NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Introduction to GMD Studies

A Planner’s Summary Roadmap for GMD Planning Studies

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RELIABILITY | ACCOUNTABILITY

Acknowledgments

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  - Dr. Randy Horton
  - Dr. David Boteler
  - NERC TPL-007-1 Standard Drafting Team

GMD studies for engineers

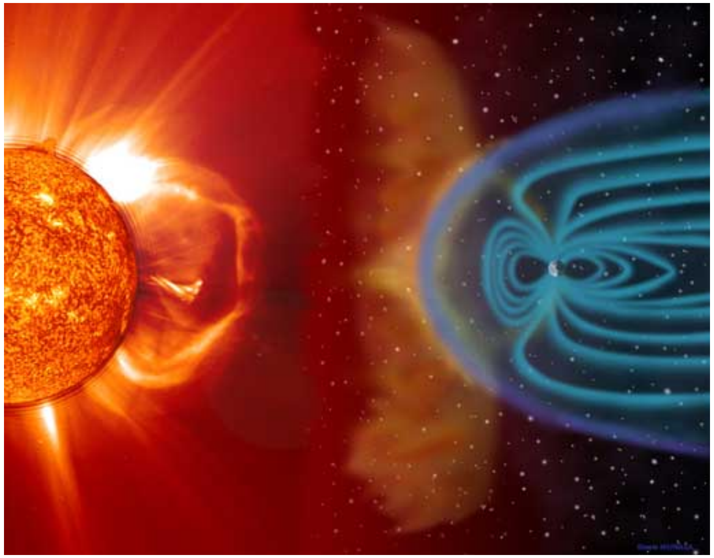
- NERC Draft Standard TPL007-1 requires that applicable entities such as transmission planners and generator owners carry out studies and establish mitigating measures (if any) to meet the reliability performance criteria established by the Geomagnetic Disturbance (GMD) benchmark event.
- The standard and its associated white papers provide references to resources that a planning engineer can use as guidance to carry out GMD assessment studies.
- This tutorial provides an introduction intended to familiarize a planning engineer with the background and salient steps needed to carry out a GMD assessment.

Objectives

- What is a Geomagnetic Disturbance (GMD)
- How does a GMD interact with the power system and what are induced geoelectric fields
- What are earth models
- What are Geomagnetically Induced Currents (GIC)
  - Dependence on earth conductivity
  - Dependence on latitude
- Modelling GIC in the power system
  - Dependence on network parameters
  - Dependence on network configuration
- Effects of GIC on power system apparatus
- What is TPL007
  - Data requirements
  - System studies required for compliance

What is a geomagnetic disturbance

- A geomagnetic disturbance (GMD) event is a consequence of the interaction of the cloud of charged particles produced by the Sun's Coronal Mass Ejections (CME) and the Earth's magnetic field.
- Unlike terrestrial weather, which is local, CMEs that cross the earth's path are global events.



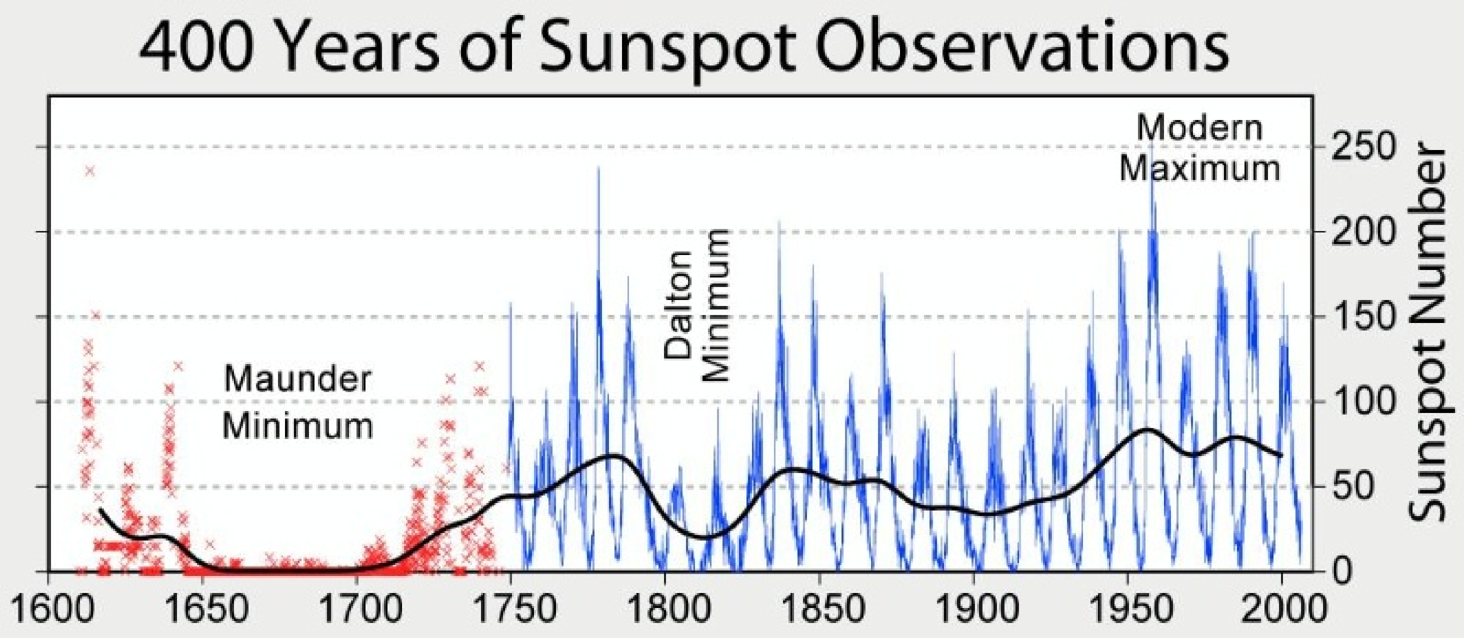
source: www.nasa.gov

[CME animation]

[Hollywood and solar flares]

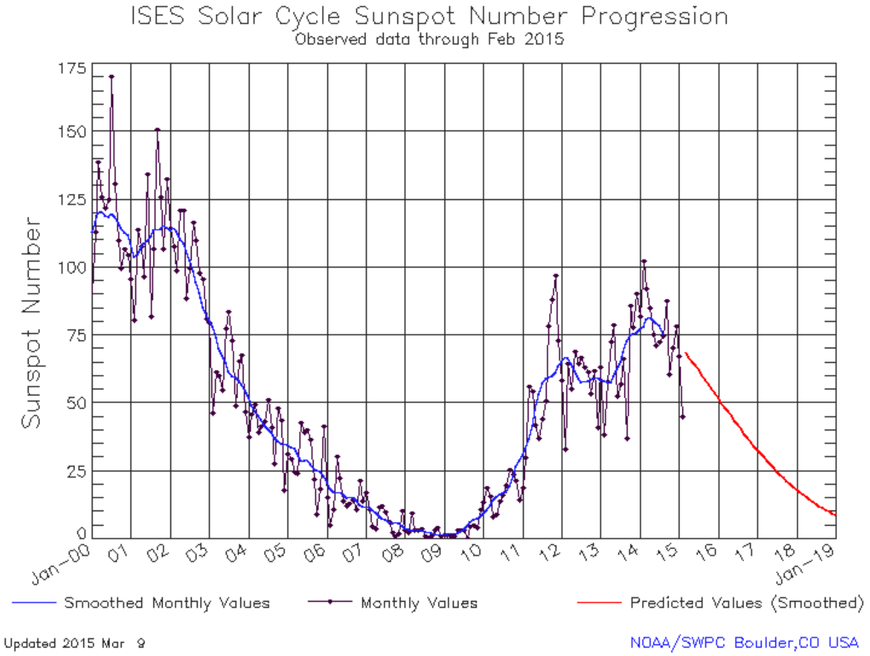
CMEs and the sunspot cycle

- The Sun undergoes an 11-year cycle, where the polarities of its north and south poles reverse.
- Most solar storms and CMEs occur during a 4-6 year period referred to as “solar maximum”

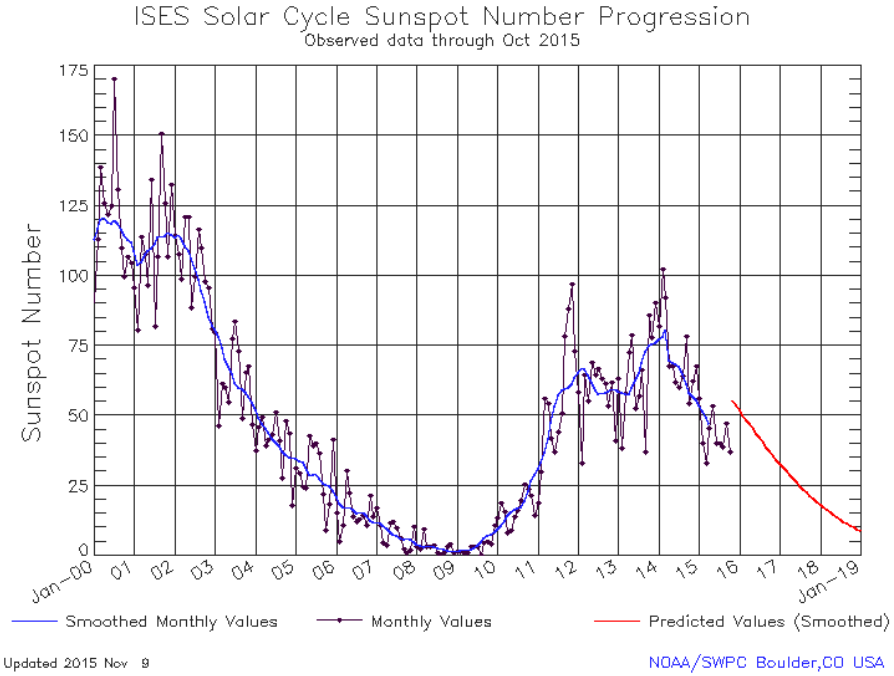


CMEs and the sunspot cycle

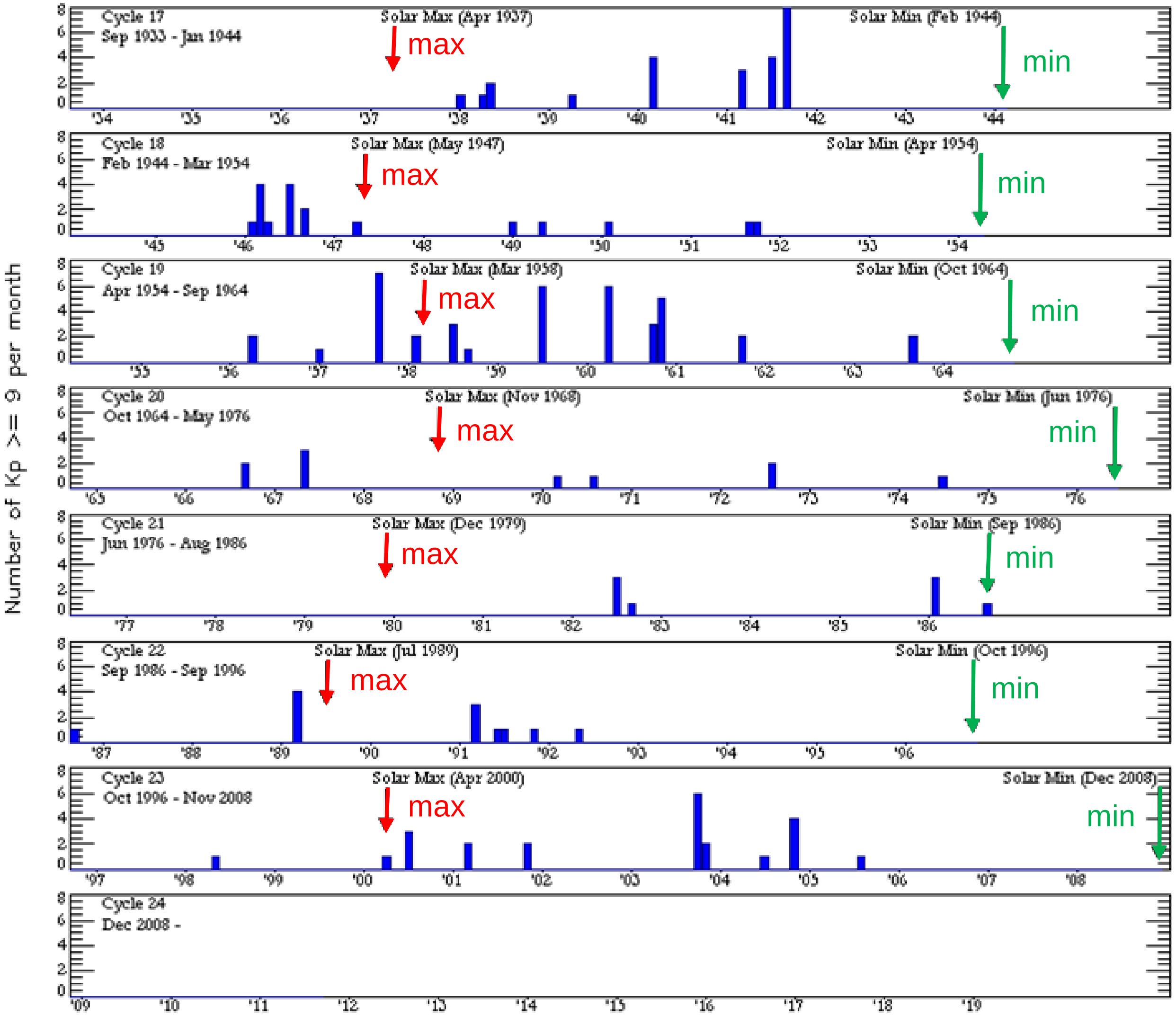
- Probability of a solar storm occurrence is greater during the peak of the solar cycle
- Severe solar storms and CMEs can occur at any time in the cycle
- However, the largest historical solar storms have not occurred at the peak of the "solar maximum"



Sunspot cycle animation



Periodicity of Extreme Events



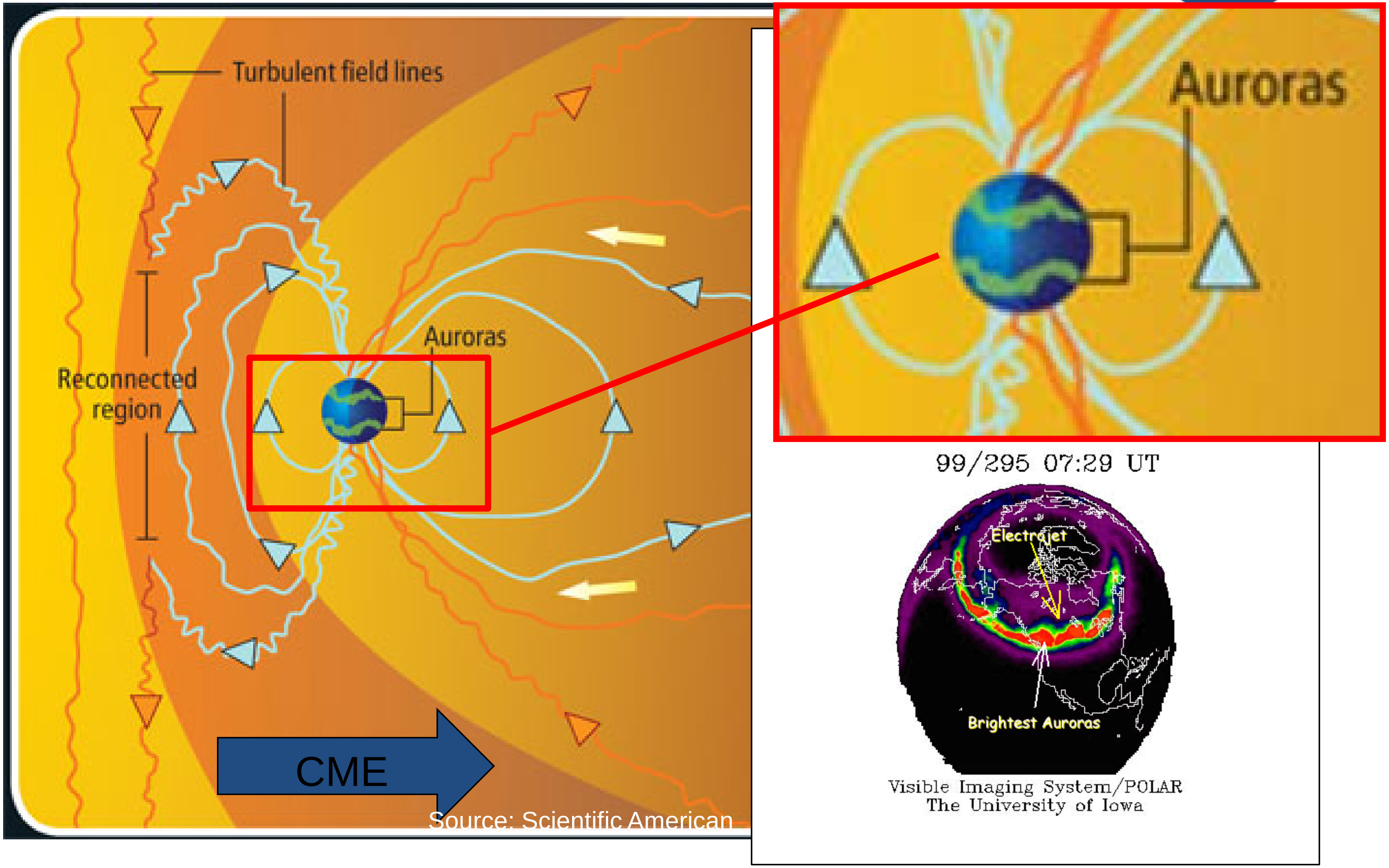
Worst case storms do not generally occur at the solar maximum (number of sunspots)

Source: NOAA Space Weather Prediction Center

CMEs and GMDs

- GMDs occur on Earth one to four days after an earth-directed flare or other eruption on the Sun takes place
  - A CME moves at a rate of about one to five million miles-per-hour.
  - Larger CMEs arrive faster
- If CMEs are Earth-directed, they interact with the Earth’s magnetosphere and increase in the magnitude electrojet currents as well as their width

GMD and CME



Source: Scientific American

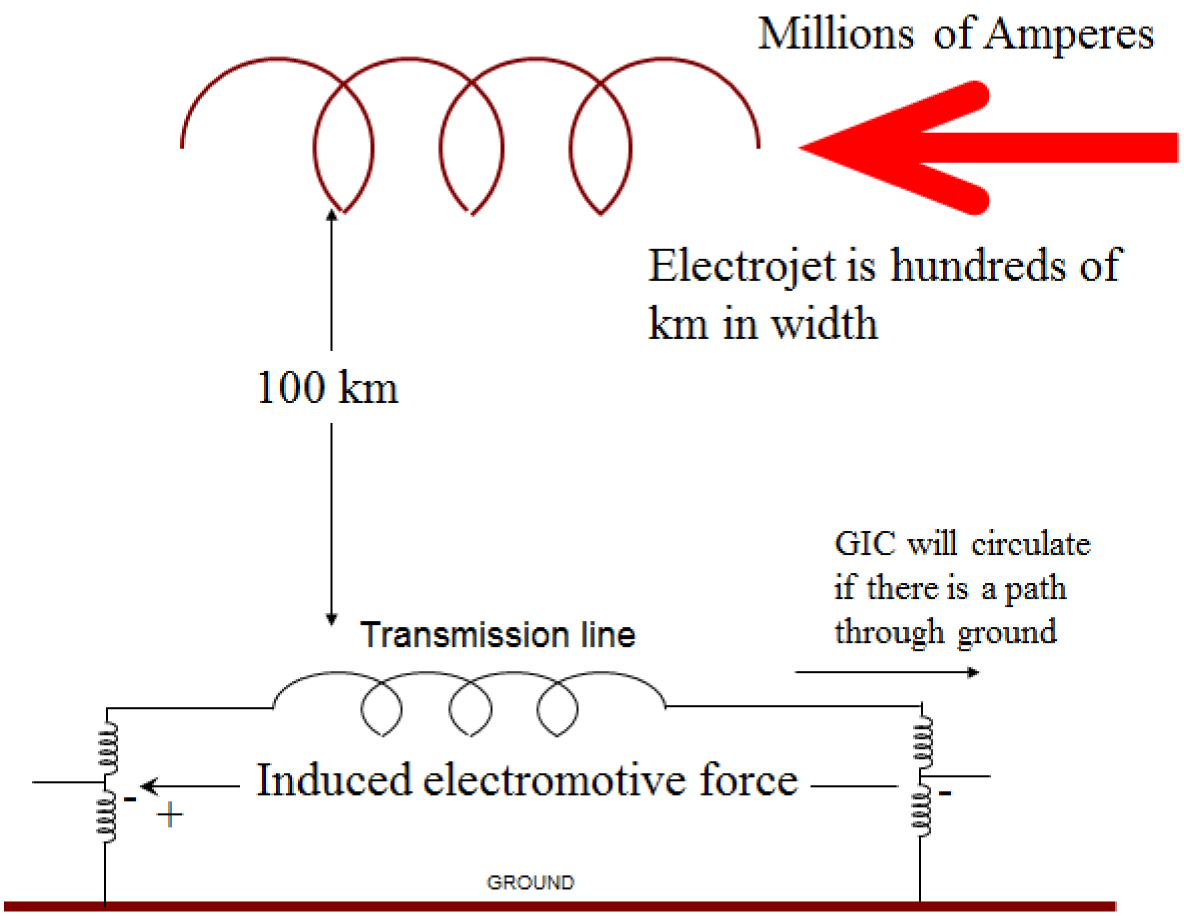
Visible Imaging System/POLAR
The University of Iowa

CMEs and GMDs

- From a power engineer’s point of view, the electrojet can be viewed as a large conductor about 100 km above the earth’s surface carrying currents that can exceed 1,000,000 A
- The interaction of the CME with the electrojet causes slow fluctuations in the electrojet currents which translate into changes in the magnetic field at ground level (geomagnetic field)

How does a GMD interact with the power system?

This is one way to look at it



Take away points

- GMD events do not have to coincide with the solar sunspot maximum
- Likelihood is higher during a sunspot maximum
- Sunspot cycle 24 (now) has been relatively quiet

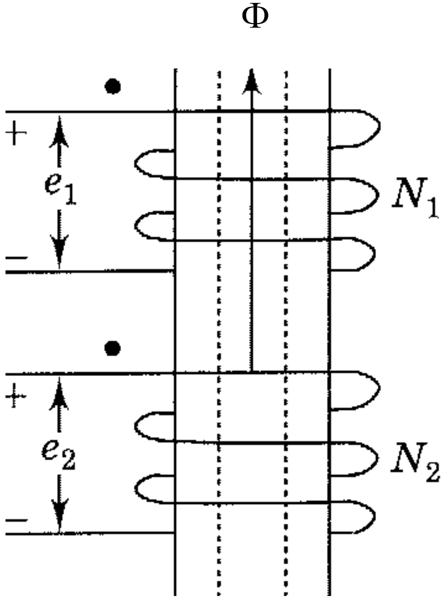
How does a GMD interact with the power system?

Magnetic coupling

- The electrojet can be visualized as a conductor 100 km above the earth carrying slow-varying currents (10 microHertz to 100 milliHertz)
- The electrojet is magnetically coupled with transmission lines at ground level
- The stronger the magnetic coupling between two conductors, the larger their coupling factor
- The earth resistivity determines the coupling factor (high resistivity means large coupling factor - low frequency means high penetration depth)
- After the coupling factor is taken into consideration, the earth is assumed to be a zero resistance return path

Faraday’s Law

- A changing magnetic field through a coil will generate a emf (electromotive force) across the coil
- The change in magnetic environment around the coil could be caused
  - by a change in the flux
  - A change in the distance between the coil and the magnetic field
- The generated emf is proportional to
  - the number of turns
  - Magnetic flux density
  - Rate of change of flux

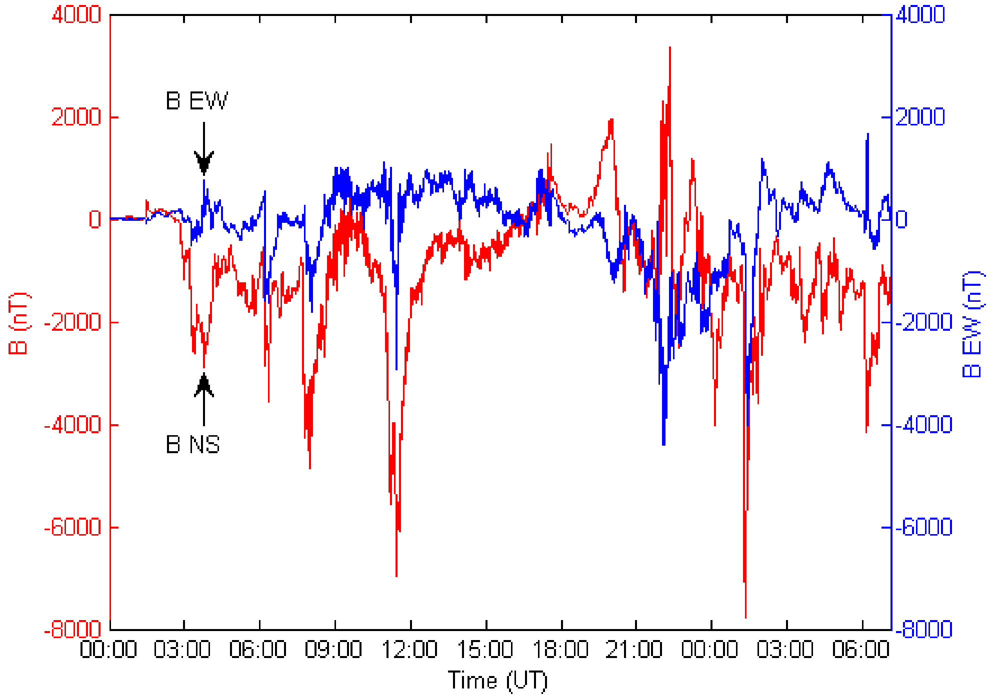


$$v_1 = e_1 = N_1 \frac{d\phi}{dt}$$

$$v_2 = e_2 = N_2 \frac{d\phi}{dt}$$

Magnetic coupling

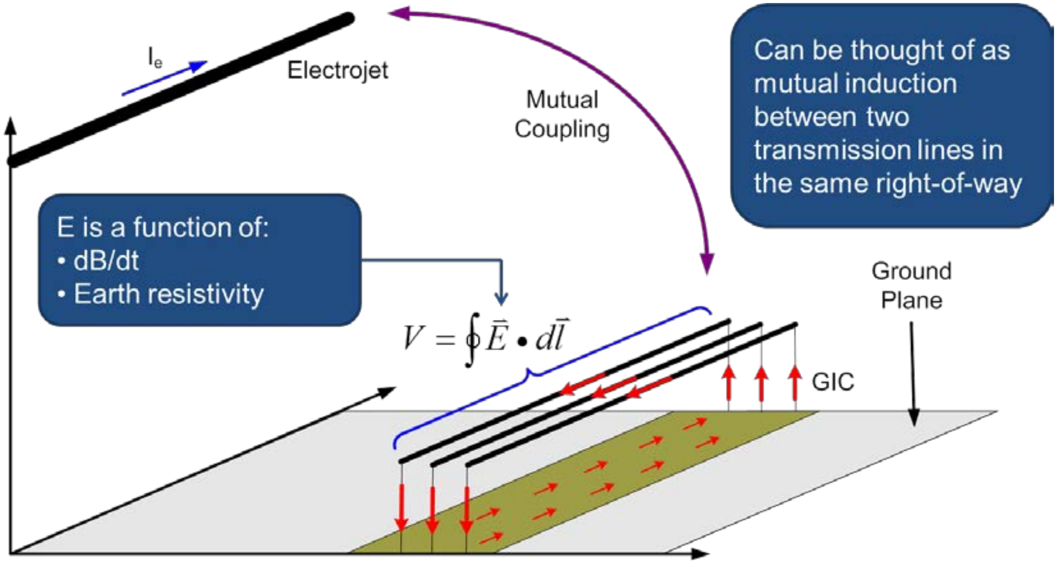
- The geomagnetic field at ground level changes direction and amplitude continuously (but slowly)
- The induced emf or geoelectric field induced on a line depends on the relative orientation of the line and the geomagnetic field



Coupling Factor

Coupling factor depends on the relative orientation of the conductors

- Conductors at right angles means zero coupling
- Geomagnetic field perpendicular to transmission line results in maximum induced geoelectric field



Can be thought of as mutual induction between two transmission lines in the same right-of-way

E is a function of:
- dB/dt
- Earth resistivity

$$V = \oint \vec{E} \bullet d\vec{l}$$

Induced Currents are "Quasi-dc" (mHz)

Transition to practical calculations

- Assume that we do not know (for now) the orientation of a transmission circuit
- The direction of B(t) with respect to a frame of reference (e.g., North-South, East-West) changes with time
- Using superposition we can separate B(t) into two components
  - Bx(t) in the North-South direction
  - By(t) in the East-West direction
- If a circuit is in the North-south direction

$$E_x(t) = c(t) * \frac{dB_y(t)}{dt}$$

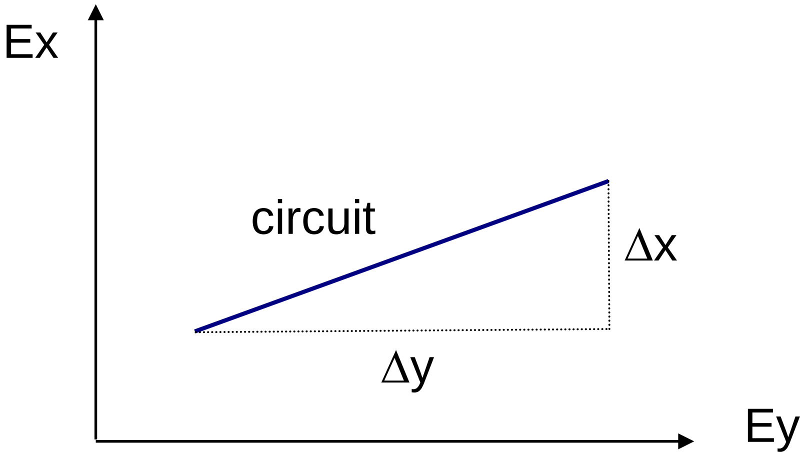
- c(t) represents the earth response (laterally uniform)

Transition to practical calculations

If a circuit is in the East-West direction

$$E_y(t) = -c(t) * \frac{dB_x(t)}{dt}$$

* Means convolution



Then we can say that the induced geoelectric field (x & y) is proportional to the circuit exposure (ΔX & ΔY Cartesian components).

$$E(t) = E_x(t) \cdot \Delta X + E_y(t) \cdot \Delta Y$$

Take away points

- If B(t) is known, the E(t) can be calculated for a given earth model
- The induced geoelectric field on a transmission line can be calculated according to the orientation of the circuit
- If for instance a line is in the N-S direction

$$E(t) = E_x(t) \cdot \Delta X + E_y(t) \cdot 0 = E_x(t) \cdot \Delta X$$

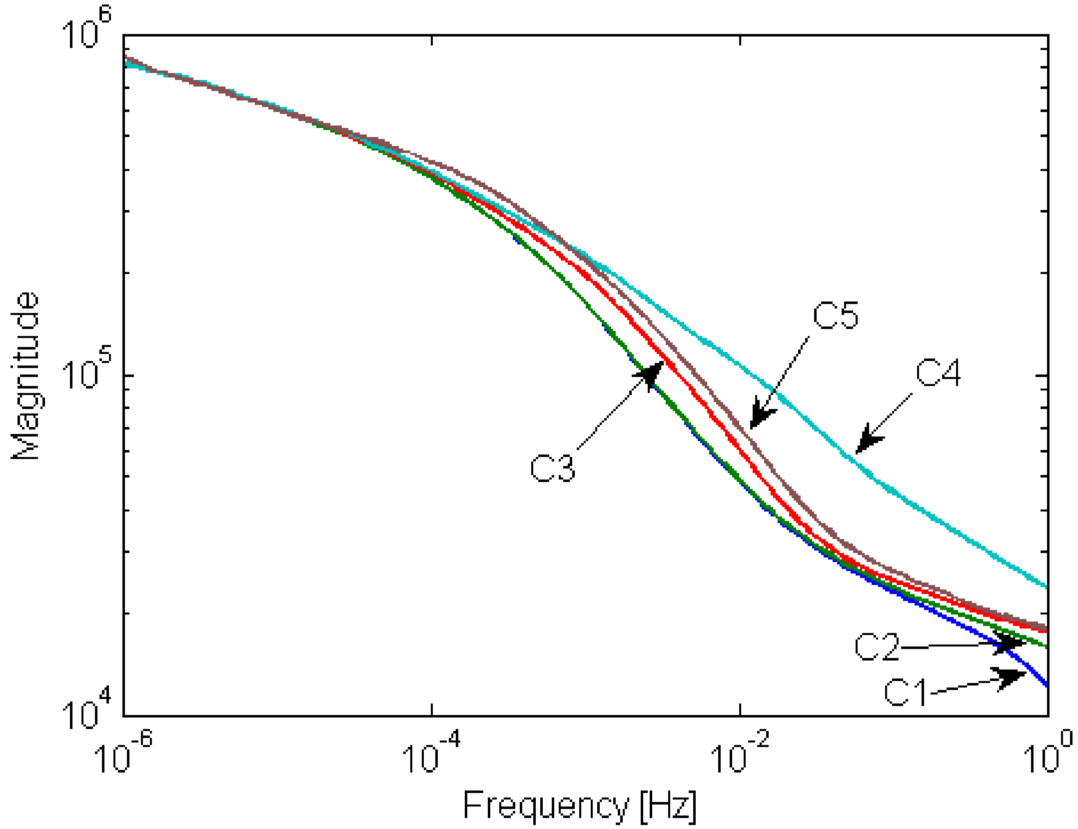
- If for instance a line is in the E-W direction

$$E(t) = E_x(t) \cdot 0 + E_y(t) \cdot 0 = E_y(t) \cdot \Delta Y$$

How do earth models fit in?

