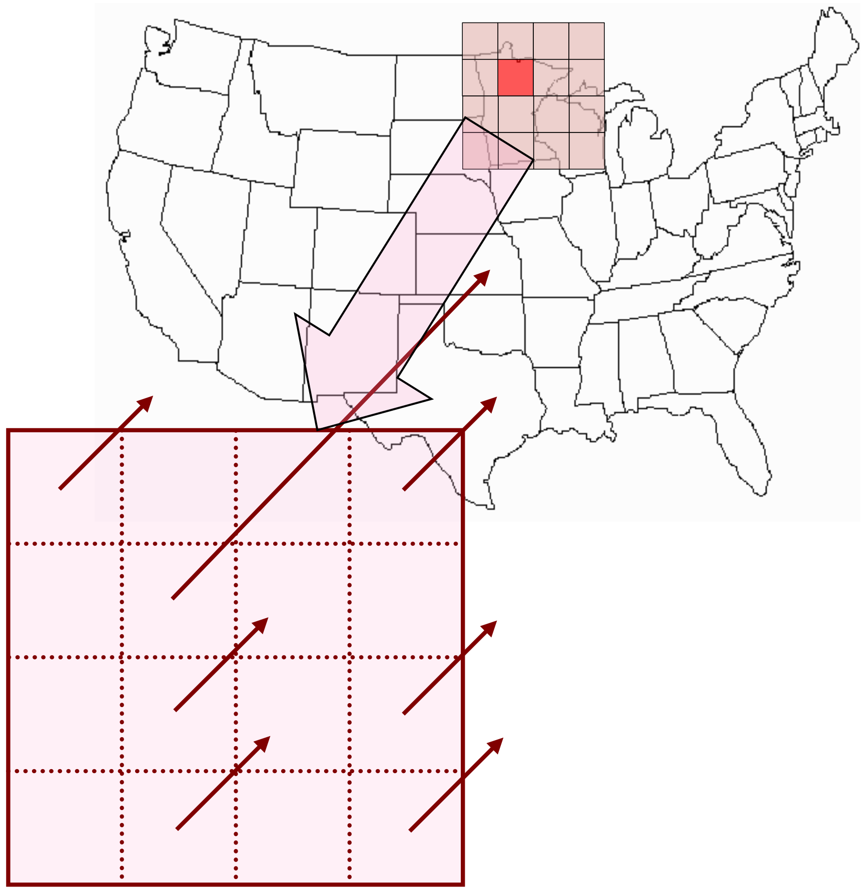
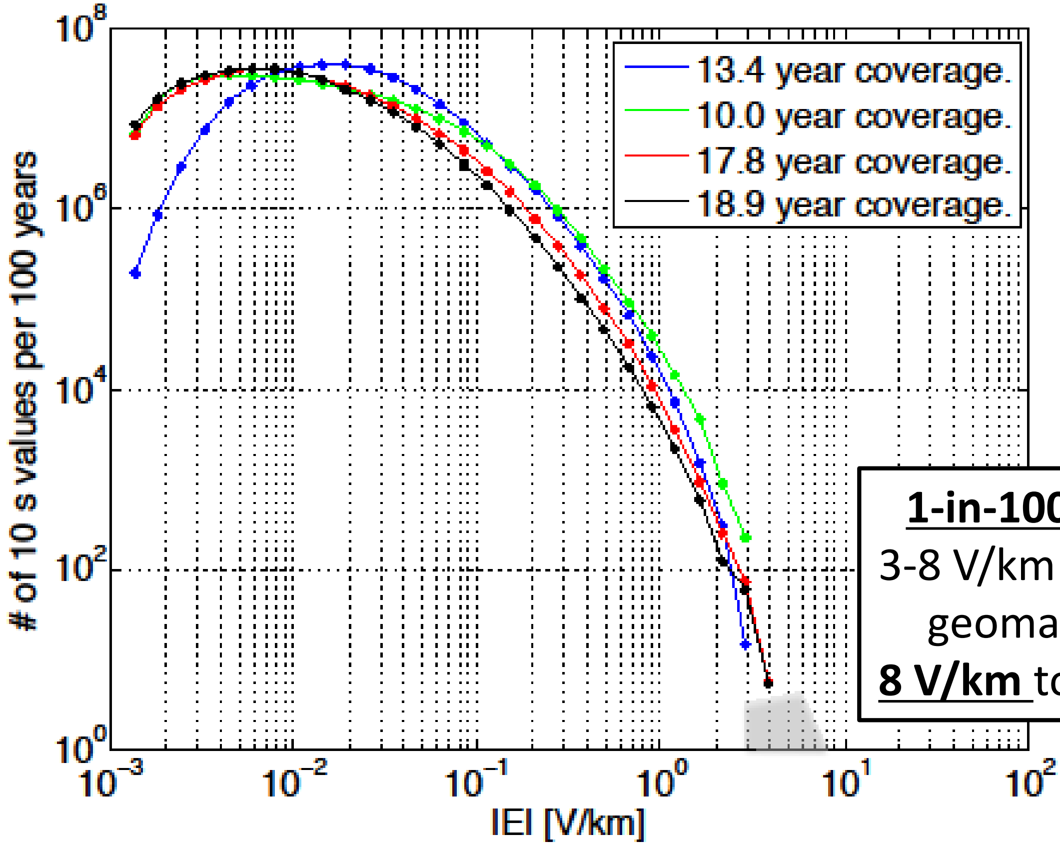


Illustration of Localized Geoelectric Field Enhancement

Reference Geoelectric Field Amplitude



1-in-100 Year Occurrence

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

8 V/km to be conservative

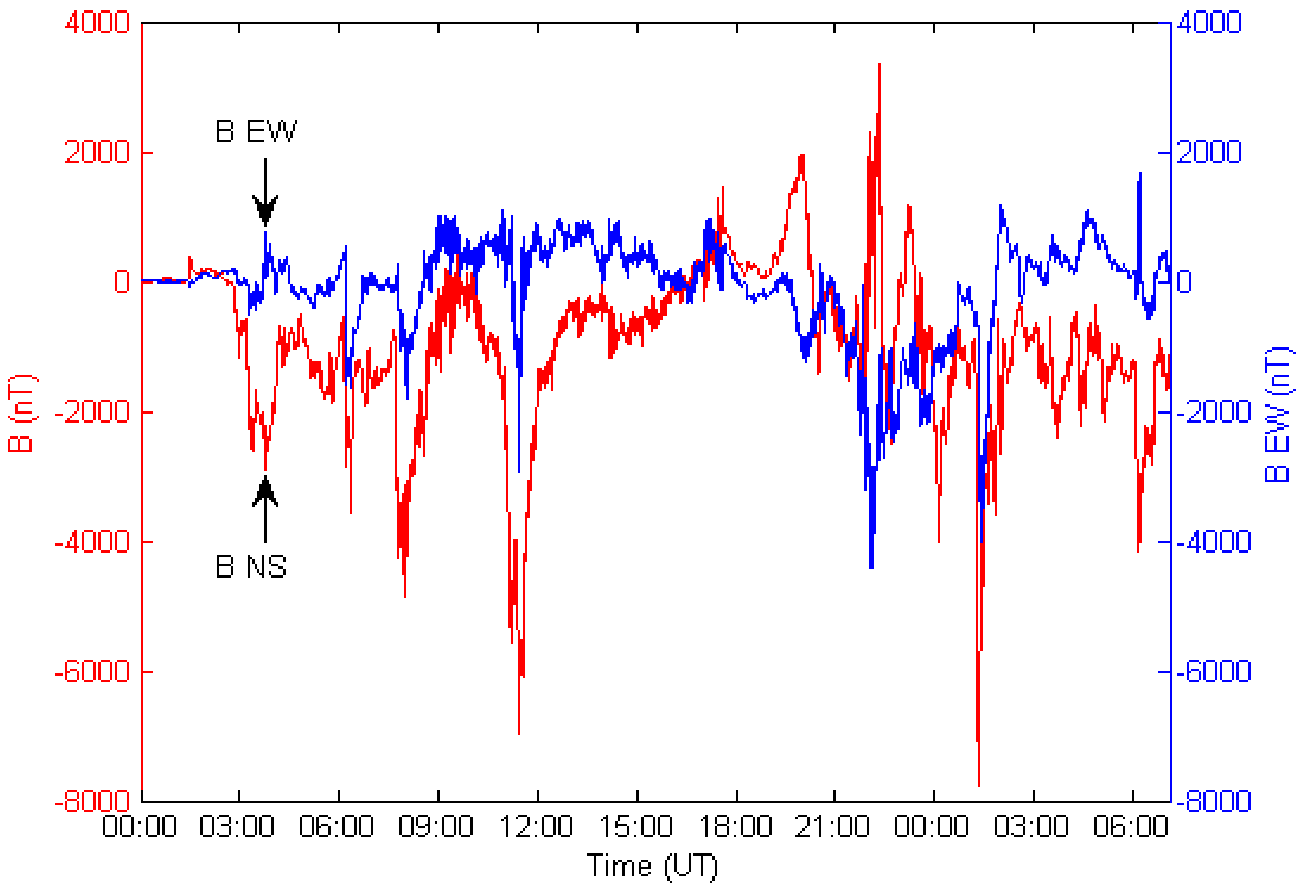
Statistical occurrence of spatially averaged high-latitude geoelectric field amplitudes from IMAGE magnetometer data (1993 – 2013)

Reference Geomagnetic Waveshape

- B(t) is 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

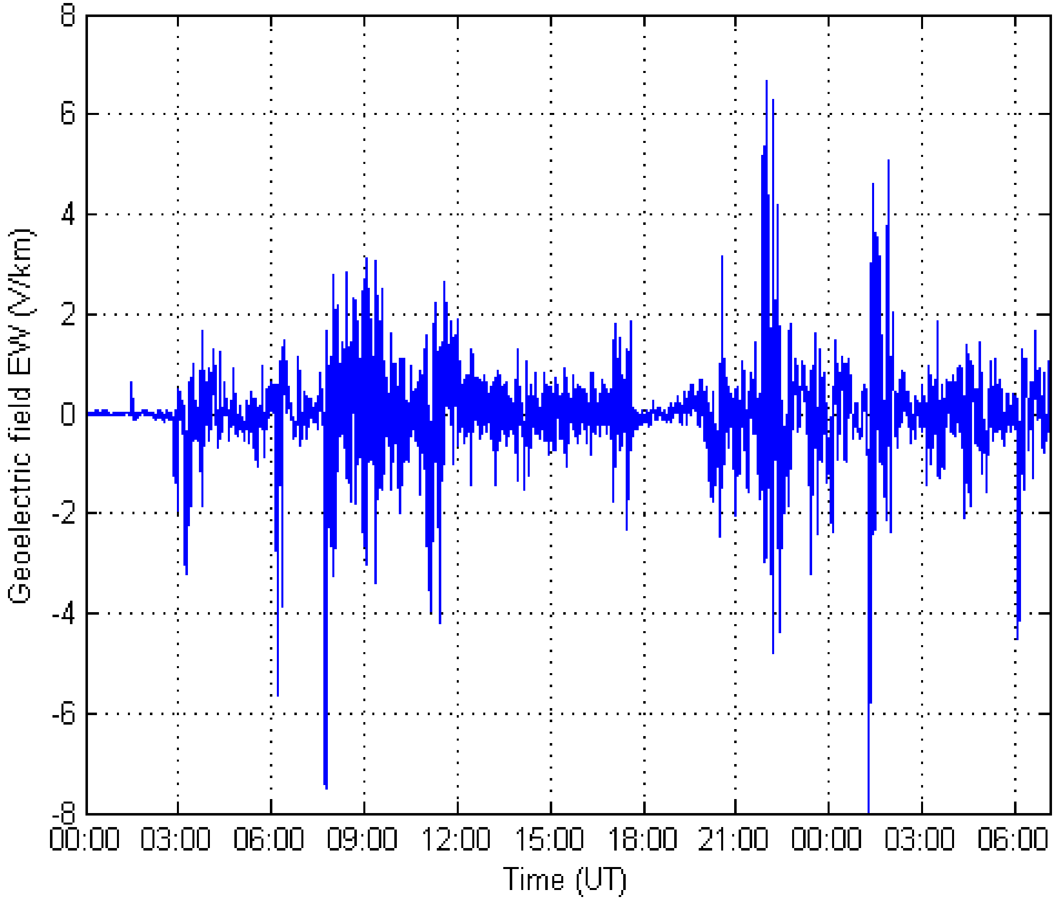
Data file available at: http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx

