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New Reliability Standard – NERC TPL-007-1

November 9, 2017

Tutorial Outline

- Introduction

- NERC TPL-007-1
  - Requirements and Measures
  - Benchmark GMD Event
  - GIC Analysis
  - GMD Vulnerability Assessment
  - Transformer Thermal Assessment
  - Corrective Action Plans

- Other Types of GMD-related studies

- TPL-007-2 Draft Version

North American Electric Reliability Corporation (NERC)

- Regulatory authority established to assure the reliability and security of the bulk power system in North America

- Develops and enforces reliability standards

- Annually assesses seasonal and long-term reliability

- Educates, trains, and certifies industry personnel

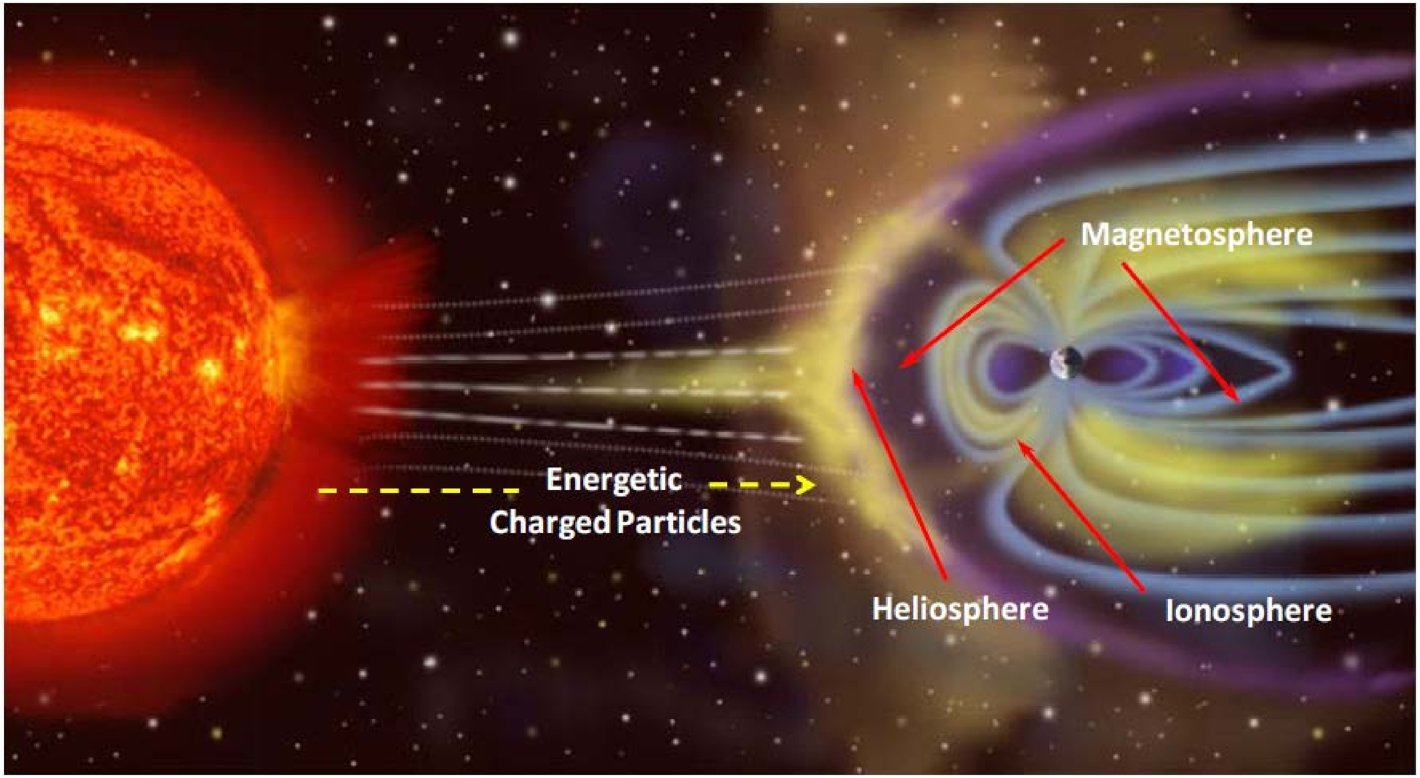
NERC Reliability Standards

- Establish reliability requirements for planning and operating the bulk power system

- US regulatory jurisdiction (14 categories, 98 standards)
  - (BAL) Resource and Demand Balancing
  - (CIP) Critical Infrastructure Protection
  - (COM) Communications
  - (EOP) Emergency Preparedness and Operations
    - EOP-010-1 – Geomagnetic Disturbance Operations
  - (FAC) Facilities Design, Connections, and Maintenance
  - (INT) Interchange Scheduling and Coordination
  - (IRO) Interconnection Reliability Operations and Coordination
  - (MOD) Modeling, Data, and Analysis
  - (NUC) Nuclear
  - (PER) Personnel Performance, Training, and Qualifications
  - (PRC) Protection and Control
  - (VAR) Voltage and Reactive
  - (TOP) Transmission Operations
  - (TPL) Transmission Planning
    - TPL-007-1 Transmission System Planned Performance for Geomagnetic Disturbance Events

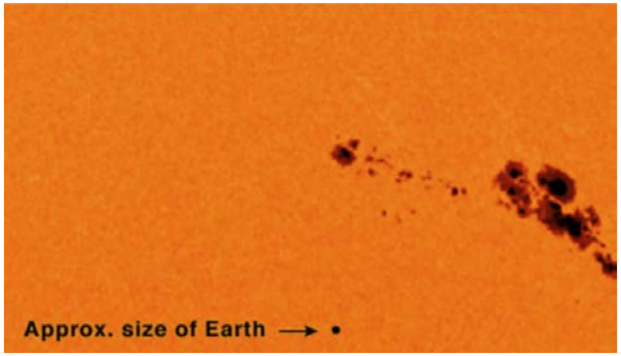
Geomagnetic Disturbance (GMD)

Geomagnetic Disturbance (GMD)



Source: NERC 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System

Geomagnetic Disturbance (GMD)



- Disturbances to Earth’s magnetic field.
- GMD events are natural hazards that can occur during solar events driven by Solar Coronal Holes and Coronal Mass Ejections (CME) .
- CMEs are huge explosions of magnetic field and charged particles from the Sun's corona.
- CMEs may take14 to 36 hours to reach Earth.
- A severe GMD can occur due to a large CME that is directed at Earth.

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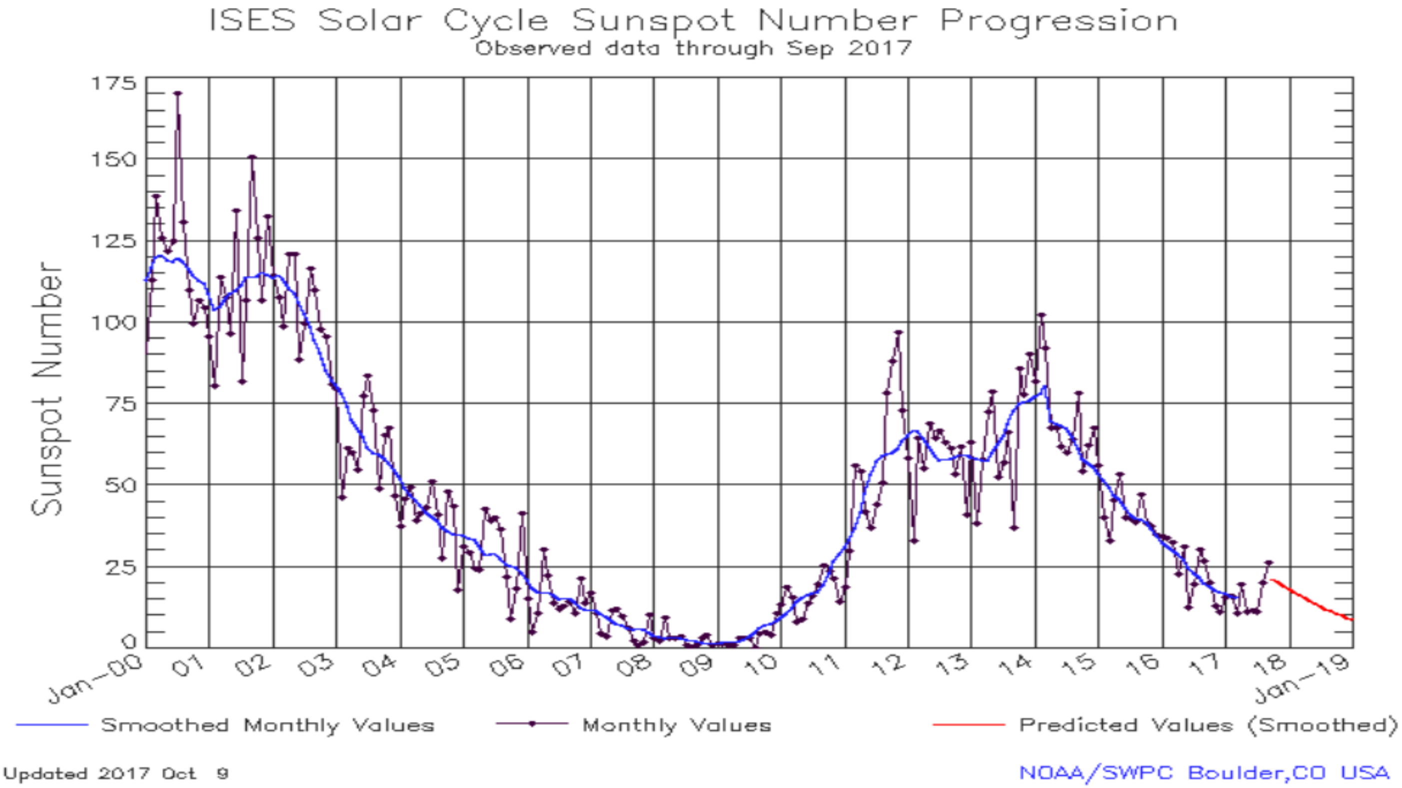
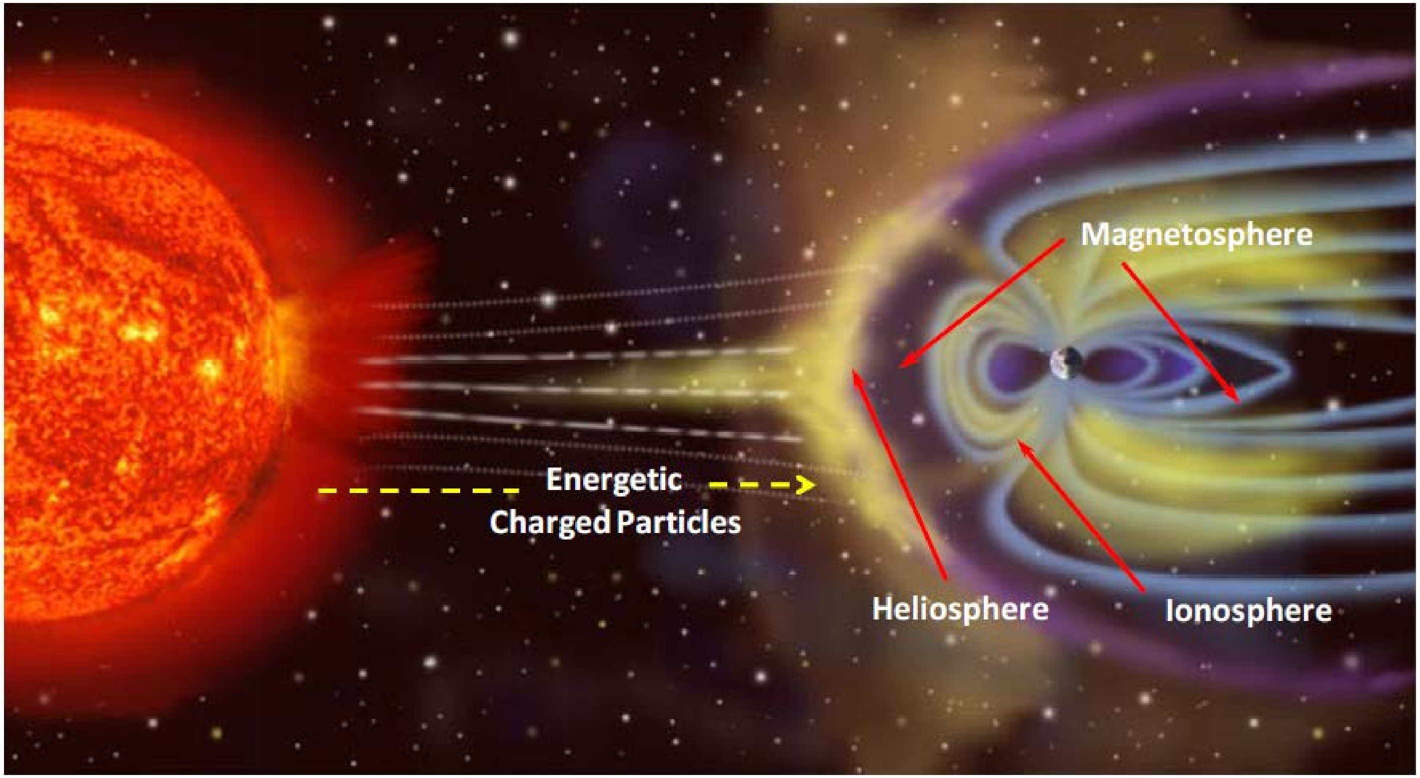
Sunspots/Solar Cycle

Sunspot Number Progression



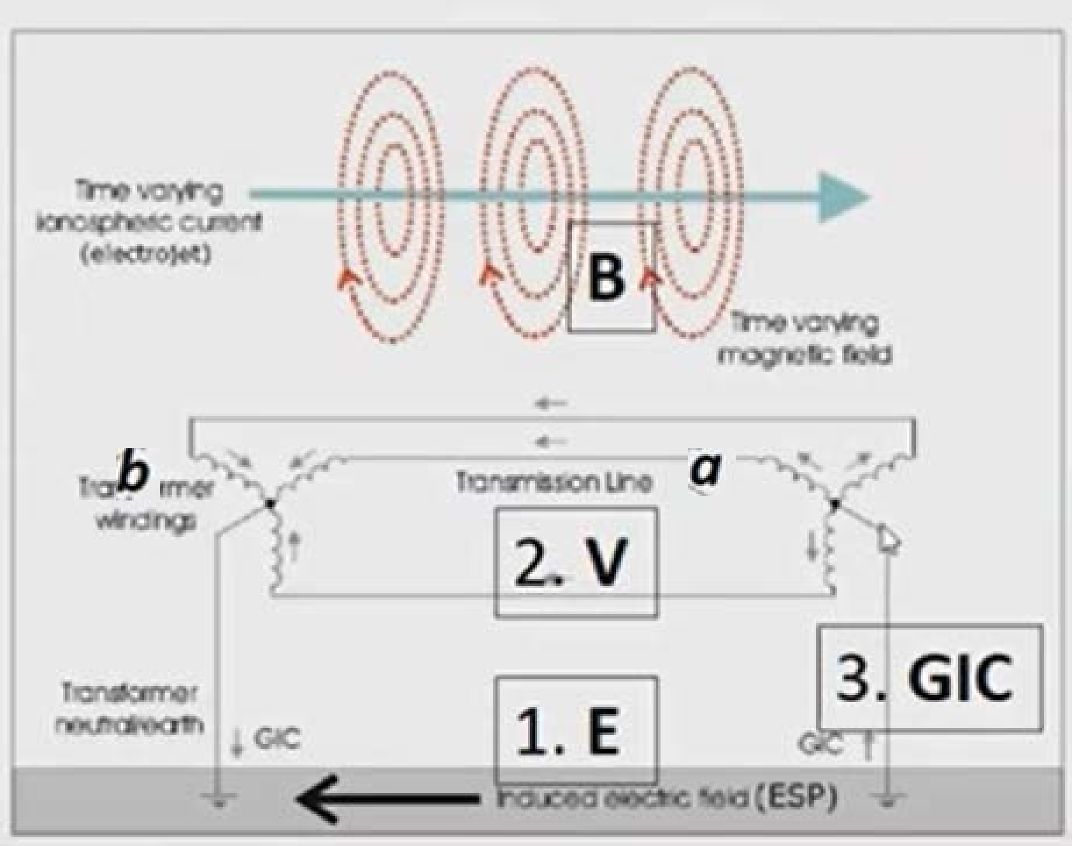
Source: http://www.swpc.noaa.gov/products/solar-cycle-progression

Geomagnetic Disturbance (GMD)



Source: NERC 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System

Geomagnetic Disturbance (GMD)



$$E_x(\omega)=Z(\omega)H_y(\omega);$$

$$E_y(\omega)=-Z(\omega)H_x(\omega)$$

$$B(\omega)=-\mu_0 H(\omega)$$

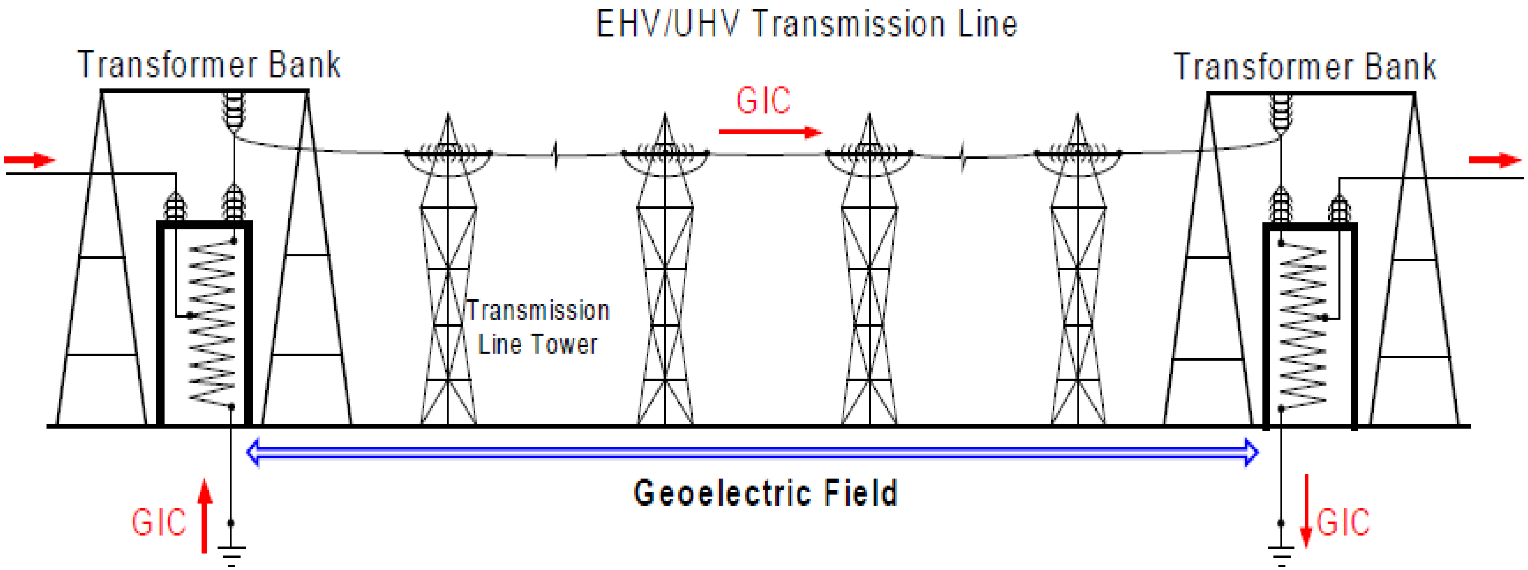
$$V_{ab}=\int_a^b \vec{E}\bullet d\vec{l}$$

Source: Introduction to Geomagnetic Disturbance, Iowa State University Spring GMD Webinar Series