The Laterally Uniform Earth Model

- In the frequency domain c(t) looks like this (depending on physiographic region)



$$E_x(\omega) = C(\omega) \cdot G_y(\omega)$$

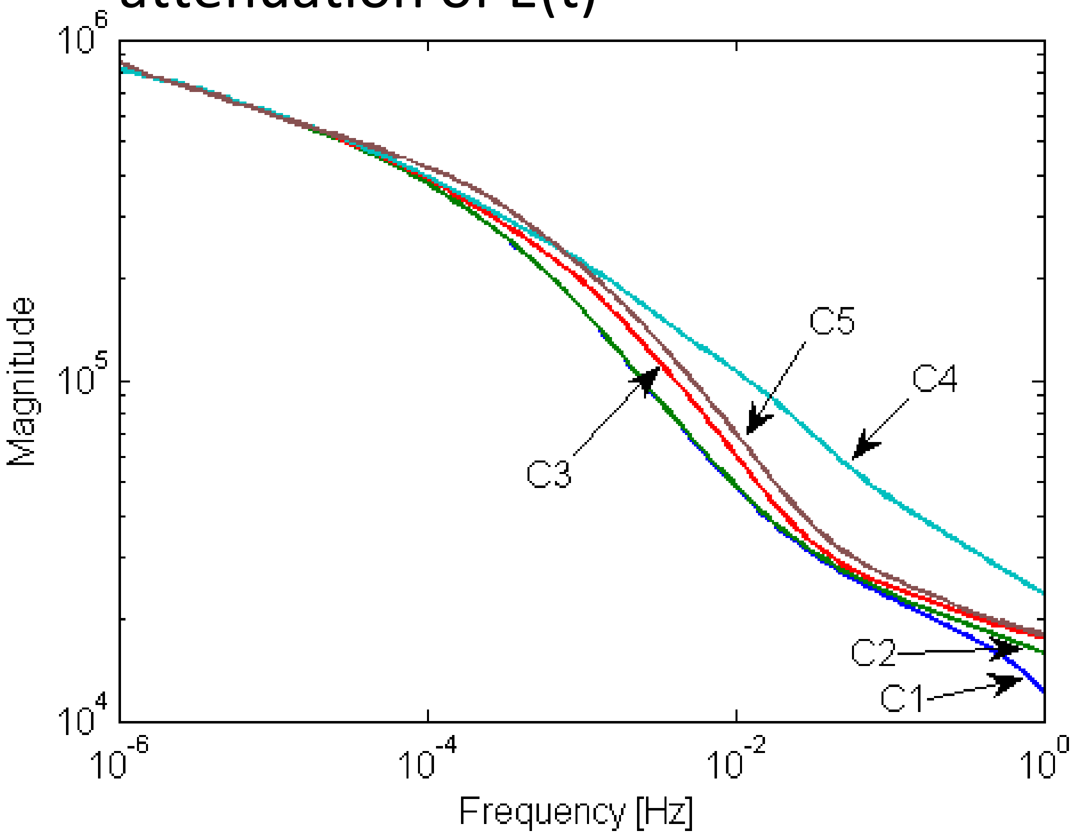
$$E_y(\omega) = -C(\omega) \cdot G_x(\omega)$$

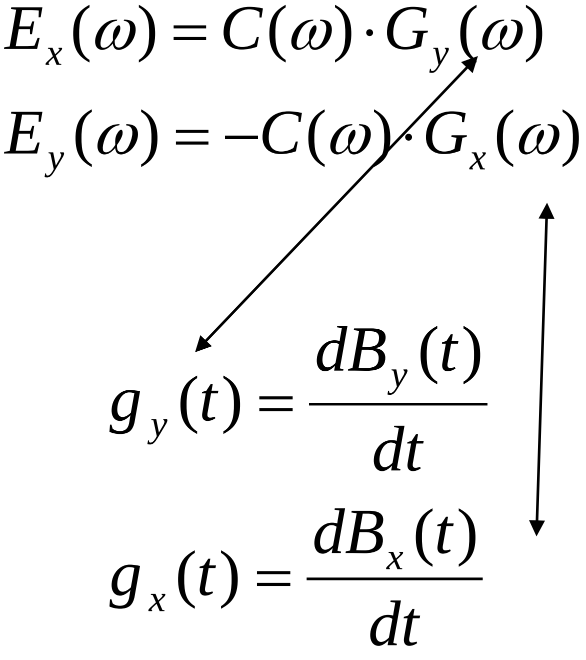
$$g_y(t) = \frac{dB_y(t)}{dt}$$

$$g_x(t) = \frac{dB_x(t)}{dt}$$

The Laterally Uniform Earth Model

- The higher the frequency content of dB(t)/dt, the higher the attenuation of E(t)





$$E_x(\omega) = C(\omega) \cdot G_y(\omega)$$

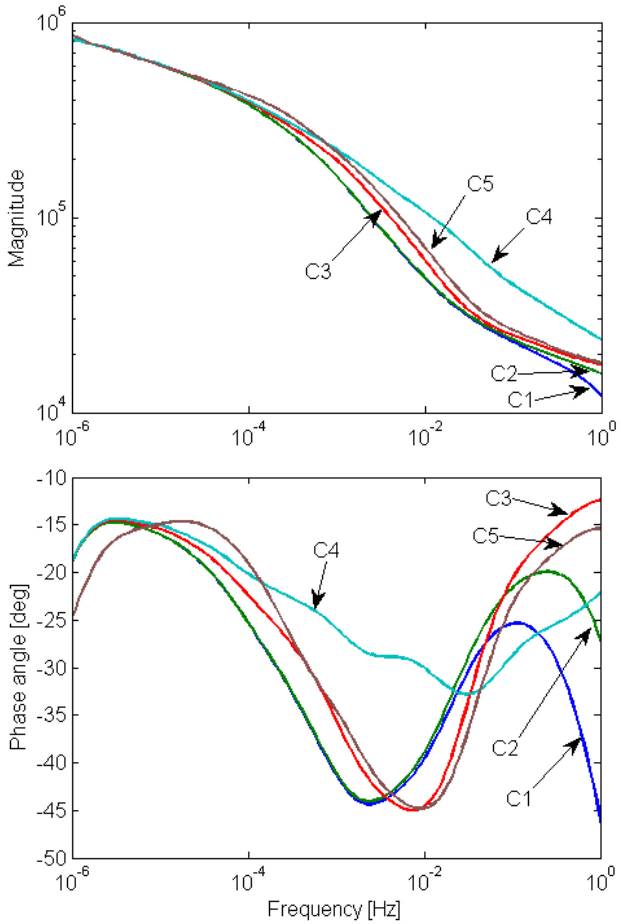
$$E_y(\omega) = -C(\omega) \cdot G_x(\omega)$$

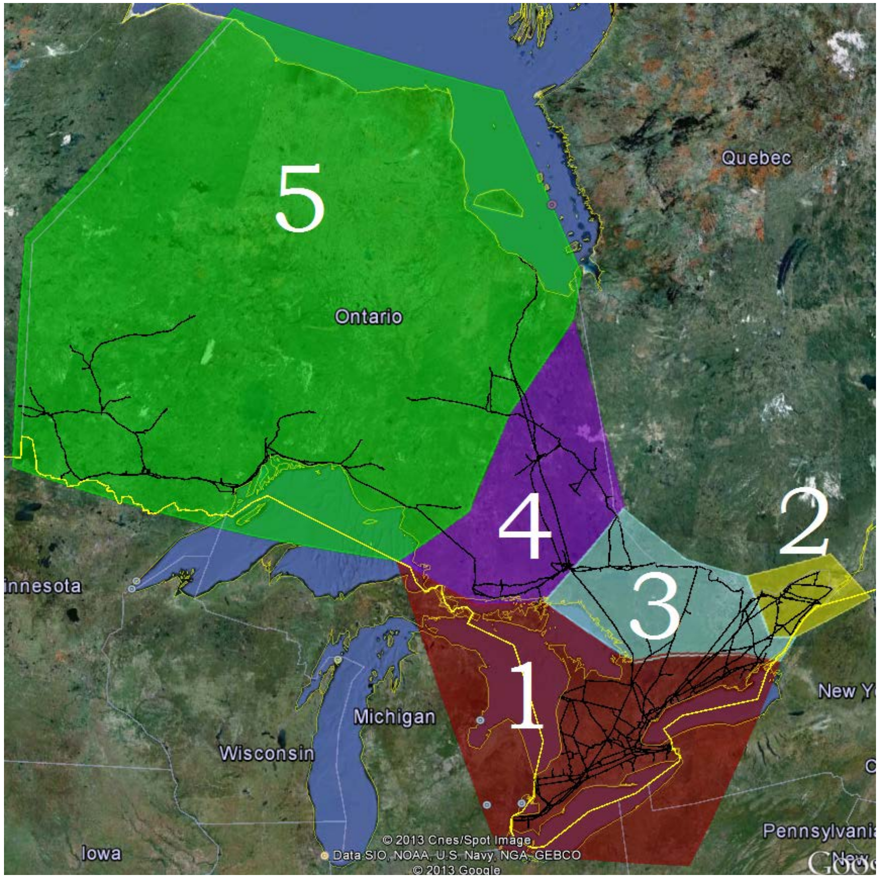
$$g_y(t) = \frac{dB_y(t)}{dt}$$

$$g_x(t) = \frac{dB_x(t)}{dt}$$

In Ontario

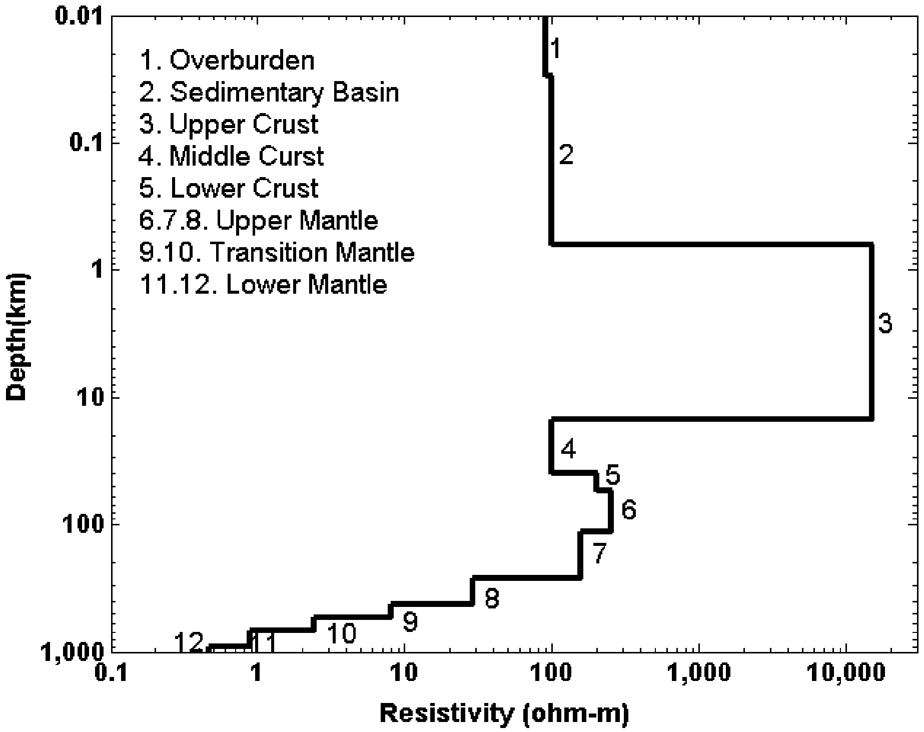
- Five major regions in parts of Ontario where there are HV transmission circuits

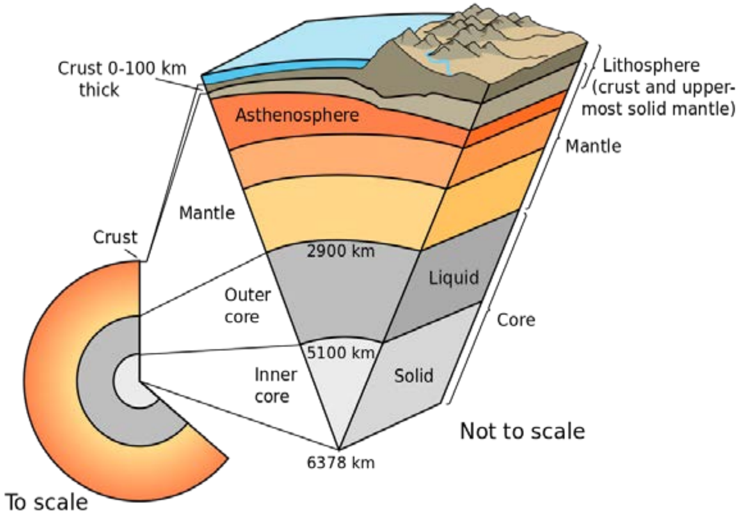




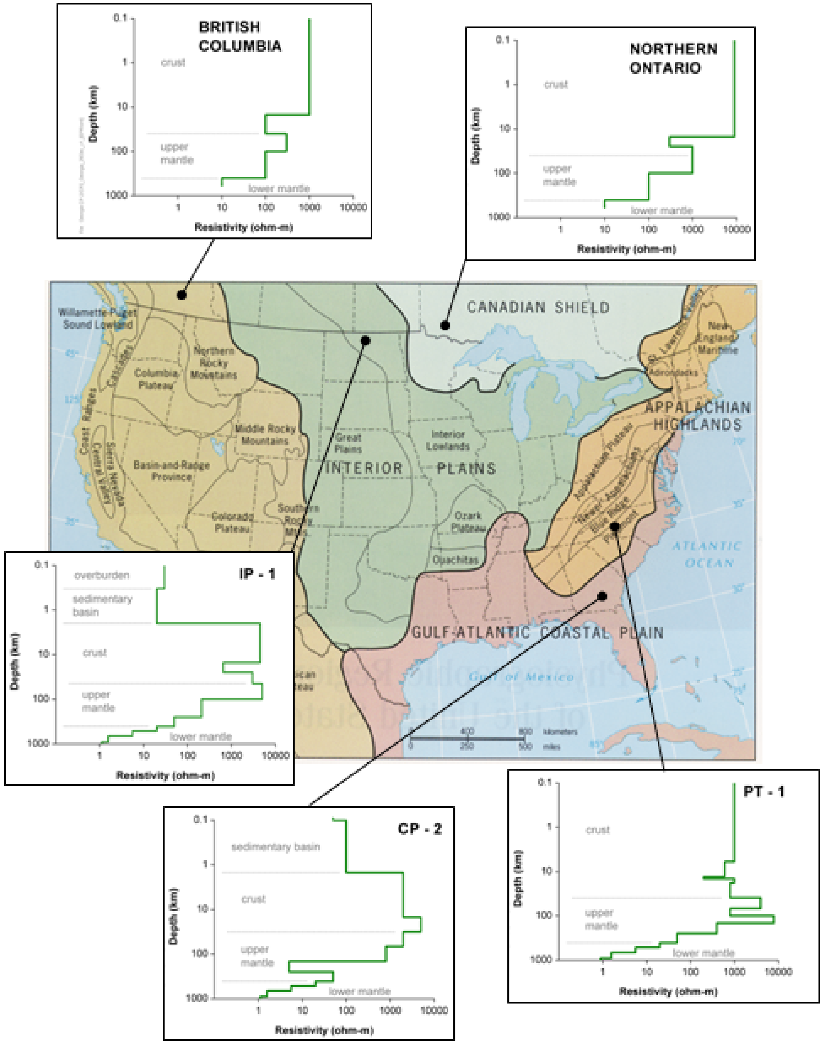
The Earth Model

- The term laterally uniform indicates that the earth is assumed to consist of "horizontal" uniform layers



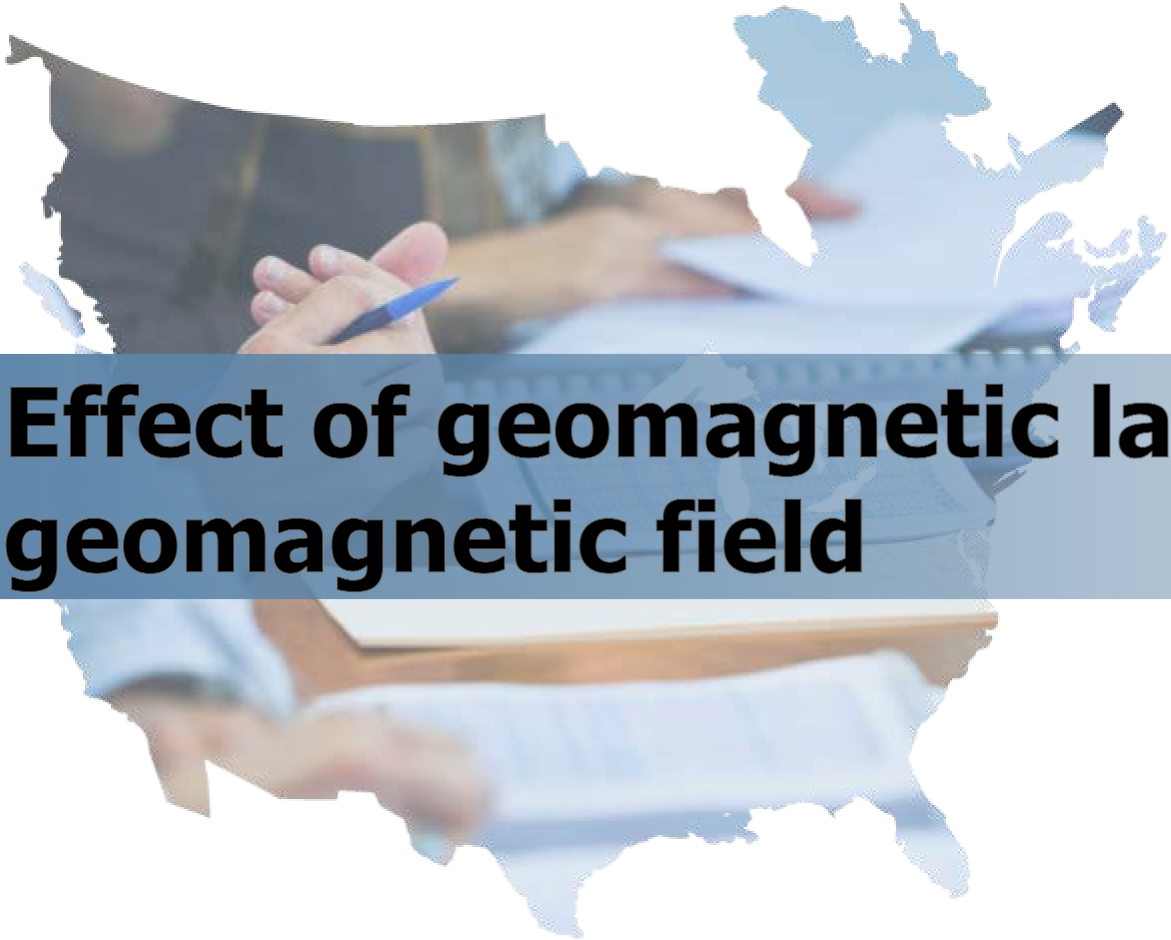


Earth Models



The E(t) is slow-varying

- E(ω) is of the order of 10 microHertz to 100 milliHertz
- Low frequency means high depth of penetration
- Layered earth models with depths of up to 1000 km must be used
- Resistivity data used to perform calculations at 60 Hz are not suitable for GIC calculations



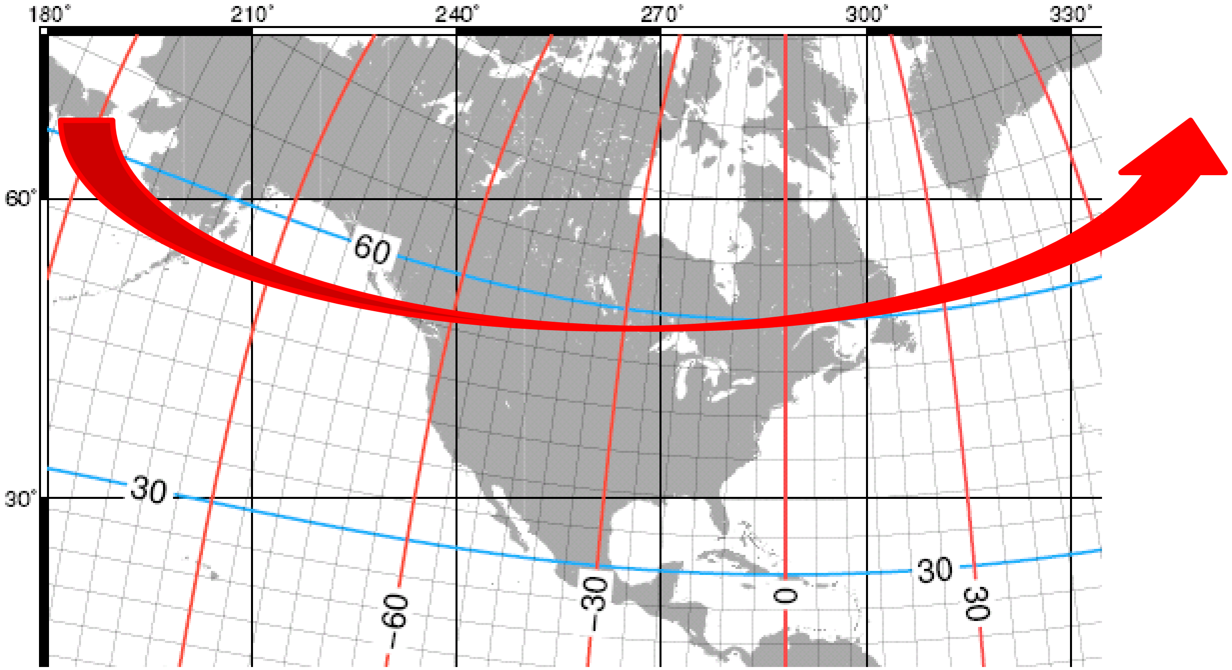
Effect of geomagnetic latitude on the geomagnetic field

Geomagnetic Latitude

- Geomagnetic latitude uses the location of the magnetic poles as points of reference, rather than the geographic poles
- Main reason is that the magnetic poles “move” over time relative to the geographical poles

Effect of Geomagnetic Latitude

- Research findings indicate that that the geoelectric field magnitudes experience a dramatic drop (factor of 10) across a boundary located at about 40-60 degrees of geomagnetic latitude
- Statistically, peak geoelectric fields also drop off according to geomagnetic latitude



Electrojet
(~line current)

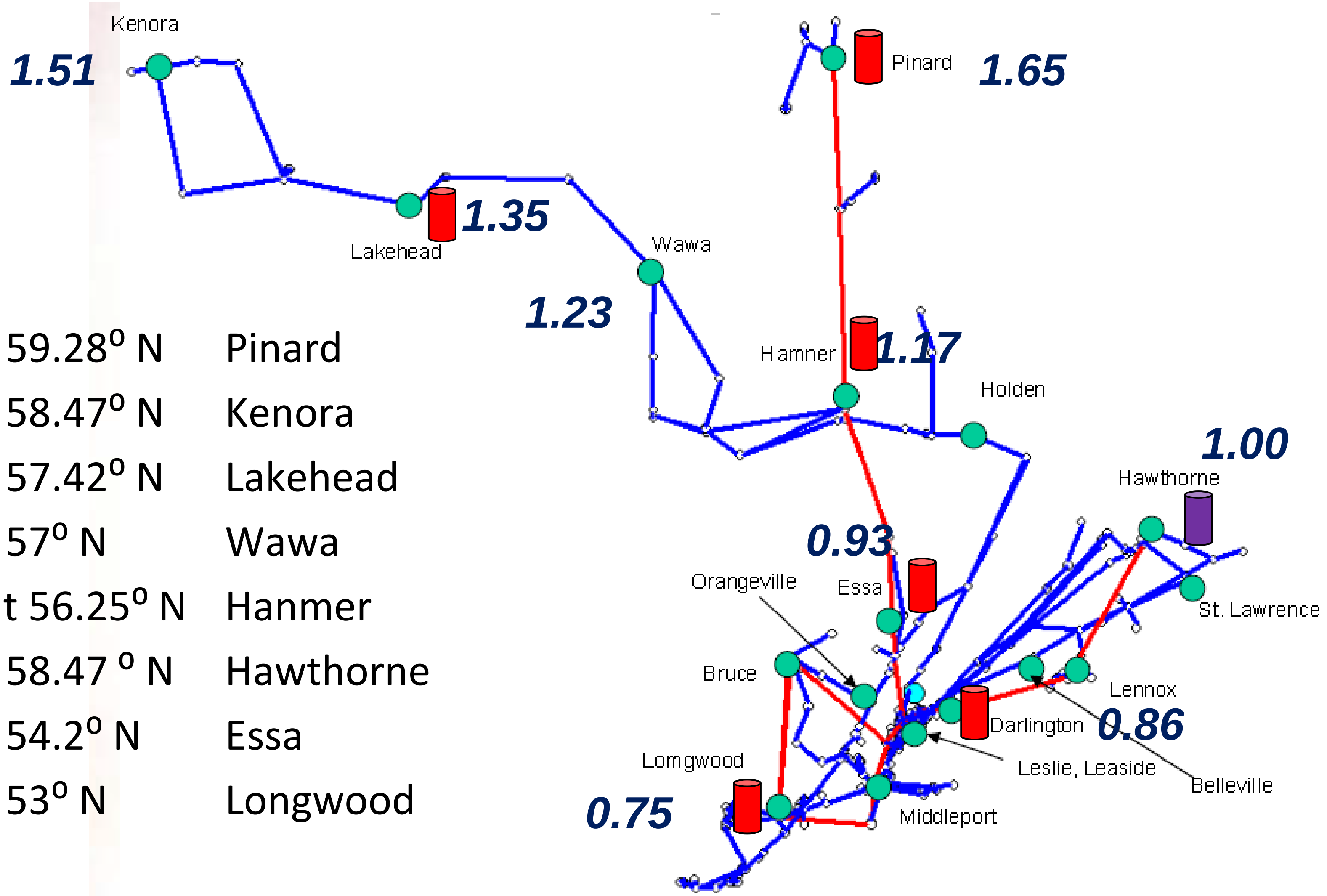
Alpha scaling factor

- Part of TPL-007
- Based on statistical observations
- As you move away from the magnetic pole the peak geoelectric field goes down

Geomagnetic Field Scaling Factors

Geomagnetic Latitude (Degrees)	Scaling Factor (α)
≤ 40	0.10
45	0.2
50	0.3
54	0.5
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

Different alpha factors in geographically large system



$\alpha = 0.91$ at 59.28° N	Pinard
$\alpha = 0.83$ at 58.47° N	Kenora
$\alpha = 0.74$ at 57.42° N	Lakehead
$\alpha = 0.70$ at 57° N	Wawa
$\alpha = 0.645$ at 56.25° N	Hanmer
$\alpha = 0.55$ at 58.47 ° N	Hawthorne
$\alpha = 0.51$ at 54.2° N	Essa
$\alpha = 0.41$ at 53° N	Longwood

Take away points

- The earth model is very important for the calculation of the E(t)
- It is frequency dependent
  - Higher frequency components of dB(t)/dt are attenuated more than lower frequency components
  - The conductivity of deeper earth layers is important for the lower frequency components of dB(t)/dt
- A simple uniform earth model is an oversimplification
- Typical 60Hz earth resistivity is not applicable to geoelectric field calculations
- Statistically, the farther away for the magnetic pole, peak geoelectric fields (for a given earth model) drop off significantly
- Physically, the farther away from the electrojet, the geomagnetic field the lower the geomagnetic field at ground level.