Reference Geomagnetic Waveshape



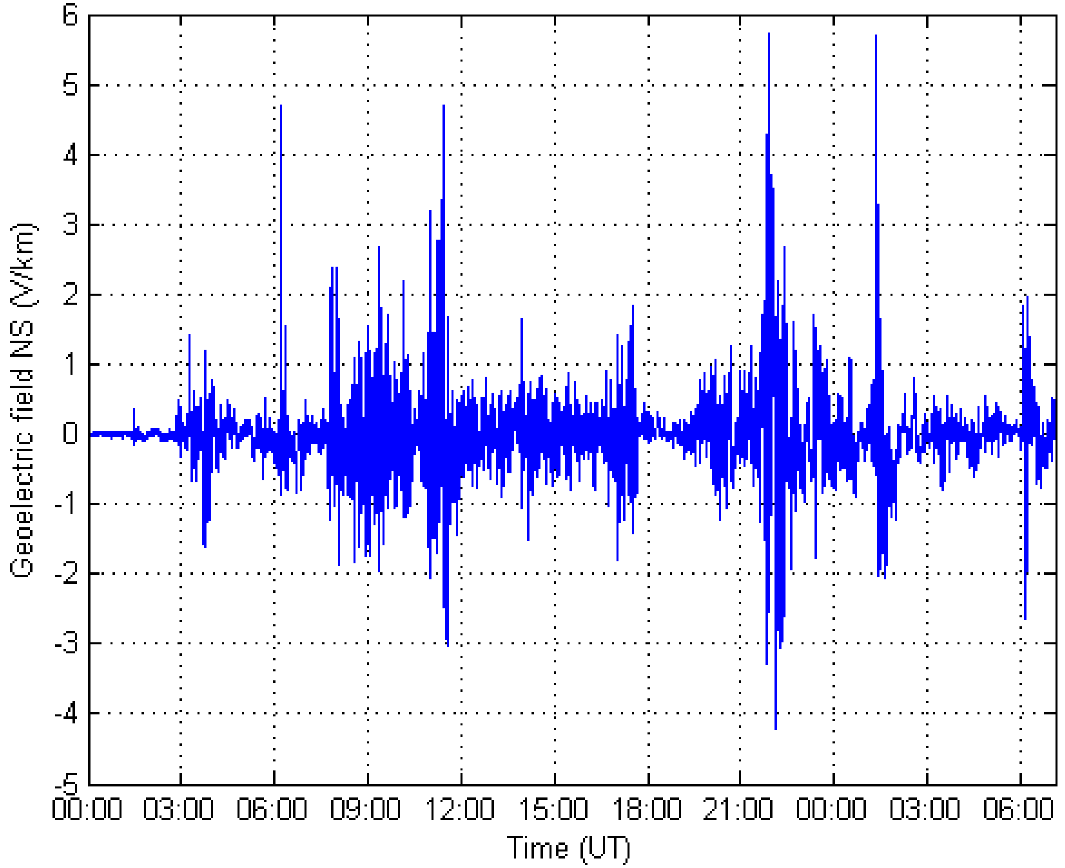
Benchmark Geomagnetic Field Waveshape. Red Bn (Northward), Blue Be (Eastward).

Reference Geoelectric Field Waveshape



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

Reference Geoelectric Field Waveshape

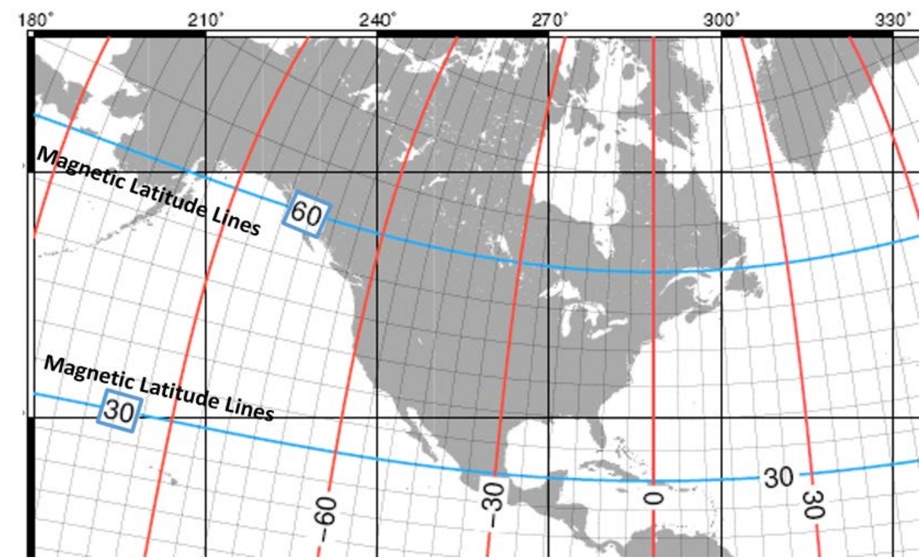


Benchmark geoelectric field waveshape at 60° North Calculated using the reference Quebec ground model. E_N (Northward).

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^{o} N	Juneau; Winnipeg; Churchill Falls, NL
0.3 at 50^{o} N	New York ; St Louis; Salt Lake City
0.1 at 40^{o} N	Jacksonville; New Orleans; Tucson



Geomagnetic Latitude Chart

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

Earth Conductivity Scaling

Earth conductivity model factor (β)

0.81 Atlantic Coastal (CP-1)

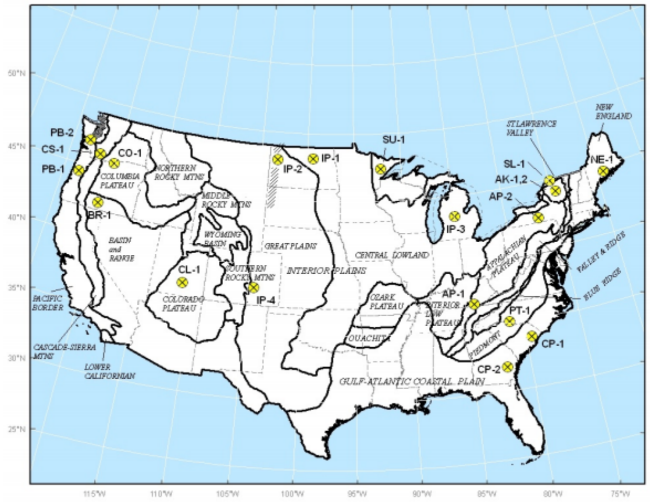
0.27 Columbia Plateau (CO-1)

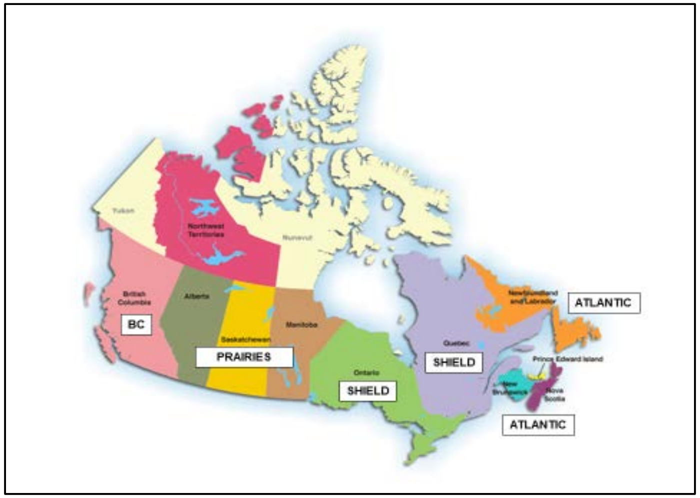
0.67 British Columbia (BC)

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

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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 reference $\beta=1$
- $E_{peak} = 8 \times 0.562 \times 1 = 4.5$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

Example 2

- Transmission service territory that lies at a geographical latitude of 45.5° (geomagnetic latitude of 55°)
- α = 0.562 (using formula $\alpha = 0.001 \times \exp(0.115 \times L)$)
- Earth conductivity NE1, β=0.81

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

- $E_{peak} = 8 \times 0.562 \times 0.81 = 3.6$V/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

Discussion

Studies Required in a GMD Assessment - Luis Marti, Hydro One

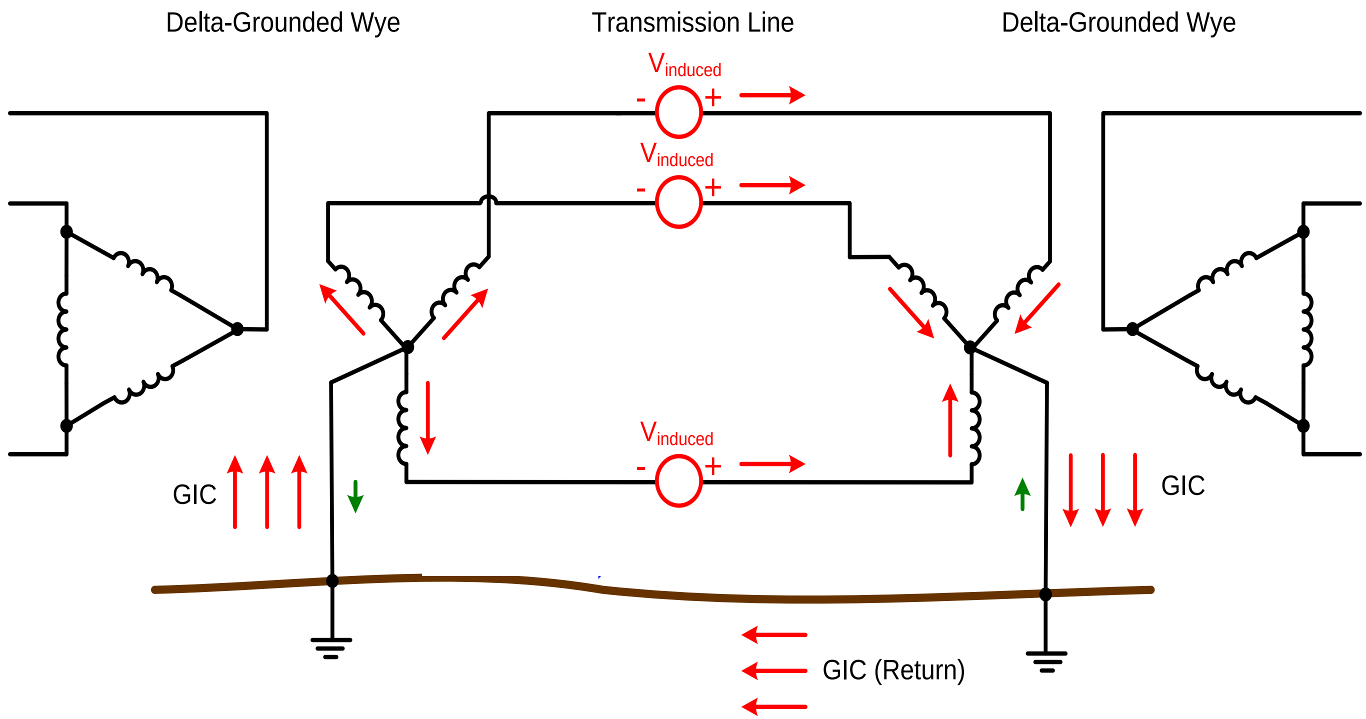
TPL-007-1 Requirement

- TPL-007 requires planning entities 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 Model

- **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.



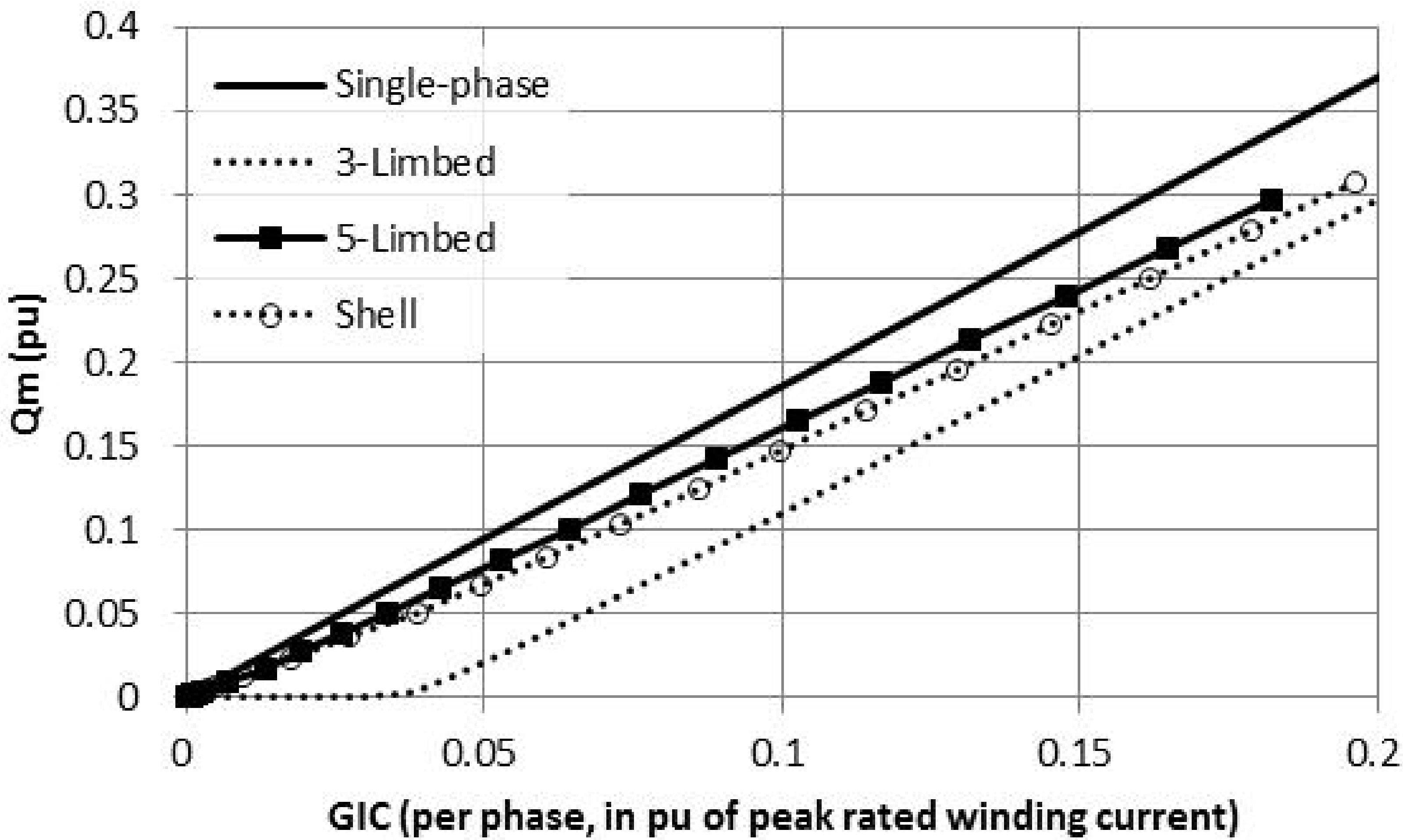
Modeling / Data Needs

- 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 modeled 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
    - 3phase 5-limb
    - 3-phase shell
    - 3-phase 3-limb
  - Software vendor defaults or user-supplied