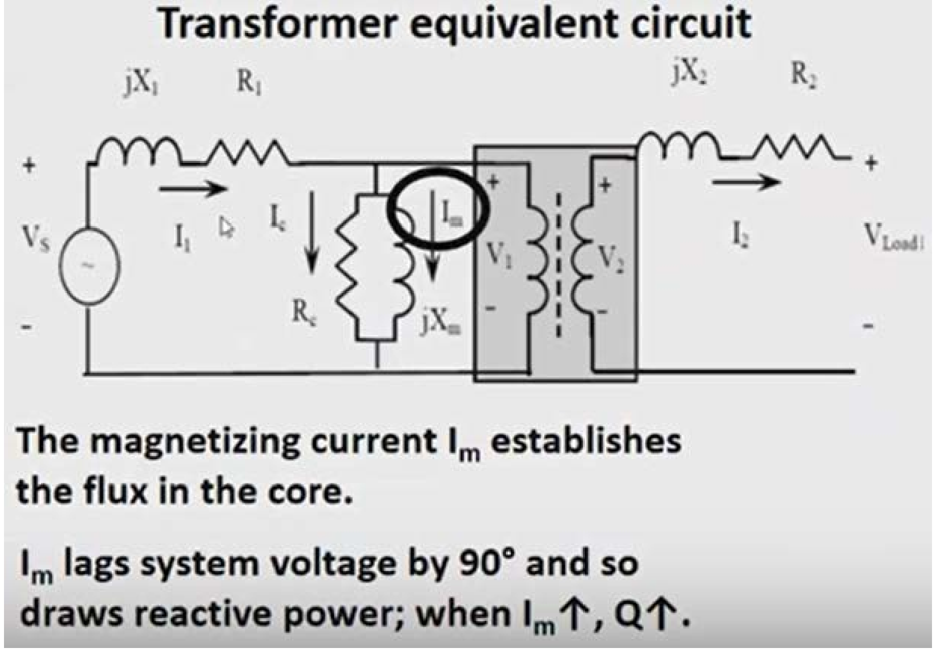
GIC

- Low frequency (0.0001 Hz – 1 Hz); quasi-dc

- From power system modeling perspective GIC is considered as dc



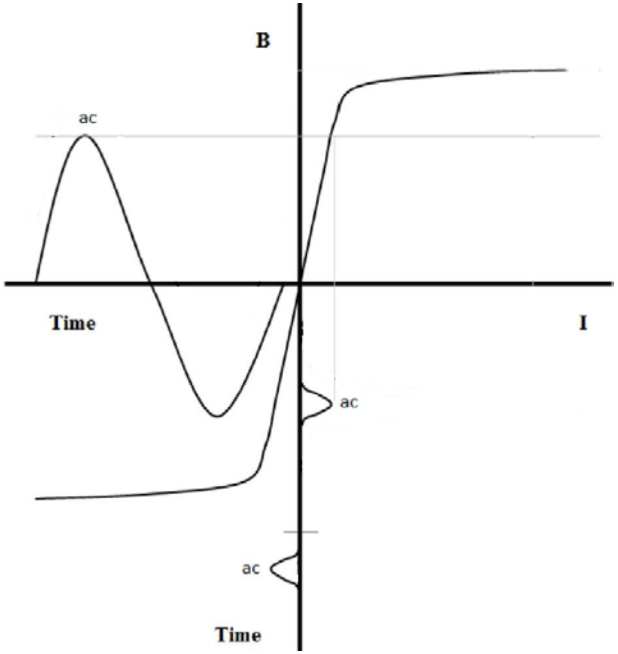
Transformer – Normal Operation



Transformer equivalent circuit

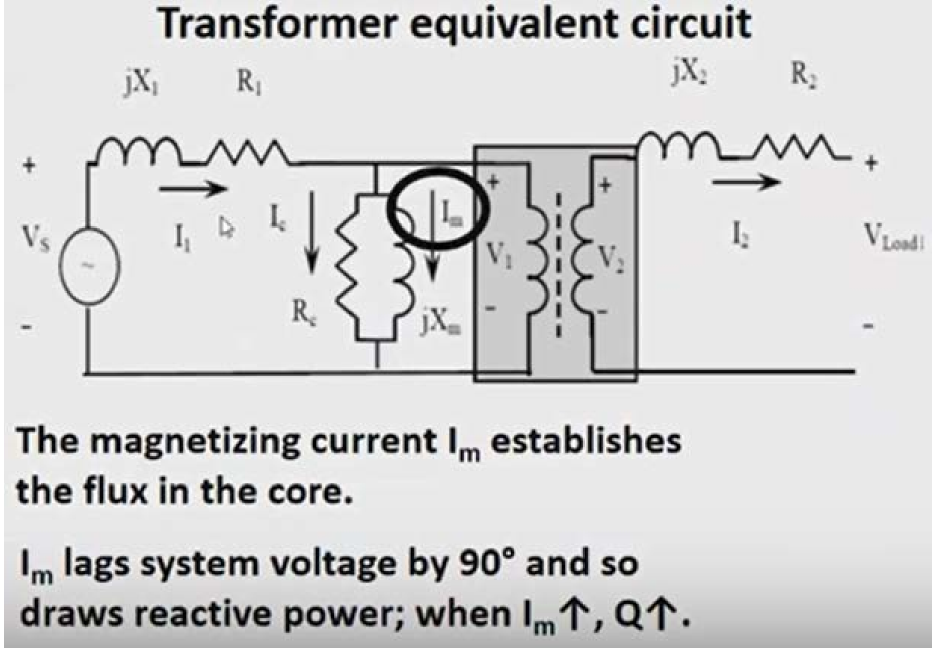
The magnetizing current I_m establishes the flux in the core.

I_m lags system voltage by 90° and so draws reactive power; when I_m↑, Q↑.



Source: Introduction to Geomagnetic Disturbance, Iowa State University Spring GMD Webinar Series

Transformer – Half-cycle Saturation



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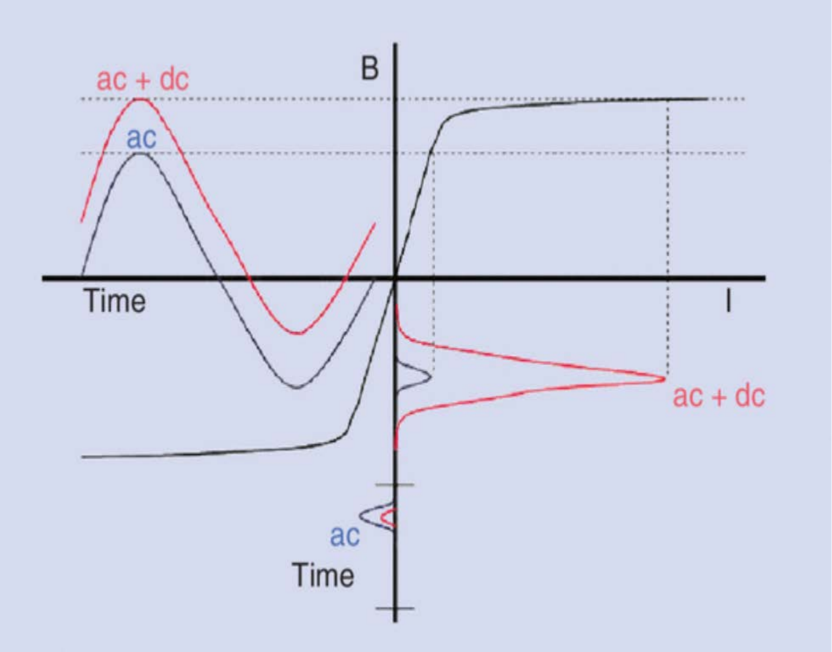
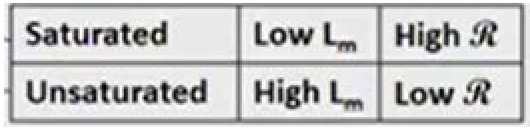
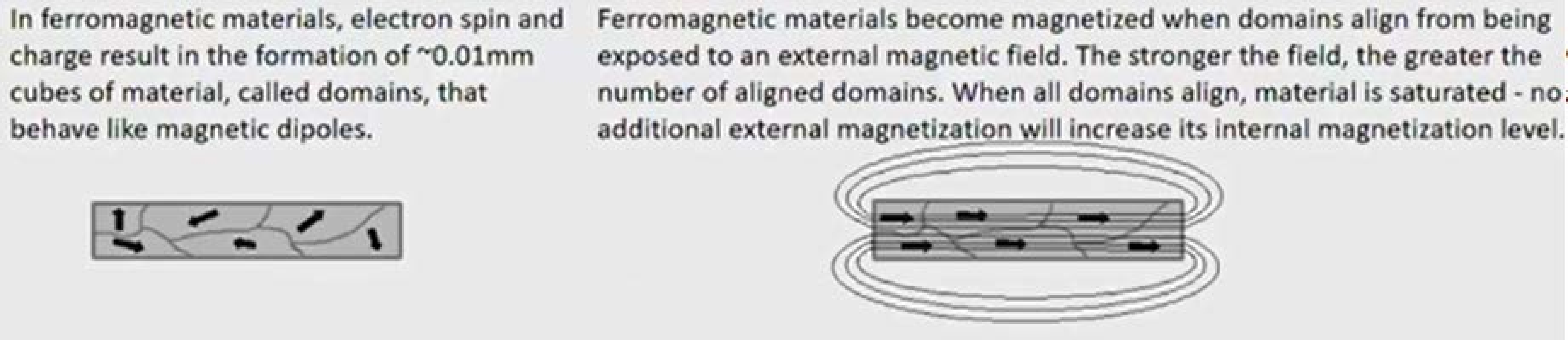




Saturated	Low L_m	High $\mathcal{R}$
Unsaturated	High L_m	Low $\mathcal{R}$

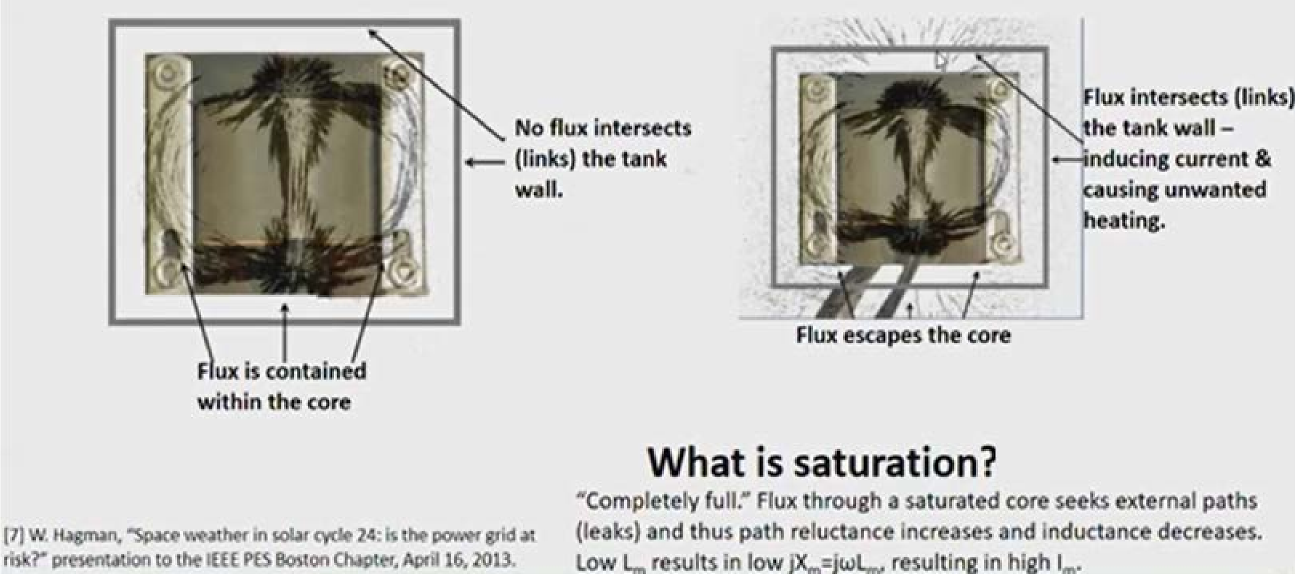
Source: Introduction to Geomagnetic Disturbance, Iowa State University Spring GMD Webinar Series

Transformer Saturation



In ferromagnetic materials, electron spin and charge result in the formation of ~0.01mm cubes of material, called domains, that behave like magnetic dipoles.

Ferromagnetic materials become magnetized when domains align from being exposed to an external magnetic field. The stronger the field, the greater the number of aligned domains. When all domains align, material is saturated - no additional external magnetization will increase its internal magnetization level.



No flux intersects (links) the tank wall.

Flux is contained within the core

Flux intersects (links) the tank wall – inducing current & causing unwanted heating.

Flux escapes the core

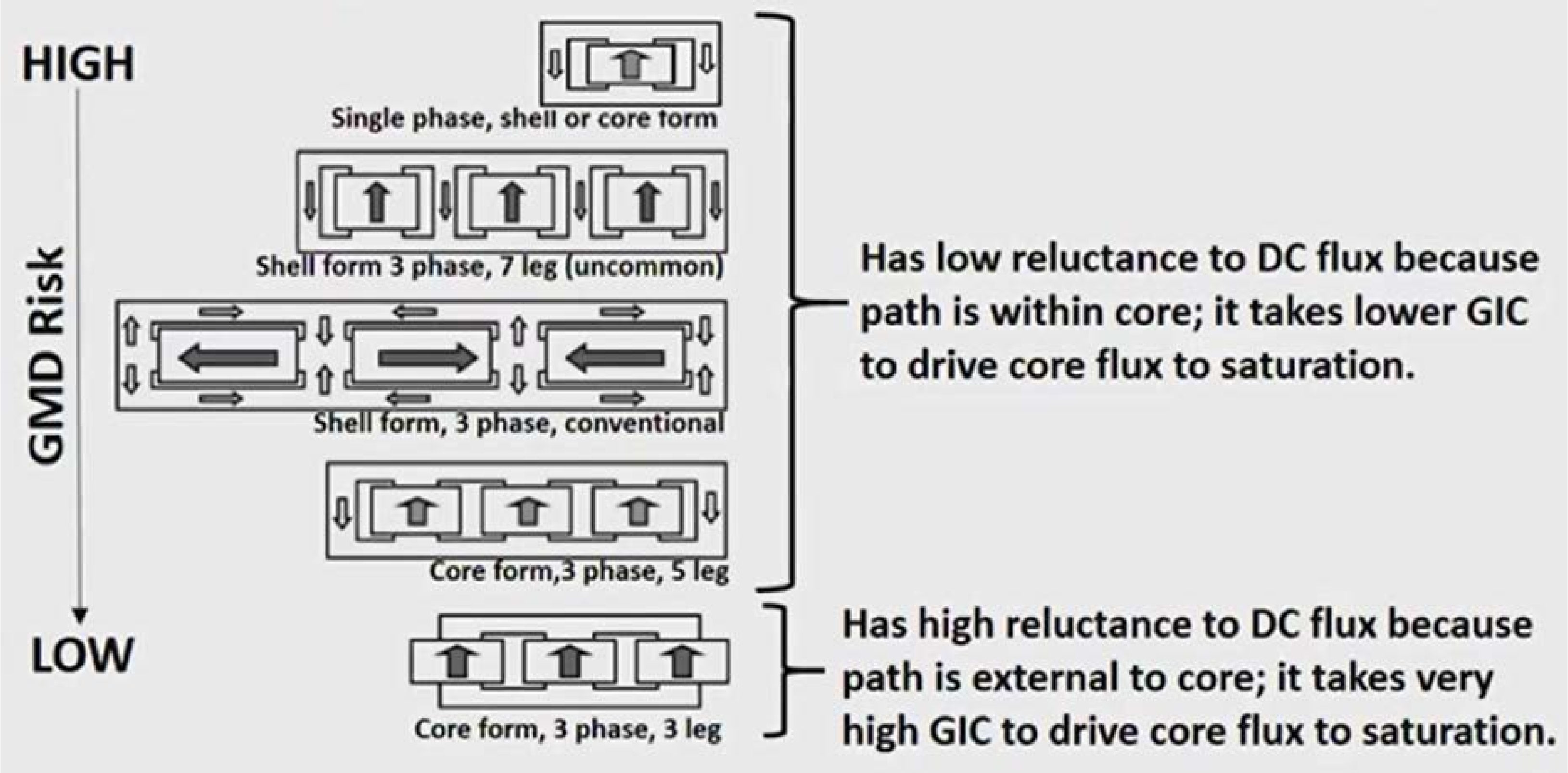
What is saturation?

"Completely full." Flux through a saturated core seeks external paths (leaks) and thus path reluctance increases and inductance decreases. Low L_m results in low $jX_m=j\omega L_m$, resulting in high I_m.

[7] W. Hagman, "Space weather in solar cycle 24: is the power grid at risk?" presentation to the IEEE PES Boston Chapter, April 16, 2013.

Source: Introduction to Geomagnetic Disturbance, Iowa State University Spring GMD Webinar Series

Transformer Saturation – Core Design

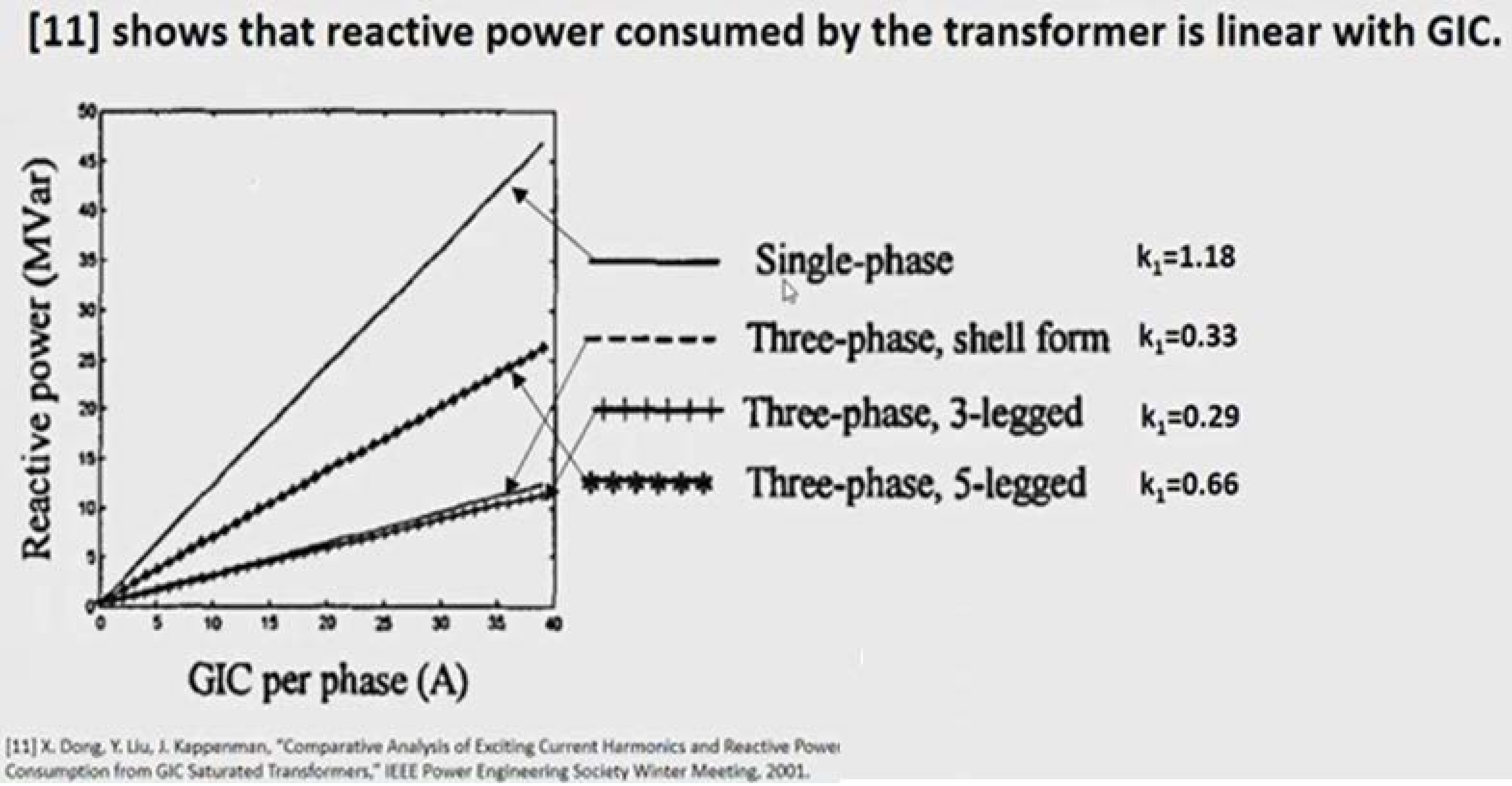


Has low reluctance to DC flux because path is within core; it takes lower GIC to drive core flux to saturation.