Modelling GIC

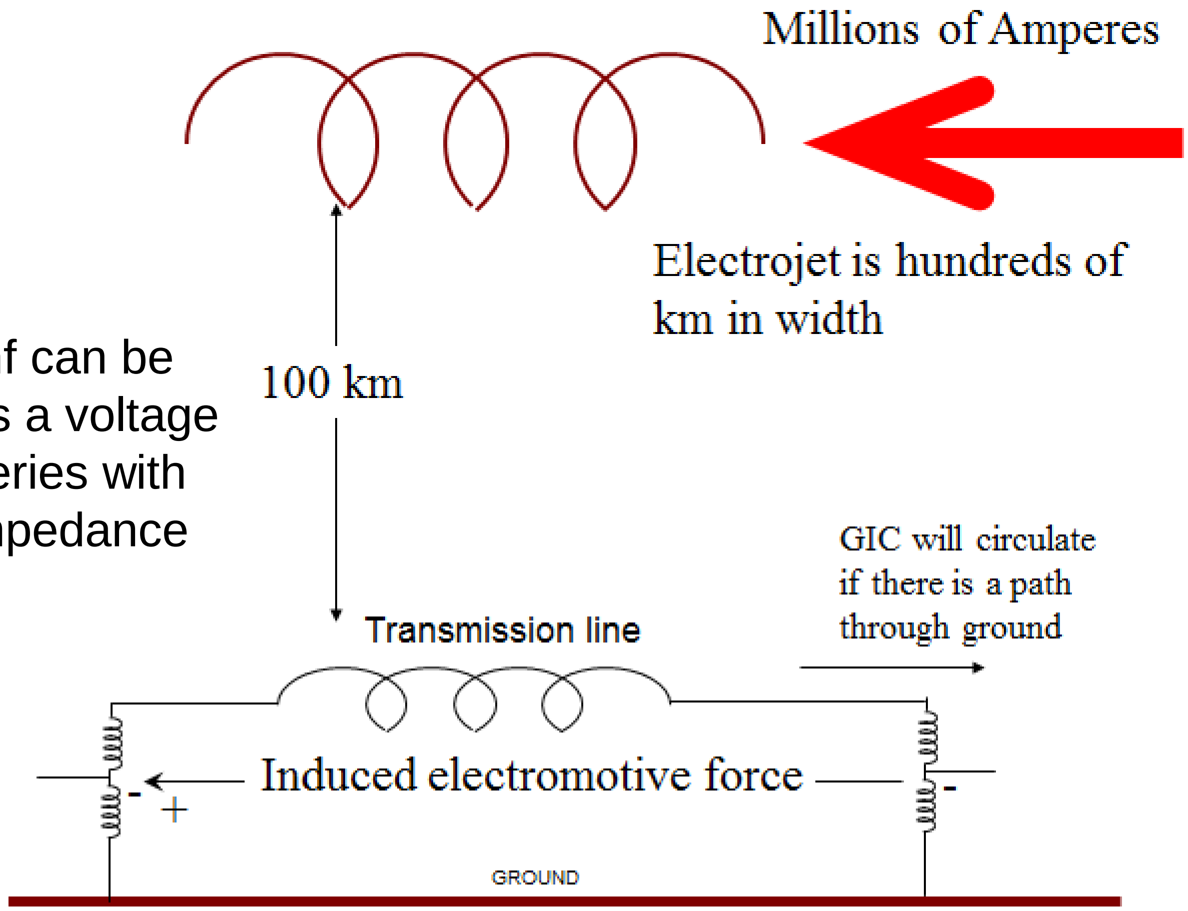
What is GIC modelling

- In the context of TPL-007:
  - Solution of a dc network to calculate the distribution of GIC in a power network
  - Path to ground forming a closed loop is required
  - GIC simulations are steady-state simulations
    - No transient GIC build-up
    - No harmonics or 60 Hz power flow
    - Geoelectric field is assumed to be constant for one given orientation and earth model: Ex and Ey

Basic modelling principles

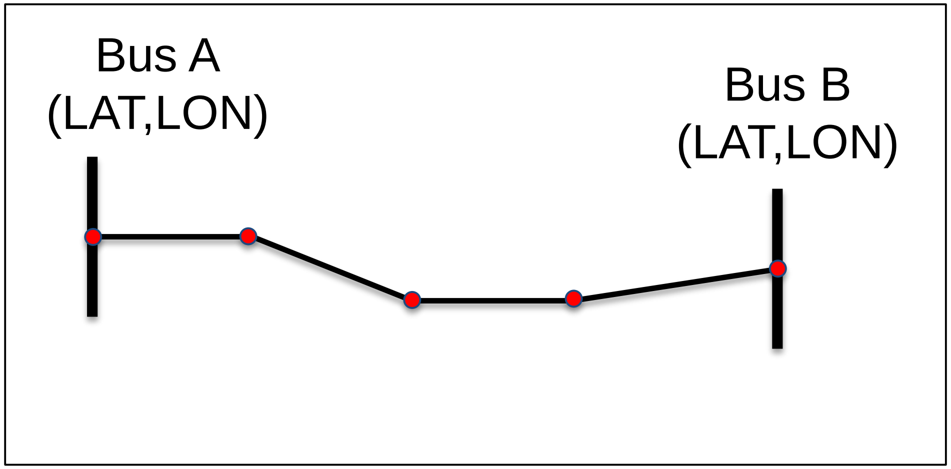
- Frequency is sufficiently low (10 microHertz to 100 milliHertz) that the network is assumed to be resistive
- X/R in the HV network at 60 Hz is between 10 and 20
- At 100 mHz X/R would 600 times smaller
- Induced emf is represented as a voltage source in series with a transmission line
- The geographical coordinates of the transmission lines must be known to calculate ΔX and ΔY
- Grounded transformers are modelled as resistive branches
- Equivalent station grounding resistance must be included
- HV shunt reactors may be included. Tertiary connected shunt reactors are not.

Geomagnetically Induced Currents (GIC)



Induced emf can be modelled as a voltage source in series with the line’s impedance

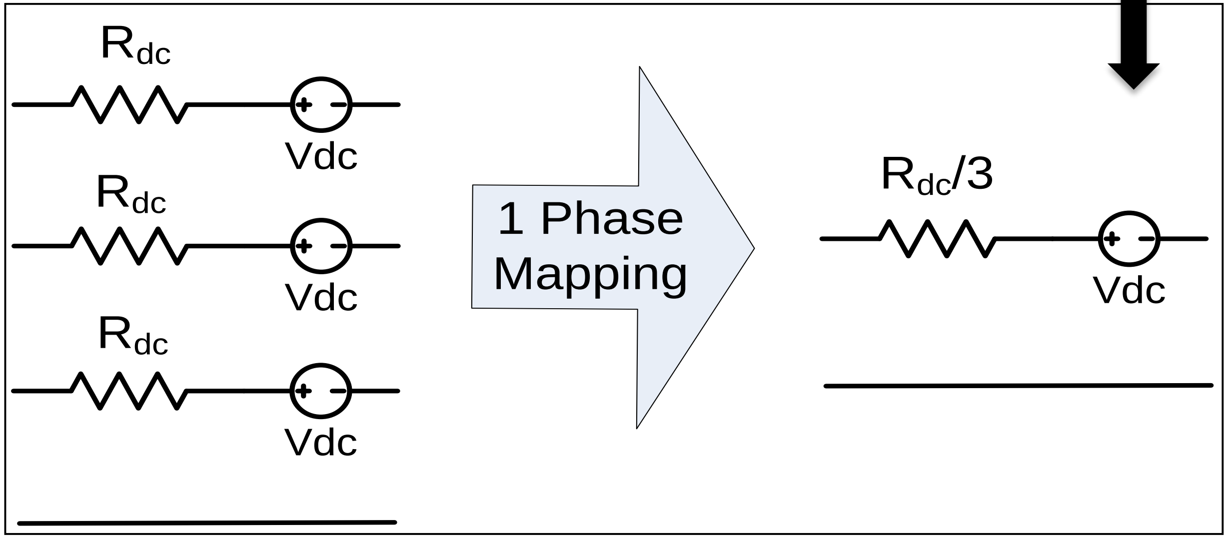
Transmission Line Model



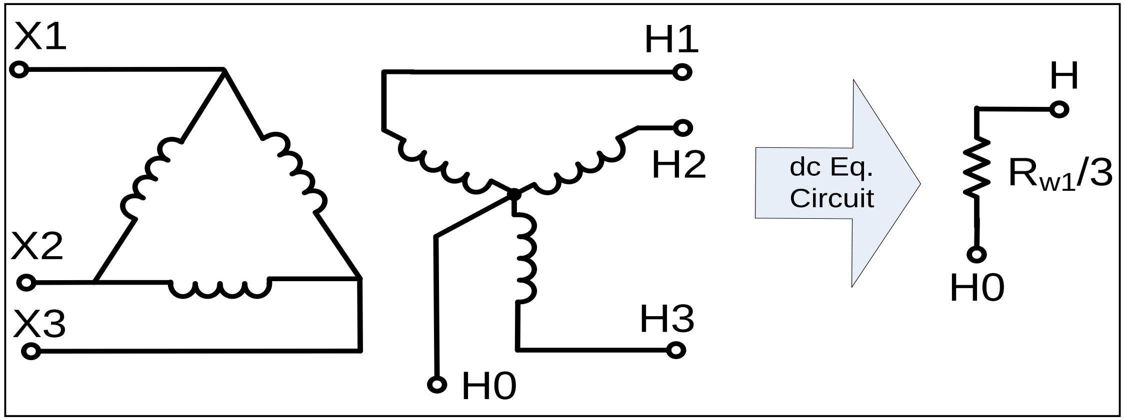
$$V = \oint \vec{E} \circ d\vec{l}$$

If uniform E field

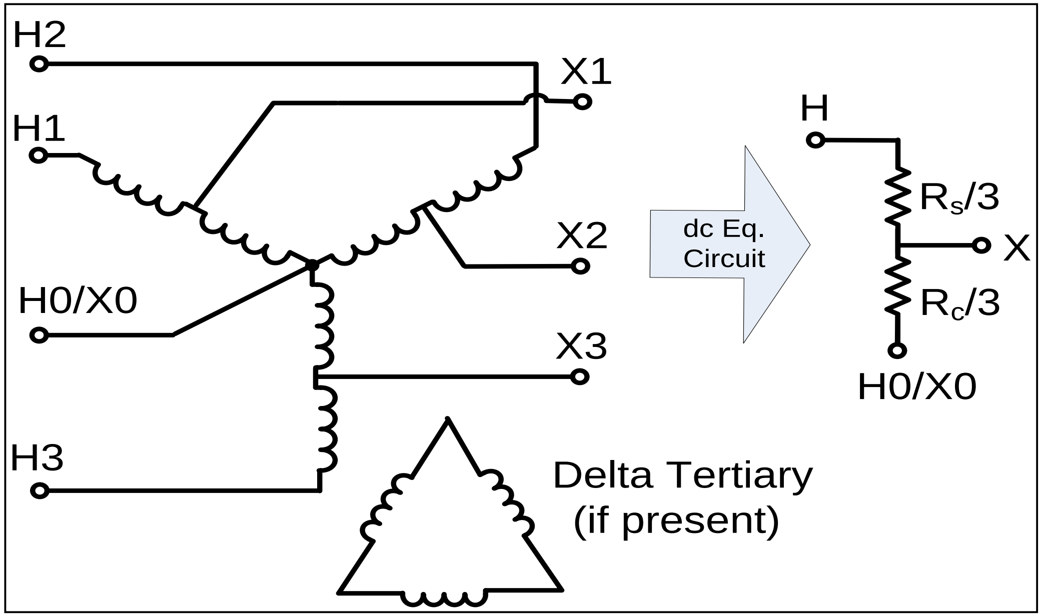
$$\vec{E} \circ \vec{L} = E_x L_x + E_y L_y$$



dc Transformer Model



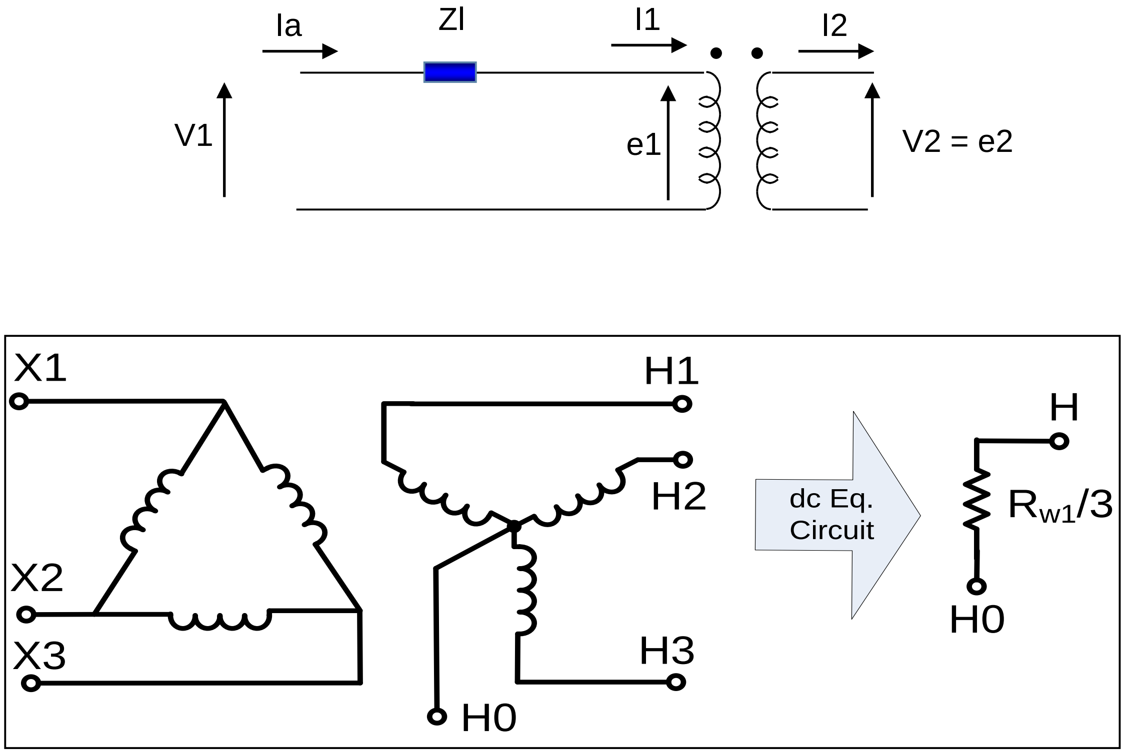
GSU Example



Autotransformer Example

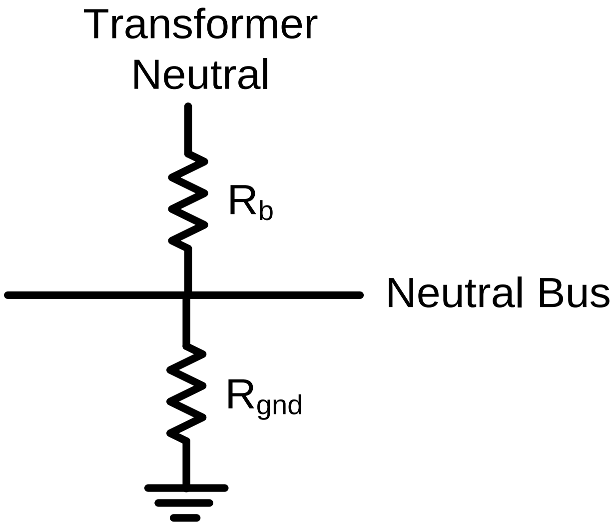
dc Transformer Model

- Must emphasize that this is a dc steady-state model



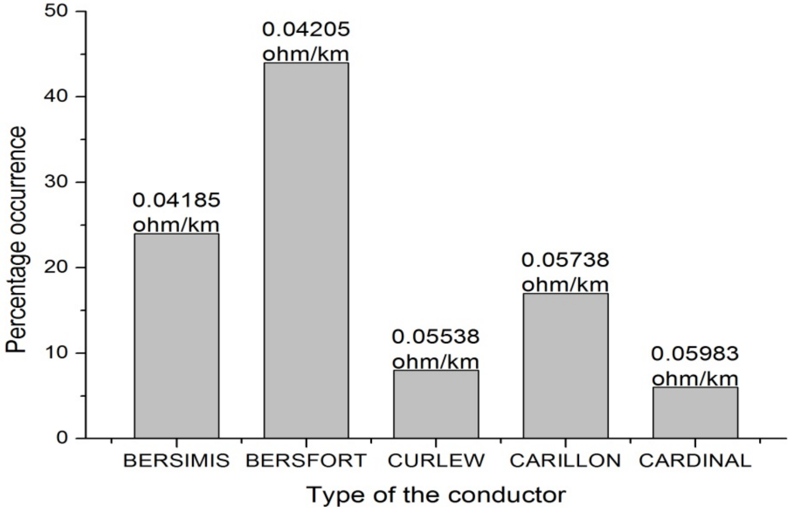
Substation Ground Grid

- The substation ground grid resistance including the effects of any grounded line conductors (e.g. shield wires or neutrals) is required



Transmission lines

- Conductor dc resistance (from datasheets). Not the real part of positive sequence impedance
  - Ohm/km Ohm/mile
- Conductor bundles
  - bundles typically dependent on voltage level
  - Line Length (Actual, not point-to-point)

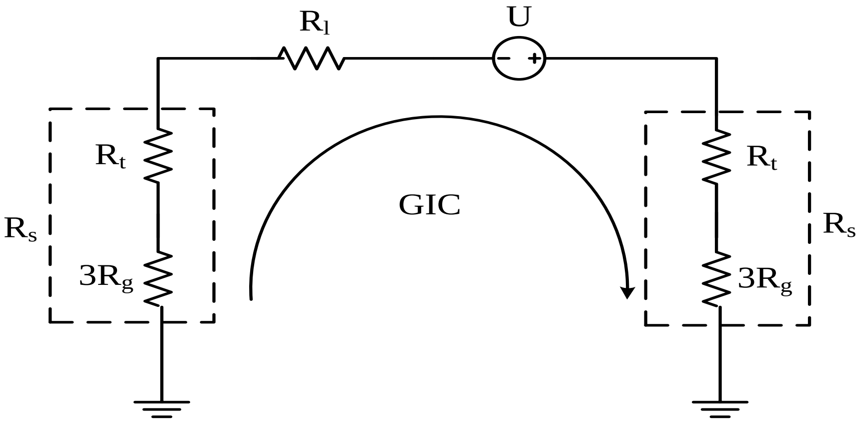


Assorted modelling details

- Shunt capacitors are infinite resistances to ground and can be ignored
- GIC does not increase indefinitely with line length
  - Geoelectric field is proportional to line length
  - dc resistance is proportional to line length

Effect of Line Length

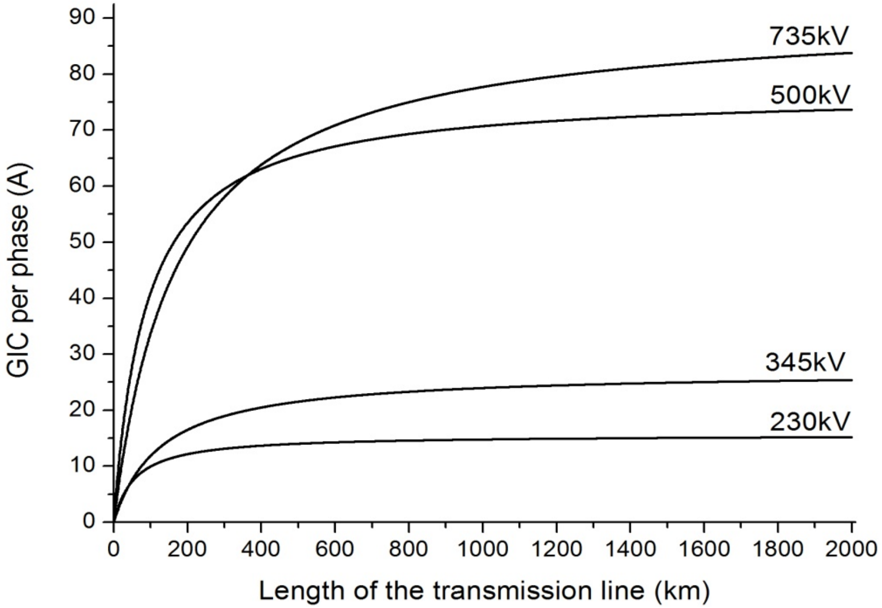
- Depends on the number of transformers and circuits in a loop



$$GIC = \frac{U}{R_l + 2R_s} = \frac{E_l \cdot l}{r \cdot l + 2R_s}$$

Maximum GIC

$$GIC_{\max} = \frac{E_l}{r}$$

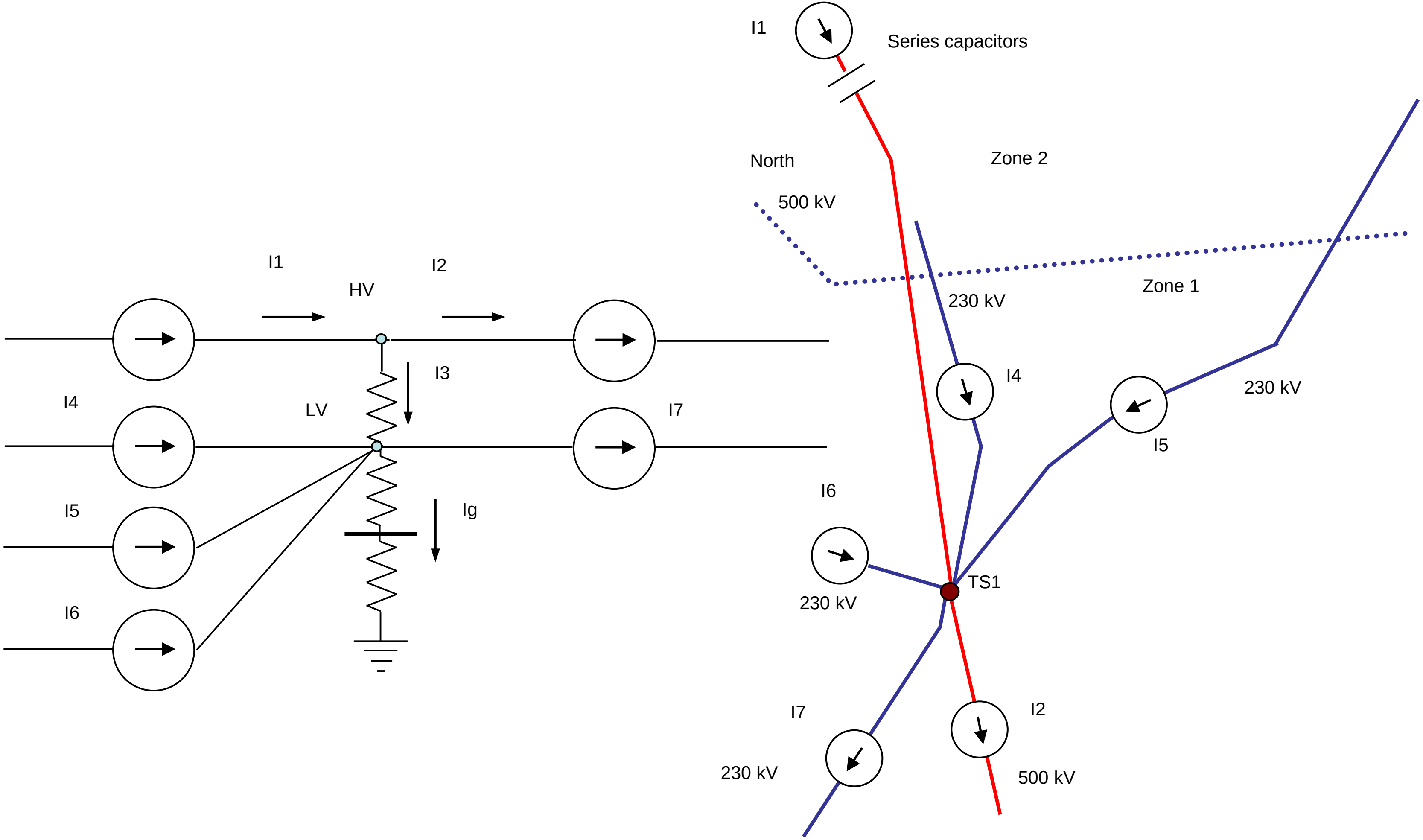


Assorted modelling details

- Series capacitors effectively block GIC on the transmission circuit in which they are in service.
    - Series capacitors used for compensation re-direct GIC flow.
- Some common intuitive expectations do not hold true
    - In power systems we are used to voltage sources connected to ground
    - In GIC calculations we deal with voltage sources in series with lines

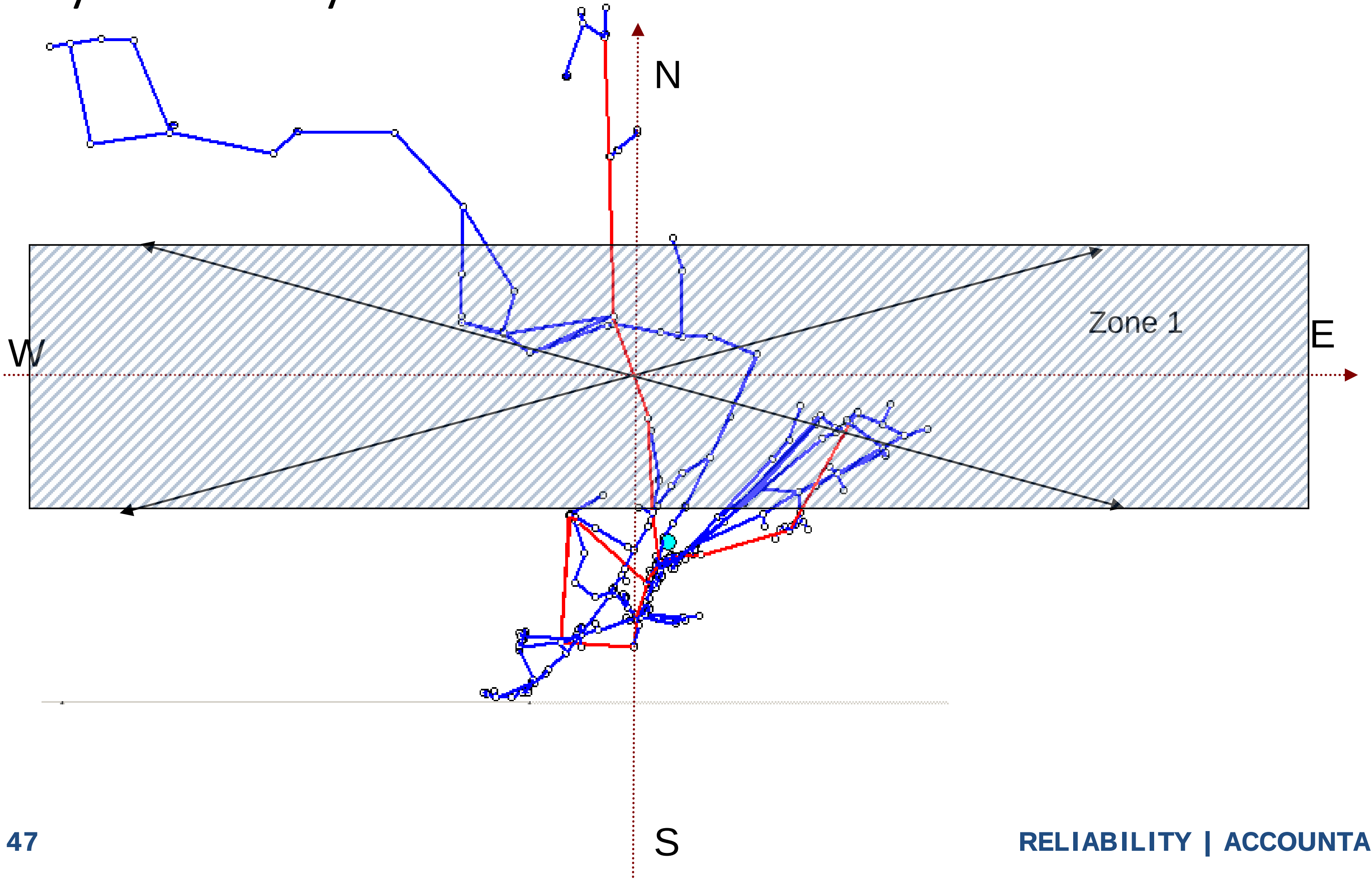
GIC redirection

- In this instance, series compensation capacitors increase GIC in TS1 when they are in service



Orientation

The orientation of the geoelectric field must be changed systematically to assess worst conditions