Example of GIC – var curves



Data Source Summary

- 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
- Interconnection equivalents
- 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 effective 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

Results of a GIC Study

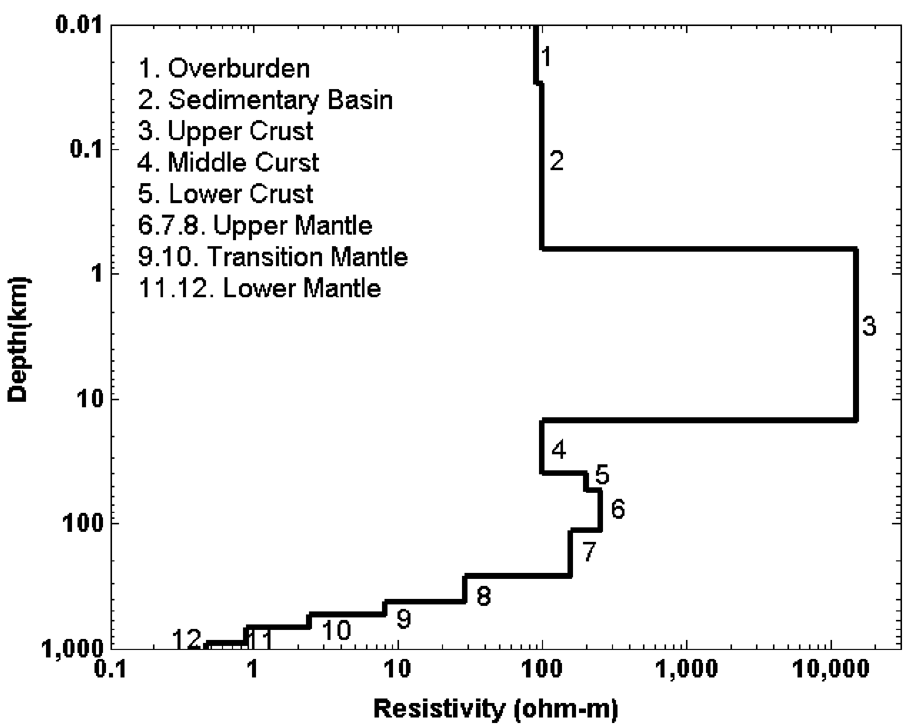
- When worst-case geoelectric field orientation in every transformer is identified, GIC_E and GIC_N must be calculated in order to generate GIC(t) for transformer thermal assessment (R6)
  - GIC_E for E_EW = 1 and E_NS = 0
  - GIC_N for E_EW = 0 and E_NS = 1
  - With $E_{EW}(t)$ and $E_{NS}(t)$ from the benchmark time series, then

$$GIC(t) = \alpha \times \beta \times \{GIC_E \cdot E\_EW(t) + GIC_N \cdot E\_NS(t)\}$$

- Alternatively, a utility can calculate $E_{EW}(t)$ and $E_{NS}(t)$ from the benchmark geomagnetic time series with a technically justifiable earth model

Earth Models

- Options:
  - Beta factor in Table II-2 from benchmark white paper
  - Technically justifiable earth model to calculate the geoelectric field directly



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
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

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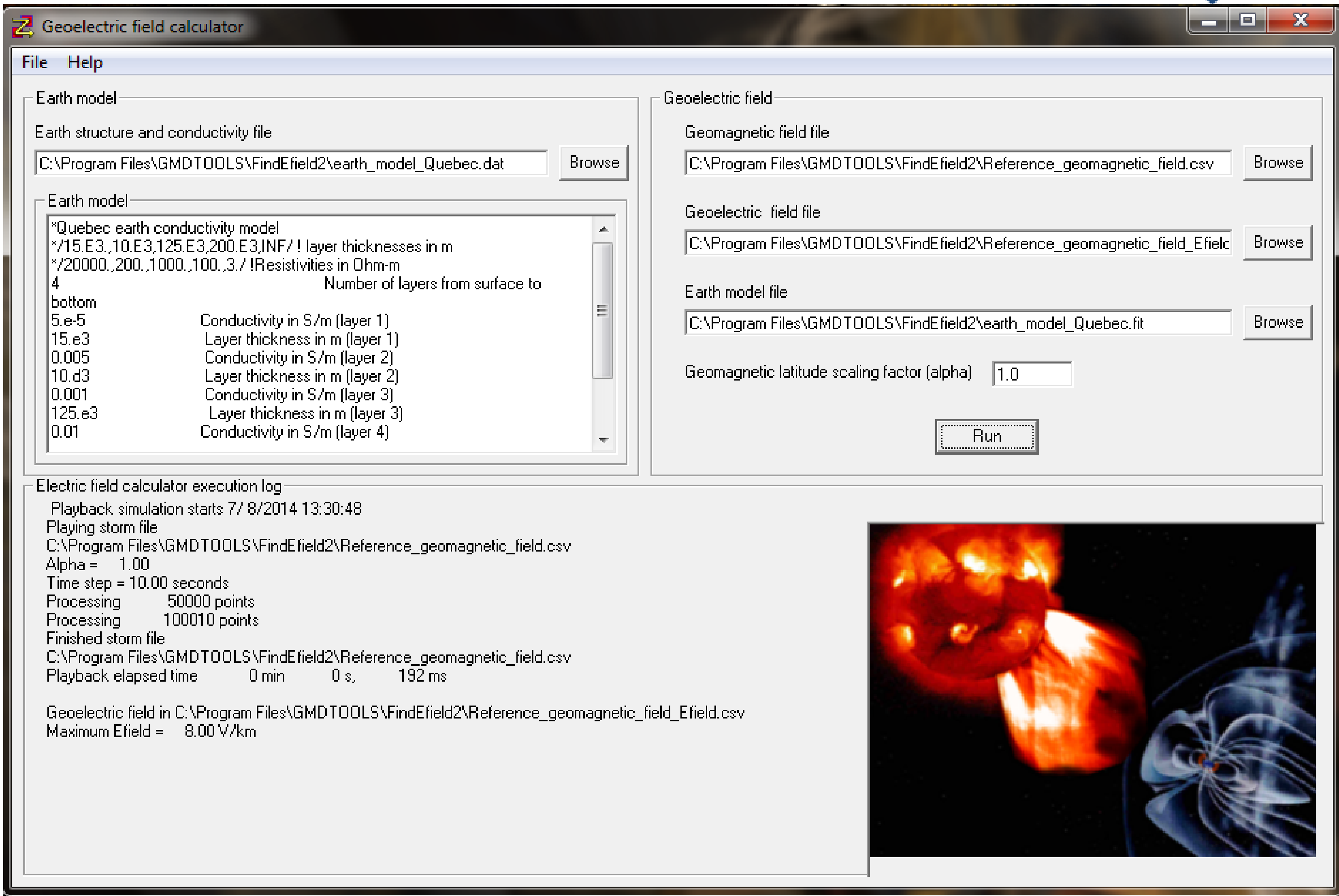
Hydro One's E-field Calculator

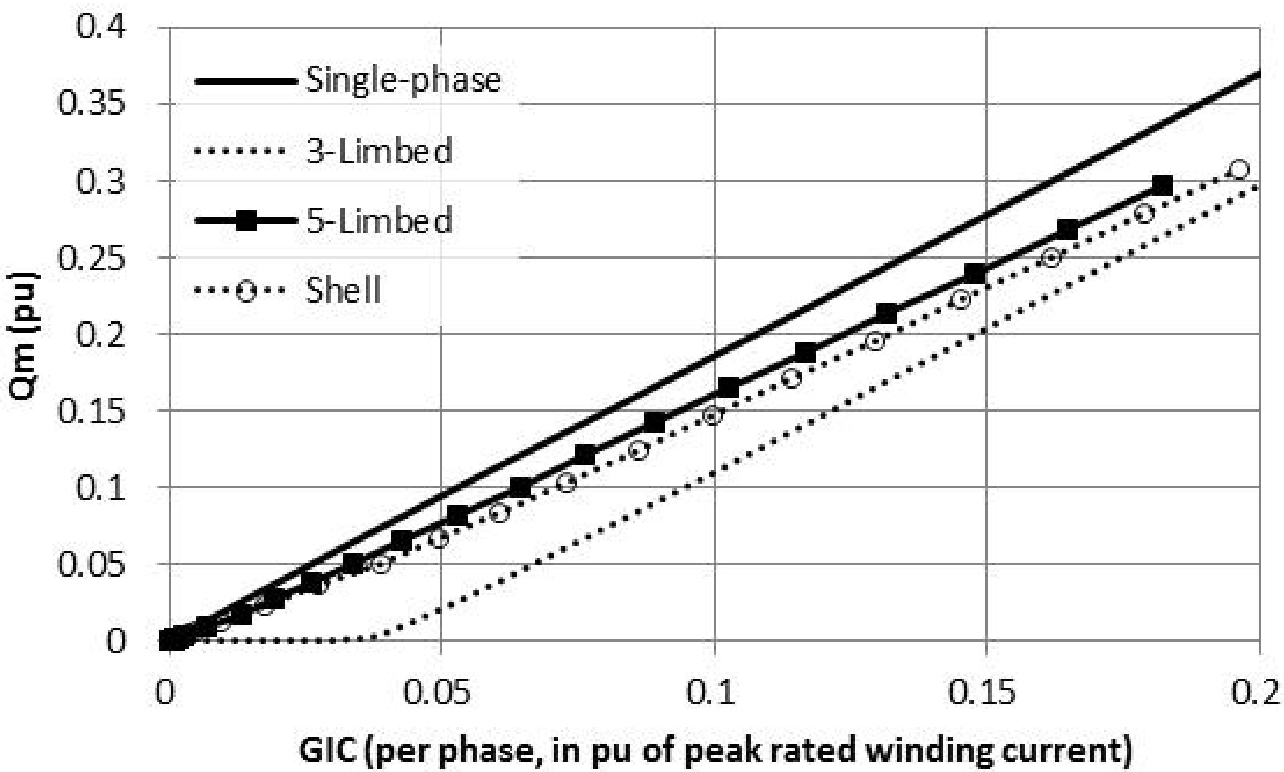


Transformer Models

- Winding resistance
  - Test-sheet data
- Reactive power absorption with GIC
- Harmonics with GIC
- Hot spot thermal response

GIC and var absorption

- Well-defined for 1-phase units
- EMTP magnetic analogues to define other constructions
- Highest uncertainty with three-limb core-type



GIC and harmonics

- Well-defined for 1-phase units
- EMTP magnetic analogues to define other constructions
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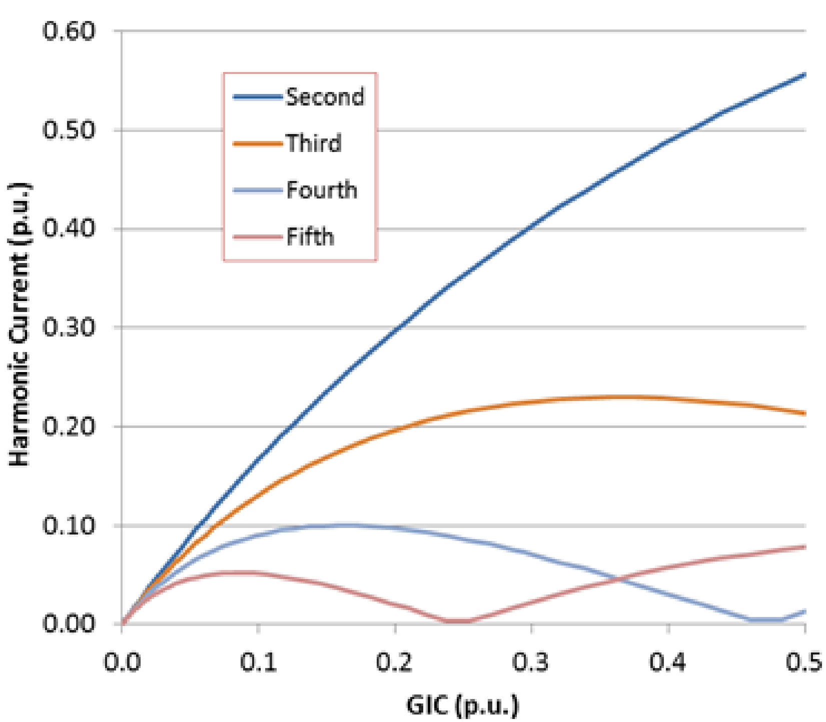
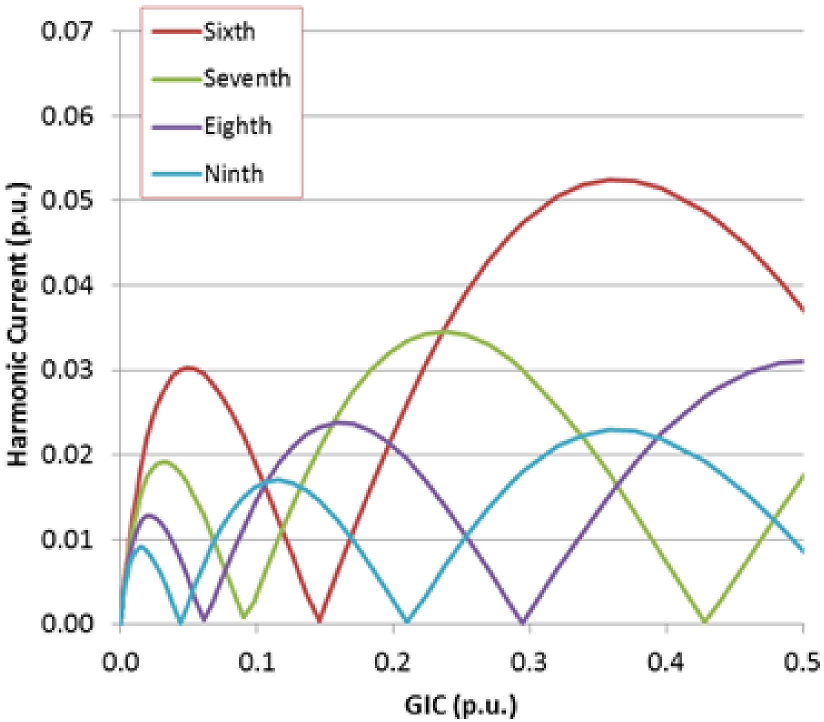