Has high reluctance to DC flux because path is external to core; it takes very high GIC to drive core flux to saturation.

Source: Introduction to Geomagnetic Disturbance, Iowa State University Spring GMD Webinar Series

Reactive Power (Q) vs GIC

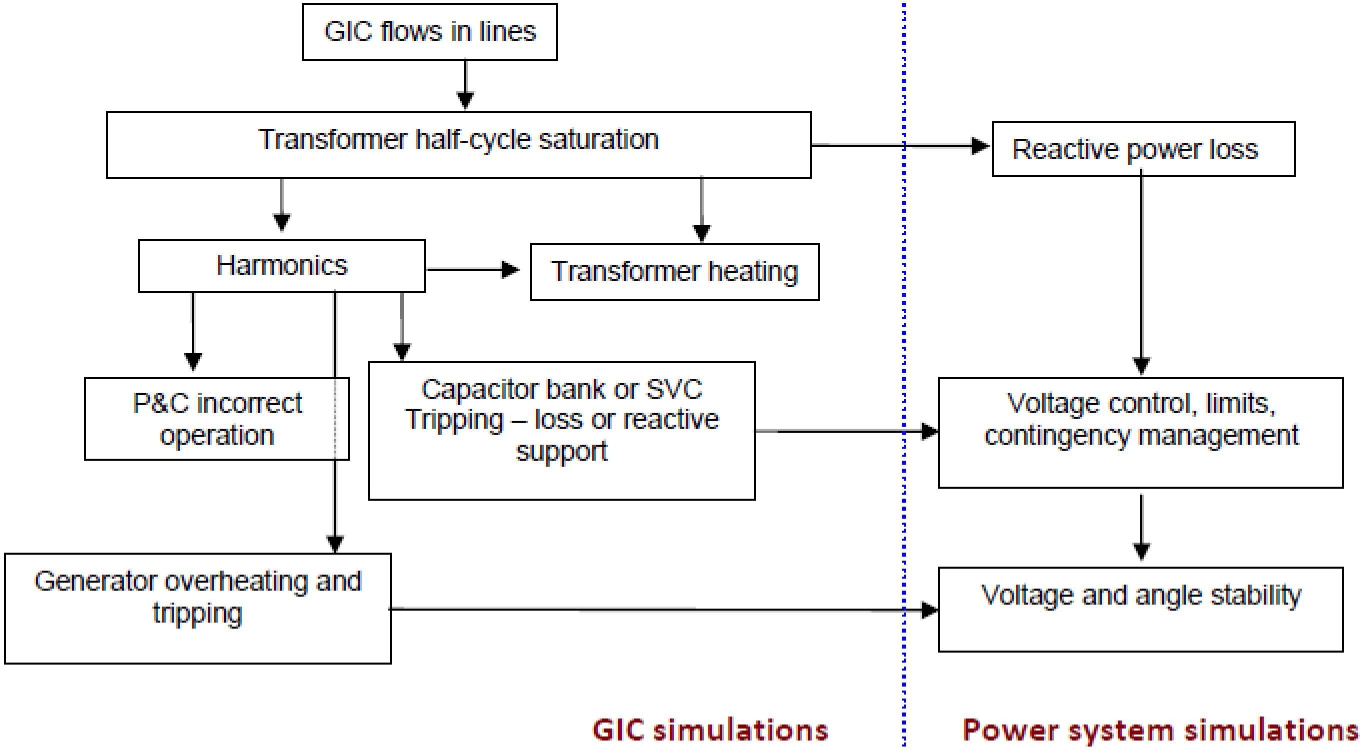


[11] shows that reactive power consumed by the transformer is linear with GIC.

[11] X. Dong, Y. Liu, J. Kappenman, "Comparative Analysis of Exciting Current Harmonics and Reactive Powe Consumption from GIC Saturated Transformers," IEEE Power Engineering Society Winter Meeting, 2001.

Source: Introduction to Geomagnetic Disturbance, Iowa State University Spring GMD Webinar Series

Effects of GIC on the Power System



Source: **NERC 2012 GMD Report**

Historical GMD Events

Historical Events

- **1859 Carrington Event (August 28, September 2)**
  - Largest recorded geomagnetic disturbance
  - Widespread Aurora observations, Telegraph operations were disrupted

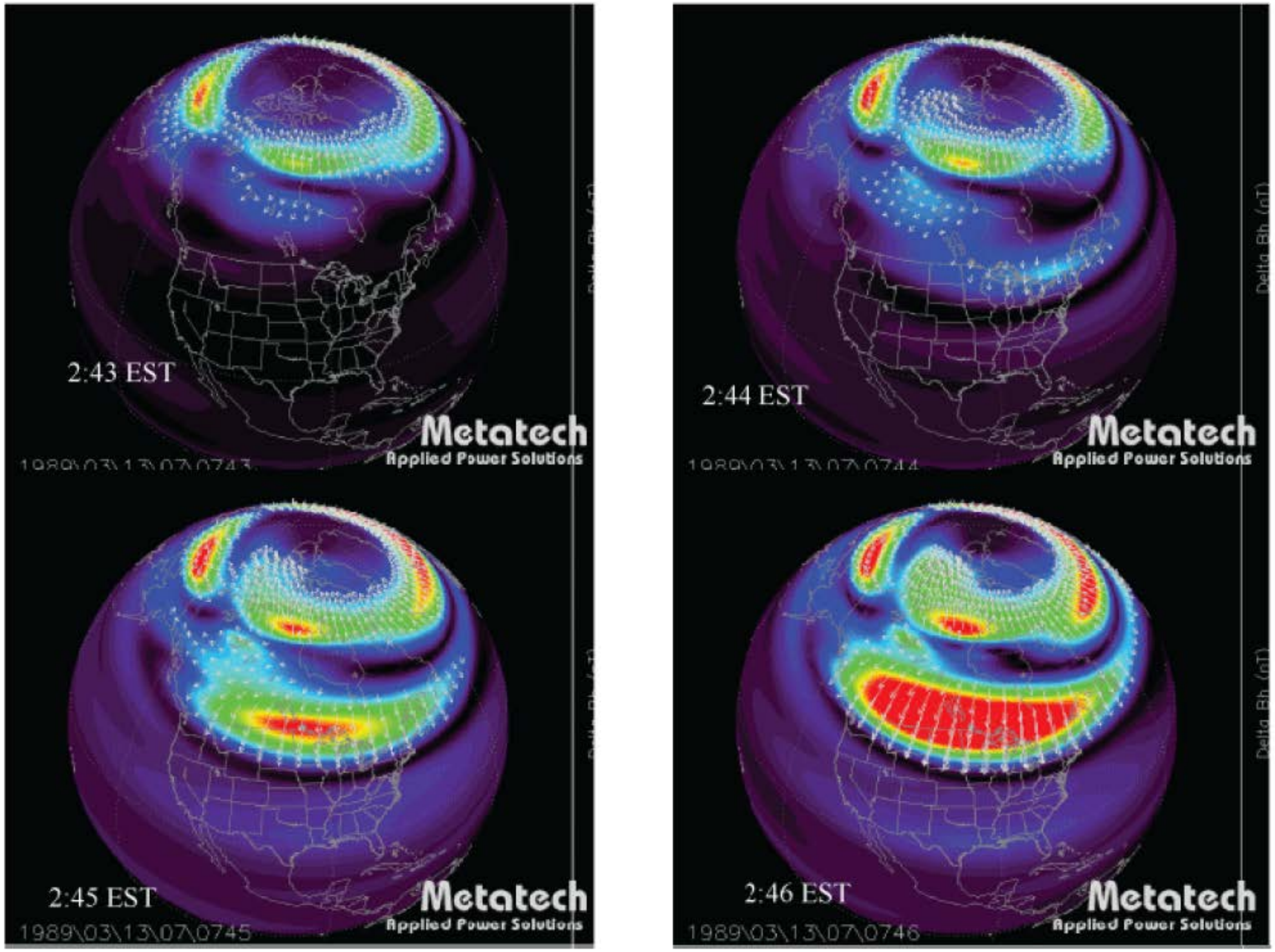
- **1921 Solar Storm (May 14-15)**
  - Widespread Aurora observations, Telegraph communications disrupted

- **1989 Québec Blackout (March 13-14)**
  - Voltage collapse and blackout Hydro-Québec system, leaving more than six million people without power for nine hours
  - SVCs unintentional tripping, Equipment damage

Historical Events

- **2003 Halloween Solar Storms (October 19-November 5)**
  - Affected spacecraft operations, deep space missions and near-Earth satellites, Caused communication degradation, high levels of neutral current, capacitor tripping
  - October 30 - GIC flows of 330 A in a large 3-phase transformer in the south of Sweden. A blackout (20-50 min) caused by line trip due to higher sensitivity to the 3rd harmonic associated with transformer saturation

March 1989 Storm – Ground Level Geomagnetic Intensification

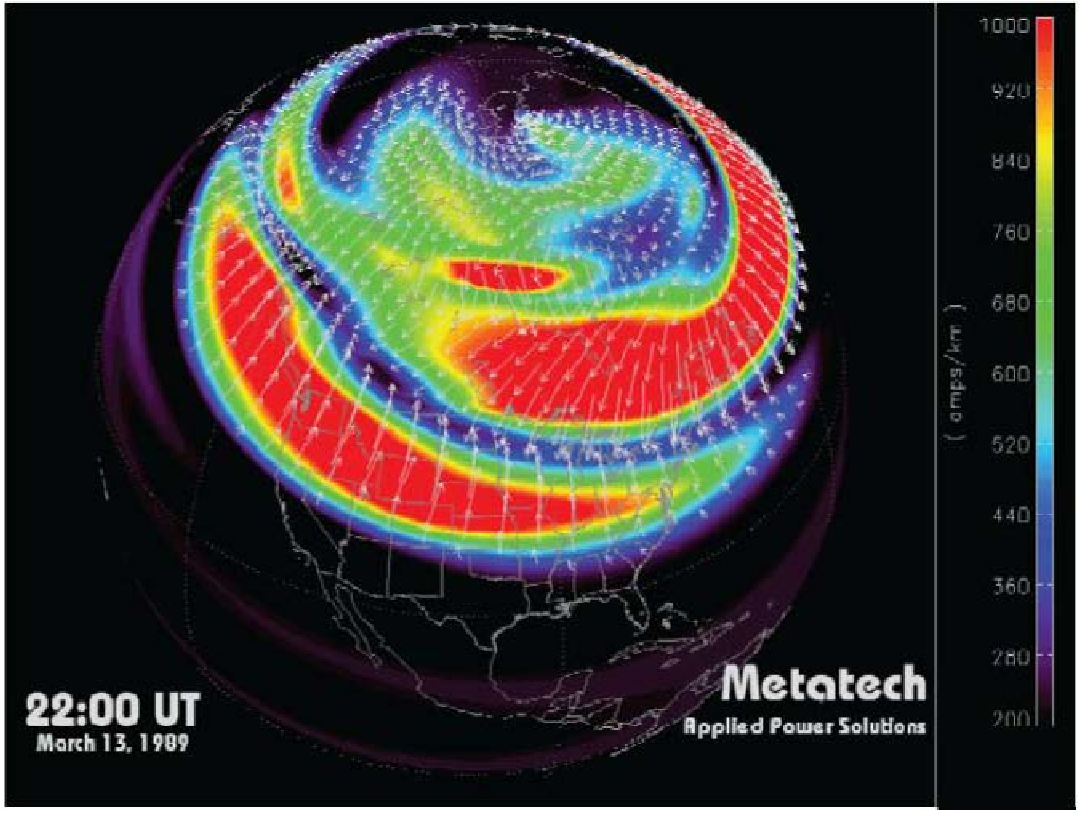


Source: High-Impact, Low-Frequency Event Risk to the North American Bulk Power System Report by NERC and DOE

March 13, 1989 GMD Event (Severe – K9)

- Sudden large variation in earth’s magnetic field resulted in voltage collapse and blackout of Hydro-Québec system in 92 seconds
  - GIC created harmonic voltages and currents of considerable intensity.
  - Voltage asymmetry on the 735-kV network reached 15%.
  - Seven static var compensators tripped
  - Voltage dropped so drastically
  - Five lines to Montréal tripped through loss of synchronism (virtual fault), and the entire network separated.
  - Loss of 9,450 MW of generation caused a very rapid frequency drop
  - Automatic underfrequency load-shedding controls functioned properly, but they are not designed for recovery from a generation loss equivalent to about half system load. The rest of the grid collapsed piece by piece in 25 seconds.

Ground Level Geomagnetic Intensification – March 13, 1989 substorm (17:00 EST)



Source: High-Impact, Low-Frequency Event Risk to the North American Bulk Power System Report by NERC and DOE

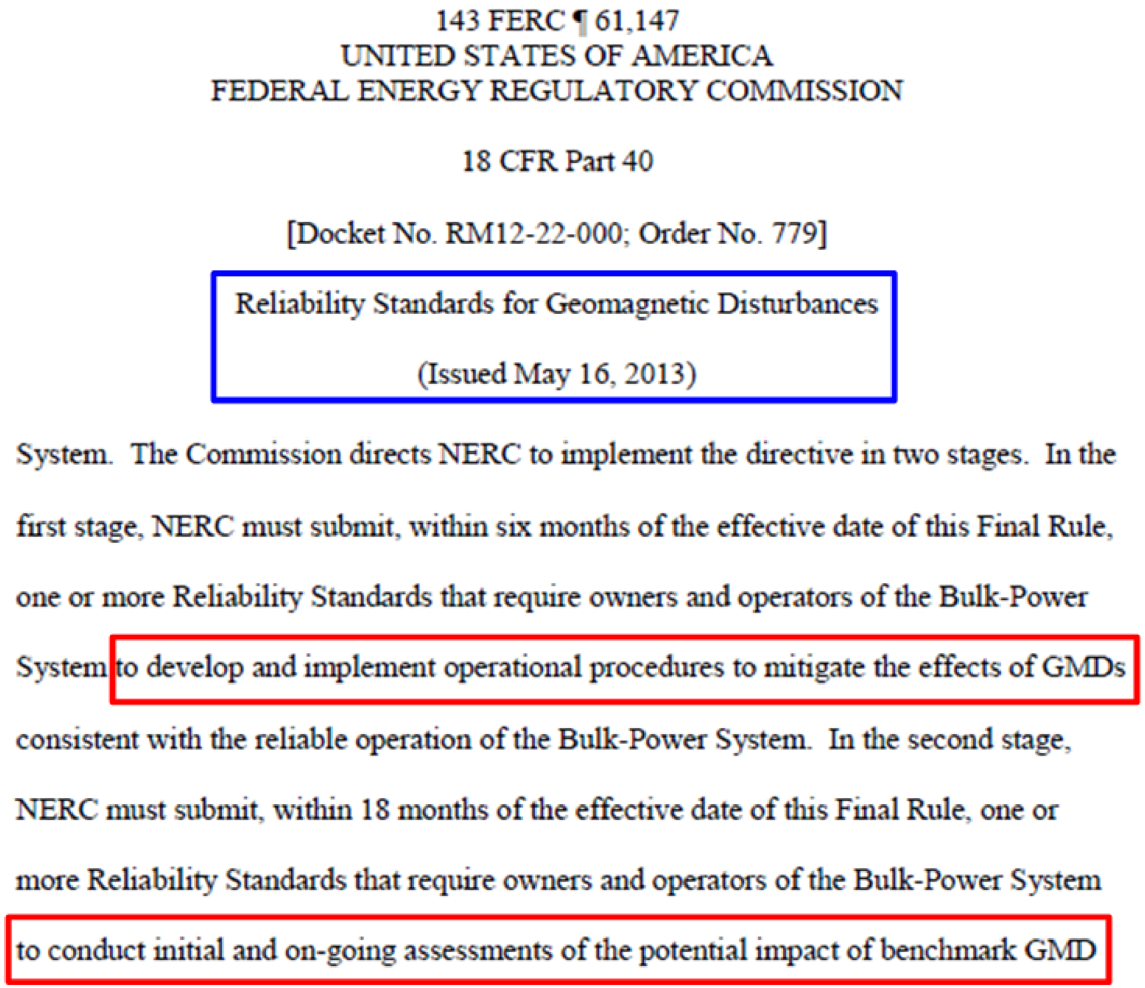
Geomagnetic Disturbance (GMD)

- GMD can have severe, widespread effects on reliable grid operation, including voltage collapse, blackouts and damage to critical or vulnerable equipment.

- Understanding the effects of these high impact, low frequency GMD events on bulk power system and the ability of the industry to mitigate their effects are important to managing system reliability.