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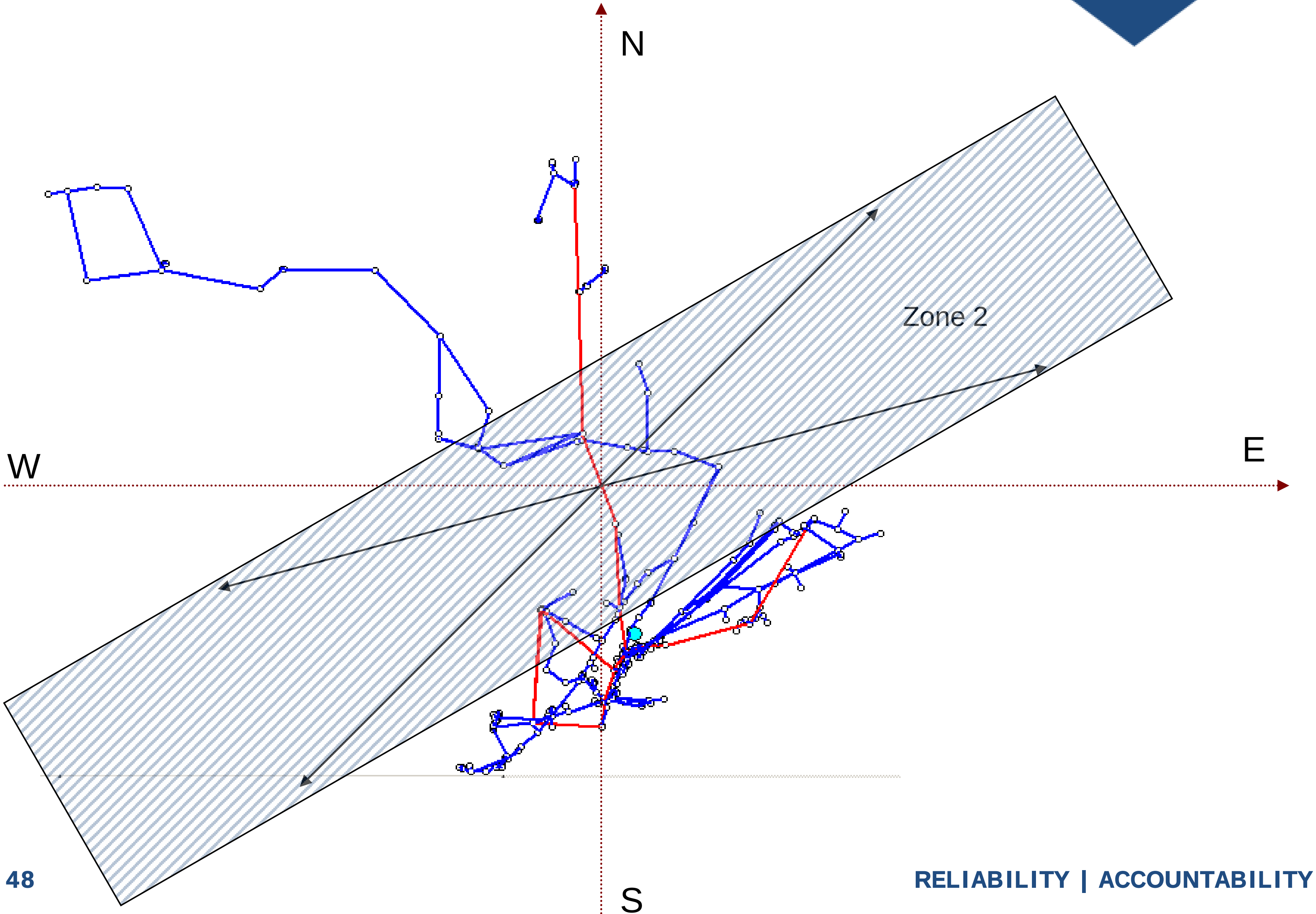

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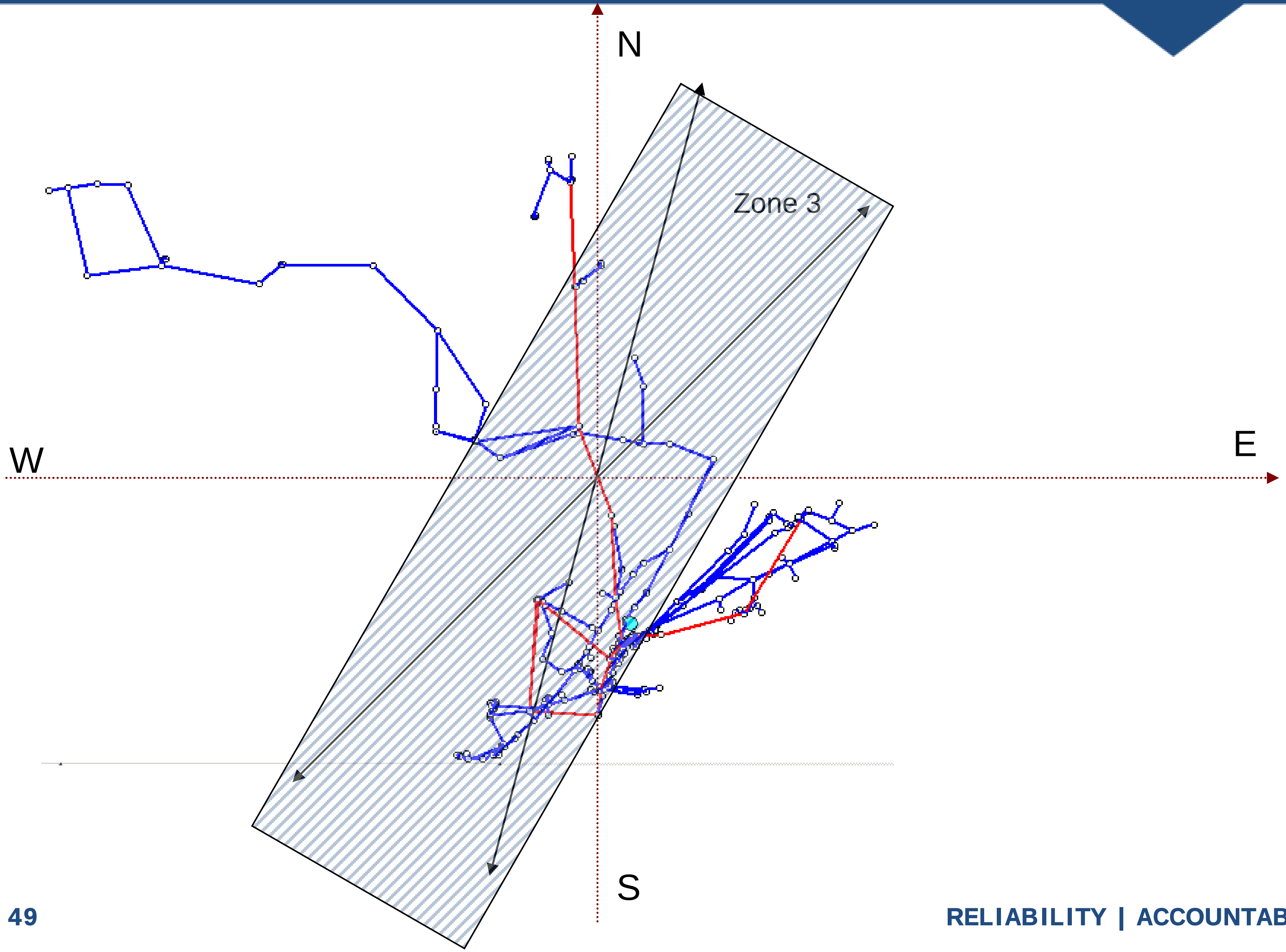

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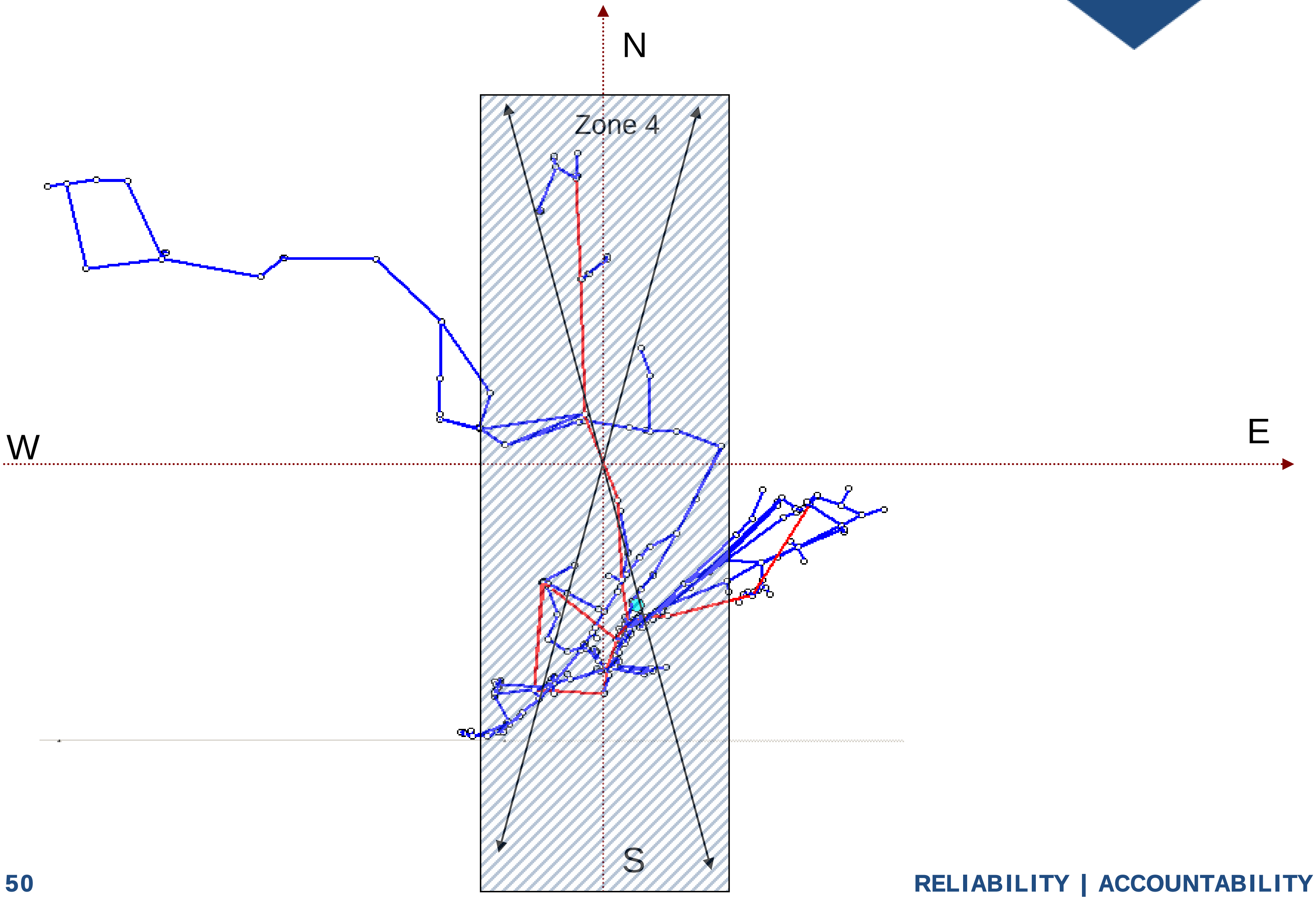

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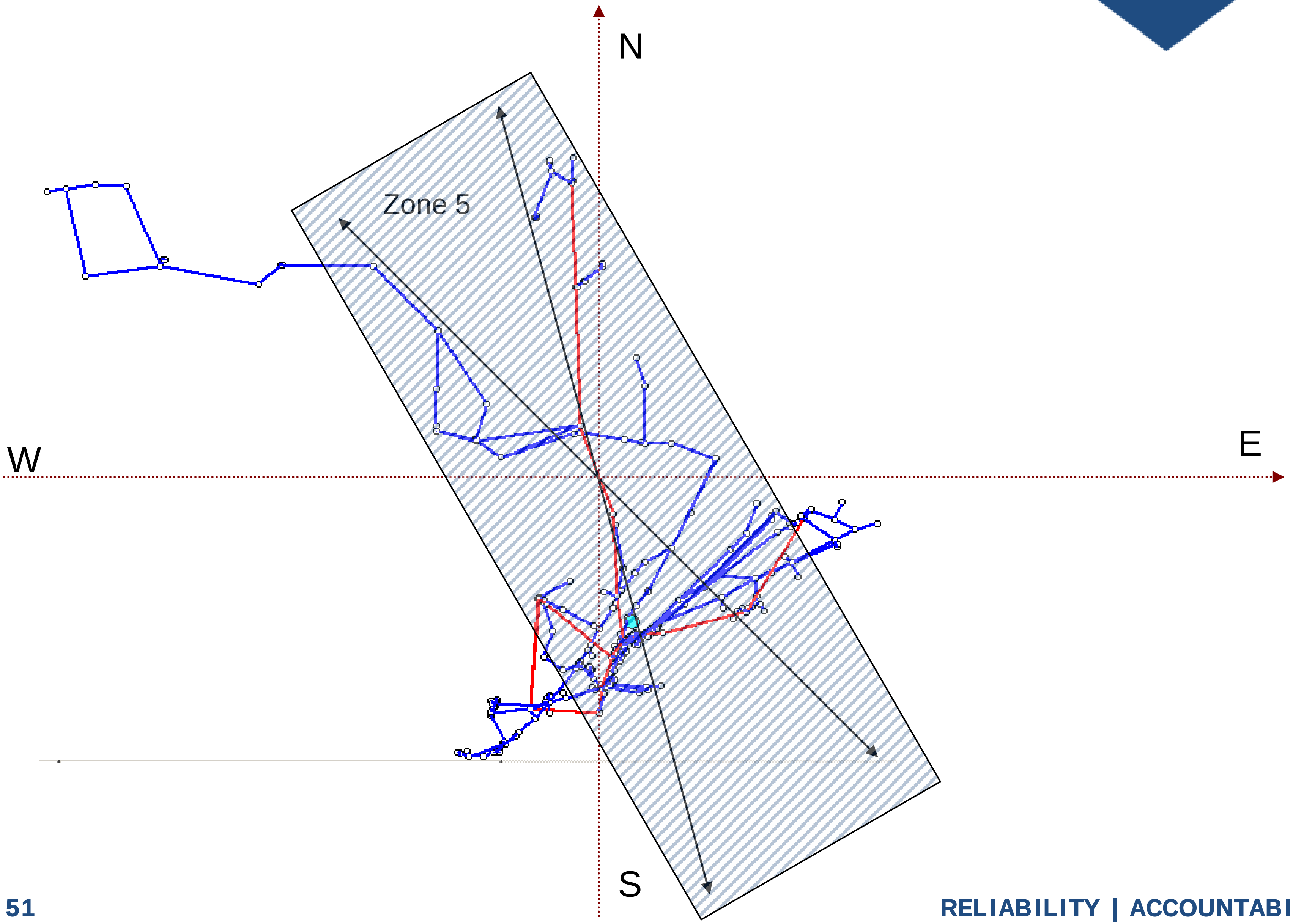

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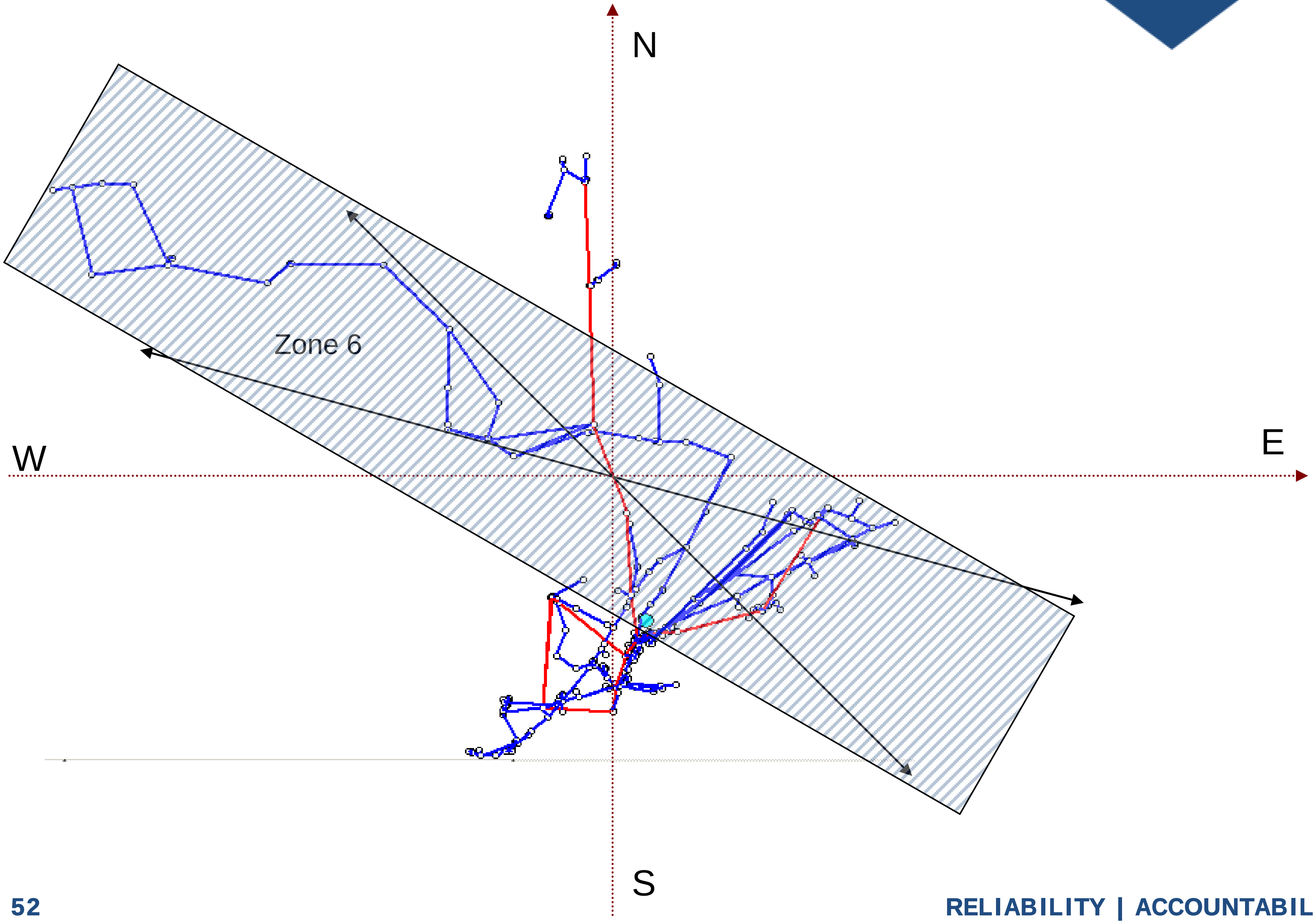

Take away points

- The dc model of the network, represents steady-state conditions and is intended to calculate the distribution of GIC currents in the network
- Earth model only affects the magnitude of the line voltage sources
- Relative orientation of a transmission line with respect to the geoelectric field determines dc emf on the line (ΔX and ΔY)
- In a typical GIC study, different parts of the network will see different GIC depending on the assumed orientation of the geoelectric field
  - Maximum GIC in the system generally does occur for a particular orientation
- With the exception of EMTP simulations, today's tools decouple the distribution of GIC in the system from the effects of GIC in the transmission network

This was the easy part…

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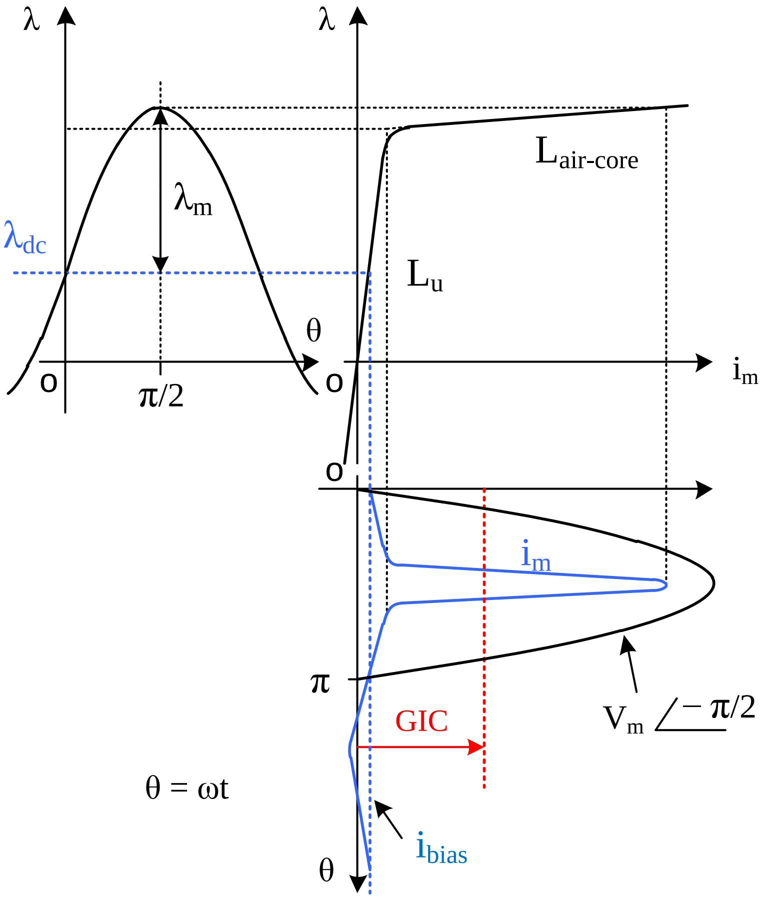
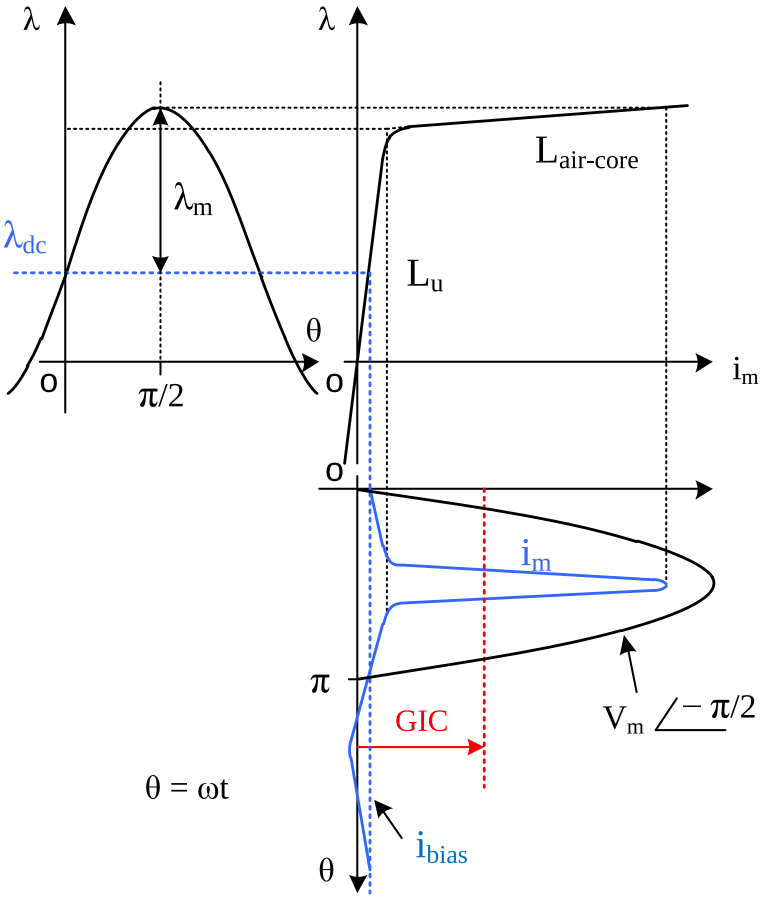
GIC in a power transformer

- When GIC flows through a transformer winding there is a nearly constant flux offset (from a 60 Hz frame of reference) which causes asymmetrical or half-cycle saturation
- Half cycle saturation causes persistent large magnetizing currents similar to inrush currents during transformer energization
- These magnetizing currents are rich in even and odd harmonics. The 60 Hz component of these large magnetizing currents are seen by the system as transformer reactive power absorption.

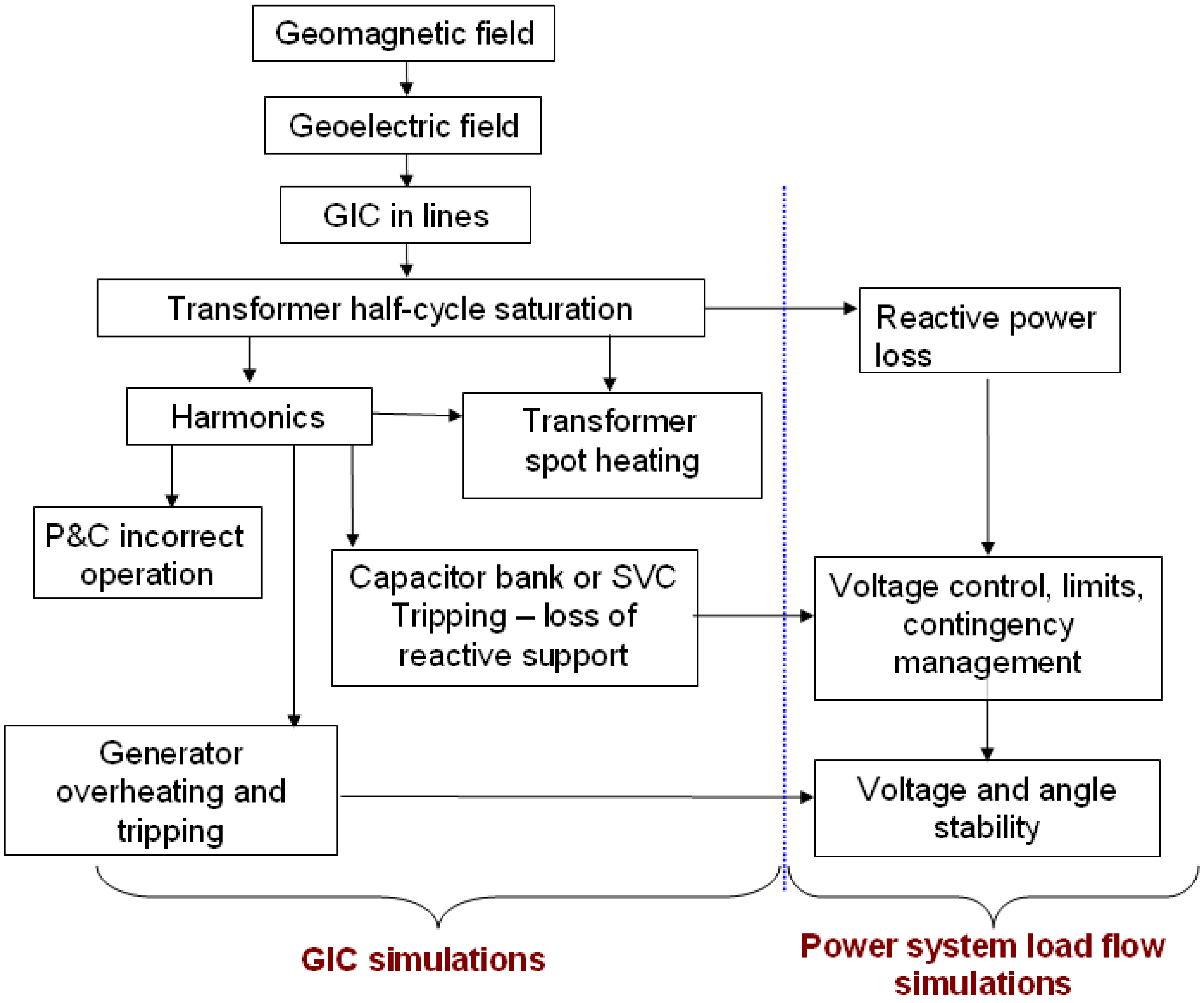


GIC in a power transformer

- Another effect of half-cycle saturation is hot spot heating of the transformer windings, which causes undue ageing of paper-oil insulation
- Additionally, there is hot spot heating of the tank and other structural parts, which causes gassing, which in turn can result in dielectric breakdown



Effects of GIC on Power System Apparatus



Geomagnetic field

Geoelectric field

GIC in lines

Transformer half-cycle saturation

Reactive power loss

Harmonics

Transformer spot heating

P&C incorrect operation

Capacitor bank or SVC Tripping – loss of reactive support

Voltage control, limits, contingency management

Generator overheating and tripping

Voltage and angle stability

GIC simulations

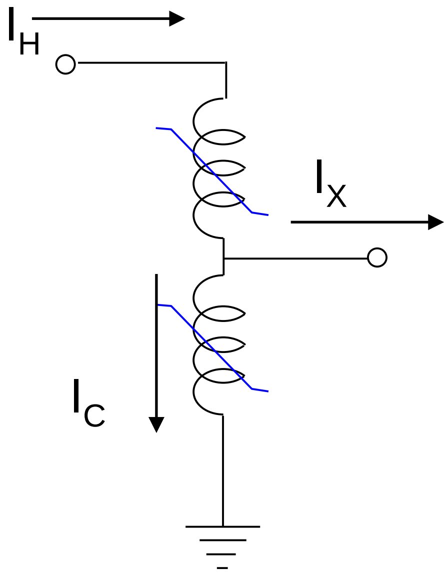
Power system load flow simulations

To summarize the chart

- GIC flows into a grounded transformer
  - Half-cycle saturation takes place. Half-cycle saturation causes:
    - Even and odd current harmonics, which may
      - cause incorrect P&C operation;
      - exceed harmonic current ratings of shunt capacitor banks;
      - cause generator overheating due to negative sequence-like currents caused by even harmonics.
    - Additional transformer var absorption, which in turn can
      - reduce var reserves in the system;
      - violation of voltage and thermal limits;
      - contribute to voltage and angle instability.
    - Transformer winding and structural part hot spot heating, which can lead to
      - Undue ageing of paper-oil insulation;
      - Gassing that can lead to dielectric failure.