Hot spot thermal response

- Manufacturer's models have had limited experimental validation
  - Situation is improving
- Measurement-based data sources
  - Limited
  - Measurements are meant to validate models
  - Situation is improving
- Published (conservative) screening thermal response
- Manufacturer's capability curves
  - No generic curves available
  - Limited experimental validation since they depend on manufacturer's models

Technical Resources for GIC Modeling

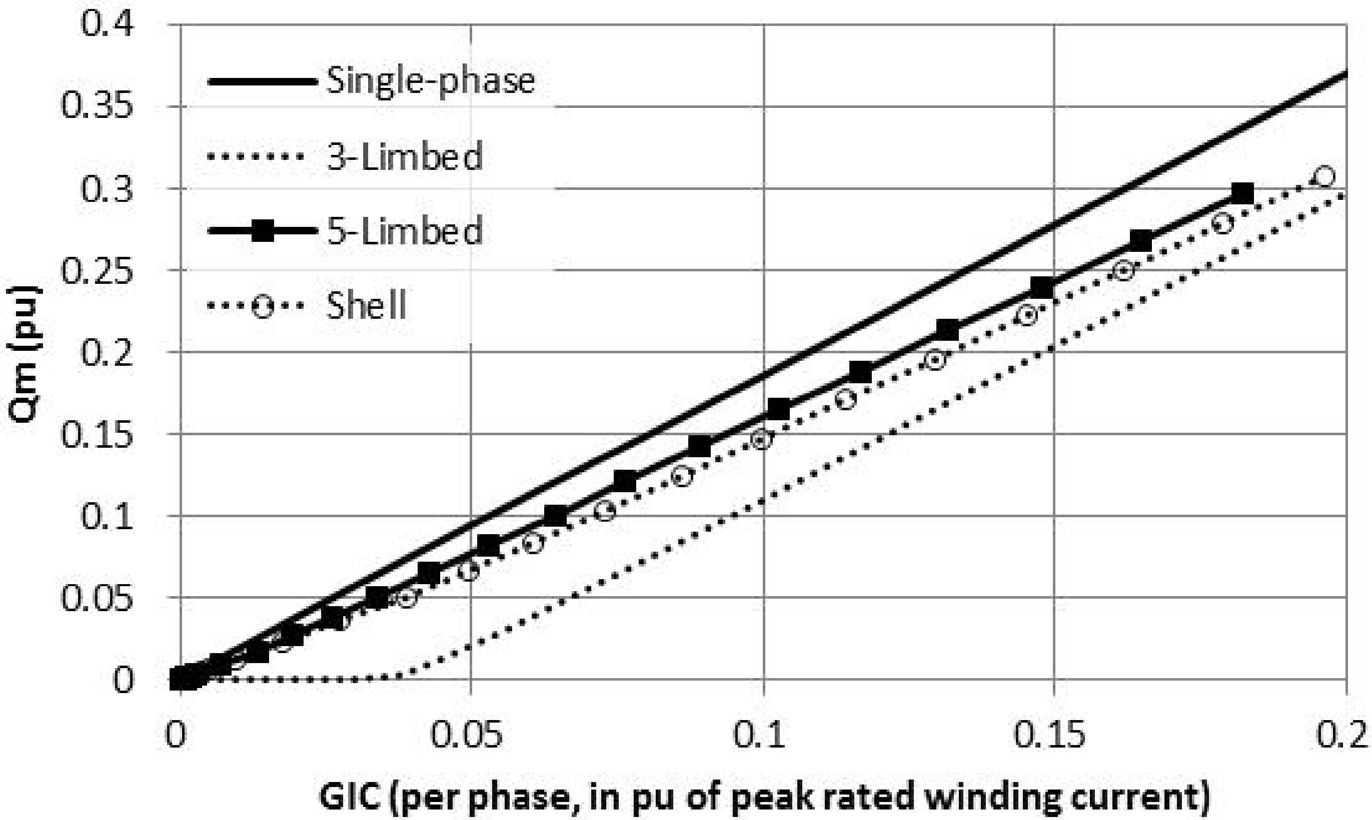
- Technical resources on the GMD TF Project page http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx
  - GIC Application Guide (PC approved December 2013)
  - GMD Planning Guide (PC approved December 2013)
  - 2012 GMD Report
- Technical resources are also available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

Load Flow Study – Randy Horton, Southern Company

TPL-007-1 Requirements

- Planning entities are required to perform a GMD Vulnerability Assessment steady state analysis every 60 months
- Details and performance criteria are contained in Table 1
- Commercial software packages are available with features to support GIC and power flow analysis
  - 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

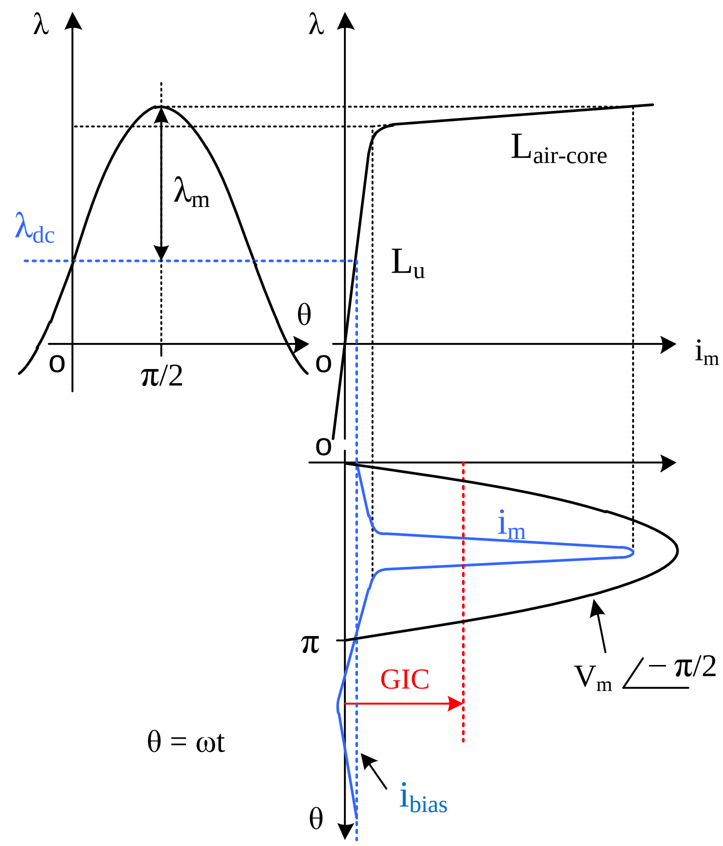
- The objective of the GMD Vulnerability Assessment is to prevent voltage collapse, Cascading, and uncontrolled Islanding of the System during a GMD event.
- System performance evaluation is based on:
  - System steady-state voltage and power flow limits established by the Transmission Planner and Planning 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

Transformer Thermal Assessment – Luis Marti, Hydro One

Half Cycle Saturation

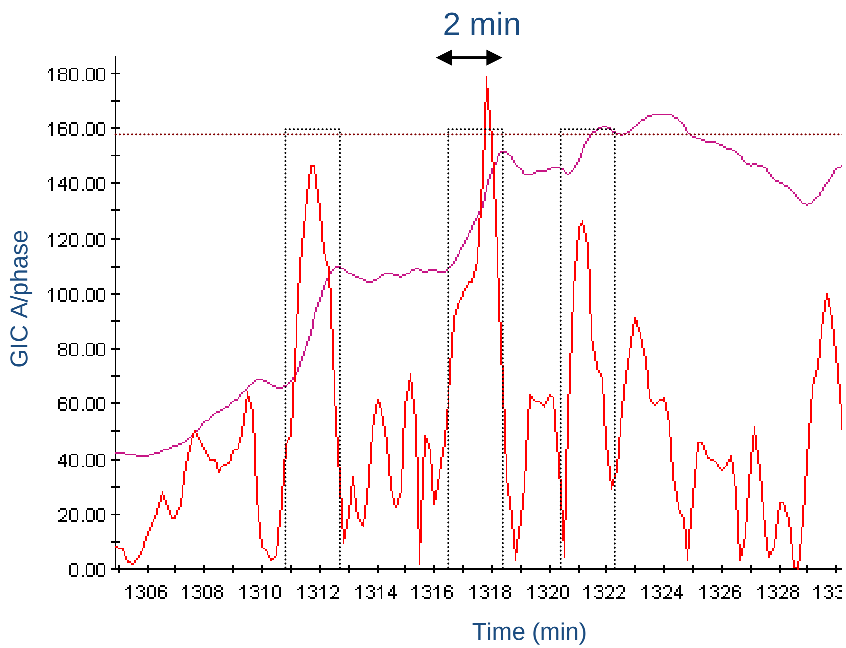
- GIC produces a dc offset of the ac sinusoidal flux within the transformer resulting in:
  - Harmonics
  - Increase in reactive power absorption
  - Hot-spot heating of windings due to stray flux
  - Hot-spot heating of non-current carrying parts due to stray flux
    - Fitch-plate, tie-plate, tank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

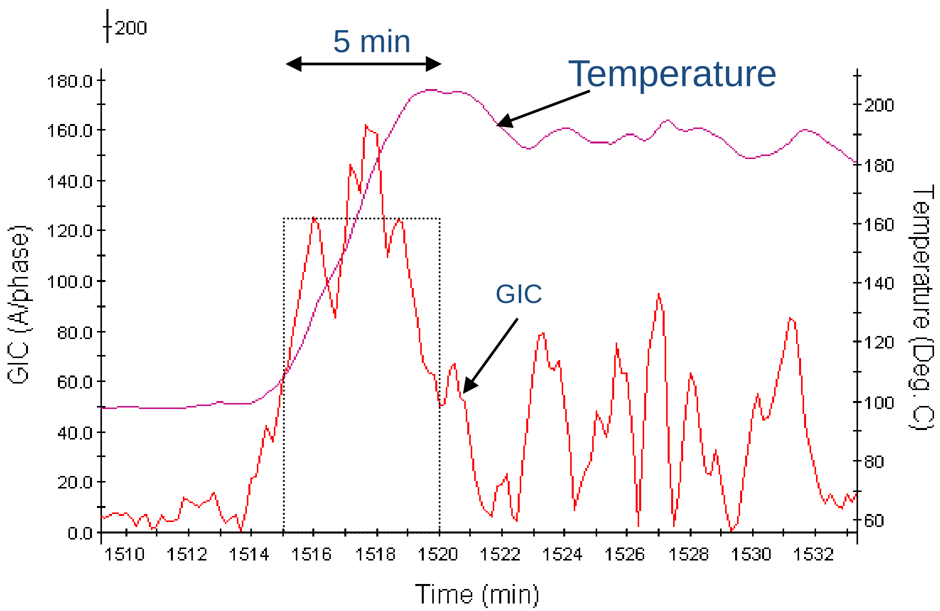


Thermal Effects

- 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% 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 waveshape. Every transformer sees a different GIC(t)