TPL-007 Reliability Standard Development

FERC Order 779



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)

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

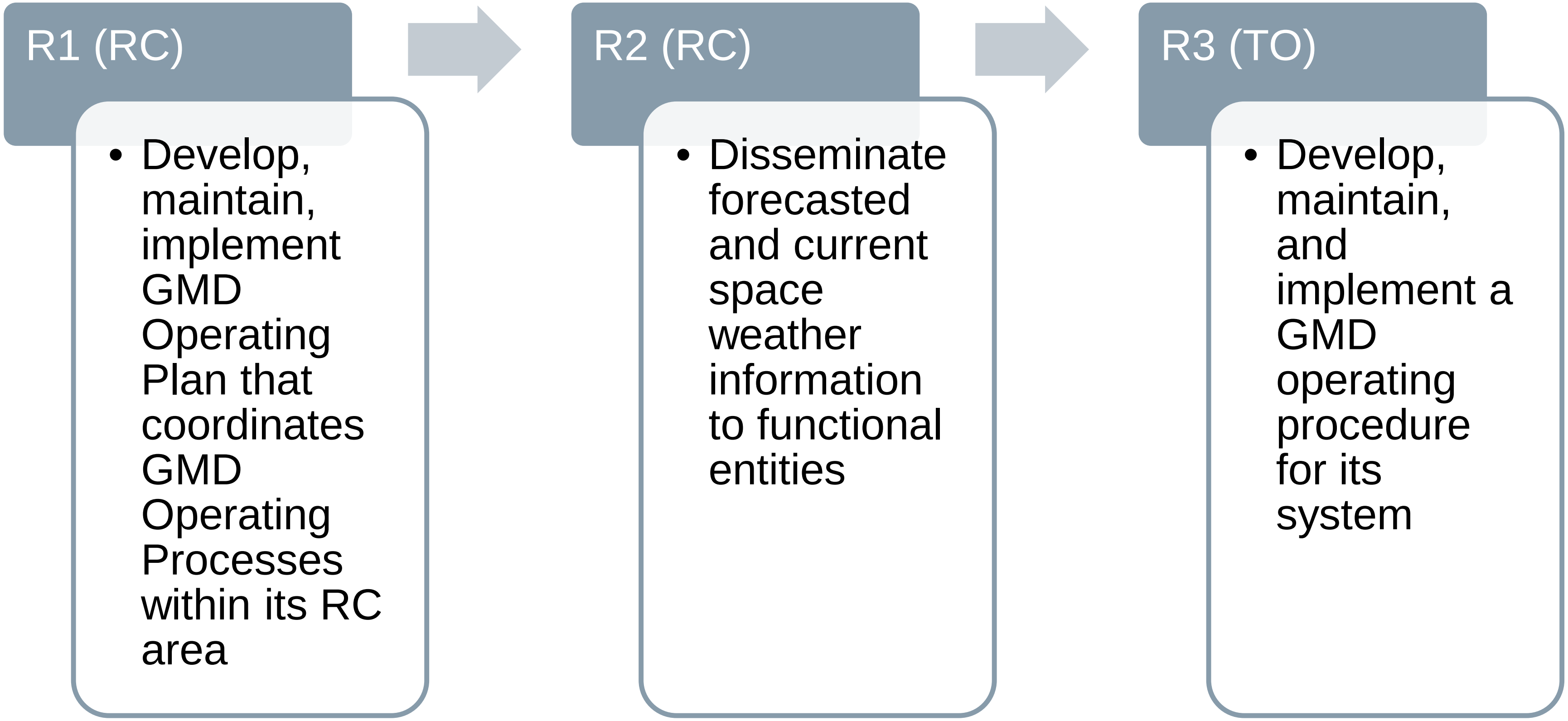
FERC Order 779 (continued)

- 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 (Initial and ongoing Planning Studies)

- Standards project 2013-03 (GMD Mitigation) began in June 2013

- Two standards were developed:
  - **EOP-010-1** – Geomagnetic Disturbance Operations was approved by FERC in June 2014.
  - **TOP-007-1** – Transmission System Planned Performance for Geomagnetic Disturbance Events

EOP-010-1 – Geomagnetic Disturbance Operations



R1 (RC)

- Develop, maintain, implement GMD Operating Plan that coordinates GMD Operating Processes within its RC area

R2 (RC)

- Disseminate forecasted and current space weather information to functional entities

R3 (TO)

- Develop, maintain, and implement a GMD operating procedure for its system

GMD Monitoring & Forecasting

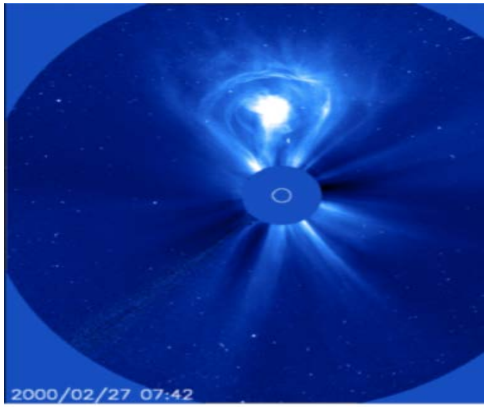
Space Weather real-time monitoring and forecasting

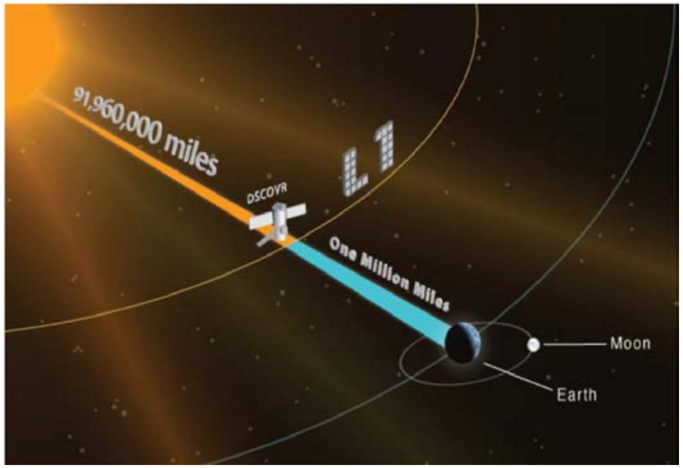
- US – Space Weather Prediction Center SWPC, Boulder, Colorado; part of NOAA
- Canada – Canadian Space Weather Forecast Centre, Ottawa, Ontario

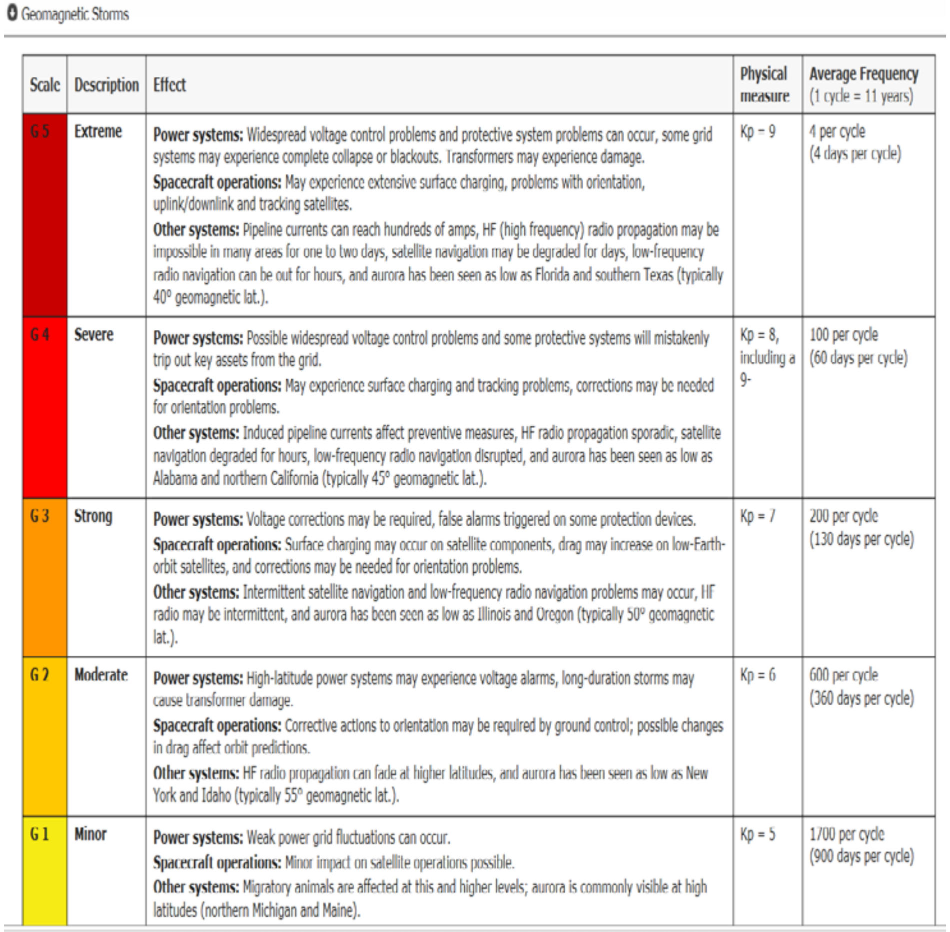
Earth’s Geomagnetic field monitoring (Monitors Magnetic observatories and distributes magnetometer data in real-time)

- US – US Geological Survey (USGS)
- Geological Survey of Canada (GSC)

Space Weather Monitoring (CME, DSCOVR, ACE)







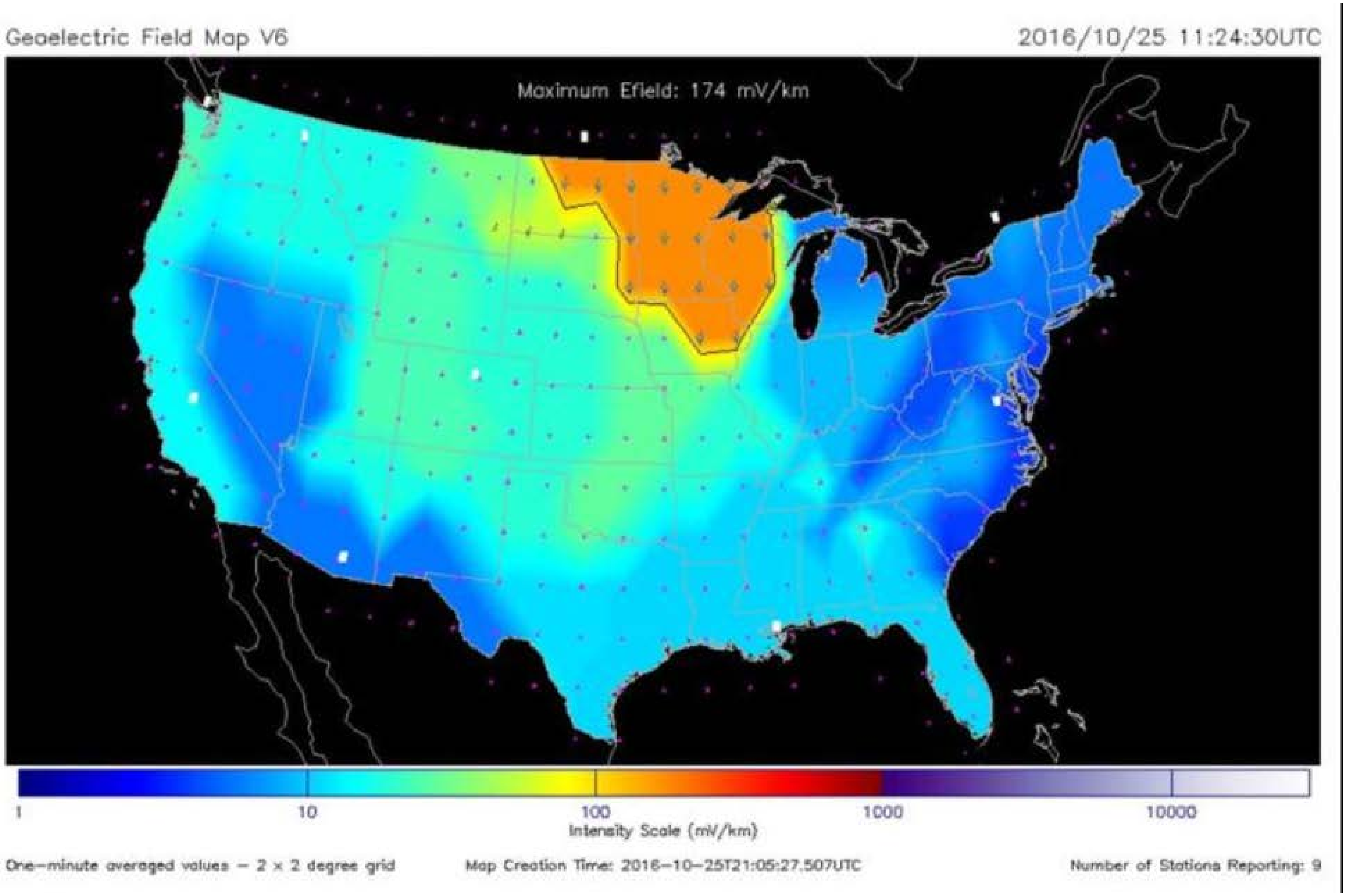
Geomagnetic Storms

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Source: http://www.swpc.noaa.gov/phenomena/coronal-mass-ejections

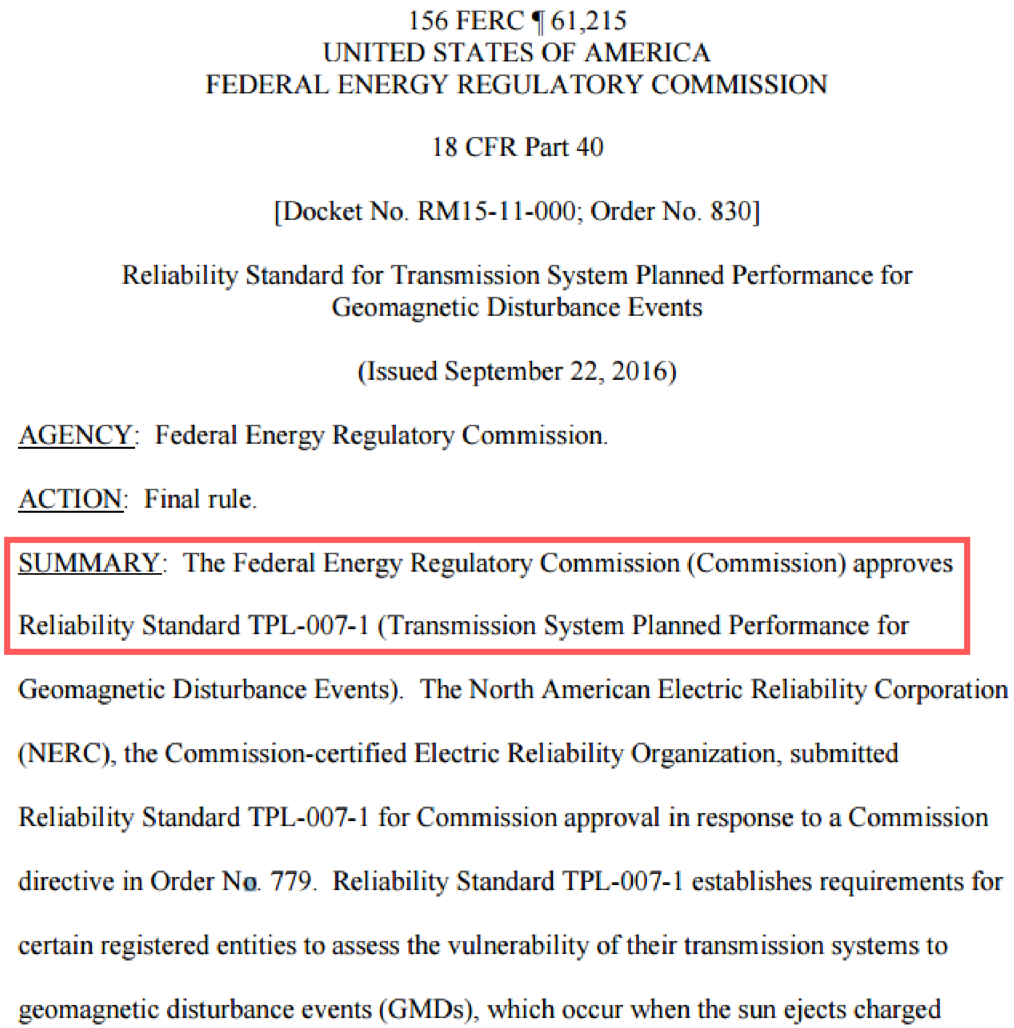
Source: http://www.swpc.noaa.gov/news/27-july-2016-it%E2%80%99s-all-systems-go-noaa%E2%80%99s-first-deep-space-space-weather-satellite

New Geoelectric Field Model for Real-Time Situational Awareness (expected in 2018)



http://www.swpc.noaa.gov/news/new-space-weather-model-geoelectric-field-model-announced-today

FERC Order 830



156 FERC ¶ 61,215
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

18 CFR Part 40

[Docket No. RM15-11-000; Order No. 830]

Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events

(Issued September 22, 2016)

AGENCY: Federal Energy Regulatory Commission.

ACTION: Final rule.

SUMMARY: The Federal Energy Regulatory Commission (Commission) approves Reliability Standard TPL-007-1 (Transmission System Planned Performance for Geomagnetic Disturbance Events). The North American Electric Reliability Corporation (NERC), the Commission-certified Electric Reliability Organization, submitted Reliability Standard TPL-007-1 for Commission approval in response to a Commission directive in Order No. 779. Reliability Standard TPL-007-1 establishes requirements for certain registered entities to assess the vulnerability of their transmission systems to geomagnetic disturbance events (GMDs), which occur when the sun ejects charged

FERC Order 830 (continued)

- NERC to develop modifications to Reliability Standard TPL-007-1 (due May 2018):
    - Modify the benchmark GMD event definition so it is not based solely on spatially-averaged data
    - Include data collection requirements for GIC monitoring and magnetometer data
    - Include deadlines for the development and completion of corrective action plans and mitigation actions.

TPL-007-1

NERC TPL-007-1 Components

- Requirements and Measures
- Benchmark GMD Event
- GIC Calculation (DC Network Analysis)
- GMD Vulnerability Assessment
- Transformer Thermal Assessment
- Corrective Action Plan (CAP)

NERC TPL-007-1

- **GMD Vulnerability Assessment** is a documented evaluation to find out if the system can withstand a Benchmark GMD Event without causing a wide area blackout, voltage collapse, islanding or equipment damage.

- **Transformer Thermal Assessment** is performed to find out if there are any transformers (YG HV winding) connected to 200 kV or higher going to overheat based on Benchmark GMD Event.

NERC TPL-007-1

Purpose

Establish requirements for Transmission system planned performance during geomagnetic disturbance (GMD) events.

Applicable to:

- Planning Coordinator, Transmission Planner, Transmission Owner, Generator Owner with power transformer(s) with a high side, wye-grounded winding with terminal voltage greater than 200 kV.

TOP-007-1 Requirements and Measures - R1 & M1

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R1 – Identify individual and joint roles and responsibilities

- For maintaining models and
- Performing the study or studies needed to complete GMD Vulnerability Assessment required in Requirement R4

M1 - Provide documentation on roles and responsibilities

- Agreements
- Meeting Minutes
- Email correspondence that identifies an agreement has been reached in accordance with R1

TOP-007-1 Requirements and Measures – R2 & M2

R2 – Maintain System and GIC System Models

- Each responsible entity, as determined in Requirement R1, shall maintain System models and GIC System (DC) models of the responsible entity’s planning area for performing the study or studies needed to complete GMD Vulnerability Assessment(s).

M2 - Evidence that it is maintaining System models and GIC system models

- In either electronic or hard copy format

TOP-007-1 Requirements and Measures – R3 & M3

R3 – Have Criteria for Acceptable Steady State Voltage Performance

- Each responsible entity, as determined in Requirement R1, shall have criteria for acceptable System steady state voltage performance for its System during the Benchmark GMD event

M3 - Evidence of the criteria for acceptable System steady state voltage performance

- Electronic or hard copy format

TOP-007-1 Requirements and Measures – R4 & M4

R4 – Complete GMD Vulnerability Assessment Studies

- Responsible entities complete a GMD Vulnerability Assessment of the Near-Term Transmission Planning Horizon once every 60 calendar months.
- R4.1 System On-Peak Load for at least one year, System Off-Peak Load for at least one year within near-term planning horizon

- R4.2 Conduct studies based on benchmark GMD event

- R4.3 Provide completed assessment to Reliability Coordinator, adjacent Planning Coordinators and Transmission Planners within 90 calendar days of completion
  - R4.3.1 Respond to comments received within 90 calendar days

M4 – Dated Evidence of actions performed to fulfill R4

- In either electronic or hard copies of its GMD Vulnerability Assessment meeting all of the requirements in Requirement R4.
- Provide evidence, such as email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has
  - distributed its GMD Vulnerability Assessment within 90 calendar days of completion.
  - provided a documented response to comments received on its GMD Vulnerability Assessment within 90 calendar days of receipt of those comments

TOP-007-1 Requirements and Measures – R5 & M5

R5 – Provide GIC flow Information for Thermal Impact Assessment to Transmission Owner and Generator Owner.

- Responsible entities provide GIC flow information to be used for the transformer thermal impact assessment specified in Requirement R6. The GIC flow information shall include
- R5.1 The maximum effective GIC value for the worst case geoelectric field orientation for the benchmark GMD event

- R5.2 The effective GIC time series, GIC(t), calculated using the benchmark GMD event upon request from Transmission Owner or Generator Owner within 90 calendar days and after determination of the maximum effective GIC value

M2 - Evidence of actions performed to fulfill R5

- Email records
- Web postings with an electronic notice of posting, or
- postal receipts showing recipient and date, that it has provided the maximum effective GIC value and GIC(t)

TOP-007-1 Requirements and Measures – R6 & M6

R6 – Perform Thermal Impact Assessment

- Each Transmission Owner and Generator Owner conduct a thermal impact assessment for applicable power transformers where the maximum effective GIC value provided in Requirement R5.1 is **75 A per phase or greater**. The thermal impact assessment shall
- R6.1 Be based on the effective GIC flow information provided in R5
- R6.2 Document assumptions used in the analysis
- R6.3 Describe suggested actions and supporting analysis to mitigate the impact of GICs, if any;
- R6.4 Be performed and provided to the responsible entities, as determined in Requirement R1, within 24 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1.