Effective GIC

- Heating, harmonics and reactive power absorption depend on effective GIC
- The dc flux linkages caused by GIC in an autotransformer depend on the flux linkages caused by the current flowing through the series as well as common windings
- We define the equivalent current as the current that would produce the same flux linkages as if the secondary terminal of the auto transformer were open

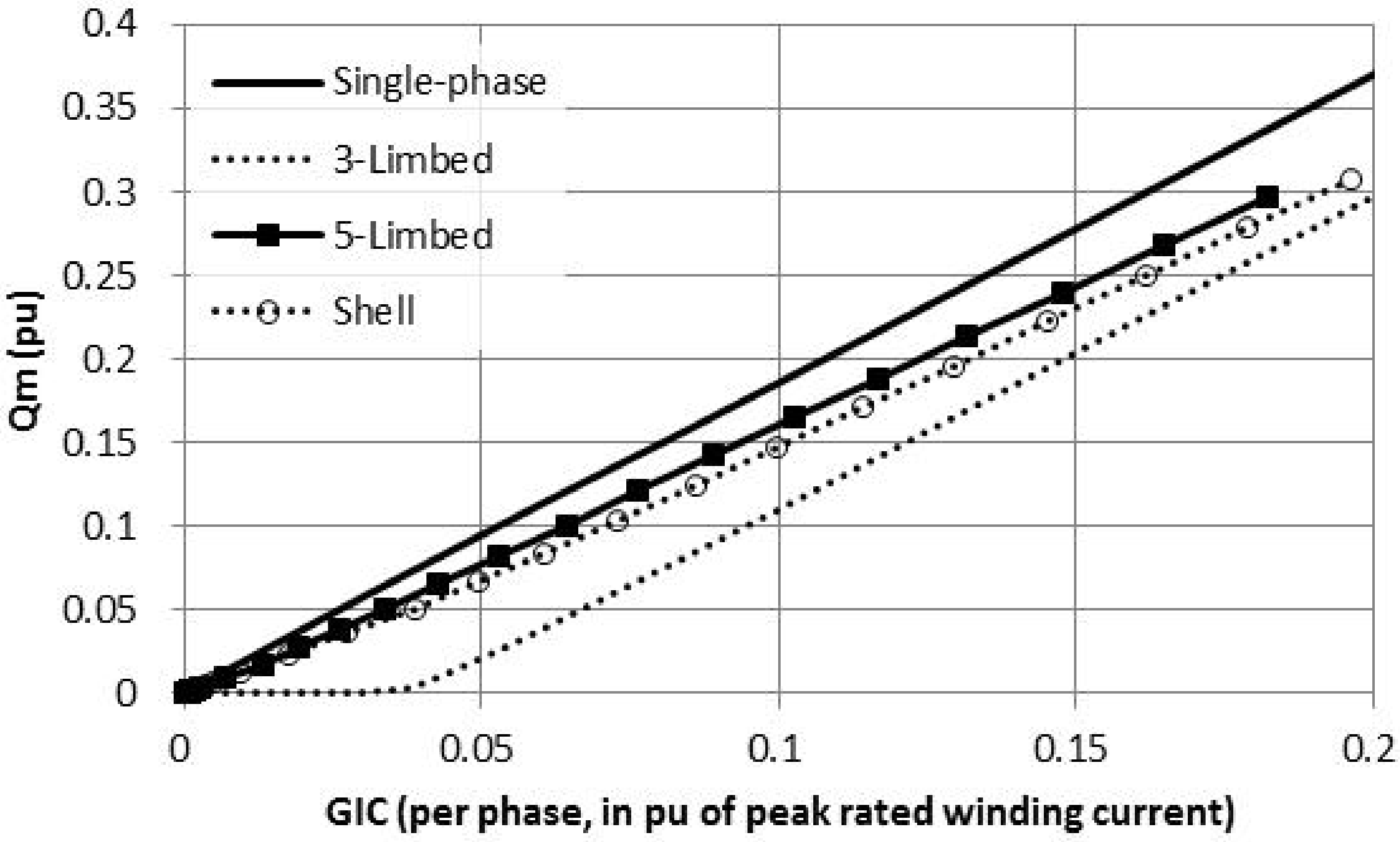


$$I_{eq} = I_H + (I_N / 3 - I_H) N_X / N_H$$

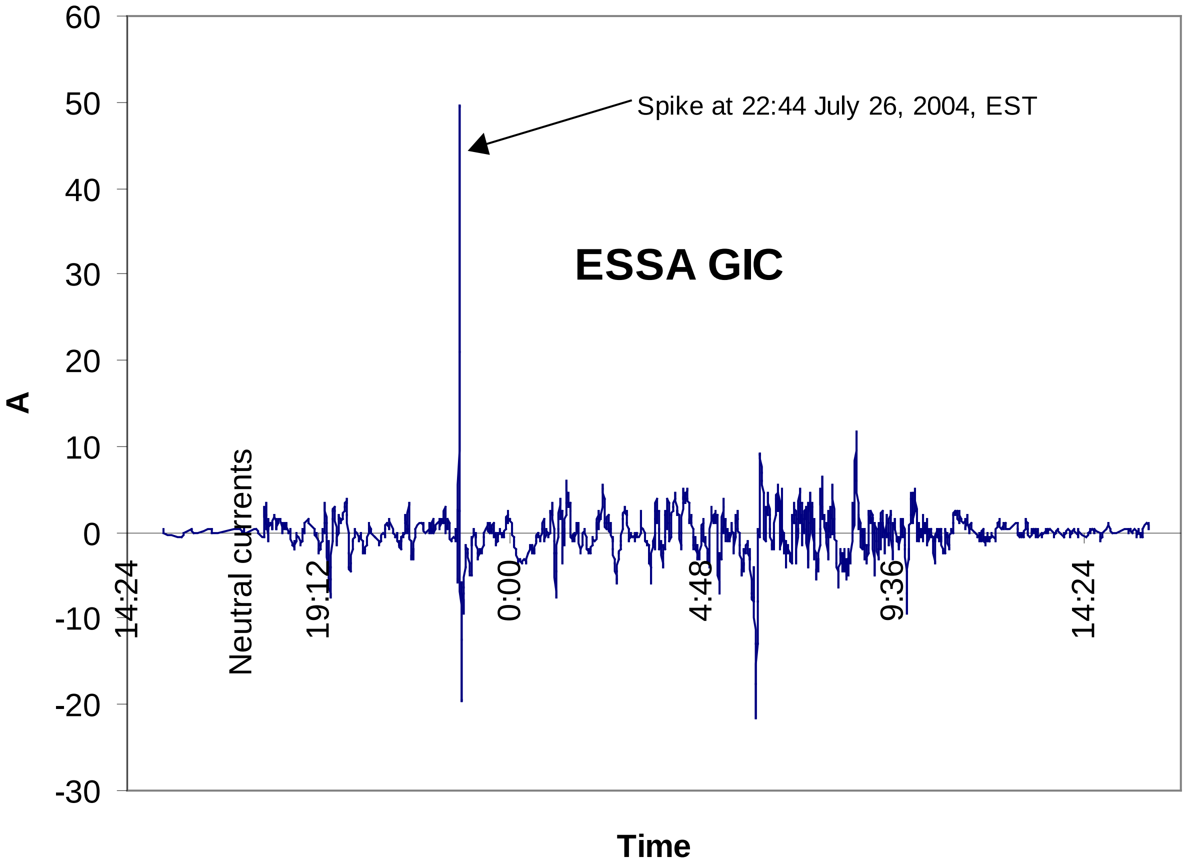
Transformer reactive power absorption

- Magnetizing currents during half-cycle saturation can be visualized as placing a small reactive branch during half the 60 Hz cycle
- The power system sees this as and “effective” reactive power absorption
- This causes RMS voltages to drop
- The difference between GIC changes and the system response, allows the assumption that transformer reactive power absorption in near instantaneous and final steady-state values for var loss can be modelled in a load flow program as a constant var source
- Reactive power absorption assumes undistorted system voltages $Q = V_{60}\ I_{60}$, where subscript 60 indicates the fundamental of voltage and current

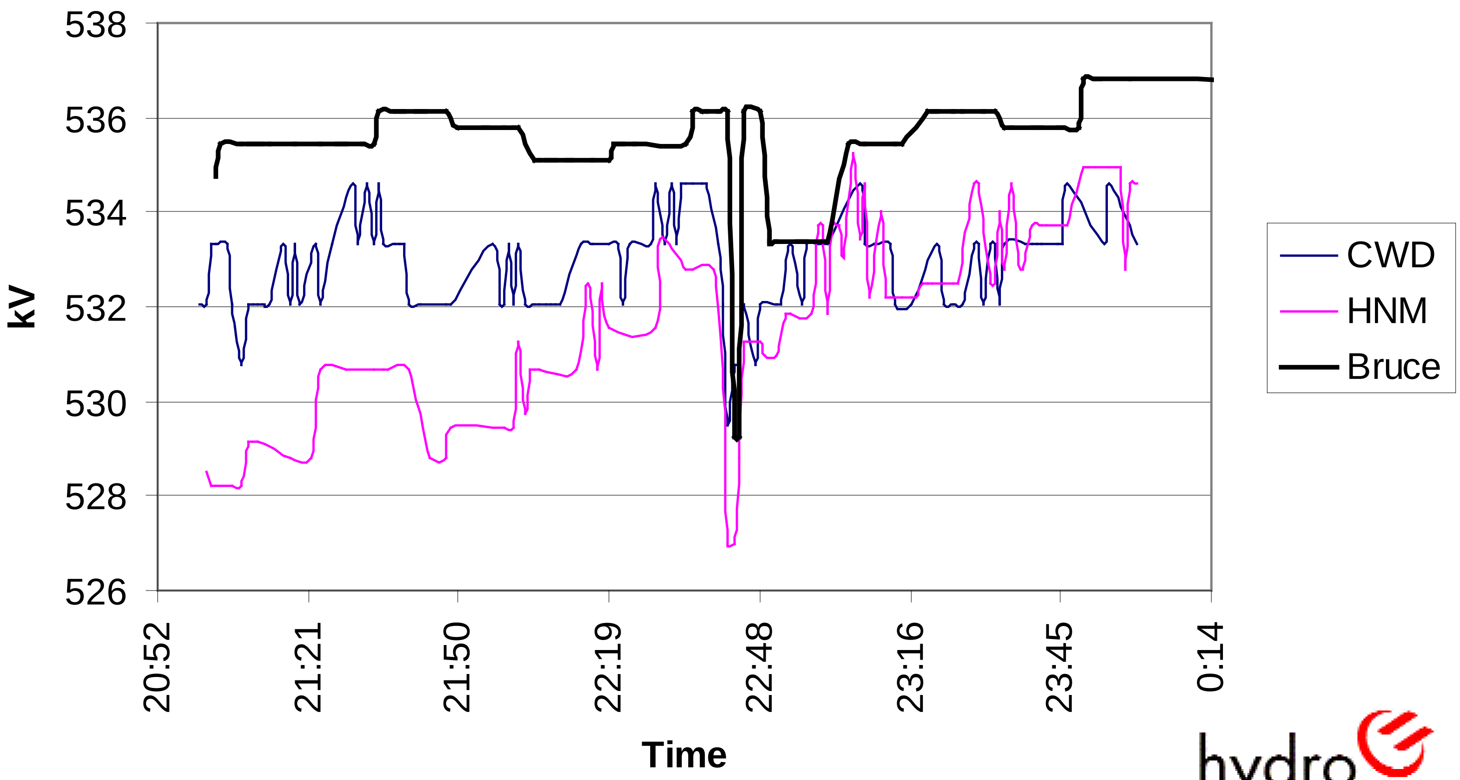
Reactive power absorption and core type



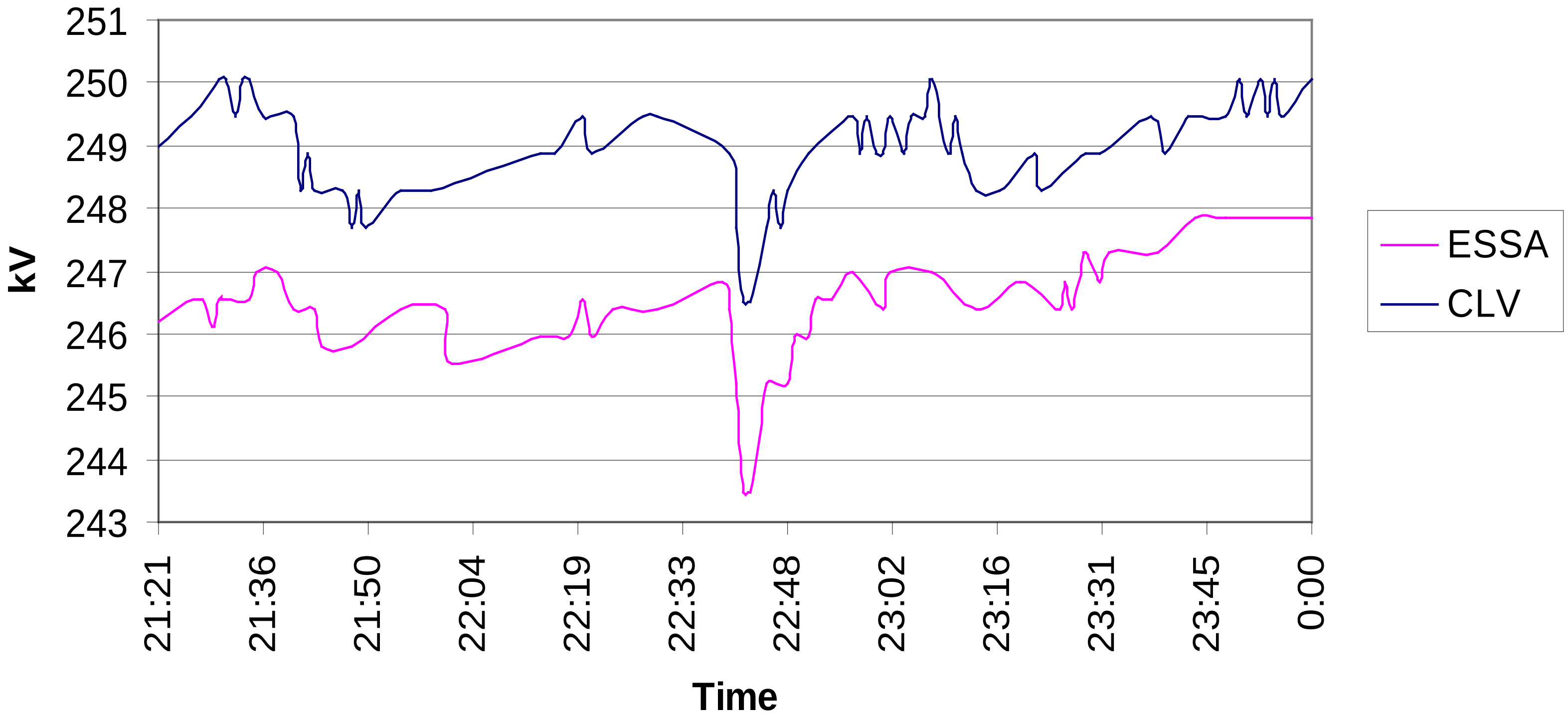
For instance…GMD event July 26-27, 2004



500kV voltage responses July 26, 2004



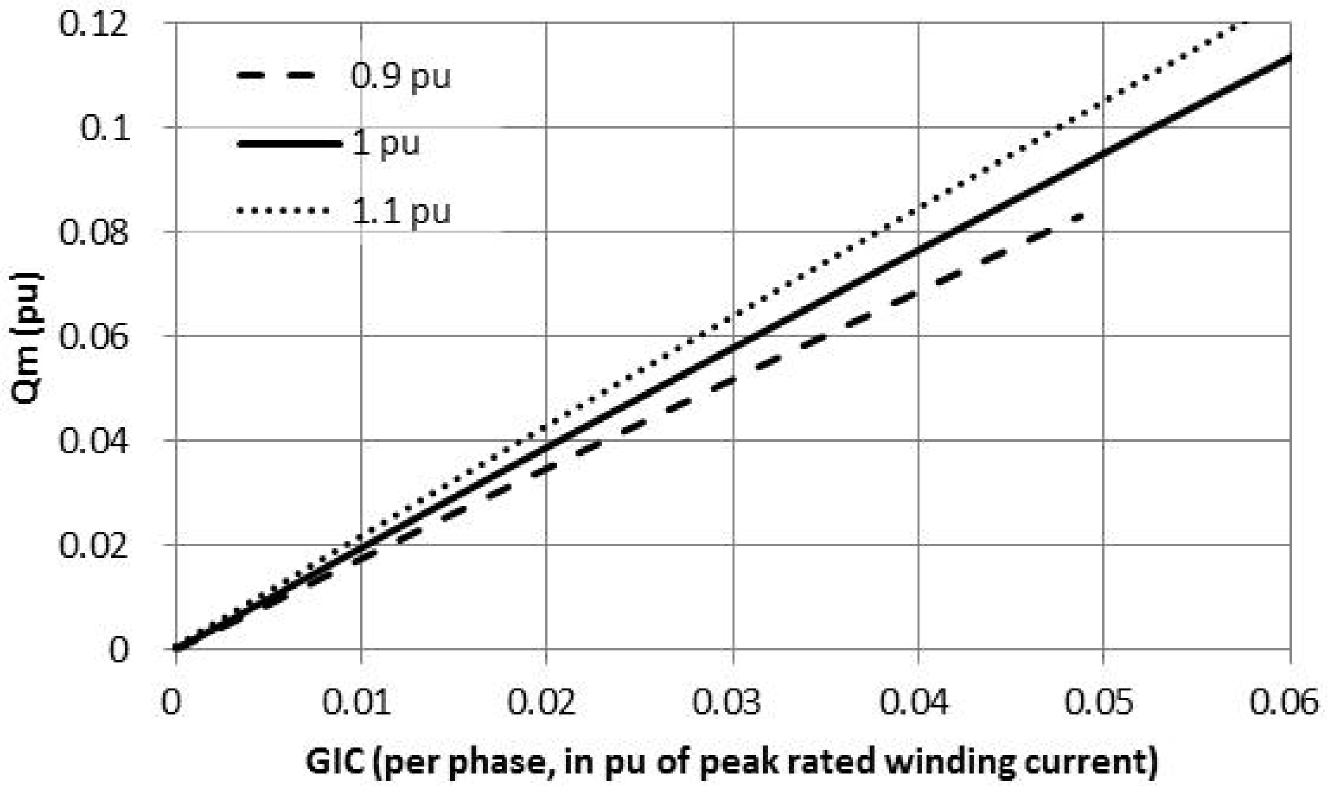
230kV voltage responses July 26, 2004



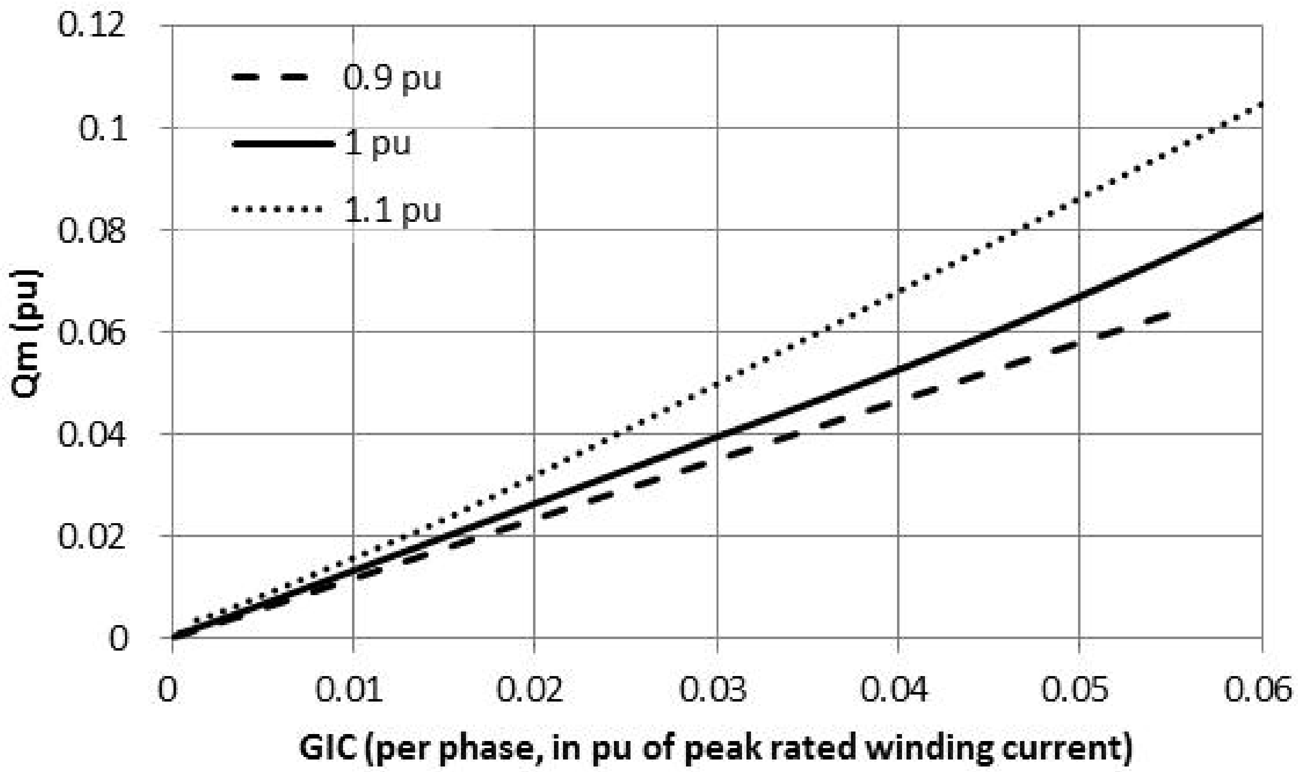
Integration of GIC distribution and load flow

- If GIC in every transformer is known for a given system configuration then the effects of var loss can be modelled in a load flow program by connecting a constant var source to the transformer terminals (constant I or constant Q)
- Some commercial software does this transparently using lookup tables or var/GIC characteristics
  - Different construction means a different lookup table
  - Lookup tables are often obtained from published calculations but can also be generated with EMTP or equivalent simulations that take into consideration the distribution of flux according to construction
  - Lookup tables always assume an infinite system source. In other words, harmonic currents do not cause harmonic voltage distortion.
    - Voltage/flux is assumed to be sinusoidal

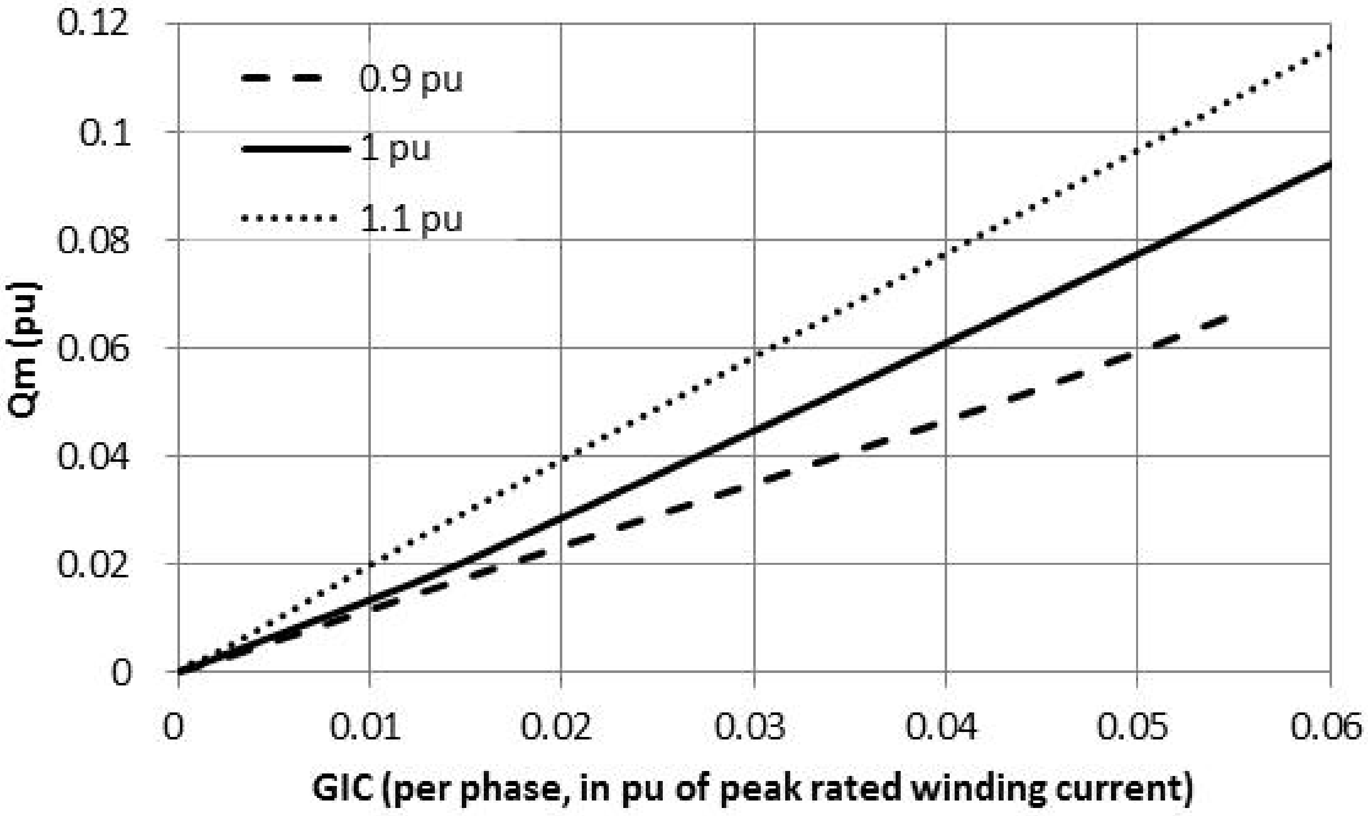
Simulated results for single-phase core topology showing sensitivity to ac voltage



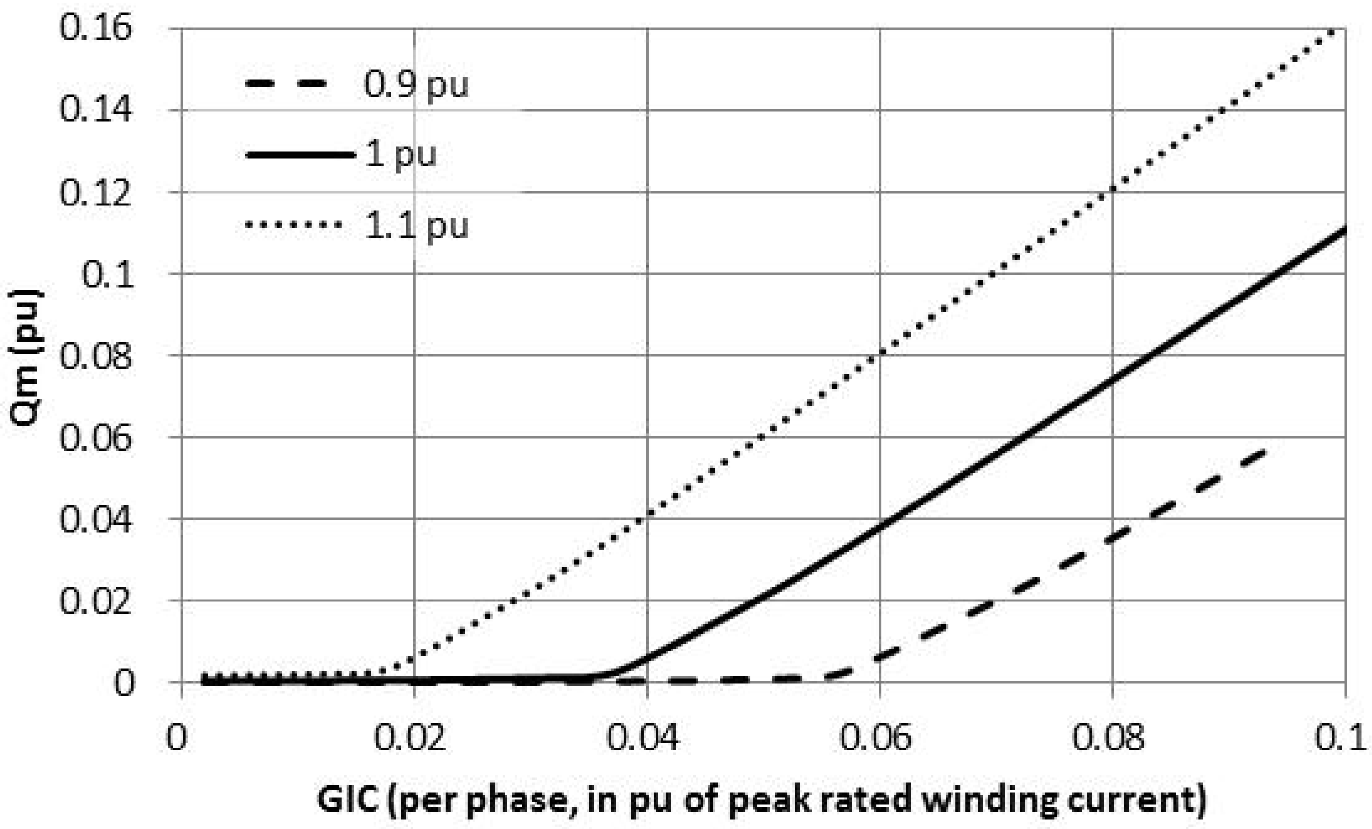
Simulated results for shell-type core topology showing sensitivity to ac voltage



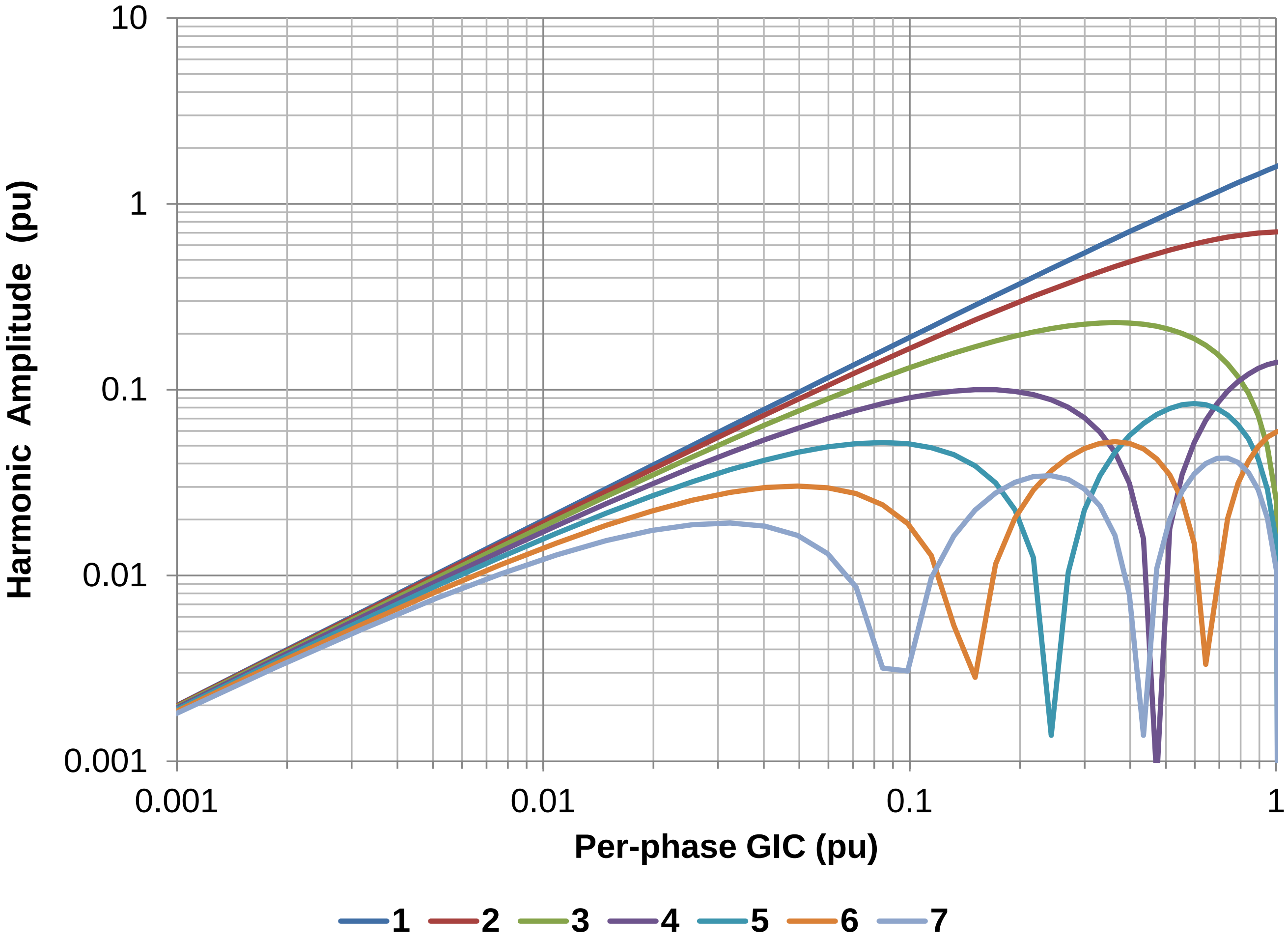
Simulated results for 5-limbed core topology showing sensitivity to ac voltage