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

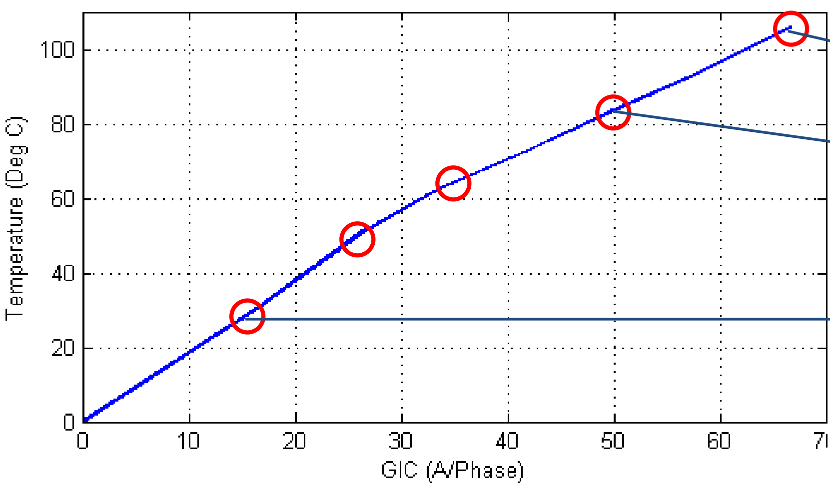




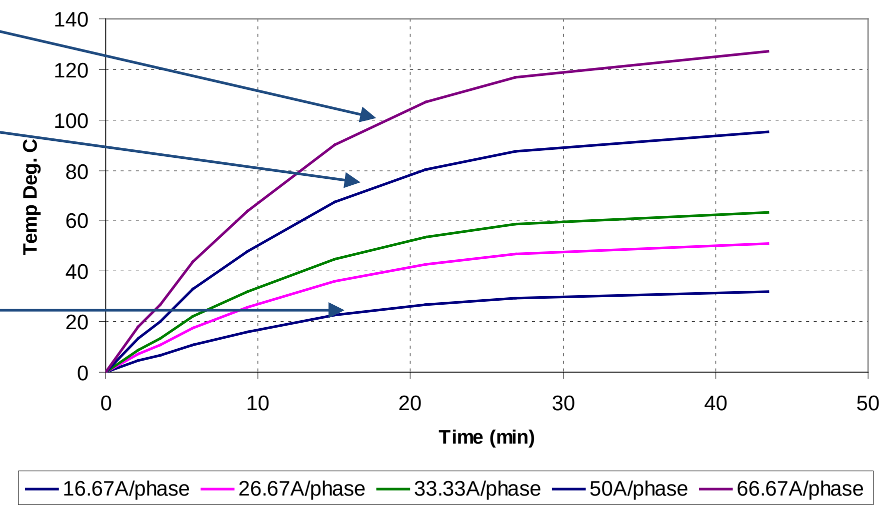
Thermal Response

- 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

Asymptotic response



Response to a GIC steps



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 Std 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

TPL-007-1 Requirements

- R6 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

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

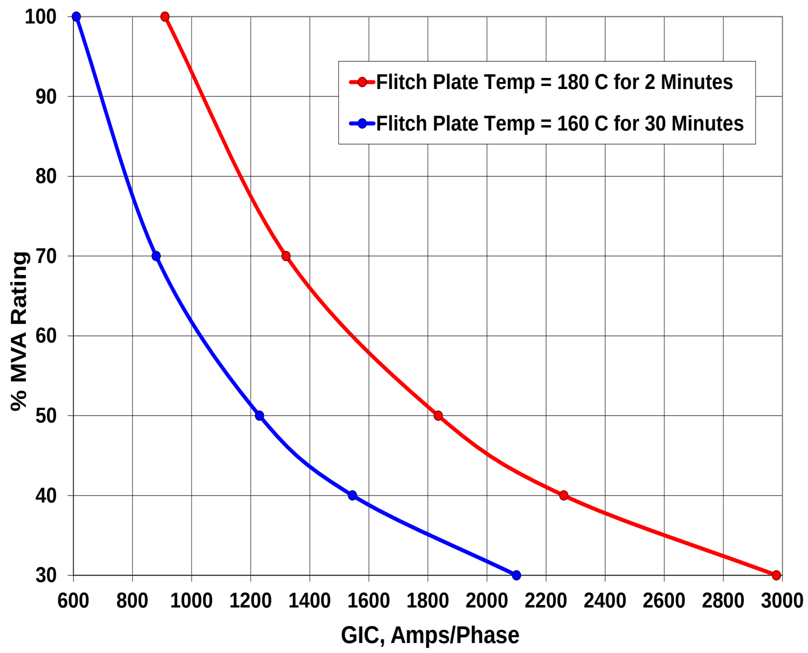
  - I_H is the dc current in the high voltage winding;
  - I_N is the neutral dc current;
  - V_H is the rms rated voltage at HV terminals;
  - V_X is the rms rated voltage at the LV terminals.
- From this GIC Study maximum $I_{dc,eq}$, GIC(t) is calculated as input for the thermal assessment process.

TPL-007-1 Requirements

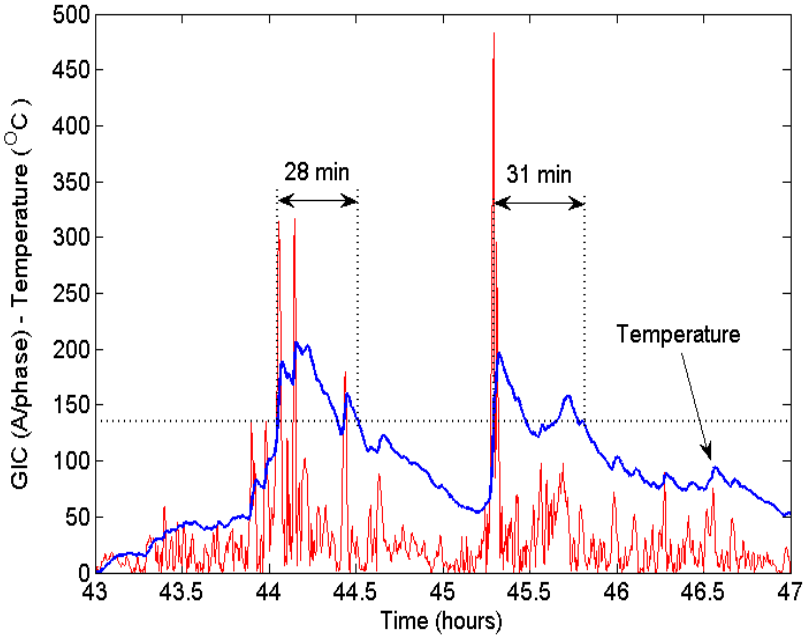
- Assessment must include suggested actions and supporting analysis which are provided to the TP and PC to mitigate identified issues
- White paper describes approaches using manufacturer capability curves or thermal response modeling

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 Std. 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

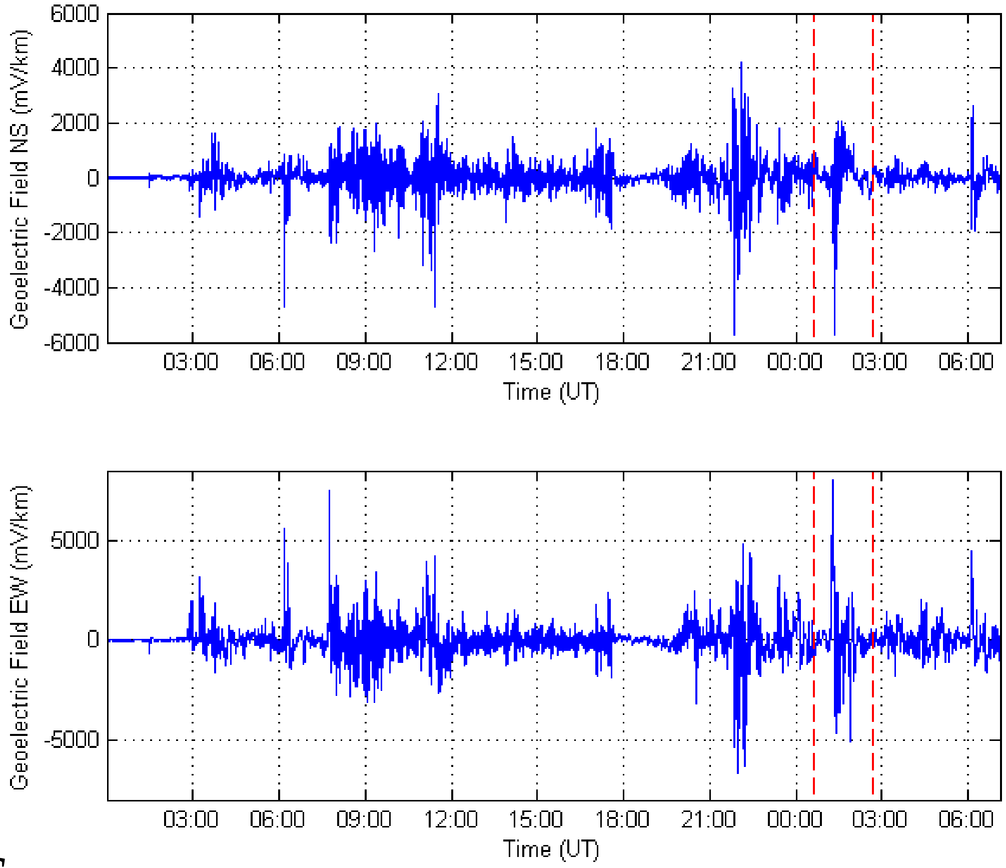
- Temperature increases due to ambient temperature and transformer loading: for planning purposes, maximum ambient and loading temperature should be used unless there is a technically justified reason to do otherwise

Steps in a Transformer Thermal Assessment

- Assessment steps for a given transformer
  - Obtain transformer effective 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)

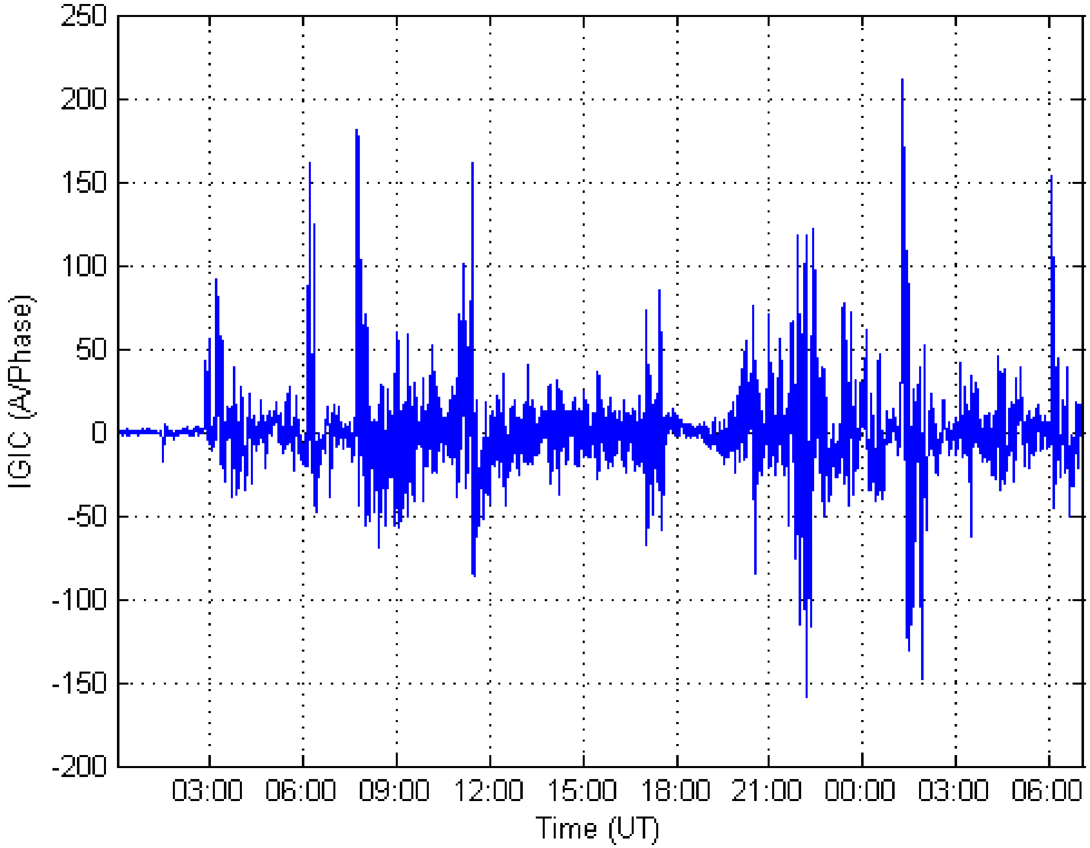
- Calculate component GIC values due to eastward and northward geoelectric fields for each transformer (GIC_E and GIC_N) for 1 V/km
- Scale each component GIC value according to using the scaled geoelectric field time series



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

$$GIC(t) = E_E(t) \cdot (-20) + E_N(t) \cdot (26)$$

GIC(t)