M6 - Evidence of actions performed to fulfill R6

- Electronic or hard copies of its thermal impact assessment for all of its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A per phase or greater
- Email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has provided its thermal impact assessment to the responsible entities as specified in Requirement R6

TOP-007-1 Requirements and Measures – R7 & M7

R7 – Corrective Action Plan

- Responsible entities develop Corrective Action Plan addressing how the performance requirements will be met in case of the GMD Vulnerability Assessment conducted as in R4 shows that the System does not meet the performance requirements of Table 1 (R4). The Corrective Action Plan shall:
- R7.1 List system deficiencies and the associated actions needed to achieve required system performance
- R7.2 Be reviewed in subsequent GMD Vulnerability Assessments until it is determined that the System meets the performance requirements
- R7.3 Be provided within 90 calendar days of completion to the responsible entity's Reliability Coordinator, adjacent Planning Coordinator(s), adjacent Transmission Planner(s), functional entities referenced in the Corrective Action Plan
  - R7.3.1 If a recipient of the Corrective Action Plan provides documented comments on the results, the responsible entity shall provide a documented response to that recipient within 90 calendar days of receipt of those comments

M7 - Evidence of actions performed to fulfill R4

- Electronic or hard copies of its Corrective Action Plan
- Email records, web postings with an electronic notice of posting, or postal receipts showing recipient and date, that it has
  - distributed its Corrective Action Plan or relevant information, if any, within 90 calendar days of its completion
  - provided a documented response to comments received on its Corrective Action Plan within 90 calendar days of receipt of those comments

TPL-007-1
Requirements and Measures – R7 and M7

R7.1 Examples of CAP:

- Installation, modification, retirement or removal of transmission and generation facilities and any associated equipment.
- Installation, modification, or removal of protection systems or special protection systems.
- Use of operating procedures, specifying how long they will be needed as part of corrective action plan.
- Use of demand-side management, new technologies etc.

TPL-007-1
Enforcement Dates

TPL-007-1 Requirements		Enforcement Date
R1	Identify roles and responsibilities	July 1, 2017
R2	Maintain System models and GIC System (DC) models	July 1, 2018
R3	Have acceptable voltage criteria	January 1, 2022
R4	GMD Vulnerability Assessment studies	January 1, 2022
R5	1) Provide maximum effective GIC flow information for worst case geoelectric field orientation 2) Effective GIC time series, GIC(t)	January 1, 2019
R6	Conduct a thermal impact assessment if max I_{eff}/phase >= 75 A	January 1, 2021
R7	Develop corrective action plan	January 1, 2022

Meeting TPL-007-1 Requirements

TPL-007-1 Requirements		How to meet?
R1	Identify roles and responsibilities	Policy document
R2	Maintain System models and GIC System (DC) models	**Power flow Models (PSS®E, PSLF...) and GIC data files (Text, excel)**
R3	Have acceptable voltage criteria	Policy document
R4	GMD Vulnerability Assessment studies	**GIC Module (PSS®E, PowerWorld, PSLF…) and other standard power flow activities**
R5	1) Provide GIC flow information for worst case geoelectric field orientation 2) Effective GIC time series, GIC(t)	**GIC module output (PSS®E…)**
R6	Conduct a thermal impact assessment if max I_{eff}/phase >= 75 Amps	Done using GIC(t) and transformer thermal response capability data
R7	Develop corrective action plan	a) Company policy: based on grid knowledge develop this **b) Implement in PSS®E Case and GIC data files**

TPL-007-1
Enforcement Dates

R1
07/01/2017

R2
07/01/2018

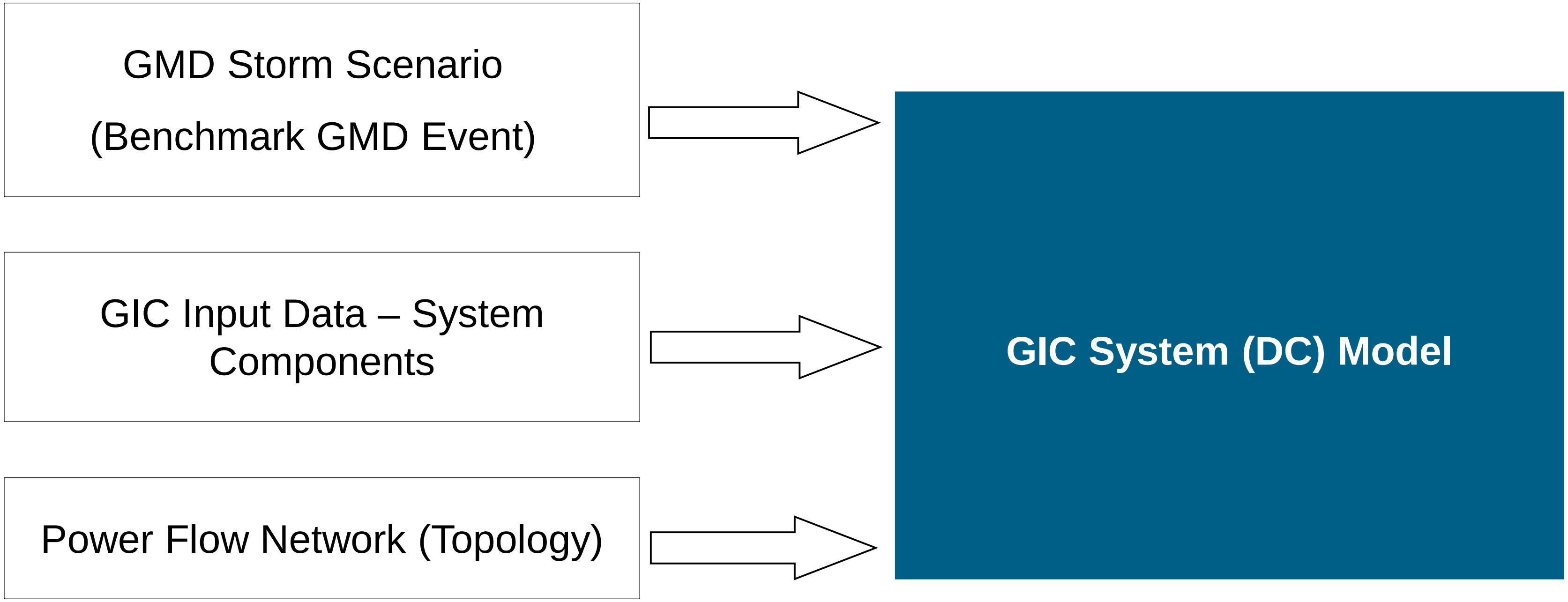
R5
01/01/2019

R6
01/01/2021

R3
R4
R7
01/01/2022

GIC System (DC) Model

GIC System (DC) Model



GMD Storm Scenario

(Benchmark GMD Event)

GIC Input Data – System Components

Power Flow Network (Topology)

GIC System (DC) Model

Benchmark GMD Event – TPL-007-1 Attachment 1

1. Defines a regional geoelectric field peak amplitude (Epeak) used to compute GIC flows that are needed to conduct assessments required by the standard.

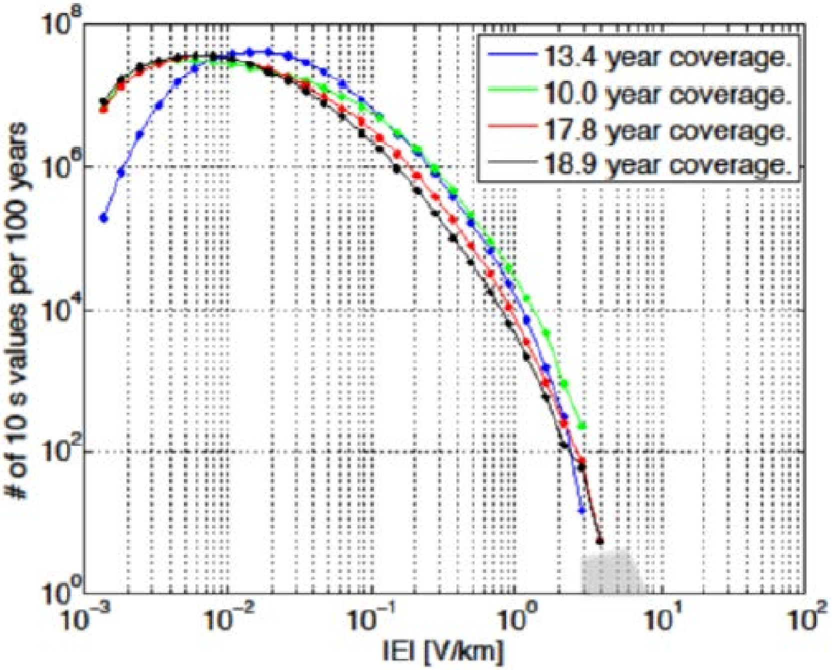
$$E_{peak} = 8 \times \alpha \times \beta \quad \text{(V/km)}$$

2. Gives a reference geomagnetic field time series or waveshape to be used to calculate GIC(t) required for transformer thermal impact assessment.

Benchmark GMD Event – Reference Peak 8 V/km

- A reference geoelectric field value of 8 V/km is derived from statistical analysis of historical magnetometer data

- Statistical occurrence of spatially averaged geoelectric field amplitudes:
  - Four curves with dots correspond to different station groups and
  - The gray area shows a visual extrapolation to 1-in-100 year amplitudes (3-8 V/km).
  - The legend shows the data coverage for each station group used in computing the averaged geoelectric field amplitudes.



Benchmark GMD Event – Regional Peak 8 V/km

- Calculated regional geoelectric field amplitude from the reference geoelectric field

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

  - α (alpha) scaling factor to account for local geomagnetic latitude.
  - β (beta) scaling factor to account for the local earth conductivity structure.

α (alpha) Scaling Factors

- Based on data from a large number of global geomagnetic field observations of all major geomagnetic storms since the late 1980s, α can be approximated as

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

where L is the geomagnetic latitude in degrees and 0.1 ≤ α ≤ 1.0.

- Geomagnetic latitude is analogous to geographic latitude, except that bearing is in relation to the magnetic poles, as opposed to the geographic poles.

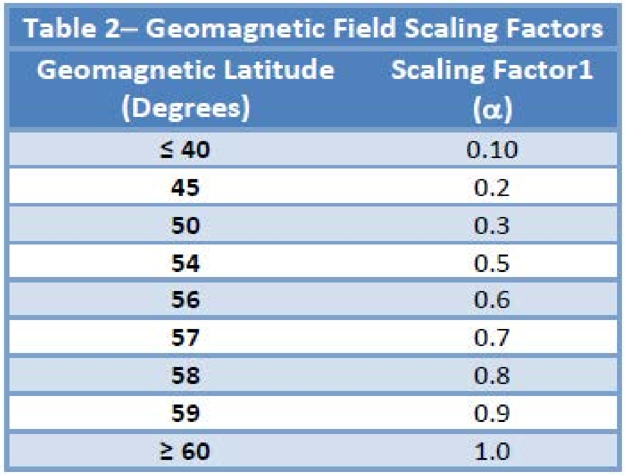
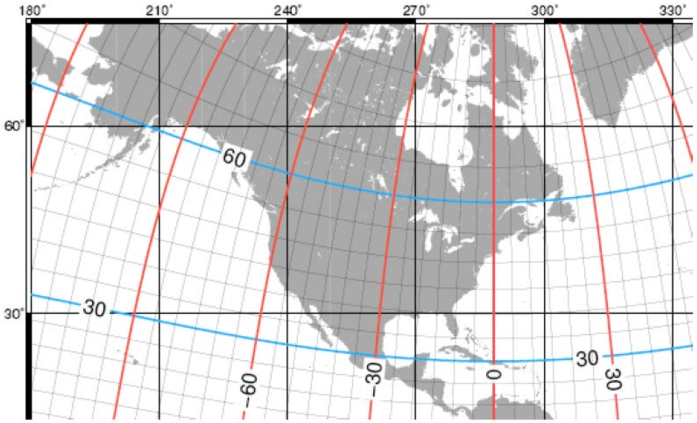


Table 2– Geomagnetic Field Scaling Factors

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

Figure 12: Geomagnetic latitude of North America



β (beta) Scaling Factors - The Earth Model

- Given the range of frequencies relevant to GIC (1 mHz to 1 Hz) and the conductivity values within the earth, magnetic field variations can penetrate hundreds of kilometers below the surface.

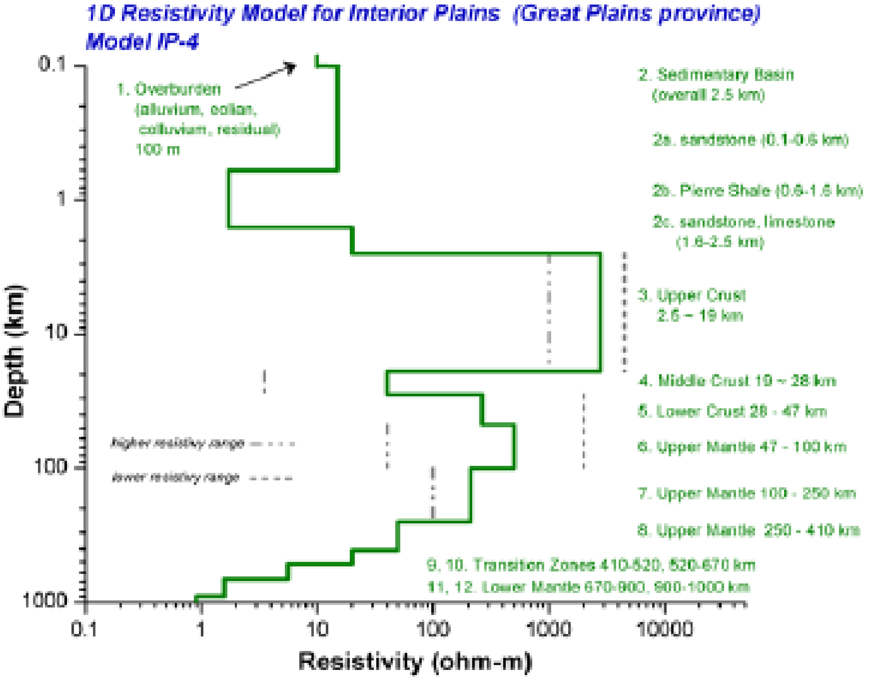
- Thus, the conductivity down through the earth's crust and into the mantle must be taken into account when determining the electric field at the surface.

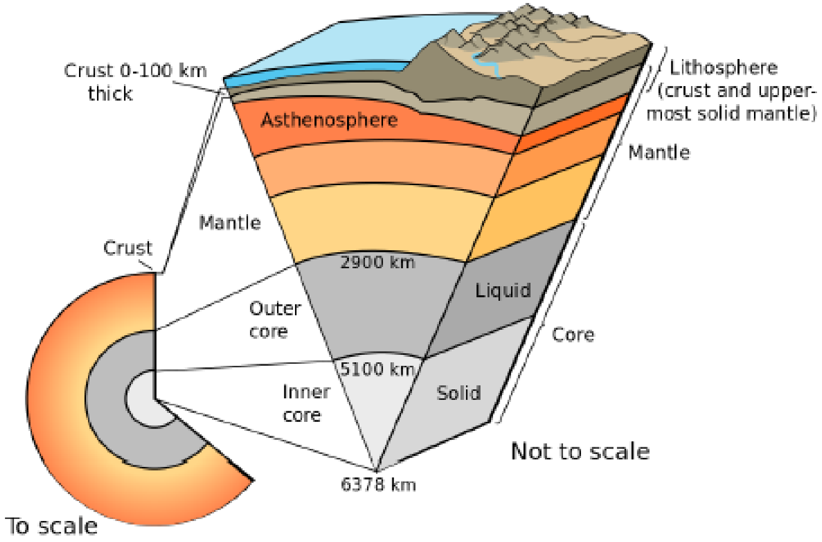
- Layered earth models with depths of up to 1000 km are considered.

The Earth Model

Laterally uniform earth models are used.

- Earth is assumed to consist of horizontal uniform layers.

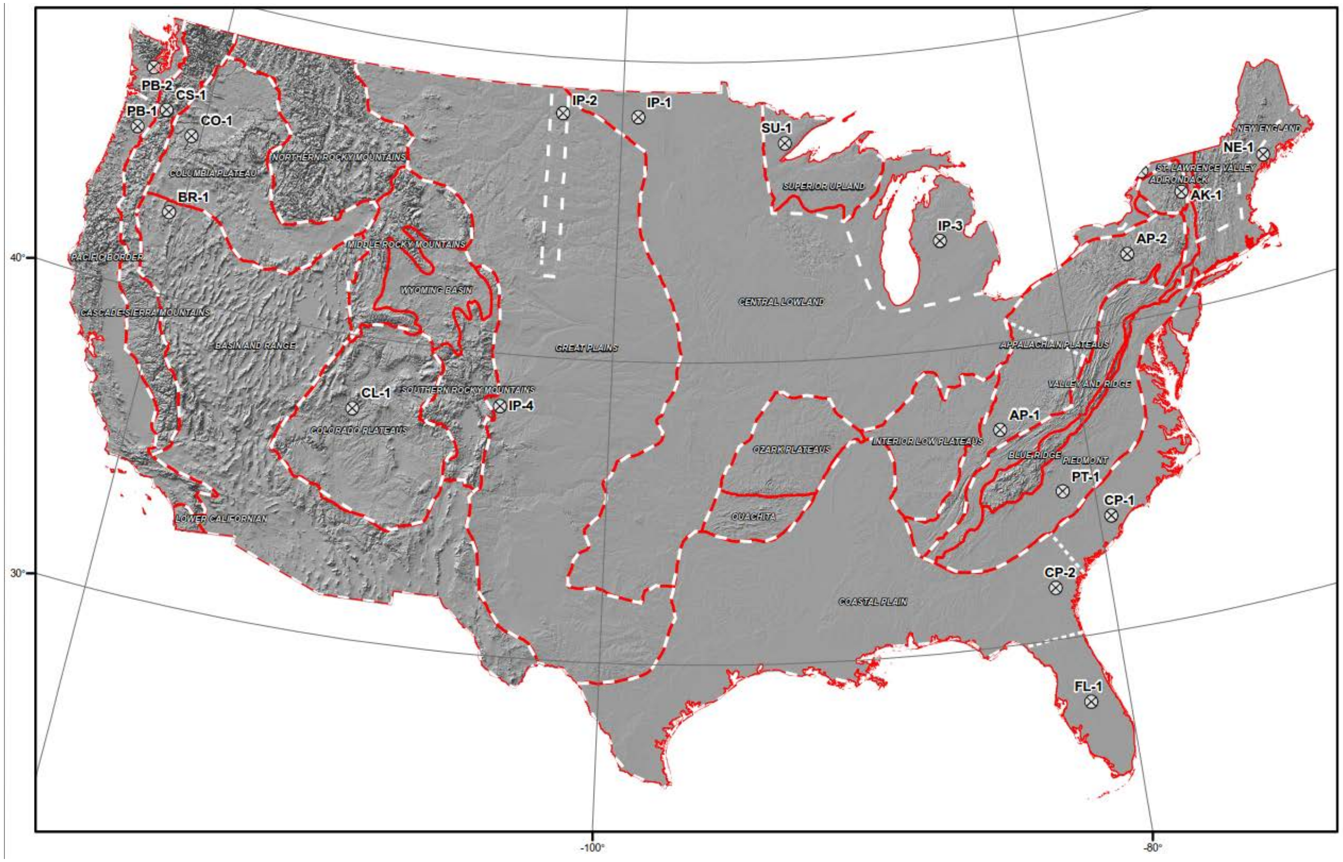




Source: NERC GMD Task Force Documents

1-D Earth Conductivity Models of United States

- Developed by United States Geological Survey (USGS) http://geomag.usgs.gov/conductivity