Simulated results for 3-limbed core topology showing sensitivity to ac voltage



Transformer harmonics



Harmonic vs. GIC for typical single-phase transformer (normalized on peak winding rating)

P&C susceptibility

- Can cause incorrect P&C operation
- Effects depend on the type of relay (IED or electromechanical)
- Effects depend on the type of protection scheme
  - Differential
  - Open phase
  - Unbalance
- Shunt capacitor bank protection can be an issue
  - IEDs may automatically filter harmonics and become desensitized to harmonic overcurrent protection
  - Electromechanical relays may not distinguish between natural bank unbalance and harmonic currents
- Each protection scheme needs to be examined assuming a maximum credible THD

Generator effects

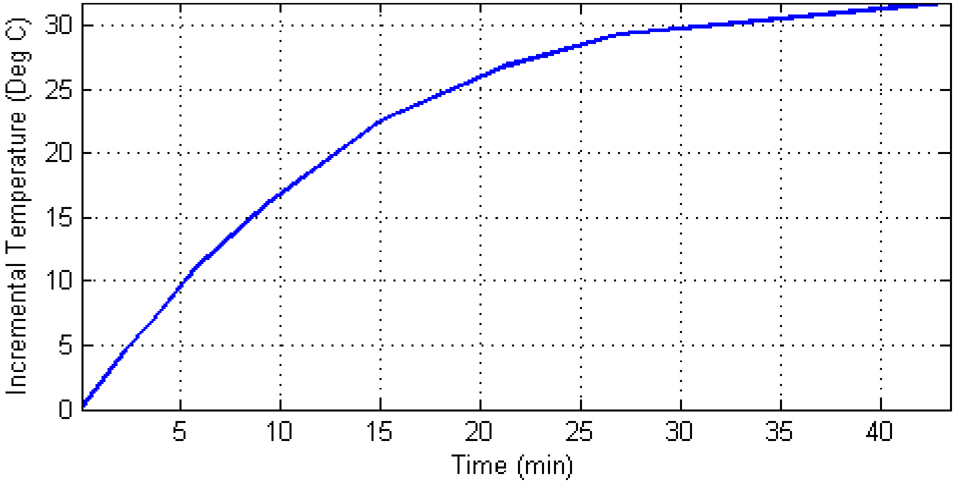
- The harmonic currents impressed on the generator due to transformer half-cycle saturation during a GMD event cause rotor heating, can result in the misoperation of protective relays if settings ignore the potential for even harmonics, and the loss of generation
- IEEE standards C50.12 and C50.13 require modifications to take into account the even harmonics of the generator current during a GMD event. These standards underestimate the effective negative sequence current which contributes to the rotor heating.
- However, assuming steady-state harmonics in the analysis of effective negative sequence currents can be overly conservative if time constants of flux build-up in the generator are not taken into account

Transformer thermal assessment

- Steady-state GIC flows is not adequate
- The behavior depends on GIC(t)
- GIC(t) is event-dependent and system dependent
- Thermal transfer functions allows the calculation of Temp(t) so long as the thermal step response of a transformer is known
  - From measurements
  - Theoretical calculations from manufacturers
- A few measured thermal responses are available today
  - HQ tests
  - Fingrid tests
  - SoCo tests
  - H1 tests
    - 1-ph SVC
    - 3-ph core-type

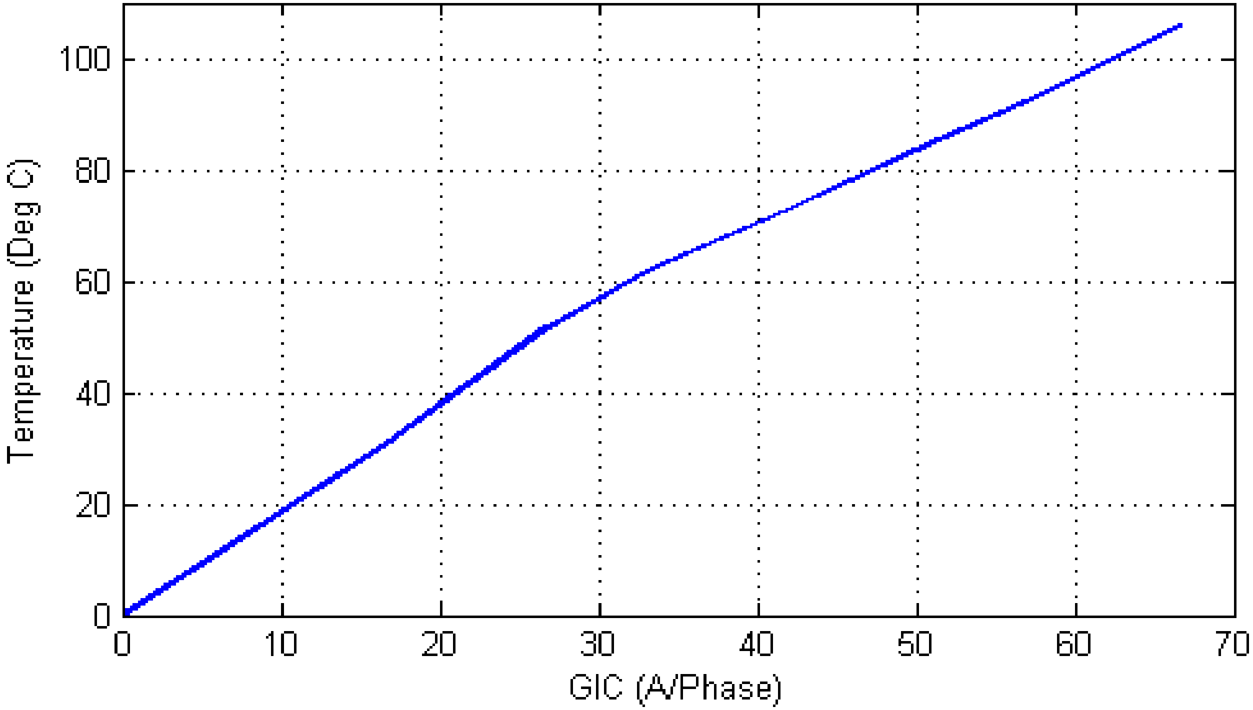
Thermal step response

- If the transformer hot spot incremental temperature rise for a dc step is calculated or measured, it is relatively simple to calculate Temp(t) for a given GIC(t)



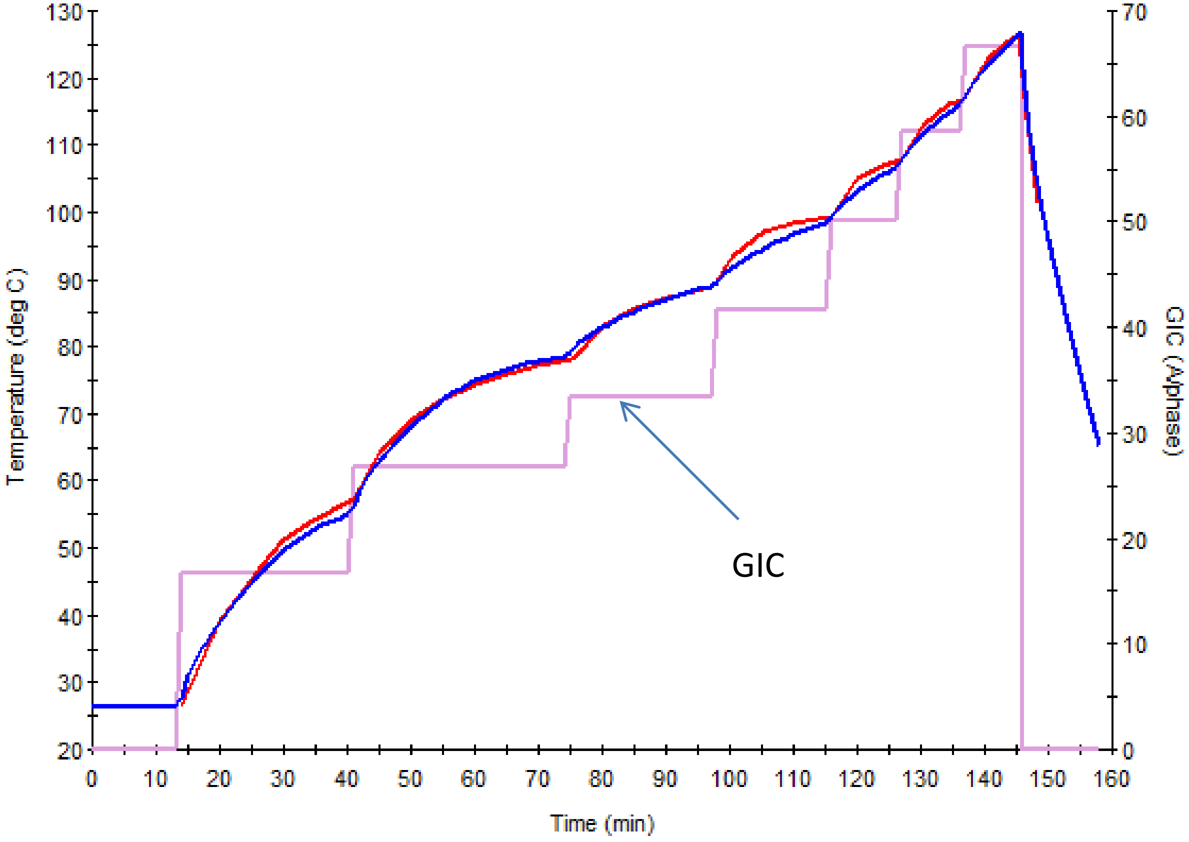
Thermal Step Response to a 16.67 Amperes per Phase dc Step Metallic hot spot heating.

Thermal step response



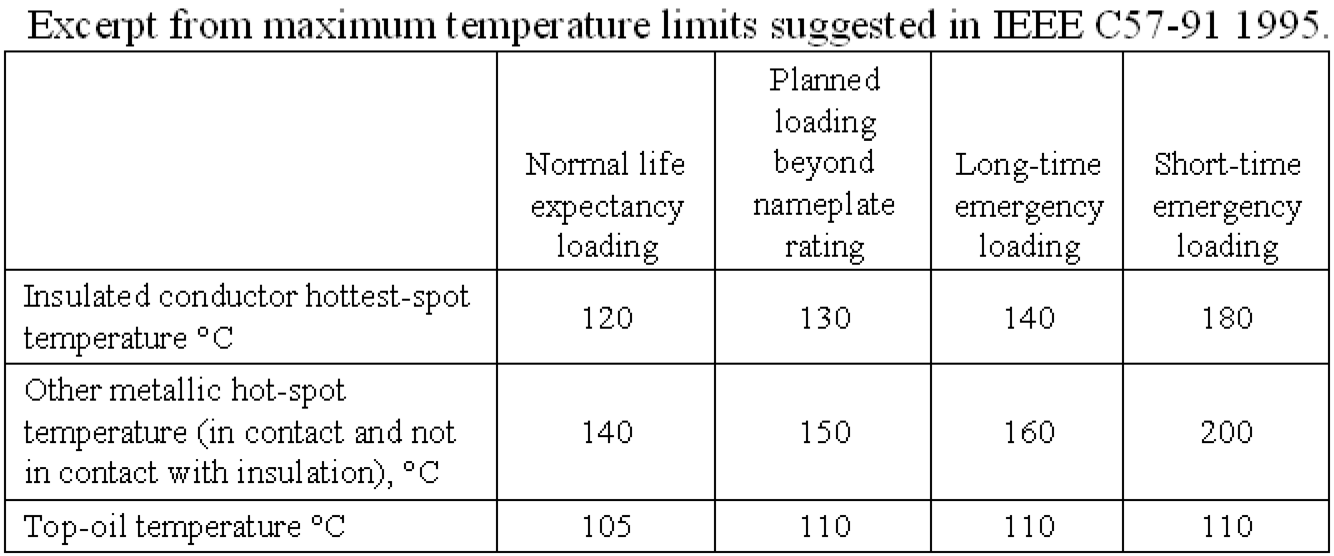
Asymptotic Thermal Step Response. Metallic hot spot heating.

Temp(t) for a given GIC(t)



Reproduction of Fingrid transformer tests

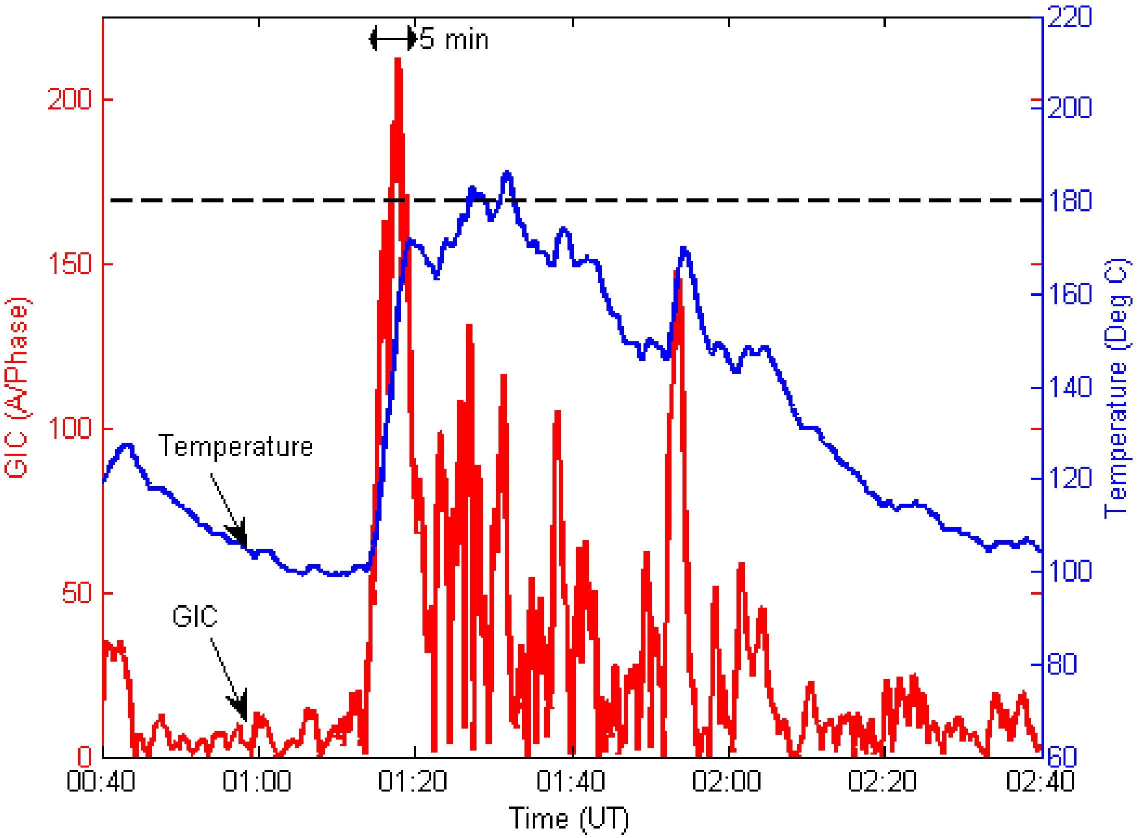
Suggested limits as a function of time



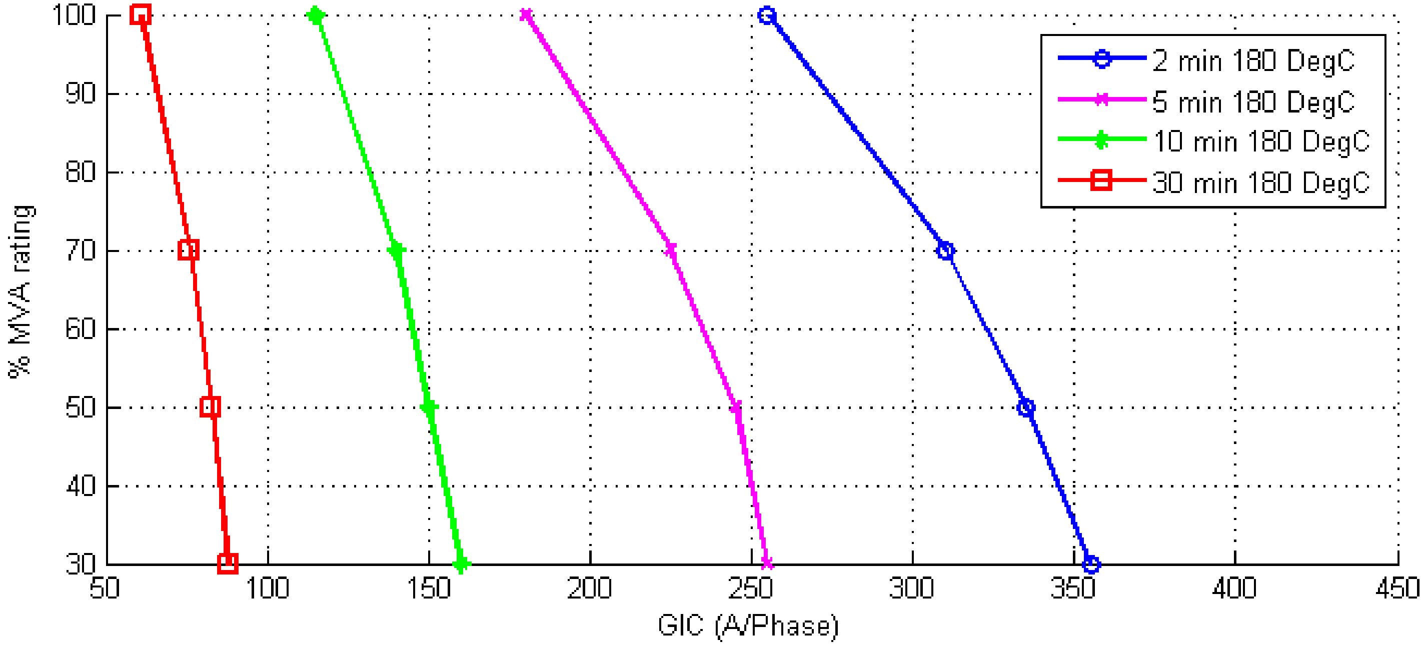
Excerpt from maximum temperature limits suggested in IEEE C57-91 1995.

	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

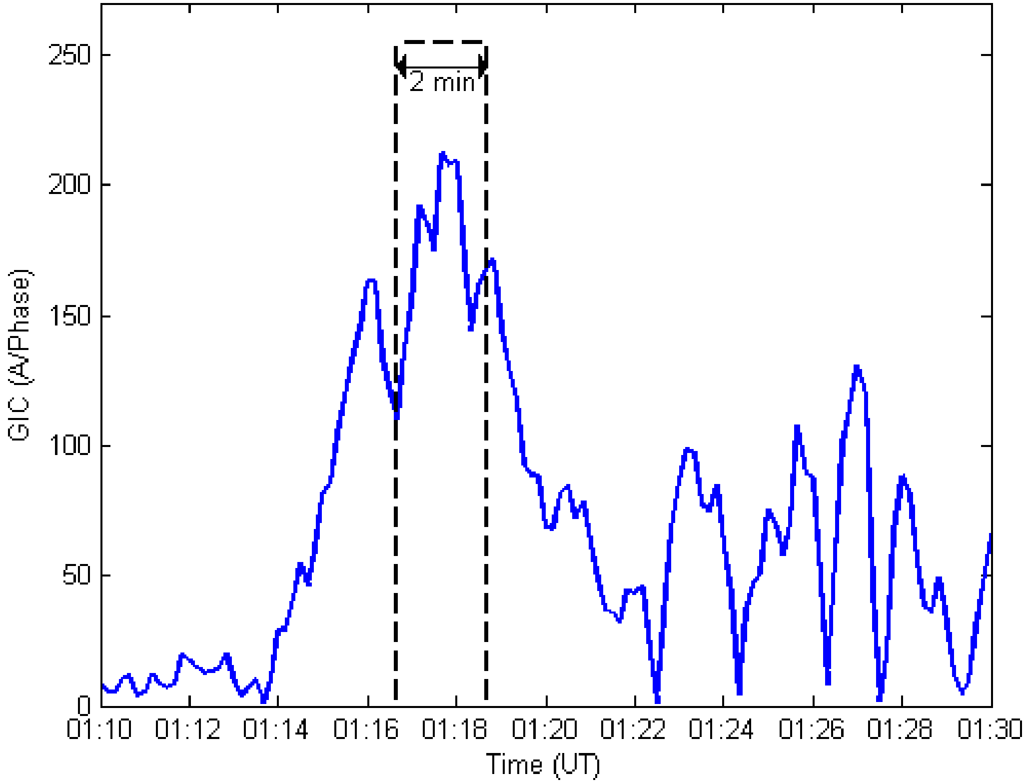
Estimation of susceptibility with a thermal assessment tool



Estimation of susceptibility using capability curves

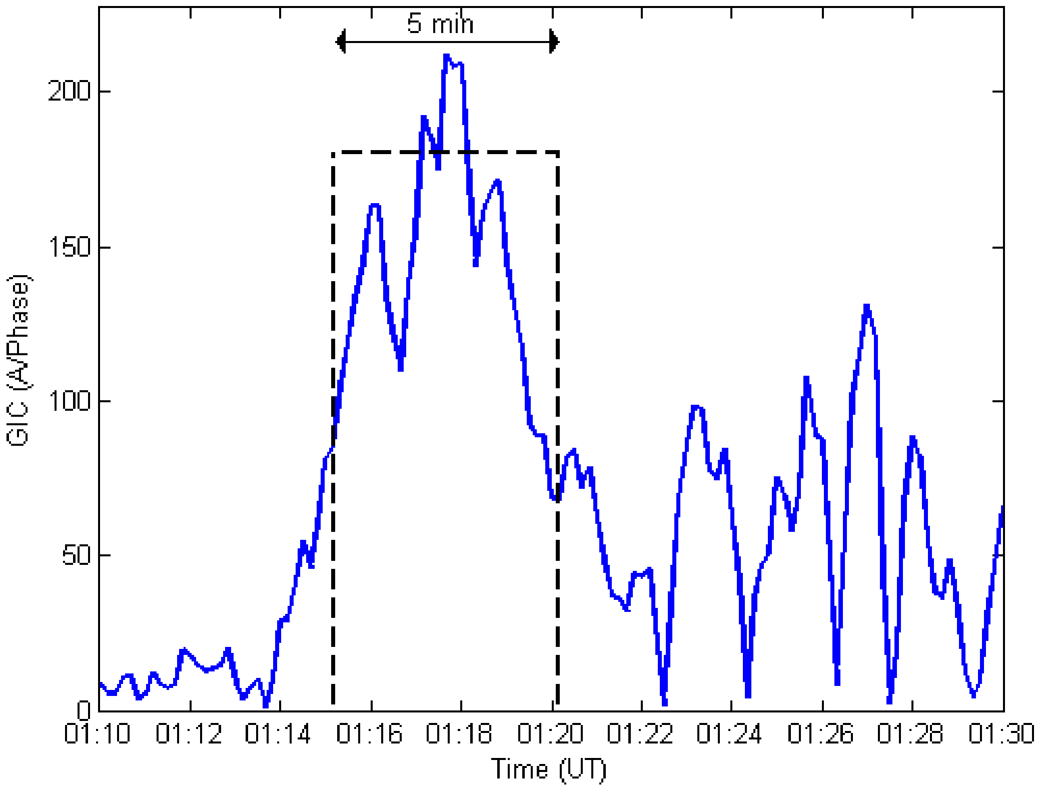


Estimation of susceptibility using capability curves



GIC(t) and a 2 minute 255 A/phase GIC pulse at full load

Estimation of susceptibility using capability curves



GIC(t) and a Five Minute 180 A/phase GIC Pulse at Full Load

Transformer thermal modelling

- Limiting factor seems to be metallic hot spot heating
- We have come a long way from the days when GIC of 90 A will kill a transformer
- Going forward we need
  - More transformer testing to validate manufacturer’s thermal models
  - Generic thermal models (as opposed to very conservative ones)
  - Instrumented units during a GMD event

NERC TPL-007 GMD standard

- Defines a benchmark event with a pre-defined peak geoelectric field
- Requires a number of studies and mitigating measures to manage such event

Benchmark GMD Event Description

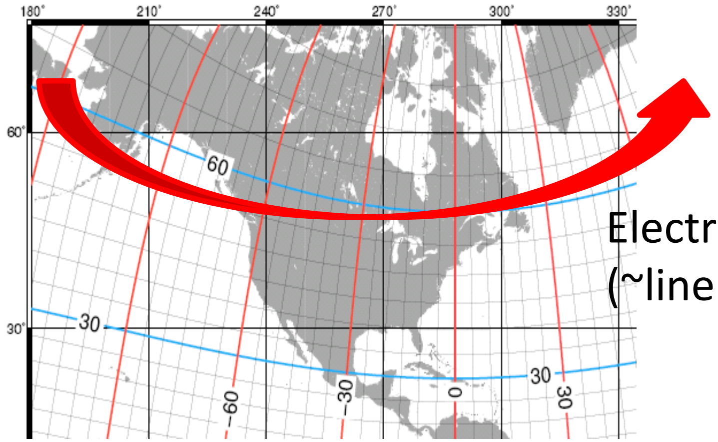
- The TPL007-1 GMD benchmark event is composed of the following elements:
  1. a reference peak geoelectric field amplitude E_{peak} in V/km derived from statistical analysis of historical magnetometer data;
  2. scaling factor α to account for local geomagnetic latitude;
  3. scaling factor β to account for local earth resistivity;
  4. a reference geomagnetic field time series or waveshape B(t) to facilitate transformer thermal impact studies.

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

- TPL007 prescribes that applicable entities shall carry out studies and take mitigation measures to manage a GMD event of this magnitude.