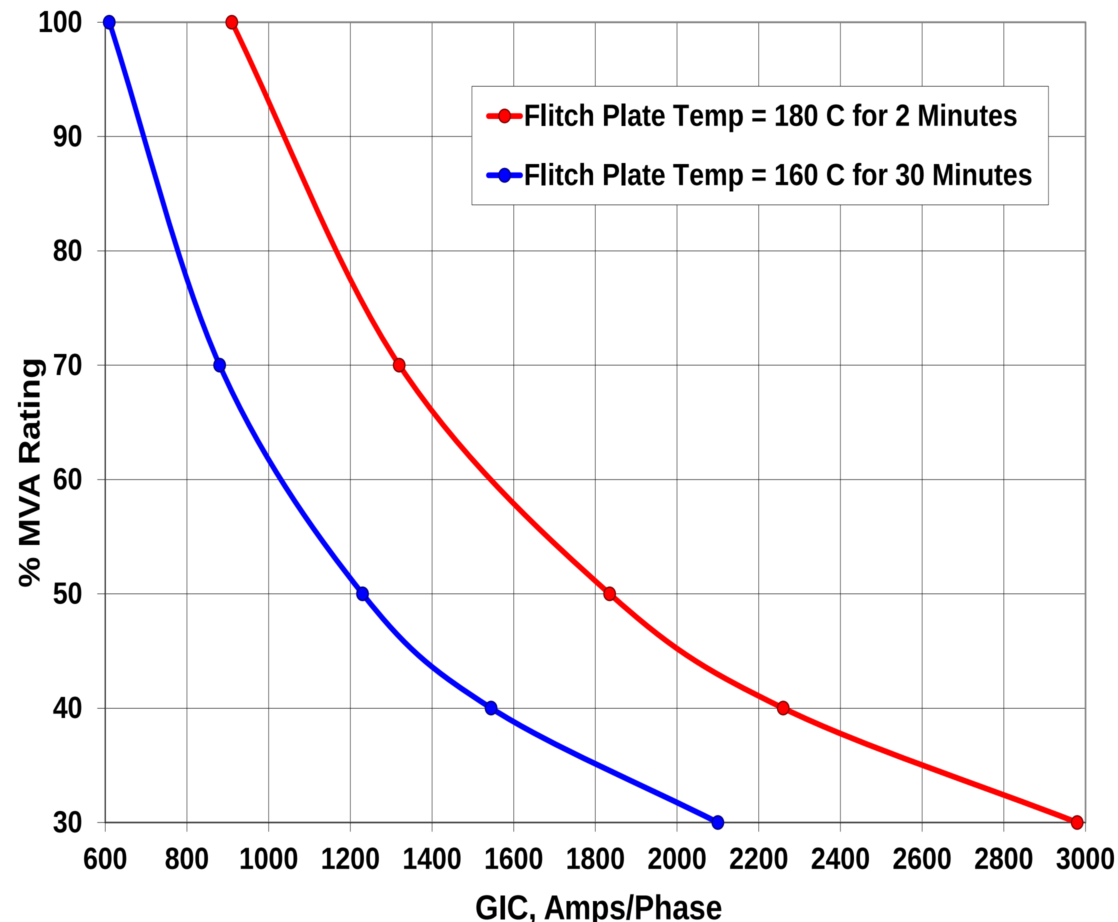


Calculated effective GIC(t) Assuming α=1 and β=1 (Reference Earth Model)

Assessment of Limit Encroaching

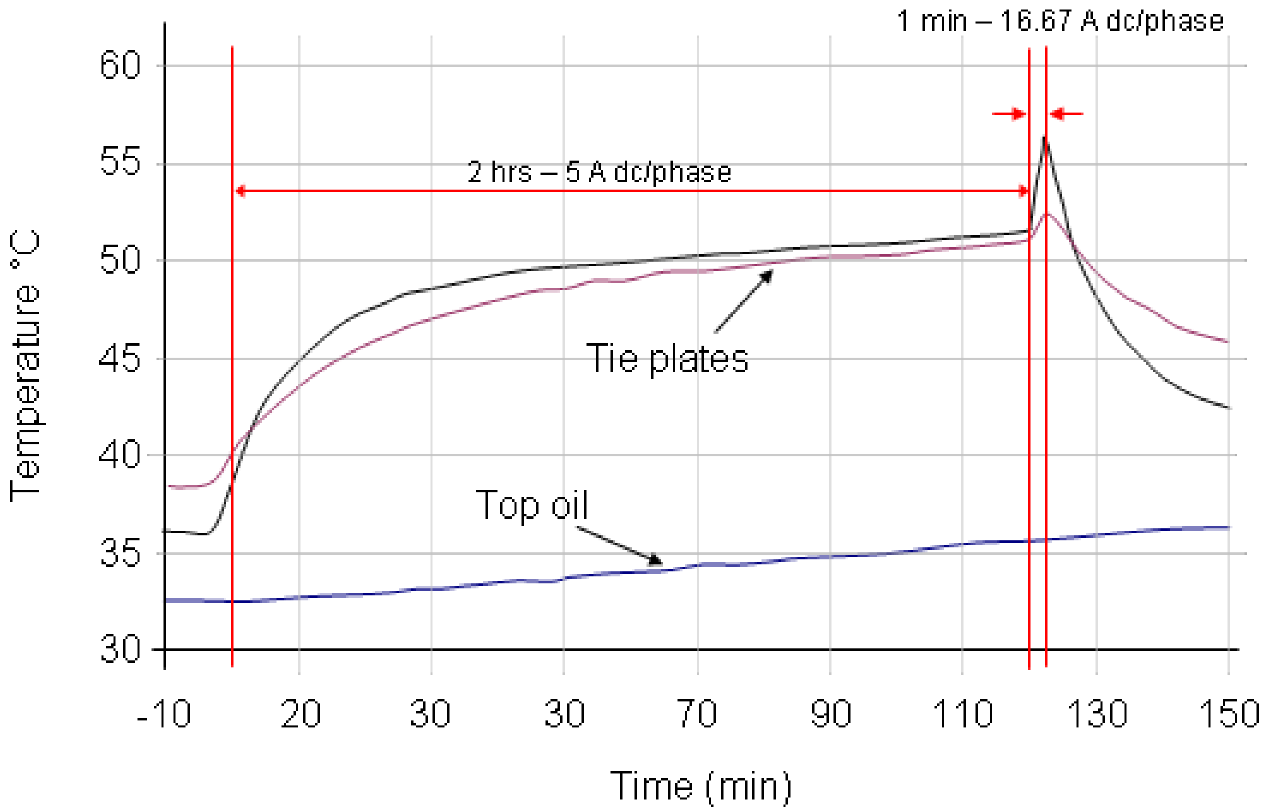
- Each transformer will see a different GIC(t)
- Assess if each transformer will be affected by GIC(t)
  - Winding hot spot
  - Metallic part hot spot
- Adjust thresholds according to age and condition
- Three ways to do this
  - Peak GIC(t) is so low compared to the transformer’s GIC capability that a detailed assessment is unnecessary. 15A/phase threshold (R6).
  - 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)

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Sample Thermal Assessment

Example to Illustrate the Methodology

- Transformer thermal behavior obtained from published literature: Fingrid tests used in the white paper.
    - Tested from the 400 kV bus
    - Minimal "weak source" effects

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 Std. 57.91 suggested hot spot temperature limits for short term emergency loading

Calculation of GIC(t)

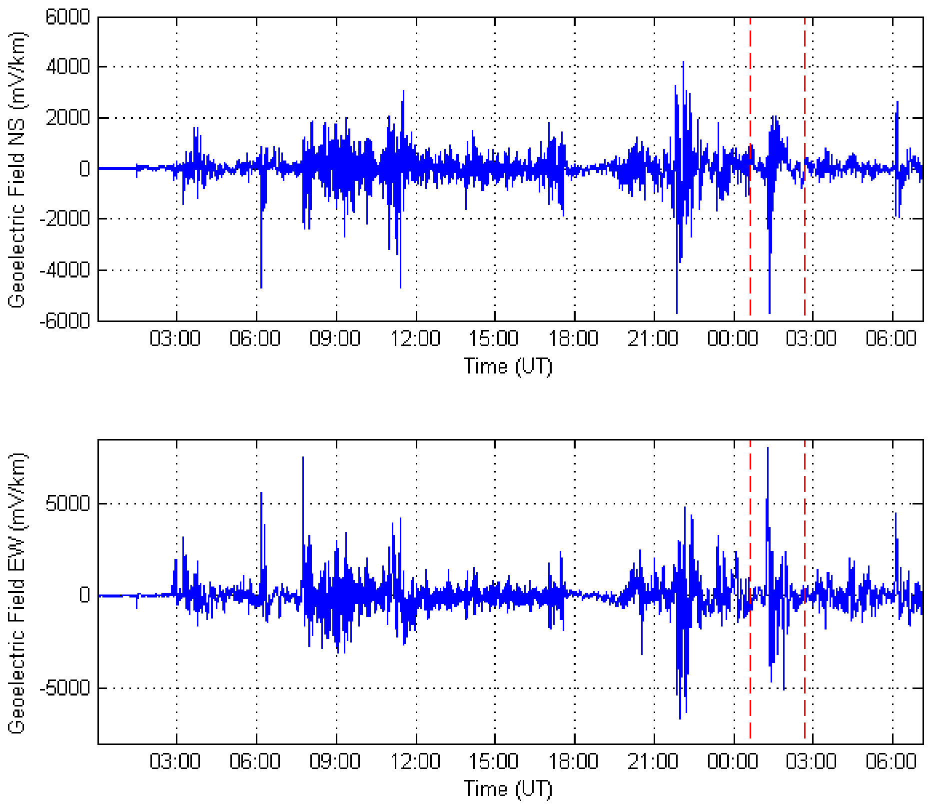
- There a number of equivalent ways to calculate GIC(t)

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

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)

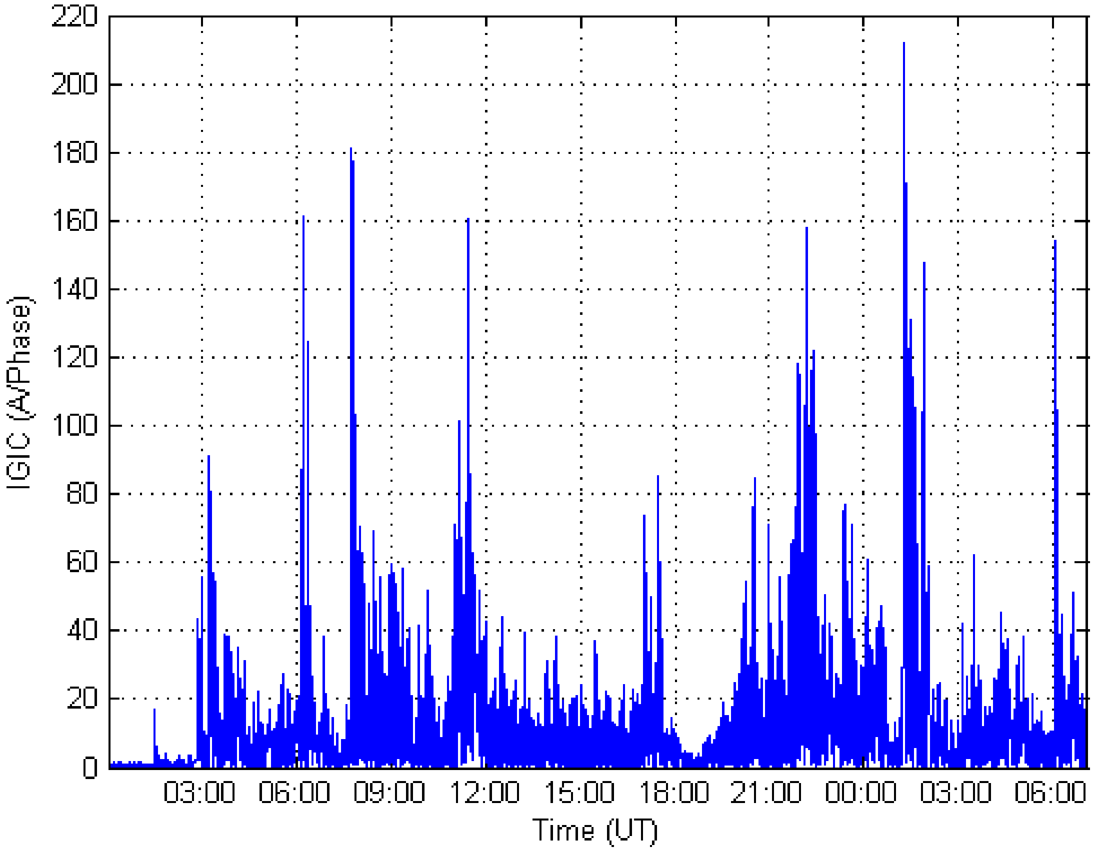
- Calculate component GIC values due to eastward and northward geoelectric fields for each transformer (GIC_E and GIC_N) for 1 V/km
- Scale each component GIC value according to using the scaled geoelectric field time series



$$GIC(t) = E_E(t) \cdot (-20) + E_N(t) \cdot (26) \text{ (A/Phase)}$$

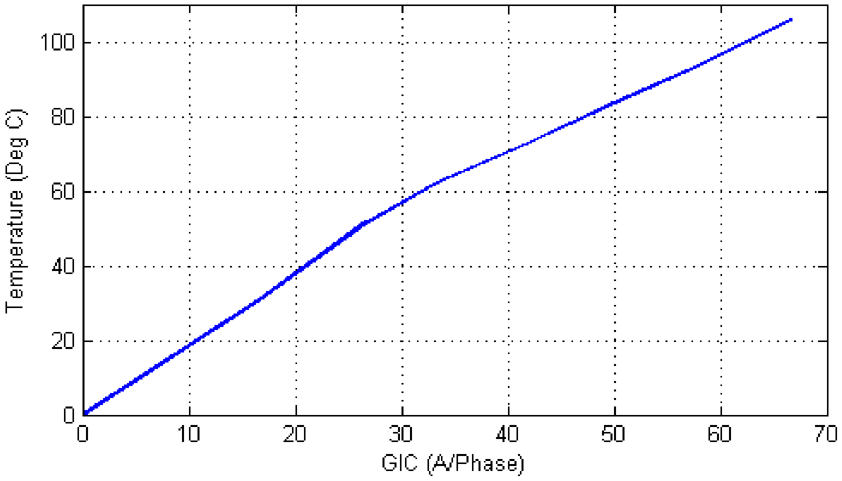
Calculation of GIC(t)