1-D Earth Conductivity Models of Canada

- Developed by Natural Resources of Canada
  http://www.nrcan.gc.ca

β (beta) Scaling Factors

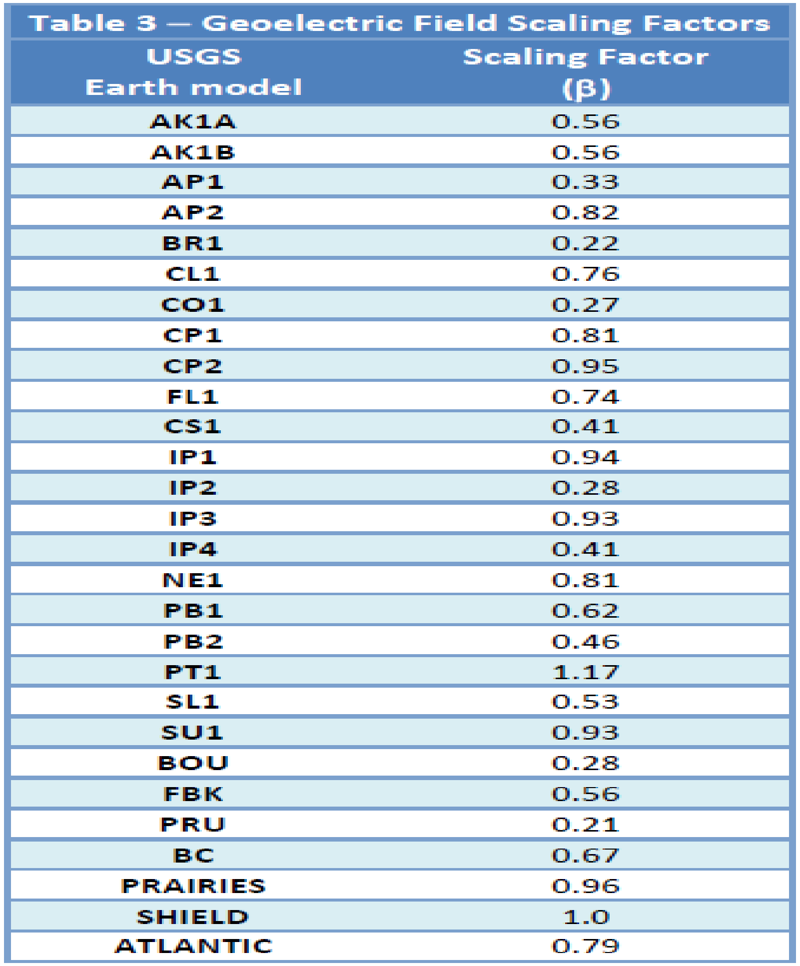


Table 3 — Geoelectric Field Scaling Factors

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
FL1	0.74
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

Source: https://geomag.usgs.gov/conductivity/IP-1/

β (beta) Scaling Factors
U.S. Geographical Regions

SIEMENS

- AK-1 - Adirondack Mountains
- AP-1 - Appalachan Plateaus
- AP-2 - Northern Appalachan Plateaus
- BR-1 - Northwest Basin and Range
- CL-1 - Colorado Plateau
- CO-1 - Columbia Plateau
- CP-1 - Coastal Plain (South Carolina)
- CP-2 - Coastal Plain (Georgia)
- CS-1 - Cascade-Sierra Mountains
- FL-1 - Florida Peninsula
- IP-1 - Interior Plains (North Dakota)
- IP-2 - Interior Plains
- IP-3 - Interior Plains (Michigan)
- IP-4 - Interior Plains (Great Plains)
- NE-1 - New England
- PB-1 - Pacific Border (Willamette Valley)
- PB-2 - Pacific Border (Puget Lowlands)
- PT-1 - Piedmont
- SL-1 - St. Lawrence Lowlands
- SU-1 - Superior Upland

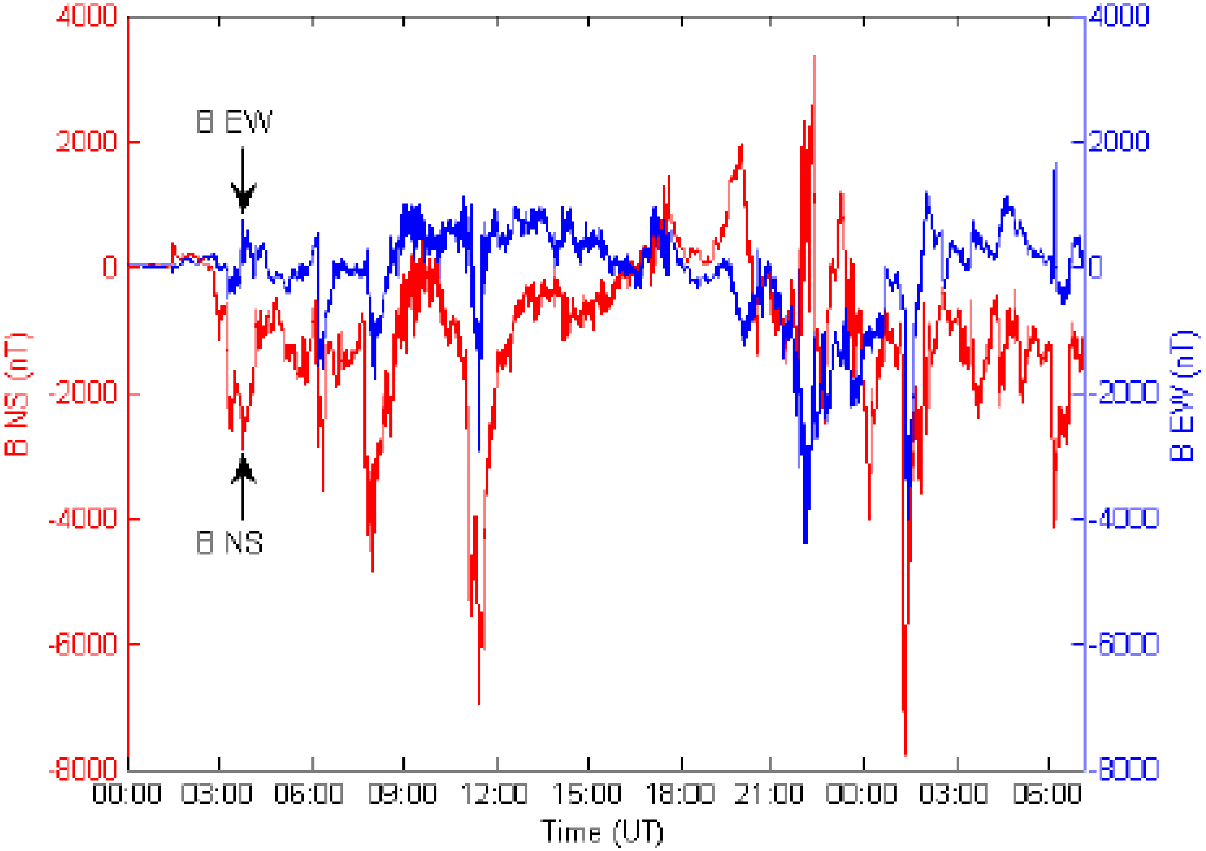
Benchmark Geomagnetic Field Waveshape

- The geomagnetic field measurement record of the March 13-14 1989 GMD event, measured at NR Canada’s Ottawa geomagnetic observatory is the basis for the reference geomagnetic field wave shape because it provides generally conservative results when performing thermal analysis of power transformers .

- The geomagnetic latitude of the Ottawa geomagnetic observatory is 55 therefore, the amplitude of the geomagnetic field measurement data were scaled up to the **60 deg reference geomagnetic latitude** such that the resulting peak geoelectric field amplitude computed using the reference Quebec earth model was **8 V/km**.

- Sampling rate for the geomagnetic field wave shape is 10 seconds.

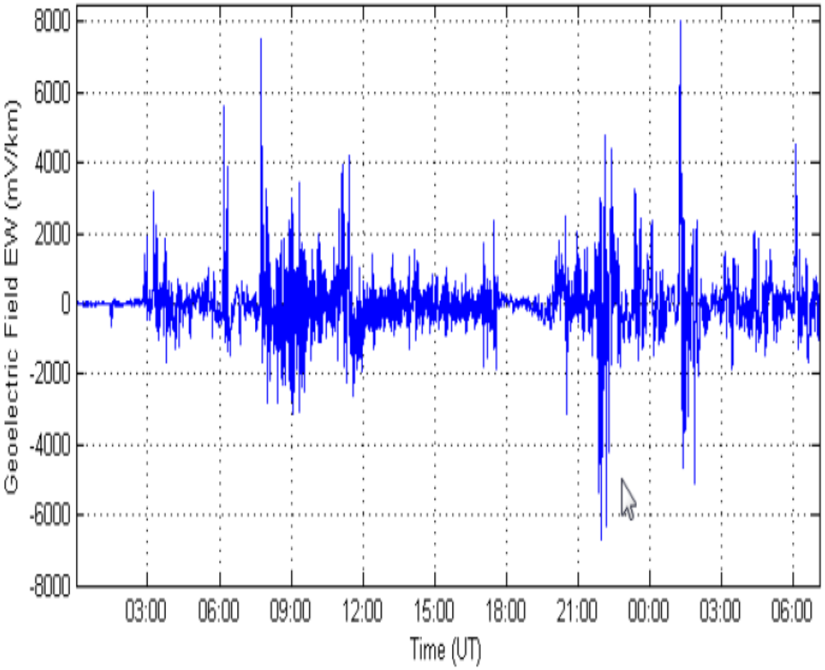
Benchmark Geomagnetic Field Waveshape



Northward Magnetic Flux Density, B_{NS} (Red)
Eastward Magnetic Flux Density, B_{EW} (Blue)

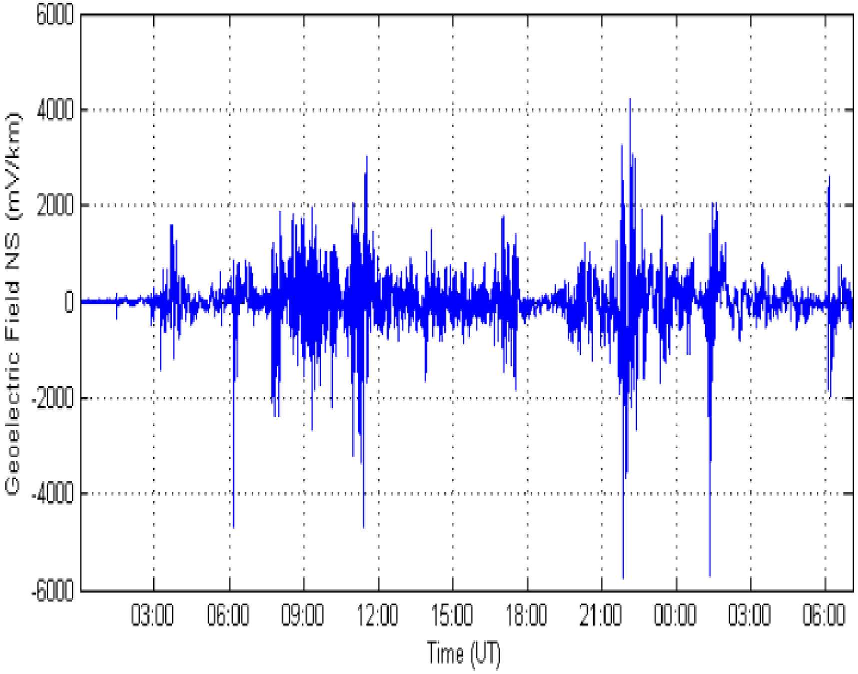
Benchmark Geoelectric Field Waveshape

$$E_E = -(z(t)/\mu_o) * B_N(t)$$



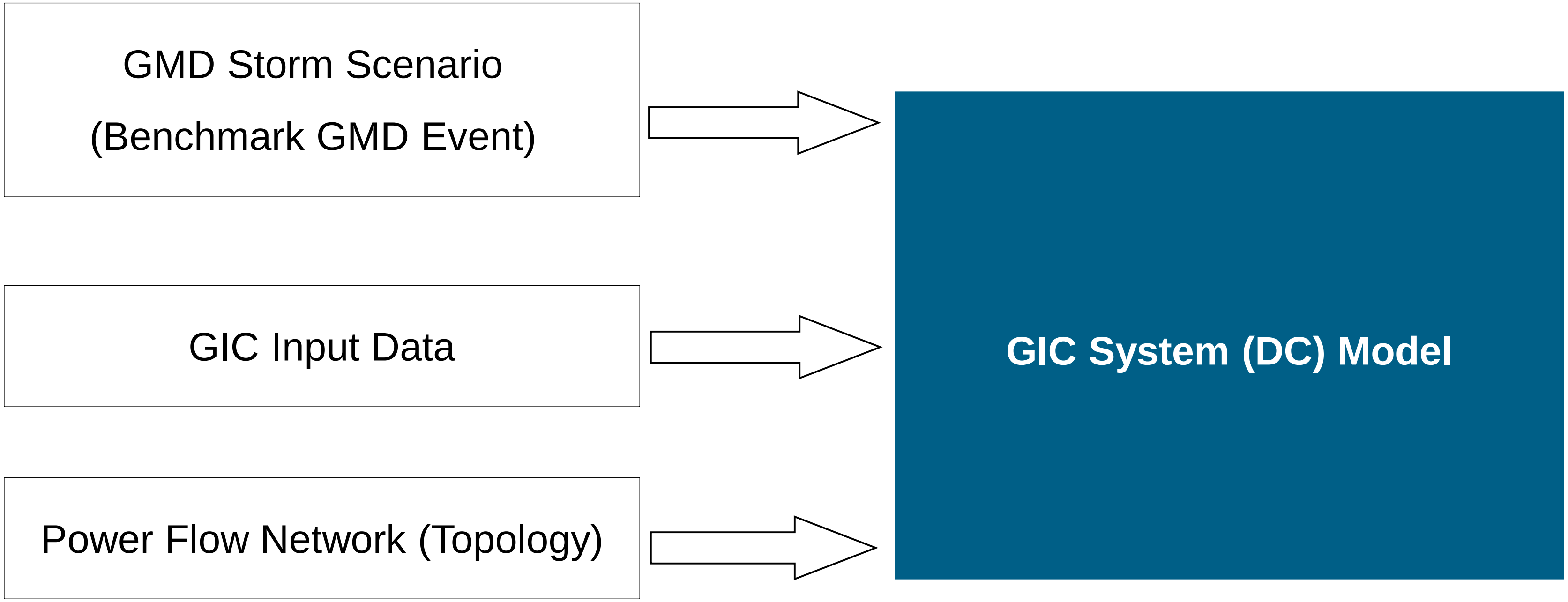
Eastward Geoelectric Field, E_E

$$E_N = (z(t)/\mu_o) * B_E(t)$$



Northward Geoelectric Field, E_N

GIC System (DC) Model



GMD Storm Scenario

(Benchmark GMD Event)

GIC Input Data

Power Flow Network (Topology)

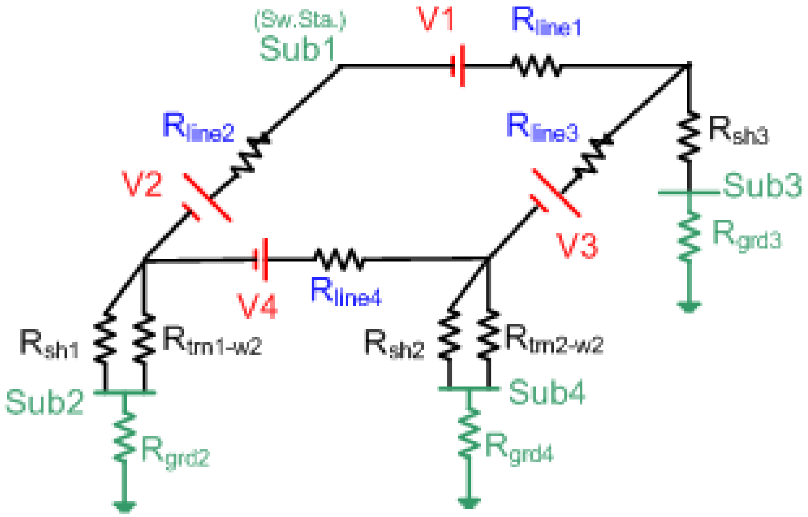
GIC System (DC) Model

GIC Data File

Development of DC system model

As GIC is very low frequency (0.0001 Hz-1Hz), power flow network data reduced to just resistance network with these modifications:

- Transmission lines modeled as resistor in series with induced voltage
- Grounded two- and three-winding transformers modeled with their winding resistance to ground
- Grounded auto-transformers are modeled with their common and series winding resistance
- Grounded Bus shunts are modeled
- Transformer GIC blocking devices are modeled
- Generators, capacitors excluded



GIC Data File

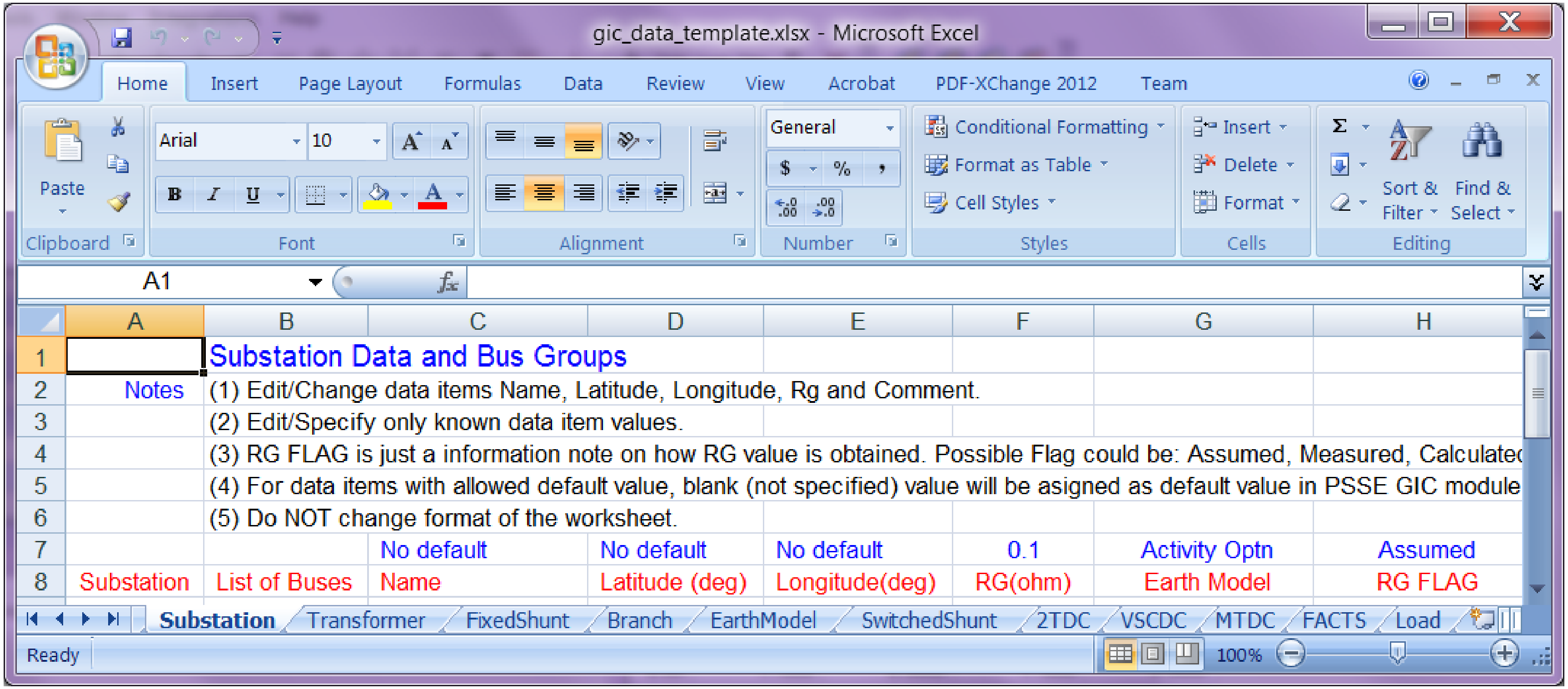
- Substation
  - Location (Latitude, Longitude)
  - Equivalent station grounding resistance
  - Earth Model