Alpha scaling factor

- Based on statistical observations
- As you move away from the magnetic pole the peak geoelectric field goes down



Electrojet
(~line current)

Geomagnetic Field Scaling Factors

Geomagnetic Latitude (Degrees)	Scaling Factor1 (α)
≤ 40	0.10
45	0.2
50	0.3
54	0.5
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

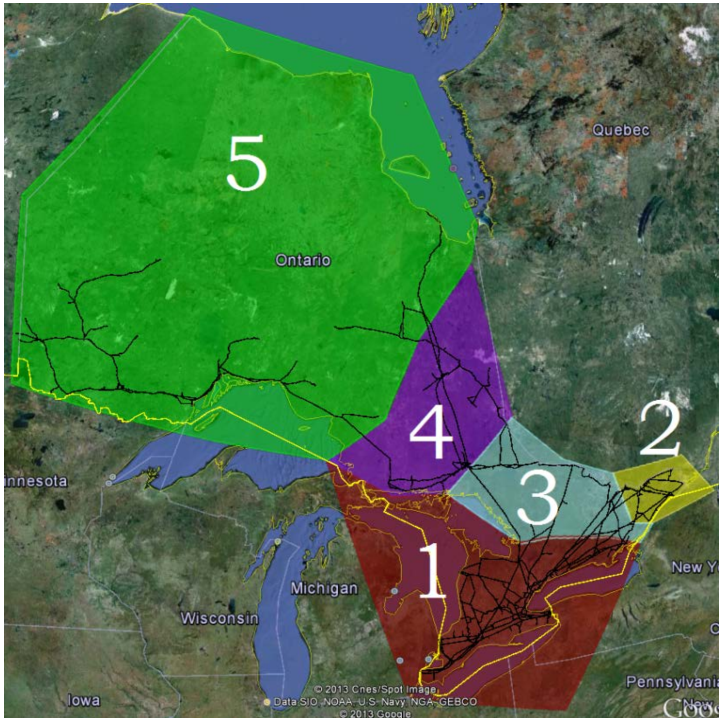
Beta scaling factor

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
CP3	0.94
CS1	0.41
IP1	0.94
IP2	0.28
IP3	0.93
IP4	0.41
NE1	0.81
PB1	0.62
PB2	0.46
PT1	1.17
SL1	0.53
SU1	0.93
BOU	0.28
FBK	0.56
PRU	0.21
BC	0.67
PRAIRIES	0.96
SHIELD	1.0
ATLANTIC	0.79

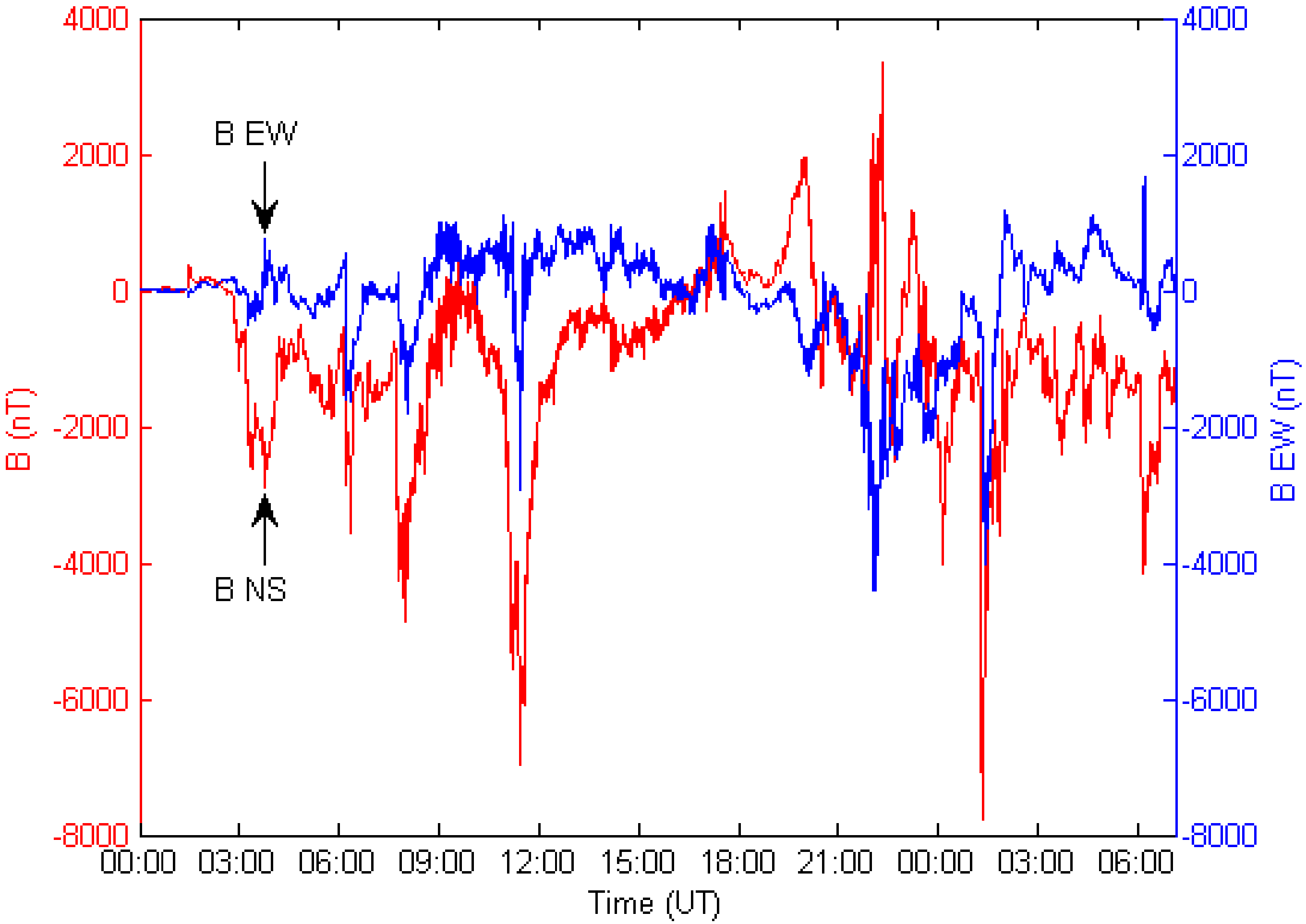
- Scaling the geoelectric field to account for “average” earth models
- Table calculated as follows:
  - Using as reference the Quebec earth model
  - Calculating the geoelectric field with different earth models and the reference benchmark waveshape assuming $\alpha = 1$
  - Ratios are for peak geoelectric fields in the benchmark event

Beta scaling factor

- A planner is permitted to use a technically-justified factor β on the basis of availability of more accurate earth models within the service territory.
- In the case of Ontario with 5 distinct earth models:
  - Use the average SHIELD earth model
  - Use the reference B(t) waveshape and bypass the notion of a single beta scaling factor altogether (allowed under technically-justified earth models)



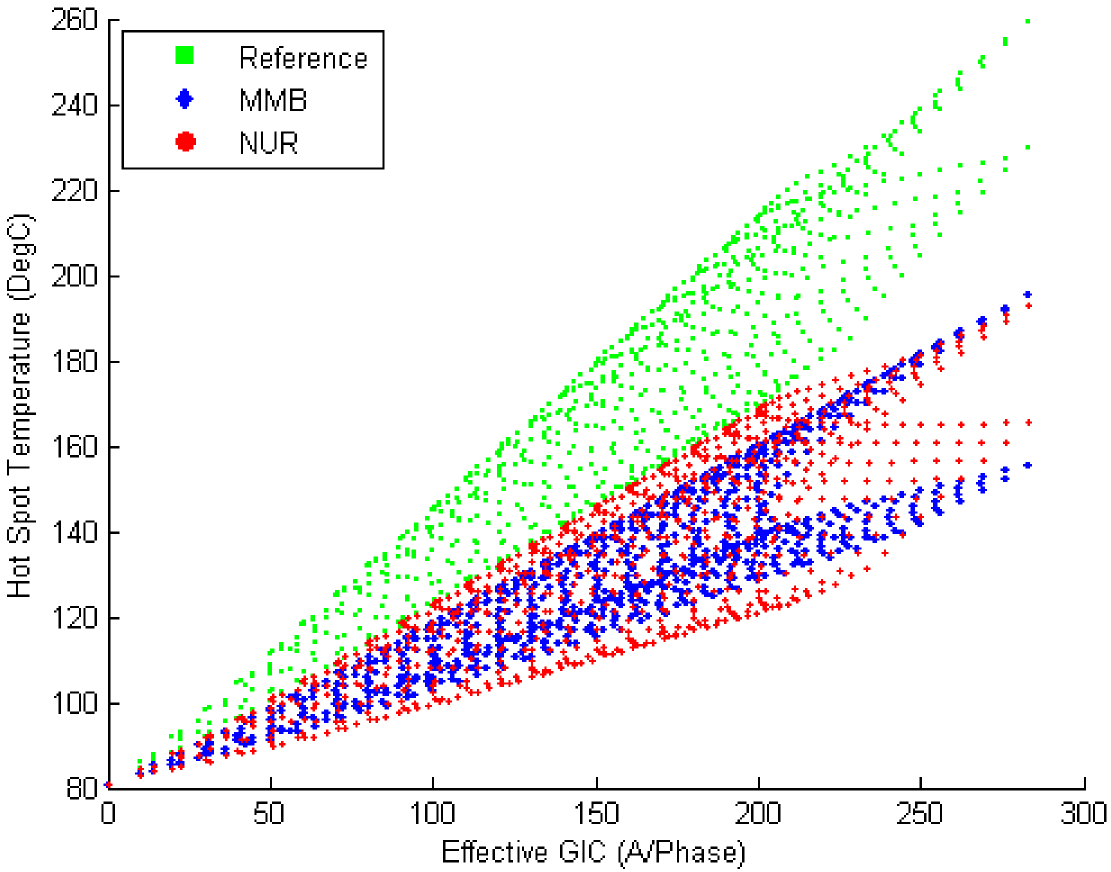
B(t) waveshape



Why a B(t) waveshape?

- Using a B(t) benchmark waveshape eliminates the argument regarding “how wide” should GIC “pulses” be when evaluating a transformer thermal response
- B(t) is used to calculate GIC(t) for every transformer in the system (effective current)
- With GIC(t) it is possible to assess thermal performance either with a thermal step response, manufacturer capability curves, or any other technically justified method
- The selected waveshape provides conservative thermal results when compared to other events

Different events same thermal model

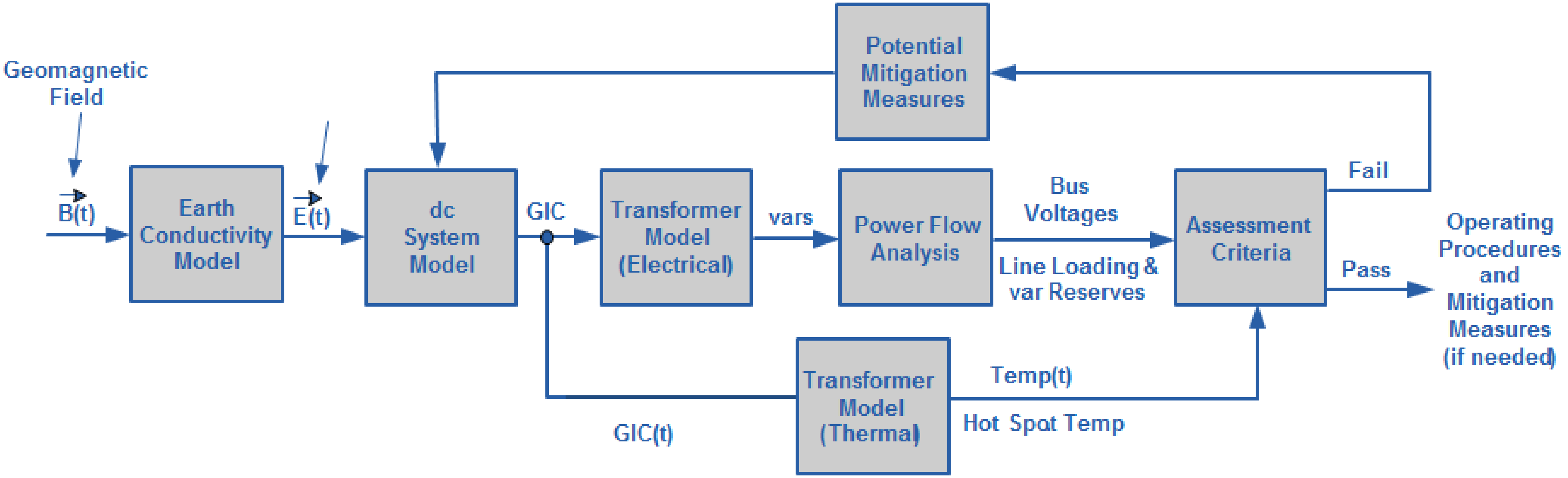


Studies required in a GMD assessment

- The GMD assessment studies required in TPL007-1 generally follow the following sequence
- GIC Study
  - Calculate GIC flow in every applicable transformer of the system using a peak geoelectric field of Epeak, as determined by the GMD benchmark event
  - Calculate reactive power absorption in every applicable transformer of the system
- Load flow Study
  - Evaluate the performance of the system taking into consideration transformer reactive power absorption calculated in the GIC Study. Some software tools can carry out the GIC and load flow studies transparently.

Studies required in a GMD assessment (cont.)

- Thermal assessment study
    - Calculate GIC(t) for every applicable transformer in the system using the results of the GIC Study and the GMD benchmark reference geomagnetic field waveshape
    - Determine if GIC(t) exceeds the allowable hot spot thermal limits of every applicable transformer in the system



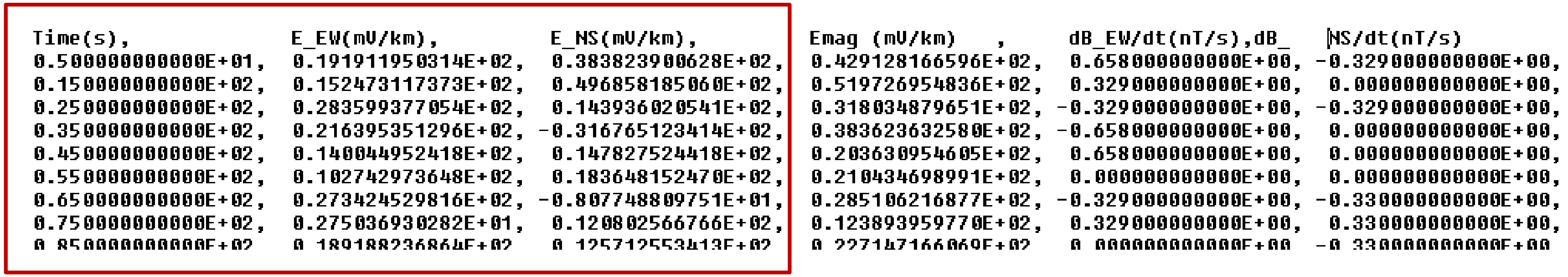
Example of a GIC & load flow study

Thermal assessment study

- Using the GIC Study software, calculate GIC_E in steady-state for the transformer under consideration assuming a uniform Eastward geoelectric field $E_E = 1$ V/km, GIC_E , and a zero Northward geoelectric field
- Using the GIC Study software, calculate GIC_N in steady-state for the transformer under consideration assuming a uniform Northward geoelectric field $E_N = 1$ V/km, GIC_E , and a zero Eastward geoelectric field
  - The units for GIC_N and GIC_E are A/phase/V/km
- Case 1: Using β scaling factor from a table
- Case 2: Using B(t) from the benchmark event and a laterally uniform earth model

Using β from a table

- Information needed:
  - E_EW(t), E_NS(t) for the reference event with the reference (Quebec) earth model



```
Time(s),            E_EW(mV/km),        E_NS(mV/km),        Emag (mV/km)    ,    dB_EW/dt(nT/s),dB_   NS/dt(nT/s)
0.500000000000E+01, 0.191911950314E+02, 0.383823900628E+02, 0.429128166596E+02, 0.658000000000E+00, -0.329000000000E+00,
0.150000000000E+02, 0.152473117373E+02, 0.496858185060E+02, 0.519726954836E+02, 0.329000000000E+00,  0.000000000000E+00,
0.250000000000E+02, 0.283599377054E+02, 0.143936020541E+02, 0.318034879651E+02, -0.329000000000E+00, -0.329000000000E+00,
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0.450000000000E+02, 0.140044952418E+02, 0.147827524418E+02, 0.203630954605E+02, 0.658000000000E+00,  0.000000000000E+00,
0.550000000000E+02, 0.102742973648E+02, 0.183648152470E+02, 0.210434698991E+02, 0.000000000000E+00,  0.000000000000E+00,
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0.750000000000E+02, 0.275036930282E+01, 0.120802566766E+02, 0.123893959770E+02, 0.329000000000E+00,  0.330000000000E+00,
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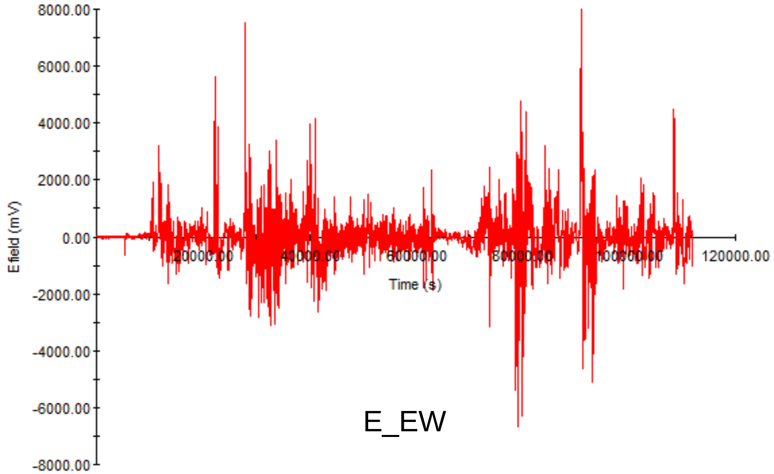
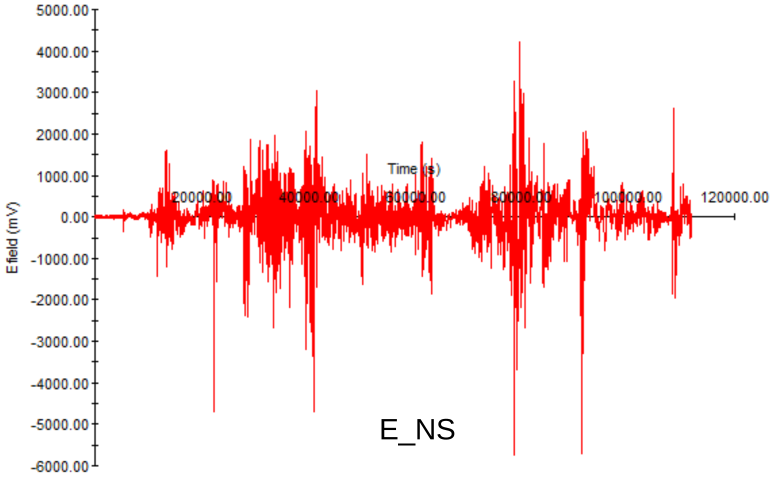


E_EW



E_NS

Using β from a table

- Information needed:
  - Beta and Alpha tables

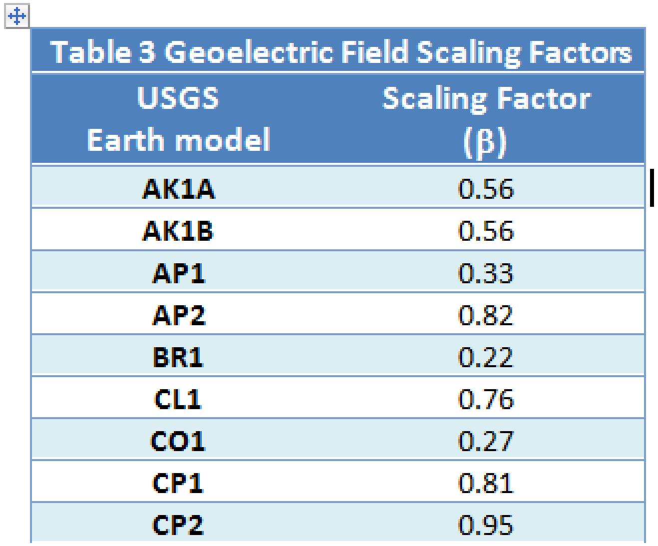


Table 3 Geoelectric Field Scaling Factors	
USGS Earth model	**Scaling Factor (β)**
AK1A	0.56
AK1B	0.56
AP1	0.33
AP2	0.82
BR1	0.22
CL1	0.76
CO1	0.27
CP1	0.81
CP2	0.95

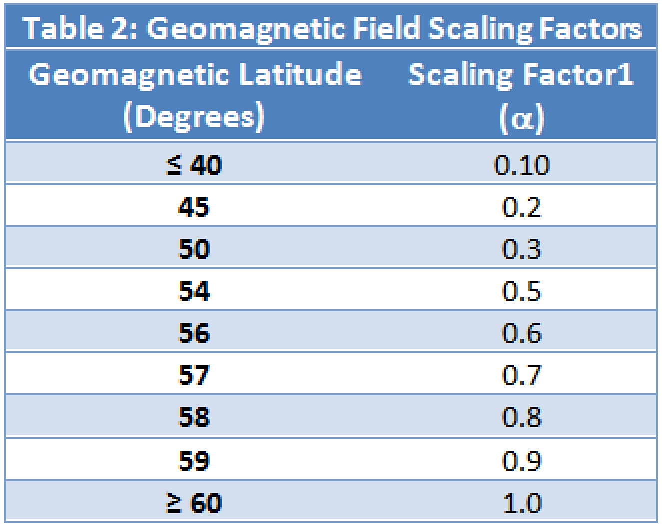
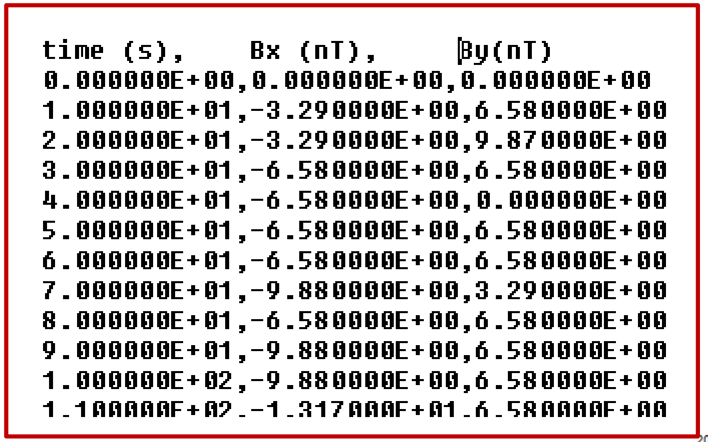


Table 2: Geomagnetic Field Scaling Factors	
Geomagnetic Latitude (Degrees)	**Scaling Factor1 (α)**
≤ 40	0.10
45	0.2
50	0.3
54	0.5
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

  - GIC_E and GIC_N from the GIC solver
  - Then $GIC(t) = \beta \times \alpha \times (E_{EW}(t) \times GIC_E + E_{NS}(t) \times GIC_N)/1000$
    - Note that E(t) is in mV/km

Using B(t) and your earth model

- Information needed:
  - B_EW(t), B_NS(t) for the reference event



```
time (s),    Bx (nT),      By(nT)
0.000000E+00,0.000000E+00,0.000000E+00
1.000000E+01,-3.290000E+00,6.580000E+00
2.000000E+01,-3.290000E+00,9.870000E+00
3.000000E+01,-6.580000E+00,6.580000E+00
4.000000E+01,-6.580000E+00,0.000000E+00
5.000000E+01,-6.580000E+00,6.580000E+00
6.000000E+01,-6.580000E+00,6.580000E+00
7.000000E+01,-9.880000E+00,3.290000E+00
8.000000E+01,-6.580000E+00,6.580000E+00
9.000000E+01,-9.880000E+00,6.580000E+00
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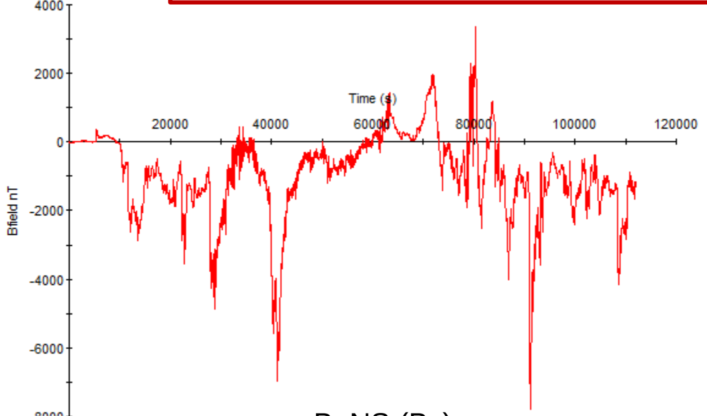
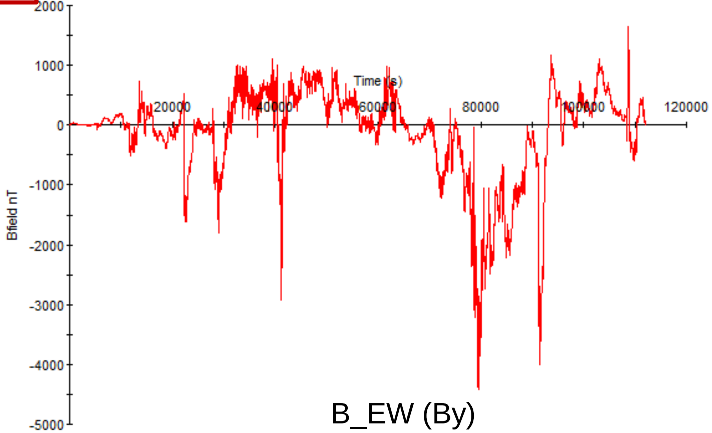


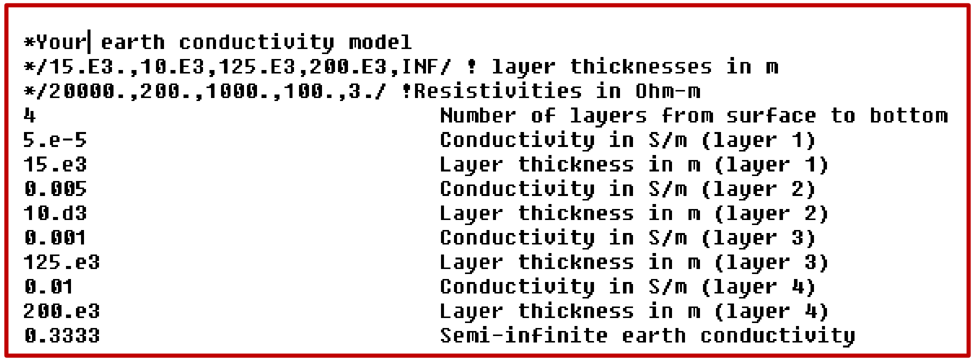
B_NS (By)



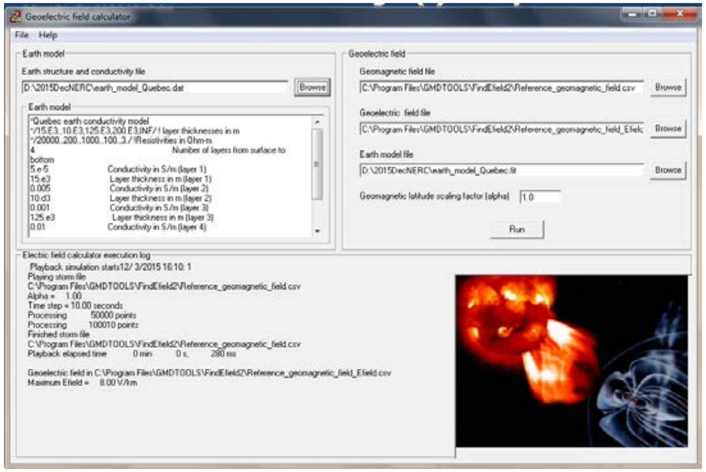
B_EW (By)

Using B(t) and your earth model

- Information needed:
  - Earth model



```
*Your earth conductivity model
*/15.E3.,10.E3,125.E3,200.E3,INF/ ! layer thicknesses in m
*/20000.,200.,1000.,100.,3./ !Resistivities in Ohm-m
4                              Number of layers from surface to bottom
5.e-5                          Conductivity in S/m (layer 1)
15.e3                          Layer thickness in m (layer 1)
0.005                          Conductivity in S/m (layer 2)
10.d3                          Layer thickness in m (layer 2)
0.001                          Conductivity in S/m (layer 3)
125.e3                         Layer thickness in m (layer 3)
0.01                           Conductivity in S/m (layer 4)
200.e3                         Layer thickness in m (layer 4)
0.3333                         Semi-infinite earth conductivity
```



Earth structure and conductivity file: D:\2015DecNERC\earth_model_Quebec.dat

```
*Quebec earth conductivity model
*/15.E3.,10.E3,125.E3,200.E3,INF/ ! layer thicknesses in m
*/20000.,200.,1000.,100.,3./ !Resistivities in Ohm-m
4                              Number of layers from surface to
bottom
5.e-5              Conductivity in S/m (layer 1)
15.e3              Layer thickness in m (layer 1)
0.005              Conductivity in S/m (layer 2)
10.d3              Layer thickness in m (layer 2)
0.001              Conductivity in S/m (layer 3)
125.e3             Layer thickness in m (layer 3)
0.01               Conductivity in S/m (layer 4)
```

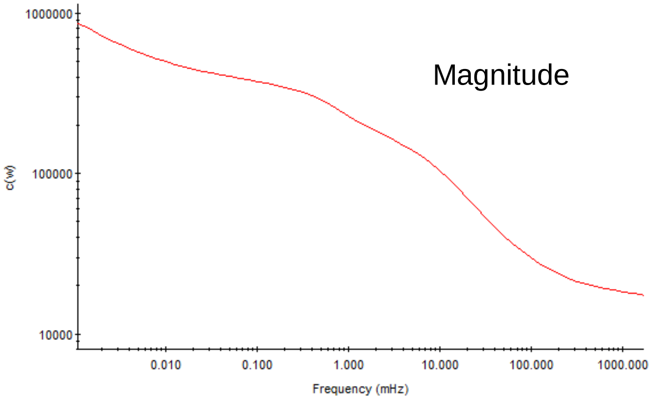
Geomagnetic field file: C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field.csv

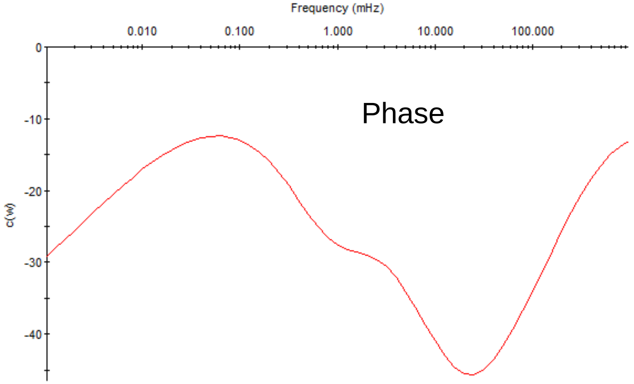
Geoelectric field file: C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field_Efielc

Earth model file: D:\2015DecNERC\earth_model_Quebec.fit

Geomagnetic latitude scaling factor (alpha): 1.0

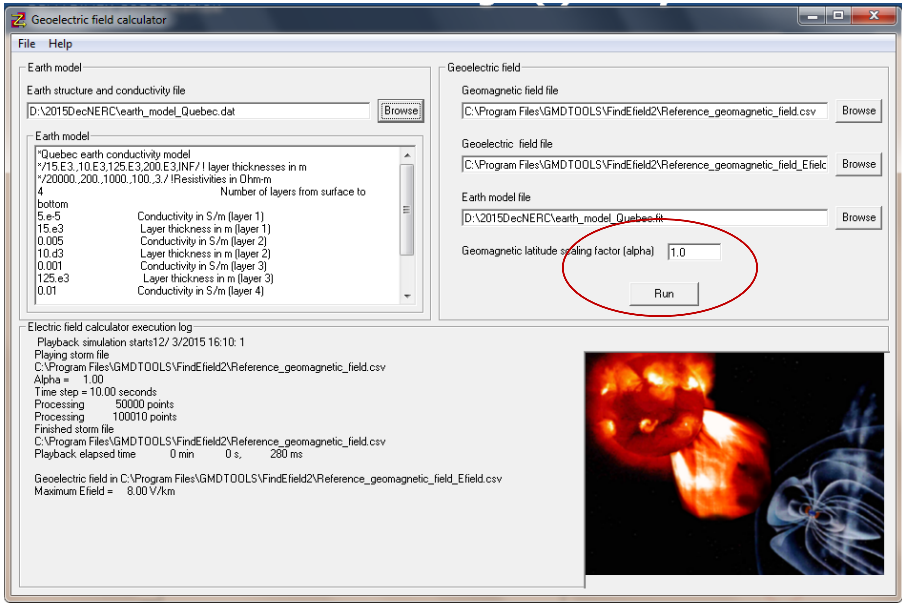
```
 Playback simulation starts12/ 3/2015 16:10: 1
Playing storm file
C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field.csv
Alpha =     1.00
Time step = 10.00 seconds
Processing         50000 points
Processing        100010 points
Finished storm file
C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field.csv
Playback elapsed time         0 min        0 s,        280 ms

Geoelectric field in C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field_Efield.csv
Maximum Efield =    8.00 V/km
```





Using B(t) and your earth model

- Next step : Calculate E_EW(t), E_NS(t) for the reference event with your earth model using tools such as



Earth model

Earth structure and conductivity file: D:\2015DecNERC\earth_model_Quebec.dat

Earth model

```
*Quebec earth conductivity model
*/15.E3.,10.E3,125.E3,200.E3,INF/ ! layer thicknesses in m
*/20000.,200.,1000.,100.,3./ !Resistivities in Ohm-m
4                                    Number of layers from surface to
bottom
5.e-5                    Conductivity in S/m (layer 1)
15.e3                     Layer thickness in m (layer 1)
0.005                     Conductivity in S/m (layer 2)
10.d3                     Layer thickness in m (layer 2)
0.001                     Conductivity in S/m (layer 3)
125.e3                     Layer thickness in m (layer 3)
0.01                     Conductivity in S/m (layer 4)
```