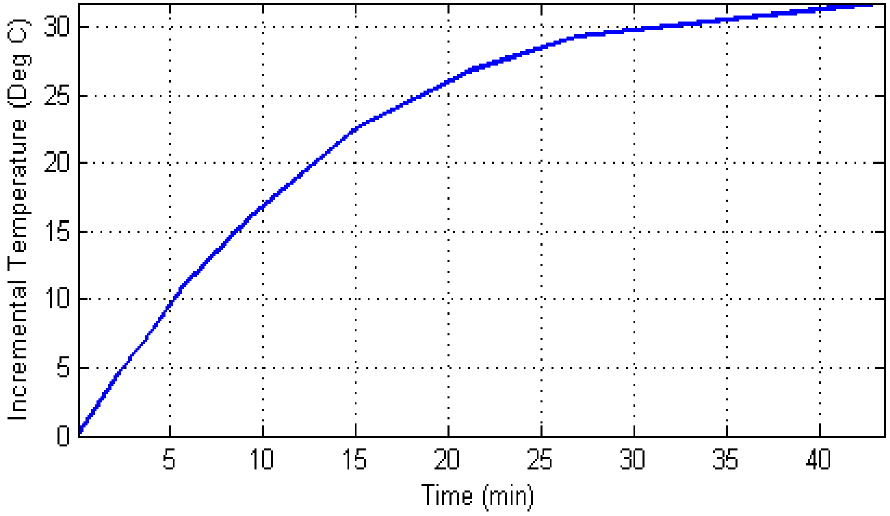
- It is easier to work with the absolute value of GIC(t)



Assessing Capability Using Thermal Response Tools

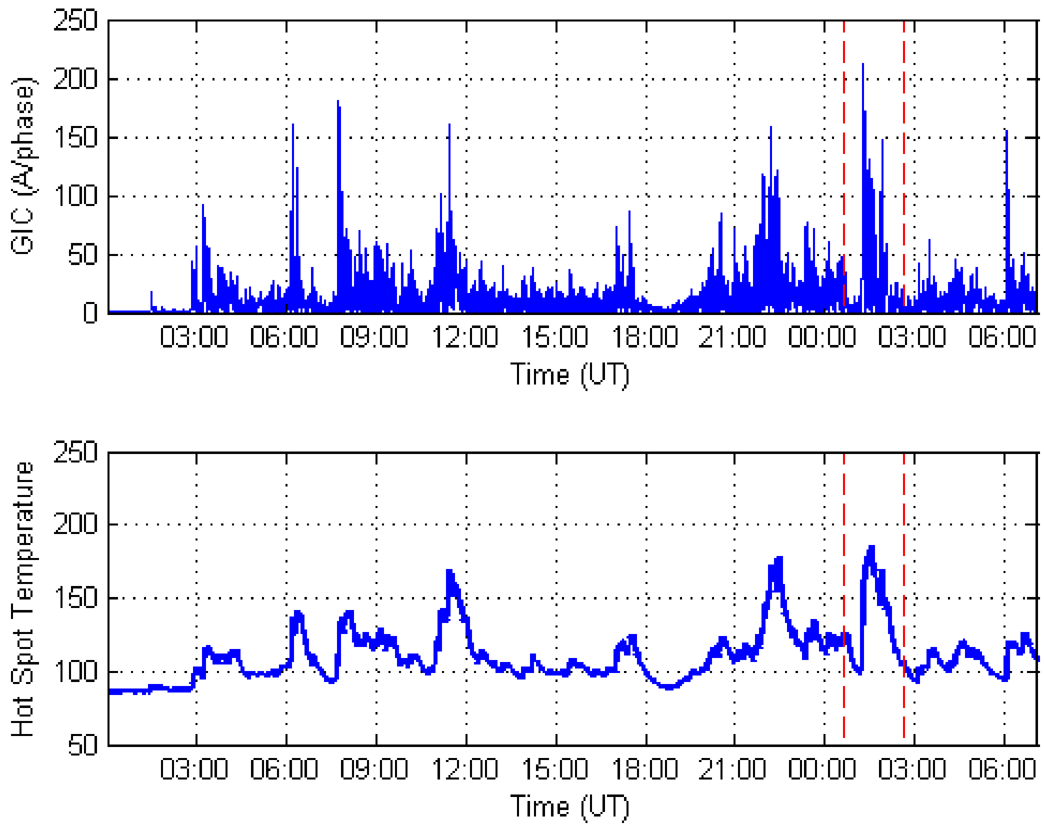
- Identify the thermal step response for winding and metallic part hot spots





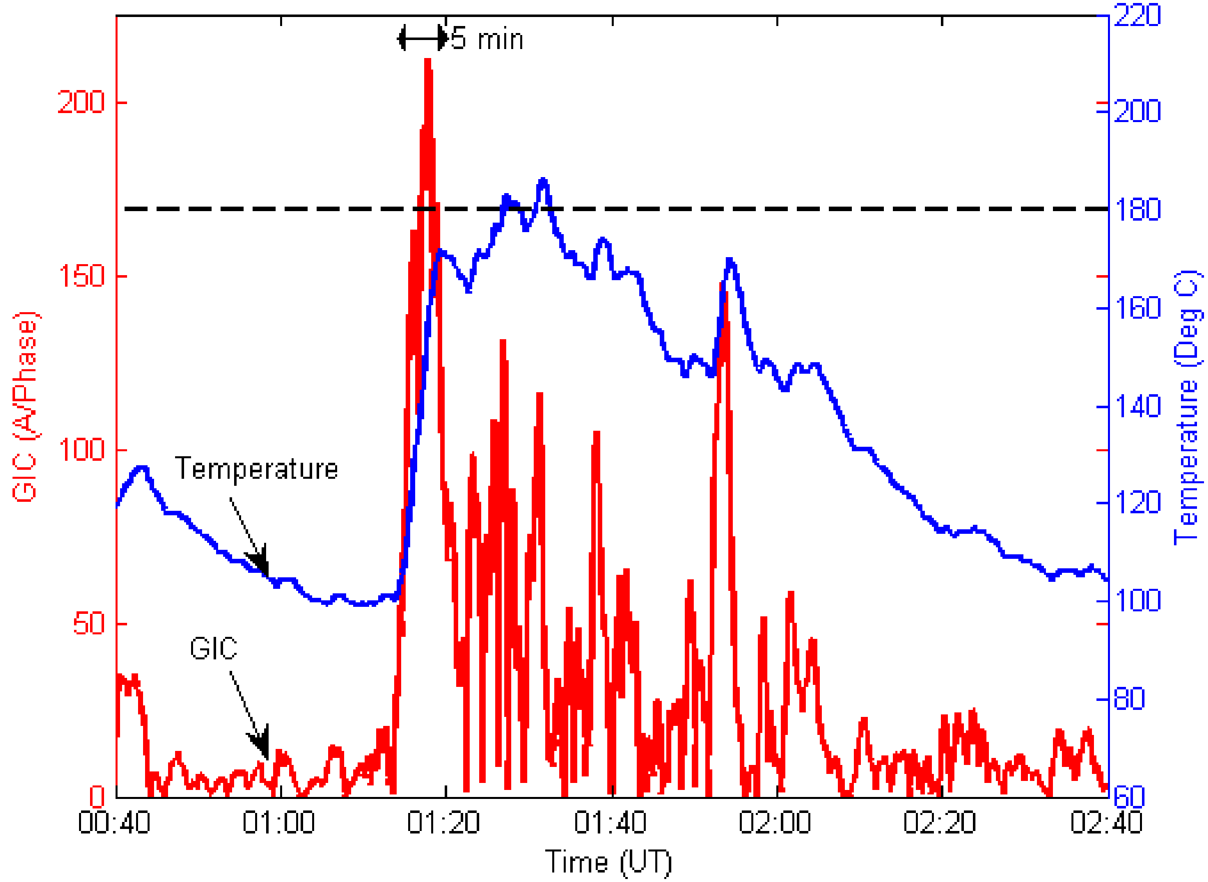
Using Thermal Response Tools

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



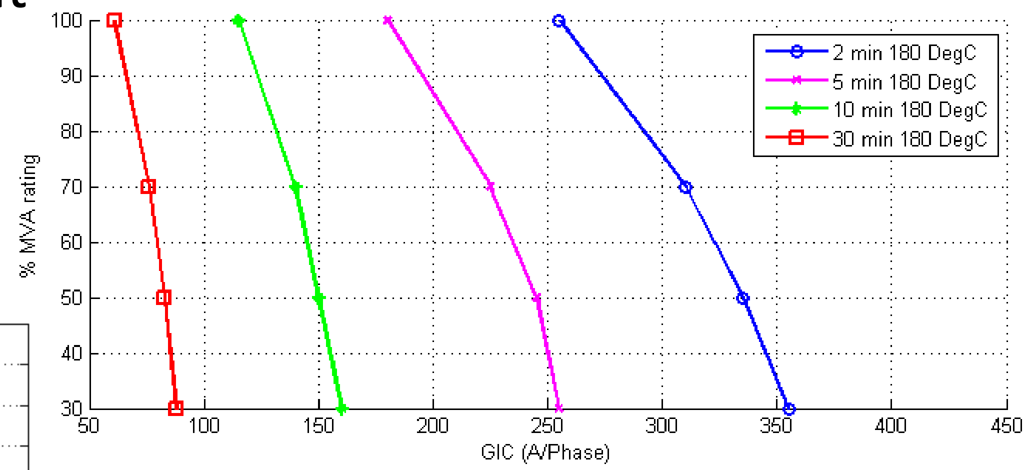
Using Thermal Response Tools

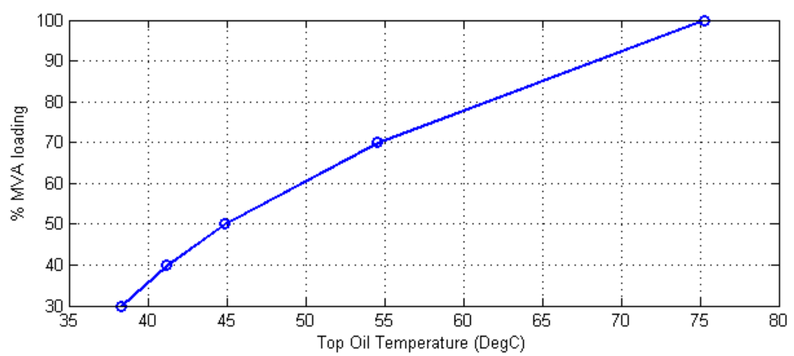
- Verify that it meets criteria



Assessing Capability Using Capability Curves

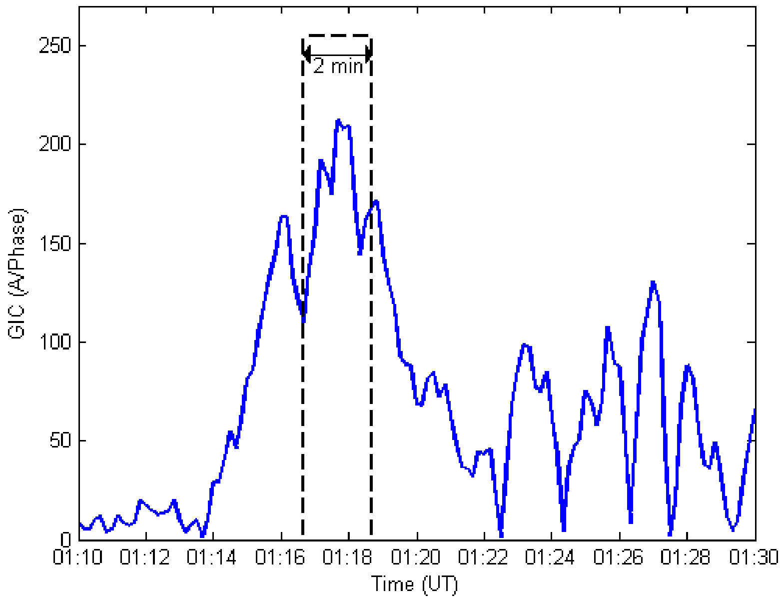
- Identify the correct capability curve from manufacturer
- For the purposes of this example the capability curve was constructed with the thermal step response and simplified loading curve
- All modeling assumptions are therefore identical. Only the methodology is different