- Transformers
  - Winding resistance
  - Core
  - K-factor
  - Vector group

- **Add comments on the data source – Assumed, Measured etc**

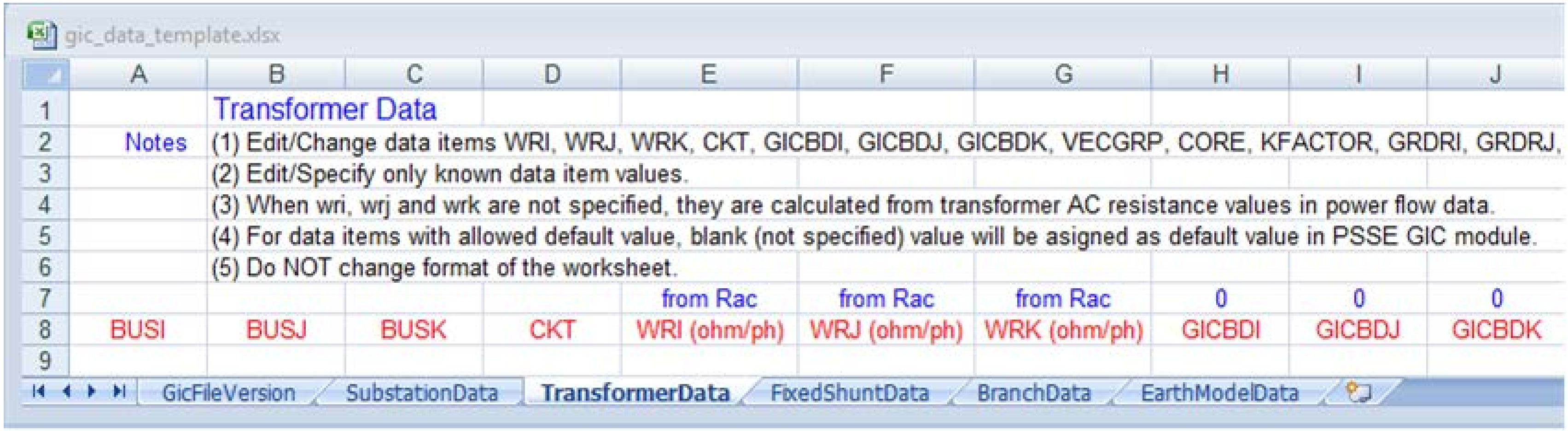
- **If study cases (System On-Peak, System Off-peak) are from different years with different topology, then additional GIC data may be needed.**

GIC Data File - Substation data



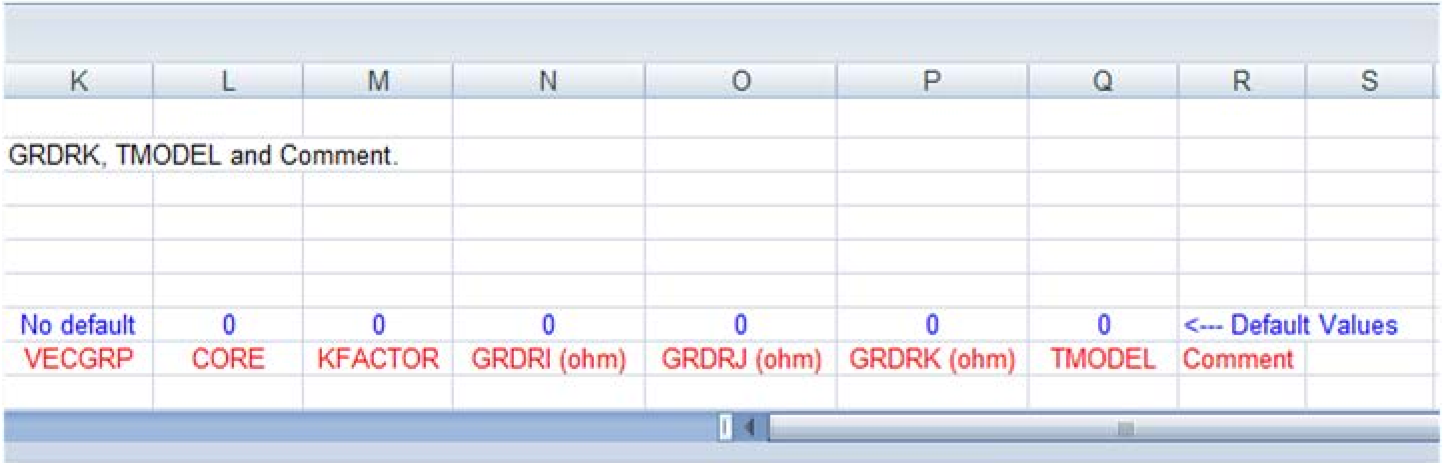
	A	B	C	D	E	F	G	H
1		Substation Data and Bus Groups						
2	Notes	(1) Edit/Change data items Name, Latitude, Longitude, Rg and Comment.						
3		(2) Edit/Specify only known data item values.						
4		(3) RG FLAG is just a information note on how RG value is obtained. Possible Flag could be: Assumed, Measured, Calculate						
5		(4) For data items with allowed default value, blank (not specified) value will be asigned as default value in PSSE GIC module						
6		(5) Do NOT change format of the worksheet.						
7			No default	No default	No default	0.1	Activity Optn	Assumed
8	Substation	List of Buses	Name	Latitude (deg)	Longitude(deg)	RG(ohm)	Earth Model	RG FLAG

GIC Data File
Transformer data



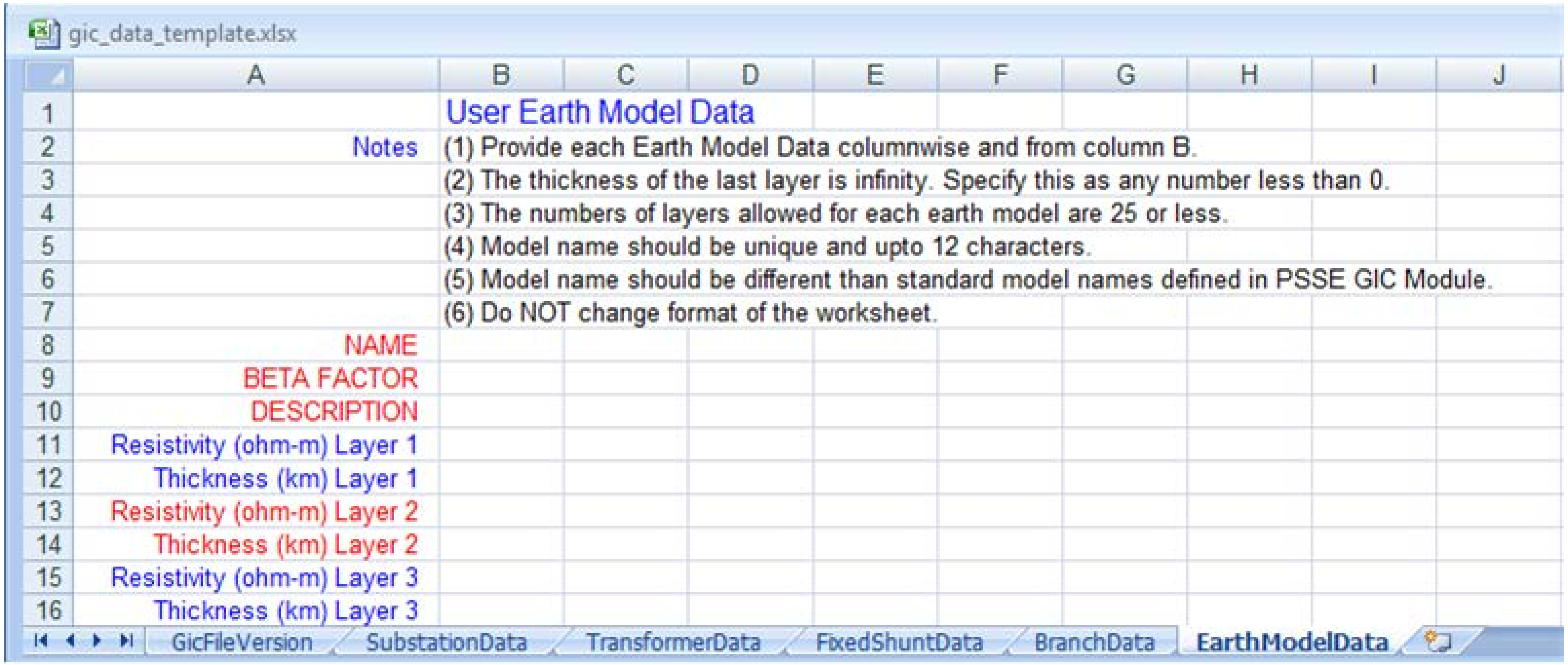
gic_data_template.xlsx

	A	B	C	D	E	F	G	H	I	J
1		Transformer Data								
2	Notes	(1) Edit/Change data items WRI, WRJ, WRK, CKT, GICBDI, GICBDJ, GICBDK, VECGRP, CORE, KFACTOR, GRDRI, GRDRJ,								
3		(2) Edit/Specify only known data item values.								
4		(3) When wri, wrj and wrk are not specified, they are calculated from transformer AC resistance values in power flow data.								
5		(4) For data items with allowed default value, blank (not specified) value will be asigned as default value in PSSE GIC module.								
6		(5) Do NOT change format of the worksheet.								
7					from Rac	from Rac	from Rac	0	0	0
8	BUSI	BUSJ	BUSK	CKT	WRI (ohm/ph)	WRJ (ohm/ph)	WRK (ohm/ph)	GICBDI	GICBDJ	GICBDK
9										

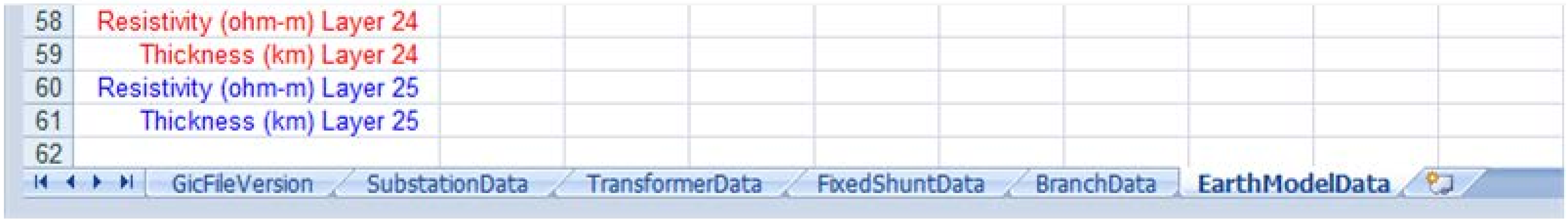


K	L	M	N	O	P	Q	R	S
GRDRK, TMODEL and Comment.								
No default	0	0	0	0	0	0	<--- Default Values	
VECGRP	CORE	KFACTOR	GRDRI (ohm)	GRDRJ (ohm)	GRDRK (ohm)	TMODEL	Comment	

GIC Data File
User Earth model data



	A	B	C	D	E	F	G	H	I	J
1		User Earth Model Data								
2	Notes	(1) Provide each Earth Model Data columnwise and from column B.								
3		(2) The thickness of the last layer is infinity. Specify this as any number less than 0.								
4		(3) The numbers of layers allowed for each earth model are 25 or less.								
5		(4) Model name should be unique and upto 12 characters.								
6		(5) Model name should be different than standard model names defined in PSSE GIC Module.								
7		(6) Do NOT change format of the worksheet.								
8	NAME									
9	BETA FACTOR									
10	DESCRIPTION									
11	Resistivity (ohm-m) Layer 1									
12	Thickness (km) Layer 1									
13	Resistivity (ohm-m) Layer 2									
14	Thickness (km) Layer 2									
15	Resistivity (ohm-m) Layer 3									
16	Thickness (km) Layer 3									



	A	B	C	D	E	F	G	H	I	J
58	Resistivity (ohm-m) Layer 24									
59	Thickness (km) Layer 24									
60	Resistivity (ohm-m) Layer 25									
61	Thickness (km) Layer 25									
62										

GIC Data File
User Earth model notes

- TPL-007-1 defined Earth Conductivity Models for US and Canada are modeled as standard earth models (just use its name in GIC data file).
- If any other Earth Model is required, use this data record to define such an earth model.
- A total of up to 50 user earth models are allowed.
- Each earth model may have up to 25 layers.
- Use as many records needed to specify the data.
- The thickness of the last layer is infinity.
  - This is specified as any value less than 0.0 (= -999.0 for example).
  - The thickness value less than 0.0 is also used as end of earth model data.

NERC – Application Guide – Guidance on Data

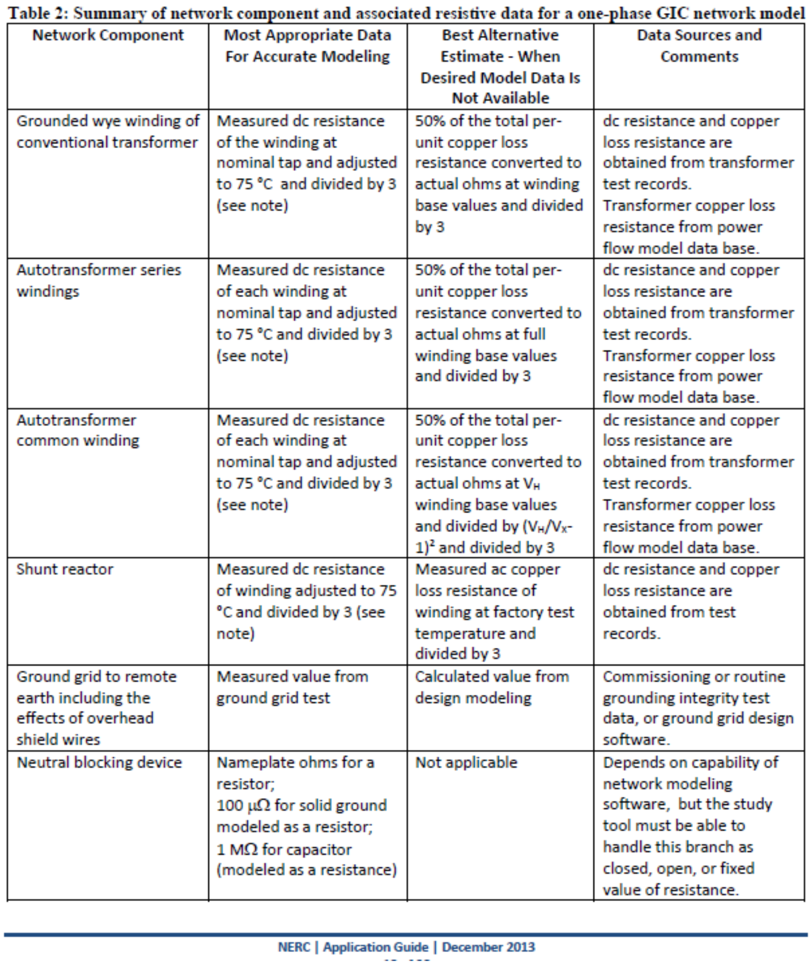
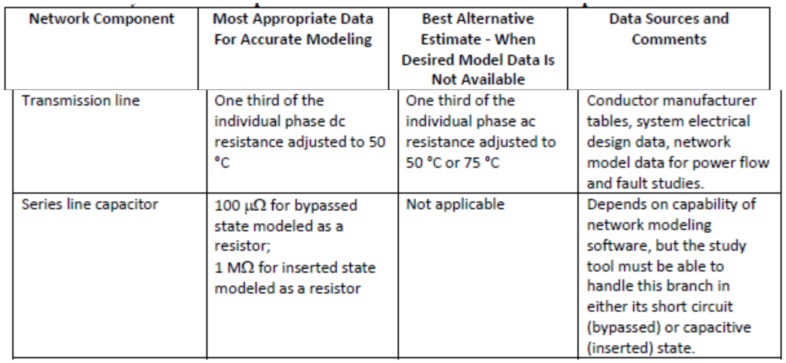


Table 2: Summary of network component and associated resistive data for a one-phase GIC network model

Network Component	Most Appropriate Data For Accurate Modeling	Best Alternative Estimate - When Desired Model Data Is Not Available	Data Sources and Comments
Grounded wye winding of conventional transformer	Measured dc resistance of the winding at nominal tap and adjusted to 75 °C and divided by 3 (see note)	50% of the total per-unit copper loss resistance converted to actual ohms at winding base values and divided by 3	dc resistance and copper loss resistance are obtained from transformer test records. Transformer copper loss resistance from power flow model data base.
Autotransformer series windings	Measured dc resistance of each winding at nominal tap and adjusted to 75 °C and divided by 3 (see note)	50% of the total per-unit copper loss resistance converted to actual ohms at full winding base values and divided by 3	dc resistance and copper loss resistance are obtained from transformer test records. Transformer copper loss resistance from power flow model data base.
Autotransformer common winding	Measured dc resistance of each winding at nominal tap and adjusted to 75 °C and divided by 3 (see note)	50% of the total per-unit copper loss resistance converted to actual ohms at V_H winding base values and divided by $(V_H/V_X-1)^2$ and divided by 3	dc resistance and copper loss resistance are obtained from transformer test records. Transformer copper loss resistance from power flow model data base.
Shunt reactor	Measured dc resistance of winding adjusted to 75 °C and divided by 3 (see note)	Measured ac copper loss resistance of winding at factory test temperature and divided by 3	dc resistance and copper loss resistance are obtained from test records.
Ground grid to remote earth including the effects of overhead shield wires	Measured value from ground grid test	Calculated value from design modeling	Commissioning or routine grounding integrity test data, or ground grid design software.
Neutral blocking device	Nameplate ohms for a resistor; 100 µΩ for solid ground modeled as a resistor; 1 MΩ for capacitor (modeled as a resistance)	Not applicable	Depends on capability of network modeling software, but the study tool must be able to handle this branch as closed, open, or fixed value of resistance.