Geoelectric field

Geomagnetic field file: C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field.csv

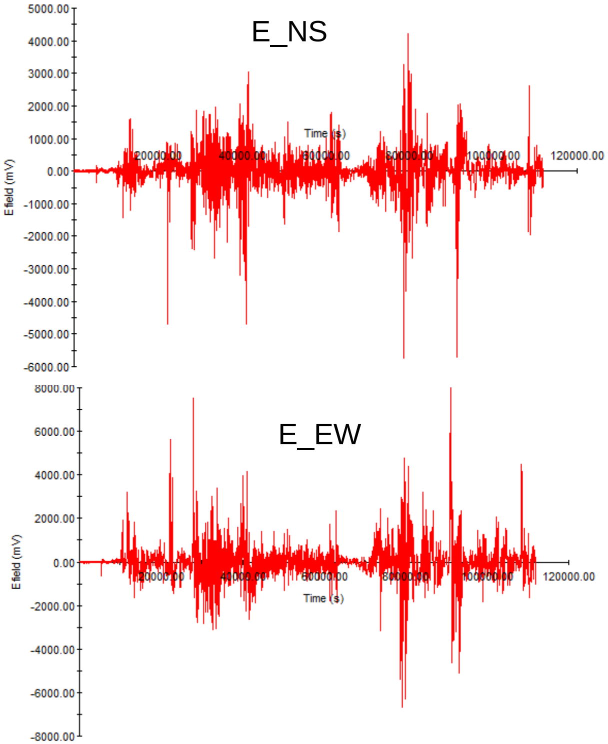
Geoelectric field file: C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field_Efielc

Earth model file: D:\2015DecNERC\earth_model_Quebec.fit

Geomagnetic latitude scaling factor (alpha): 1.0

Electric field calculator execution log

```
 Playback simulation starts12/ 3/2015 16:10: 1
Playing storm file
C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field.csv
Alpha =     1.00
Time step = 10.00 seconds
Processing         50000 points
Processing        100010 points
Finished storm file
C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field.csv
Playback elapsed time          0 min          0 s,         280 ms

Geoelectric field in C:\Program Files\GMDTOOLS\FindEfield2\Reference_geomagnetic_field_Efield.csv
Maximum Efield =     8.00 V/km
```



- Scaling factor α can be applied, and
- $GIC(t) = (E_{EW}(t) \times GIC_E + E_{NS}(t) \times GIC_N)/1000$

Using B(t) and your earth model

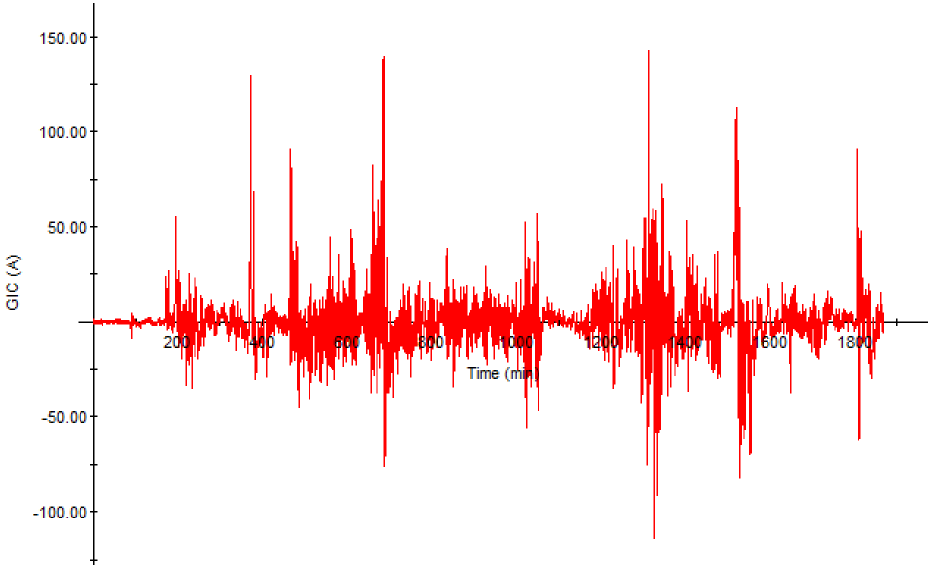
- If your app does not allow a scaling factor, then:
  - Use Alpha table

Table 2: Geomagnetic Field Scaling Factors	
Geomagnetic Latitude (Degrees)	Scaling Factor1 (α)
≤ 40	0.10
45	0.2
50	0.3
54	0.5
56	0.6
57	0.7
58	0.8
59	0.9
≥ 60	1.0

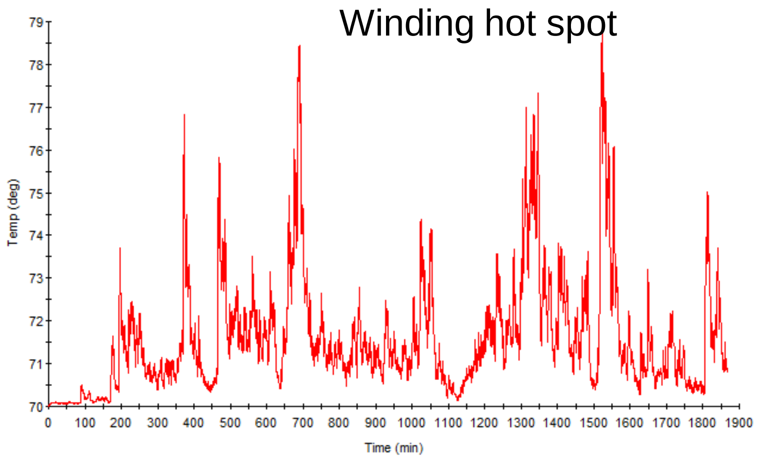
  - Then $GIC(t) = \enclose{circle}{\alpha \times} (E_{EW}(t) \times GIC_E + E_{NS}(t) \times GIC_N)/1000$

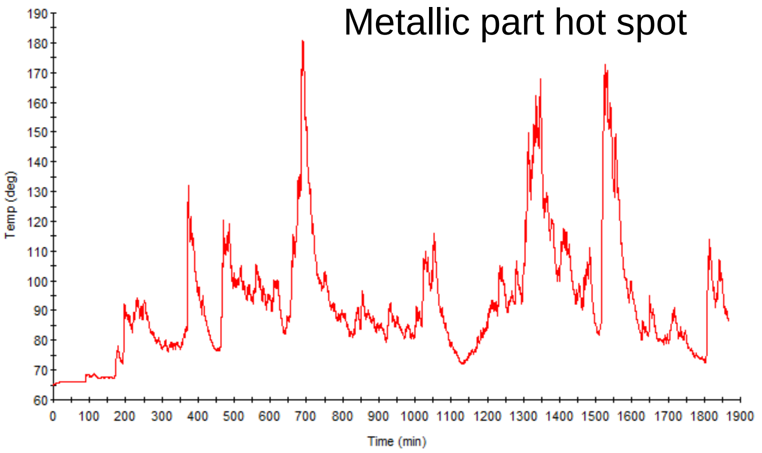
Calculating hot spot temperatures

- For example if GIC_E=10A and GIC_N= -25A, 1V/km, α=1 then:
- $GIC(t) = (E_{EW}(t) \times 10 - E_{NS}(t) \times 25\ )/1000$



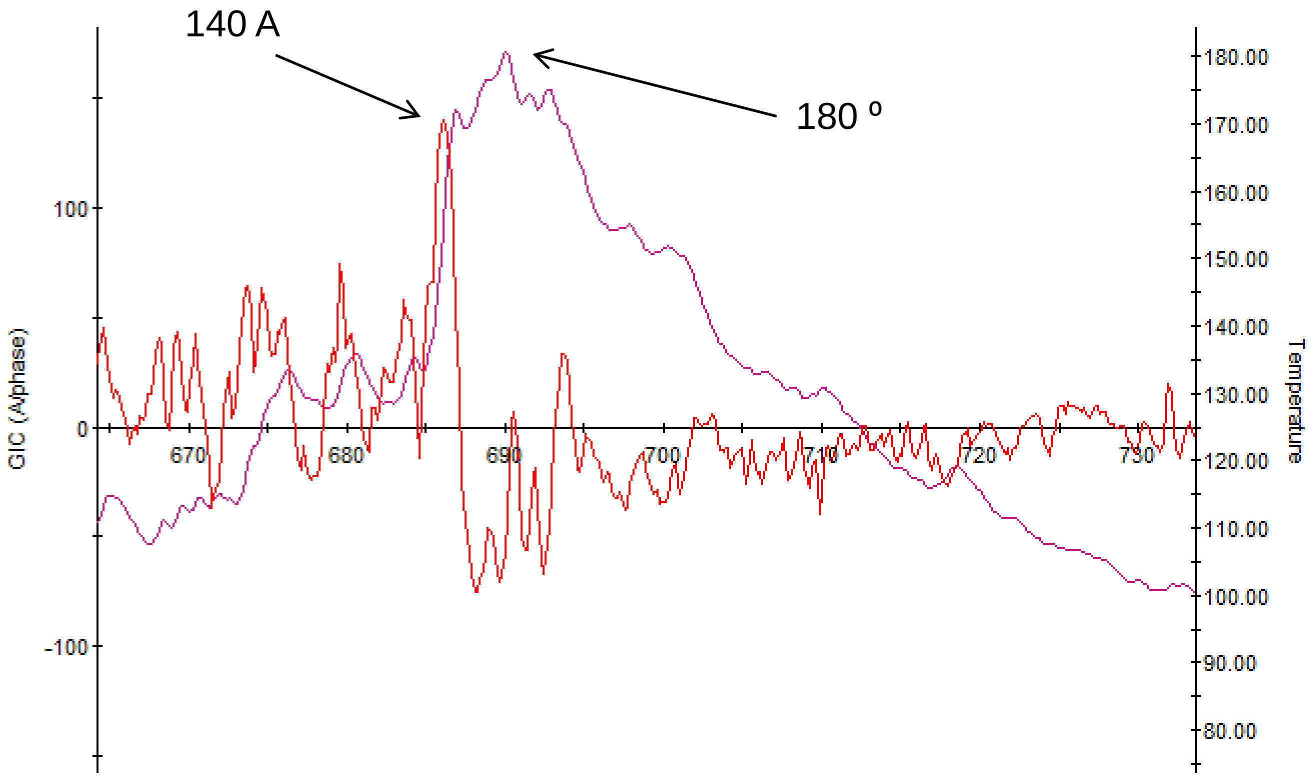
GIC


Winding hot spot


Metallic part hot spot

Calculating GIC(t)

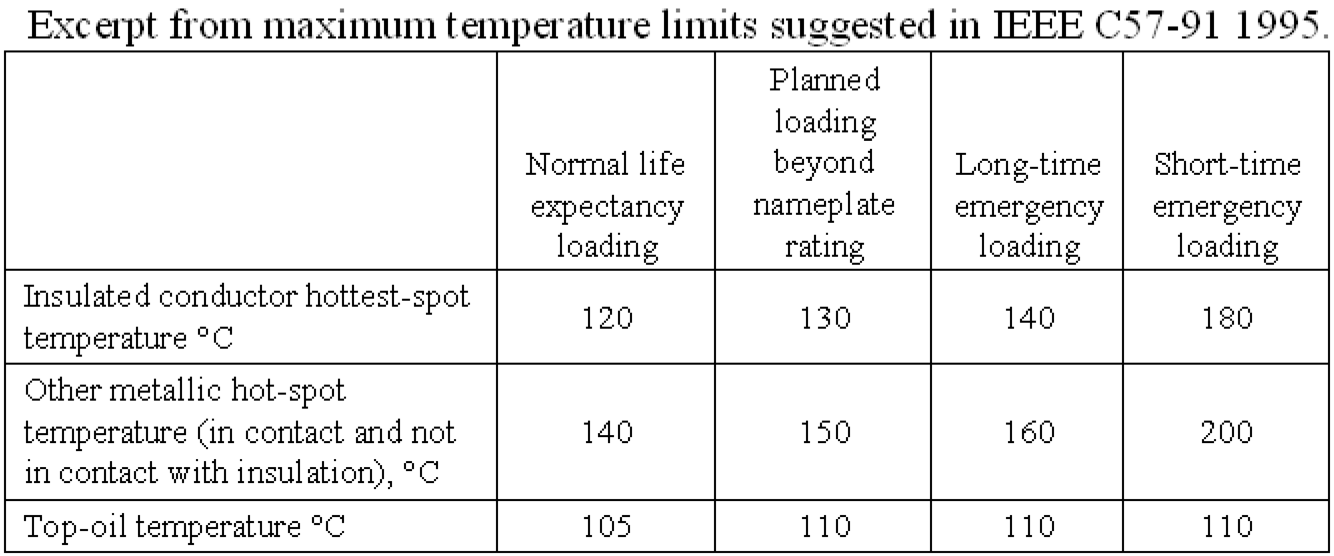
- For example if GIC_E=10A and GIC_N= -25A, 1V/km, α=1 then:
- $GIC(t) = (E_{EW}(t) \times 10 - E_{NS}(t) \times 25\ )/1000$



140 A

180 º

Suggested limits as a function of time

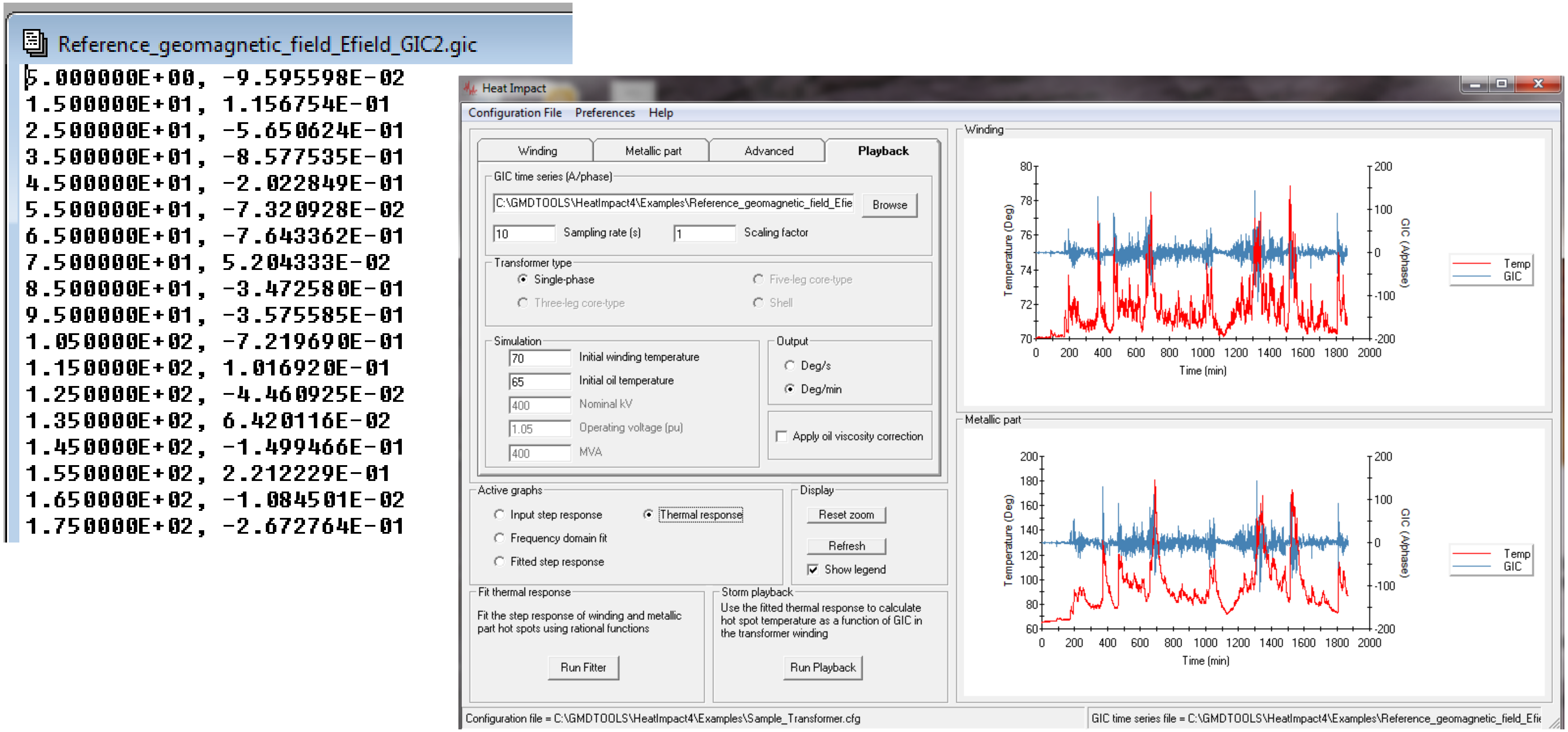


Excerpt from maximum temperature limits suggested in IEEE C57-91 1995.

	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

Calculating hot spot temperatures

- In this instance we used Heat Impact



Reference_geomagnetic_field_Efield_GIC2.gic

```
5.000000E+00, -9.595598E-02
1.500000E+01, 1.156754E-01
2.500000E+01, -5.650624E-01
3.500000E+01, -8.577535E-01
4.500000E+01, -2.022849E-01
5.500000E+01, -7.320928E-02
6.500000E+01, -7.643362E-01
7.500000E+01, 5.204333E-02
8.500000E+01, -3.472580E-01
9.500000E+01, -3.575585E-01
1.050000E+02, -7.219690E-01
1.150000E+02, 1.016920E-01
1.250000E+02, -4.460925E-02
1.350000E+02, 6.420116E-02
1.450000E+02, -1.499466E-01
1.550000E+02, 2.212229E-01
1.650000E+02, -1.084501E-02
1.750000E+02, -2.672764E-01
```

Heat Impact

GIC time series (A/phase): C:\GMDTOOLS\HeatImpact4\Examples\Reference_geomagnetic_field_Efie

10 Sampling rate (s)

1 Scaling factor

Transformer type: ● Single-phase ○ Three-leg core-type ○ Five-leg core-type ○ Shell

Simulation:
70 Initial winding temperature
65 Initial oil temperature
400 Nominal kV
1.05 Operating voltage (pu)
400 MVA

Output: ○ Deg/s ● Deg/min

☐ Apply oil viscosity correction

Active graphs: ○ Input step response ○ Frequency domain fit ○ Fitted step response ● Thermal response

Display: ☑ Show legend

Fit thermal response: Fit the step response of winding and metallic part hot spots using rational functions

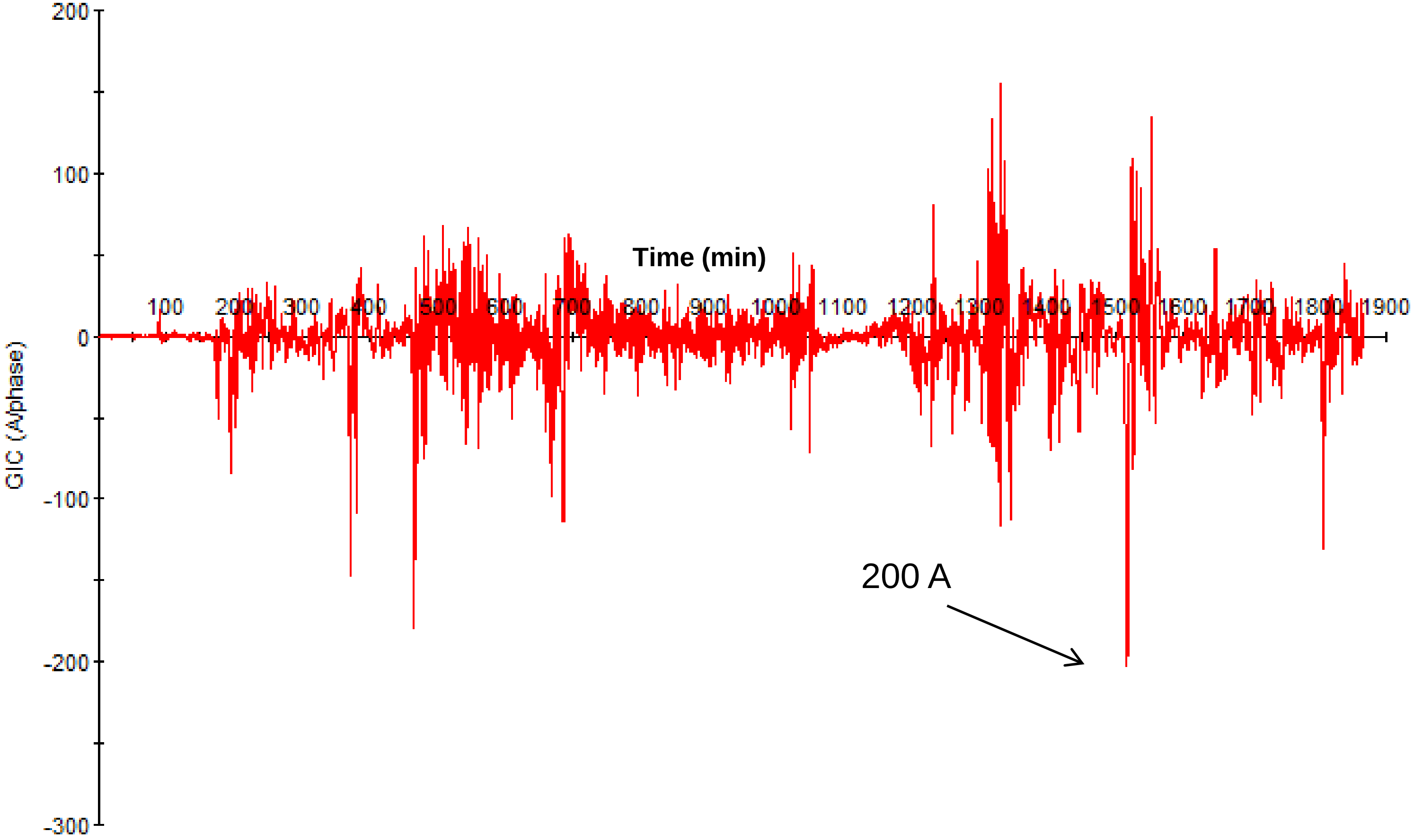
Storm playback: Use the fitted thermal response to calculate hot spot temperature as a function of GIC in the transformer winding

Configuration file = C:\GMDTOOLS\HeatImpact4\Examples\Sample_Transformer.cfg

GIC time series file = C:\GMDTOOLS\HeatImpact4\Examples\Reference_geomagnetic_field_Efie

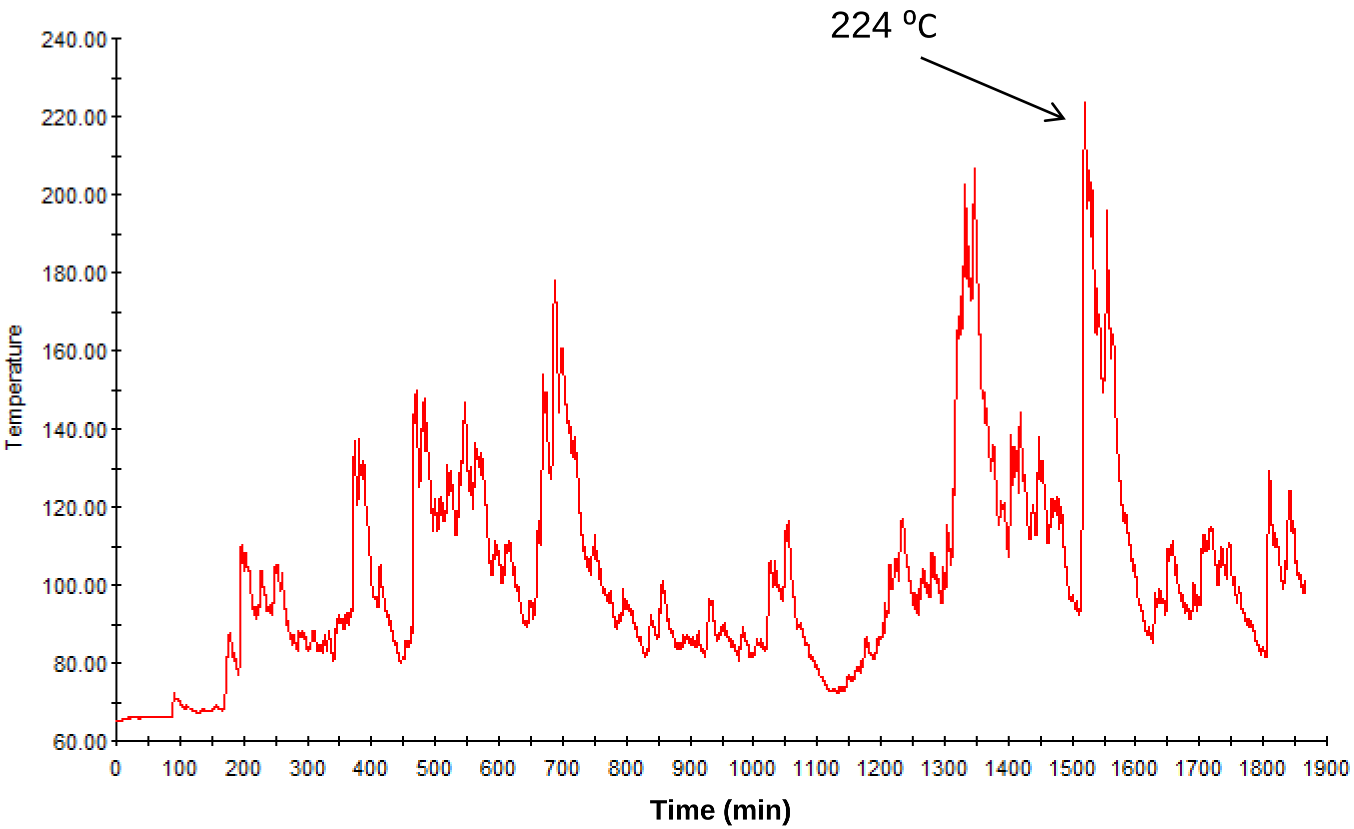
Calculating GIC(t)

- For example if GIC_E=25A and GIC_N= -10A, 1V/km, α=1 then:
- $GIC(t) = (-E_{EW}(t) \times 25 + E_{NS}(t) \times 10\ )/1000$



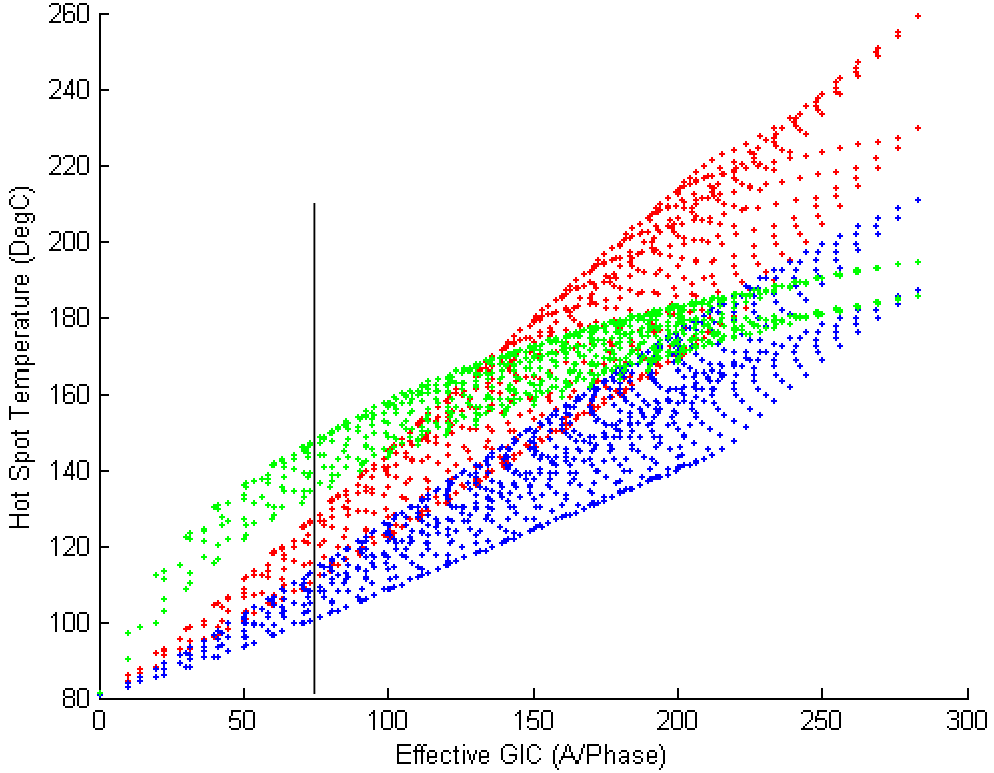
Calculating GIC(t)

- For example if GIC_E=25A and GIC_N= -10A, 1V/km, α=1 then:
- $GIC(t) = (-E_{EW}(t) \times 25 + E_{NS}(t) \times 10\ )/1000$



System configuration matters

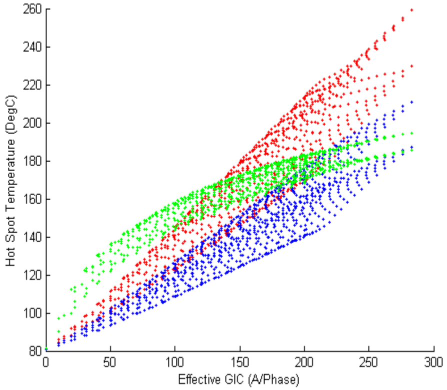
- The last two examples give different results because of the system configuration and circuit orientation
- The envelope covers all possible orientations



System configuration matters

- This table is equivalent to the envelope of the curve

Effective GIC (A/phase)	Metallic hot spot Temperature (° C)	Effective GIC(A/phase)	Metallic hot spot Temperature (° C)
0	80	140	172
10	106	150	180
20	116	160	187
30	125	170	194
40	132	180	200
50	138	190	208
60	143	200	214
70	147	210	221
75	150	220	224
80	152	230	228
90	156	240	233
100	159	250	239
110	163	260	245
120	165	270	251
130	168	280	257



More details in the introduction to GMD studies guide

- Things we have mentioned
  - Relationship between B(t) and GIC(t)
  - Basic modelling aspects of GIC studies
  - Salient points of GMD studies needed for TPL007
- Things we have glossed over
  - P&C susceptibility assessment
  - Harmonic analysis
  - Generator effects
  - Iterative process of studies and mitigation measures
- When all is said and done, GMD/GIC and the power system is an engineering problem. The more we work on it, the more we will know, and the better we will be at it.