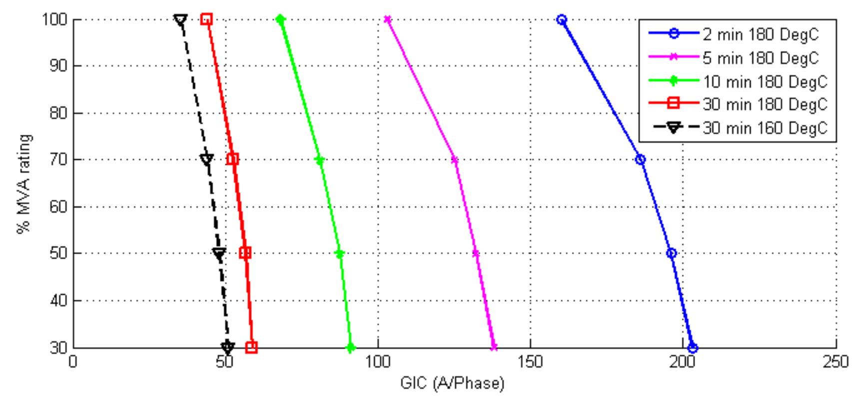




Using Capability Curves

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

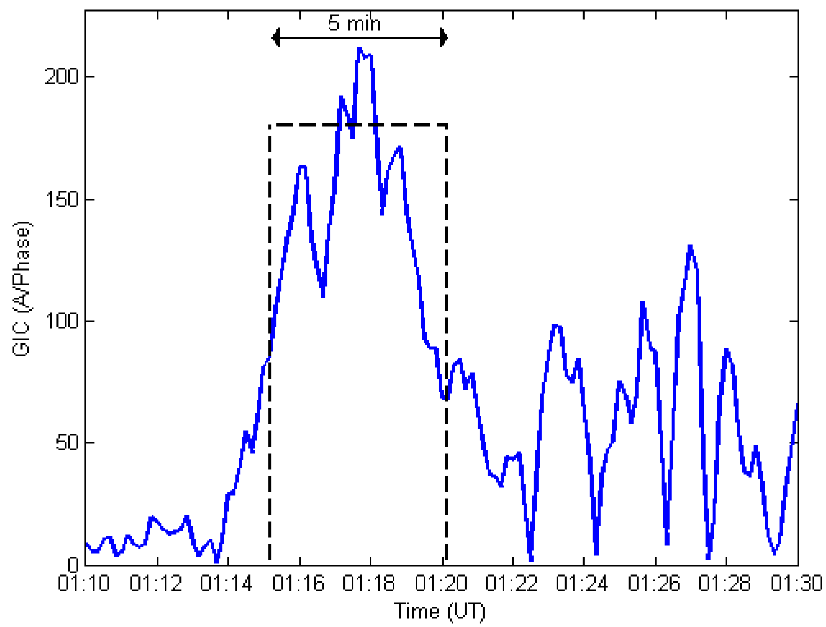


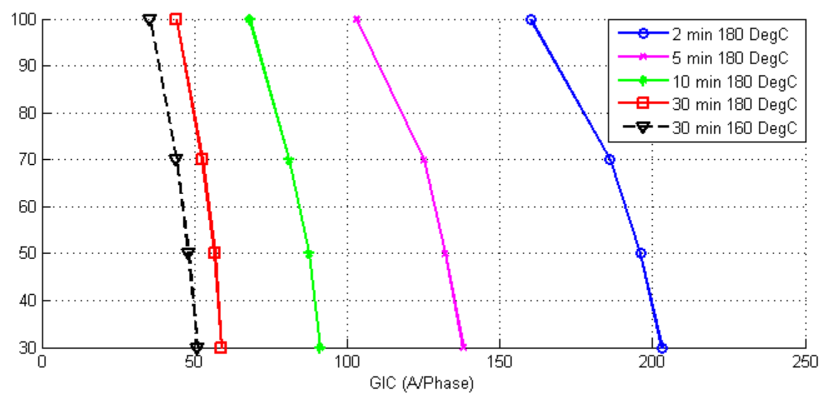


2 minute 255 A/phase GIC pulse at full load

Using Capability Curves

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

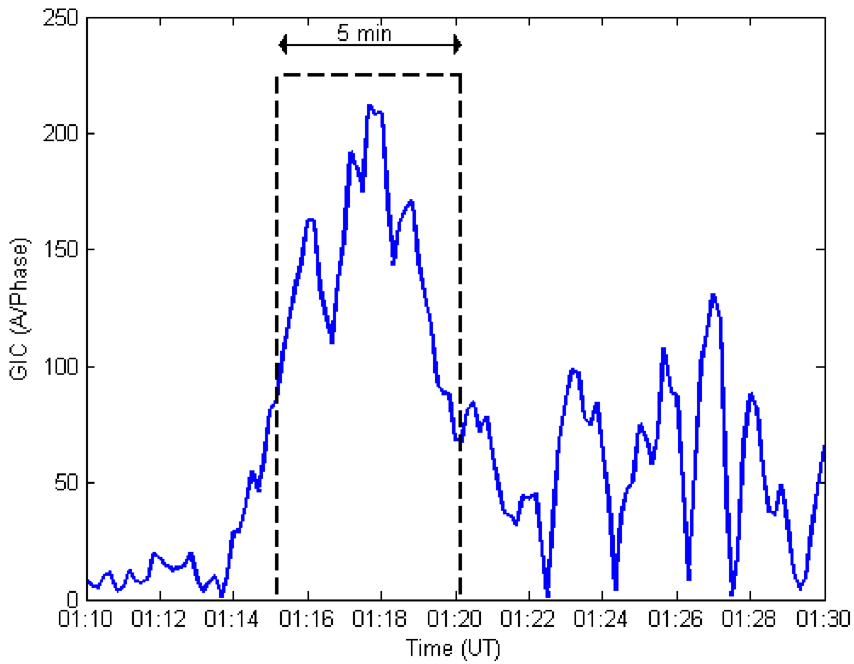




5 minute 180 A/phase GIC pulse at full load

Using Capability Curves

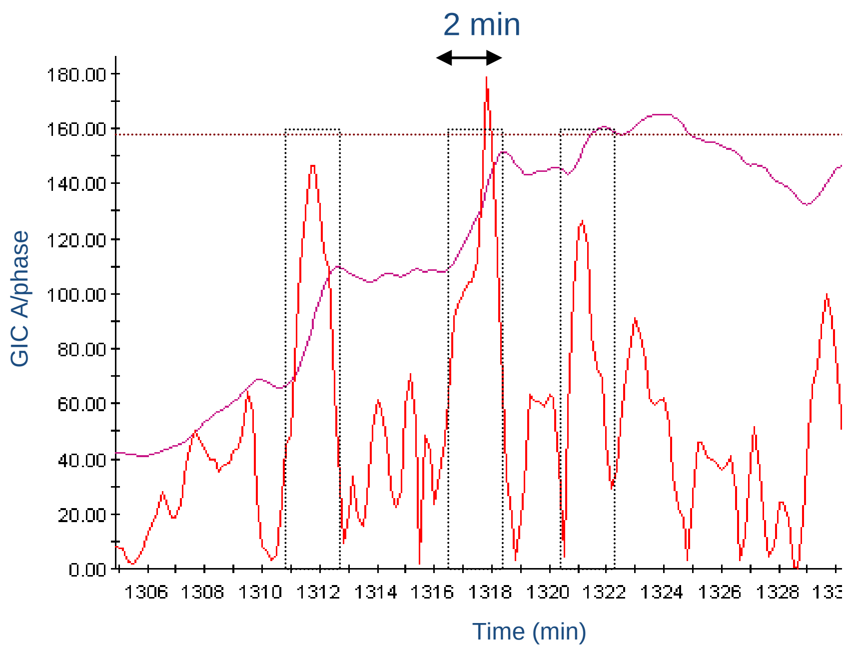
- Use engineering judgment or ask your friendly neighborhood manufacturer when the capability is marginal
- In this example, capability is close to thresholds and pencils would probably have to be sharpened for a more detailed assessment

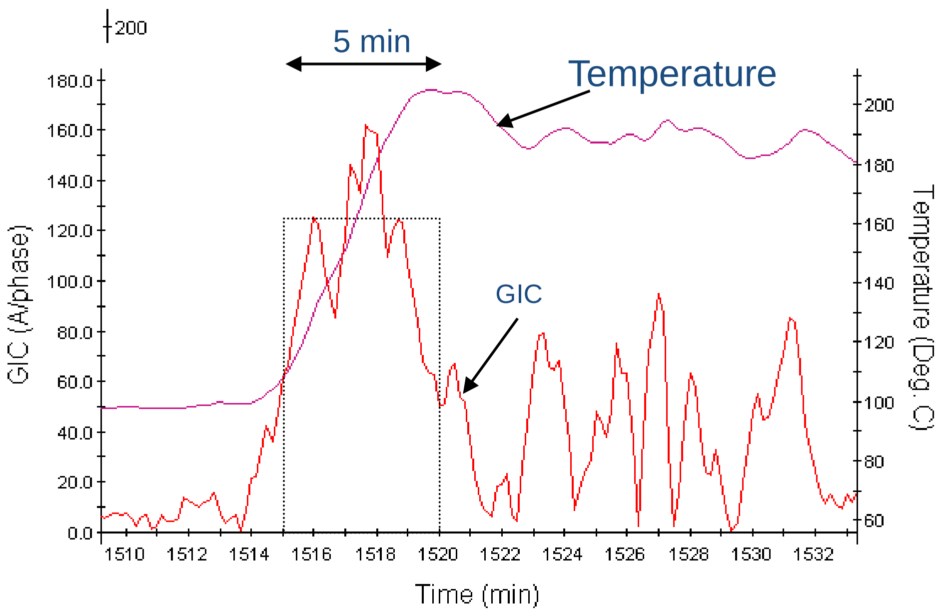


5 minute 225 A/phase GIC pulse assuming 75% load

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 R7 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

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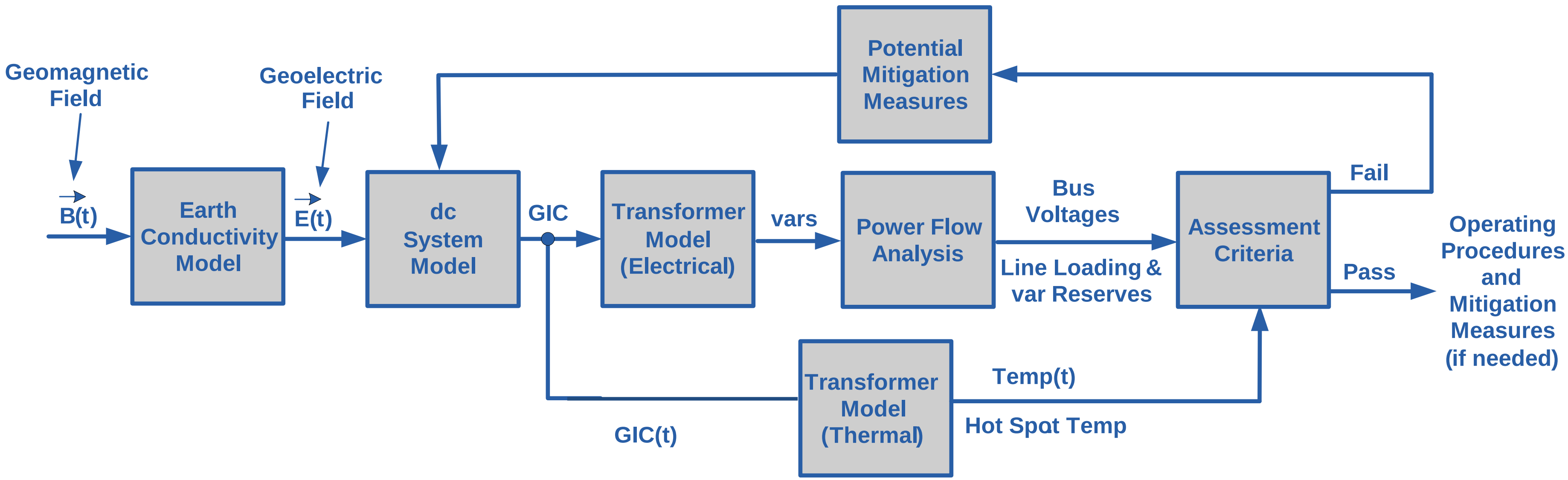
Discussion of TPL-007

TPL-007 Summary

- Requires a **GMD Vulnerability Assessment** of the system for its ability to withstand a Benchmark GMD Event without causing a wide area blackout, voltage collapse, or damage to transformers, once every five years.
  - Applicability: Planning Coordinators, Transmission Planners
- Requires a **Transformer thermal impact assessment** to ensure that all high-side, wye grounded transformers connected at 200kV or higher will not overheat based on the Benchmark GMD Event
  - Applicability: Generator Owners, Transmission Owners

Integrated View of the GMD Assessment Process



Changes Made to the Draft Standard

- Reordered the requirements
  - Comments indicated some confusion as to the order in which the requirements would be executed
- Established a floor of 15 Amperes (A) for Transformer Thermal Assessment
  - If calculated GIC is 15A or less, no further transformer thermal analysis is required
  - Technical justification: Continuous 15A exposure does not result in temperatures of concern, based on transformer testing
- Revised Implementation Plan
  - Moved earlier implementation steps (determine responsibilities, build models)
  - Maintained 4 year timeline to develop Corrective Action Plan

Implementation Plan

Date of Approval

<u>60 Days</u>

- R1
- Identify Responsibilities

<u>14 Months</u>

- R2
- System Models

<u>18 Months</u>

- R5
- GIC Flow Information

<u>36 Months</u>

- R6
- Thermal Assessment

<u>48 Months</u>

- R3, R4, and R7
- GMD Assessment
- Corrective Action Plan

Next Steps

- Formal Comment and Initial Ballot— June 13 – July 30, 2014
  - Technical Conference July 17, 2014
- SDT reviews ballot results and comments—August, 2014
- Post for a second ballot—August, 2014
- Seek NERC Board adoption at November meeting
- File with FERC by January 2015

Summary and Wrap-up