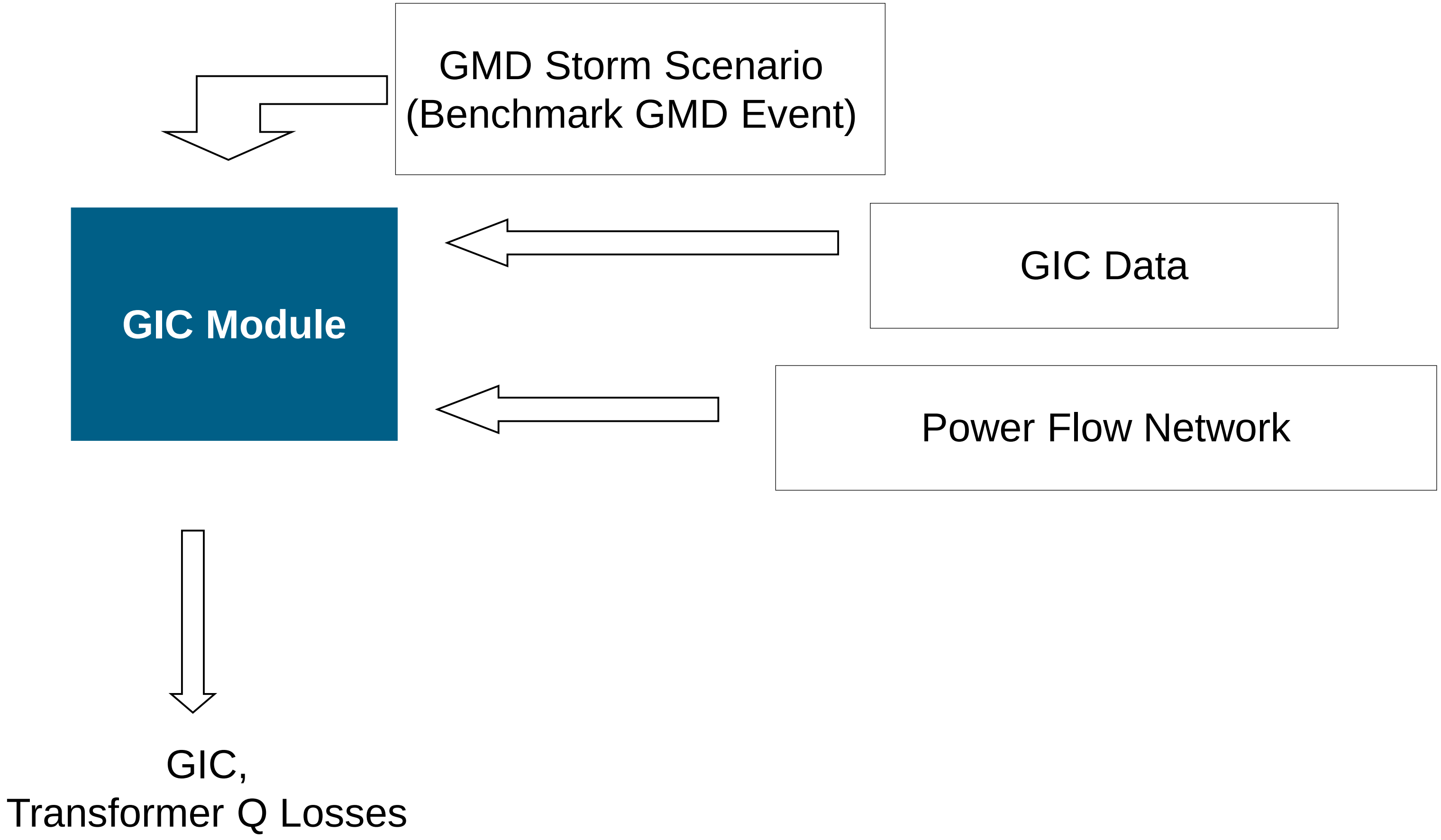
NERC | Application Guide | December 2013



Network Component	Most Appropriate Data For Accurate Modeling	Best Alternative Estimate - When Desired Model Data Is Not Available	Data Sources and Comments
Transmission line	One third of the individual phase dc resistance adjusted to 50 °C	One third of the individual phase ac resistance adjusted to 50 °C or 75 °C	Conductor manufacturer tables, system electrical design data, network model data for power flow and fault studies.
Series line capacitor	100 µΩ for bypassed state modeled as a resistor; 1 MΩ for inserted state modeled as a resistor	Not applicable	Depends on capability of network modeling software, but the study tool must be able to handle this branch in either its short circuit (bypassed) or capacitive (inserted) state.

To assure best accuracy and the data consistency needed for sharing model data with other study engineers, estimated values should only be used when the desired resistive data is not obtainable

GIC Calculation



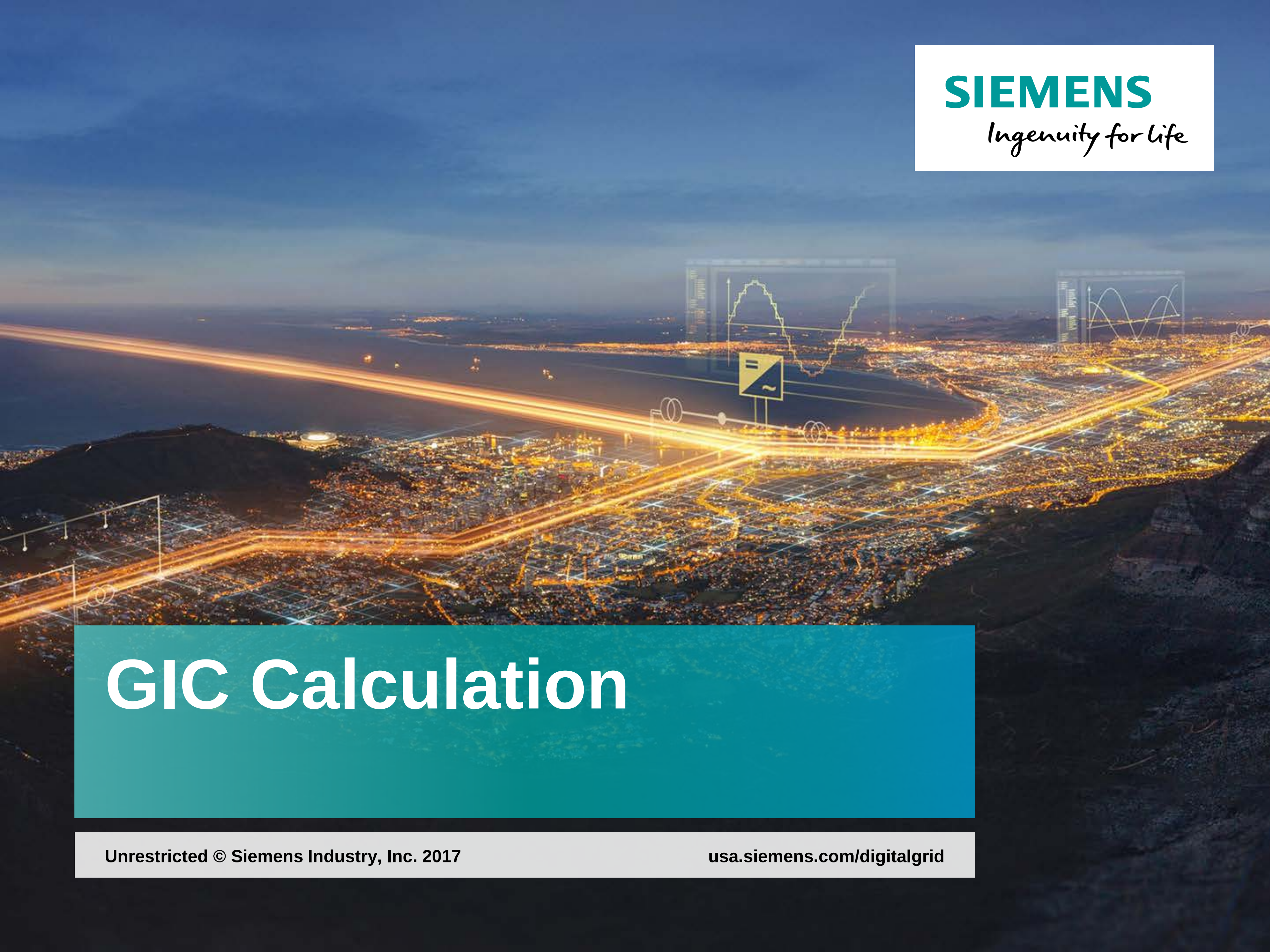
GMD Storm Scenario
(Benchmark GMD Event)

GIC Data

Power Flow Network

GIC Module

GIC,
Transformer Q Losses



GIC Calculation

usa.siemens.com/digitalgrid

Analysis Tools

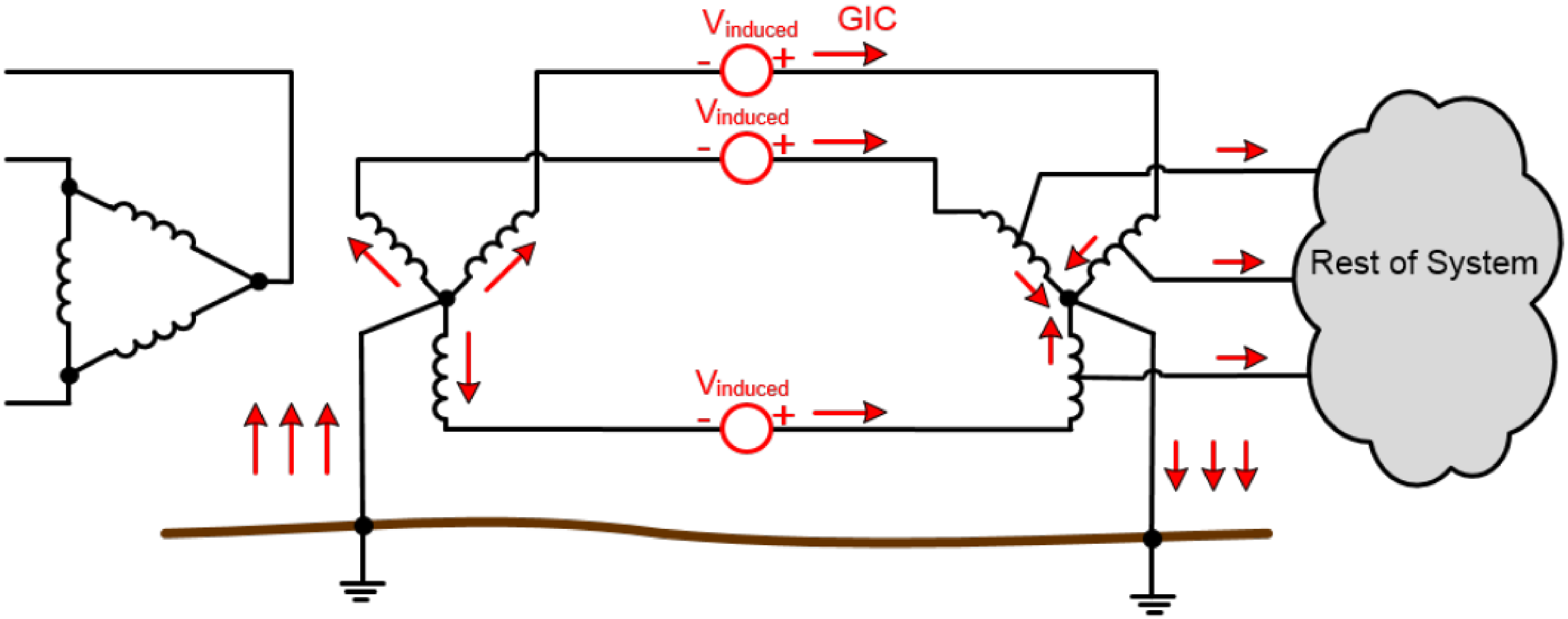
- Commercially-available GIC modules available in power system analysis software:
  - PSS/E
  - PowerWorld
  - PSLF

- These tools solve the dc network for a set of steady-state geoelectric field assumptions, and determine transformer var losses to be included into the power flow model (typically connected to a transformer as a constant current source).

Analysis Tools

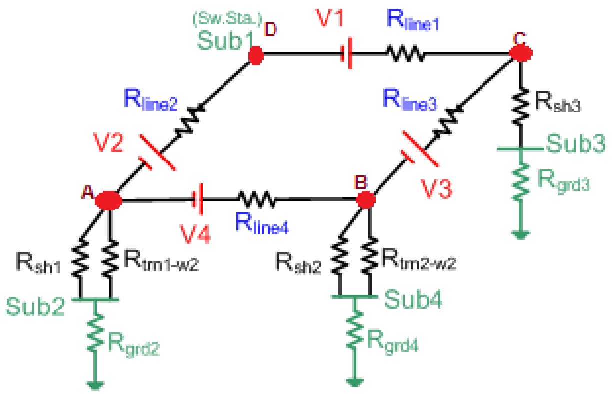
- PSS/E GIC Module
  - Integrated into Power flow application
  - Geoelectric field (Uniform, Non-uniform, Benchmark, Local Hot-Spot)
  - Options to run automatic orientation scan
  - Transformer losses embedded into powerflow case at the end of GIC calculation
  - GIC output results maps/plots
  - Generates GIC(t) waveforms for thermal impact assessment (Benchmark waveform or user defined electric field waveform)
  - Electric field magnitude scanning up to 20 V/km, solves powerflow model to find system limitation

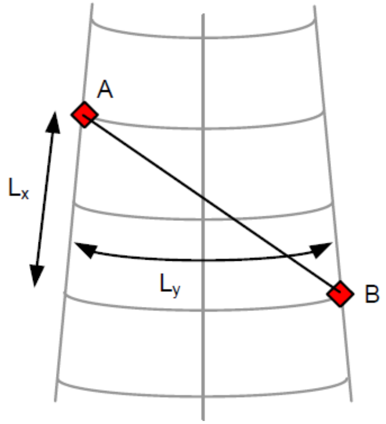
GIC Flow in a Simplified Power System



Source: NERC GMD Task Force Material – GIC Application Guide

GIC Calculation





1. **V1, V2, V3, V4 (induced voltages from geoelectric field (E))**

$$V_{dc} = E_x L_x + E_y L_y$$

Lx, Ly calculated using WGS84 Earth model used in GPS:

$$L_N = (111.133 - 0.56\cos(2\phi)) \cdot \Delta lat$$

$$L_E = (111.5065 - 0.1872\cos 2\phi) \cdot \cos\phi \cdot \Delta long$$

$$\phi = \frac{LatA + LatB}{2}$$

2. **Convert V1, V2, V3, V4 into equivalent current sources** (I1, I2, I3, I4);

   I1=V1/Rline1, …

GIC Calculations

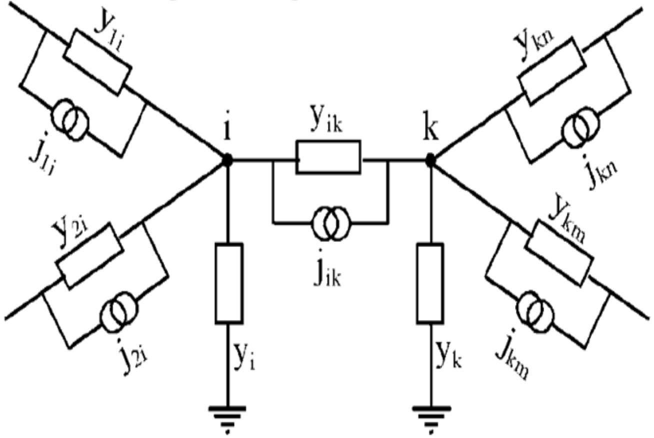
3. Apply Kirchhoff’s current law at each node

4. Construct Y matrix (1/R or G**)**

5. Calculate node voltages

6. Calculate Current flowing in the network, branches, transformers

Modelling GIC using the nodal admittance matrix method



$$[J]=[Y][V]$$

$$Y_{ii}=y_i+\sum_{k=1}^{N}y_{ki} \qquad k\neq i$$

$$Y_{ki}=-y_{ki}$$

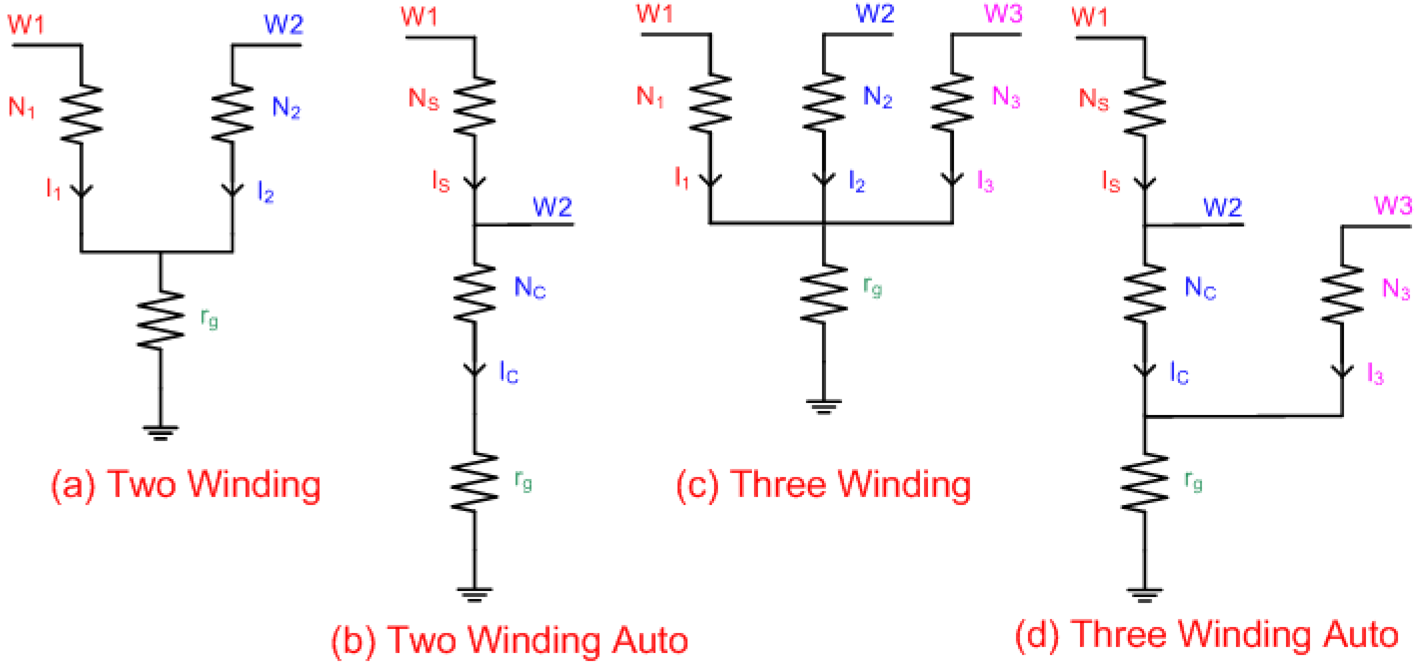
$$[V]=[Y]^{-1}[J]$$

GIC Calculations

7. Calculate Effective GIC through each transformer

Effective GIC

The effective GIC (I_{eff}) flow in a transformer due to GICs flowing in one or more of its winding is dependent upon transformer type.



(a) Two Winding

(b) Two Winding Auto

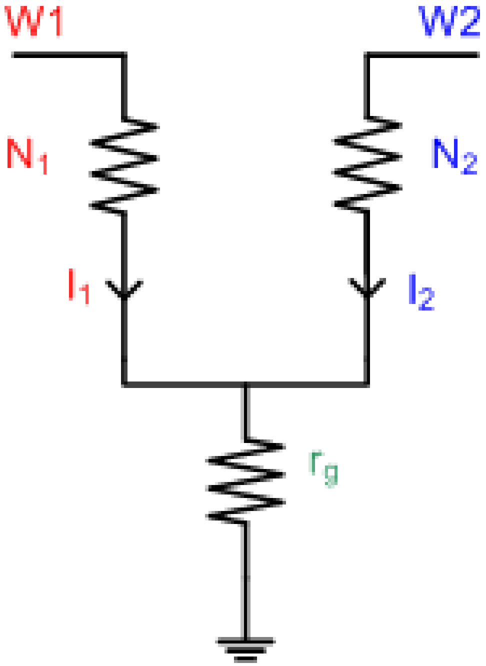
(c) Three Winding

(d) Three Winding Auto

GIC Flow in Various Transformer Configurations

Refer PSS®E Program Application Guide, Volume 1

Effective GIC
Two-winding transformer

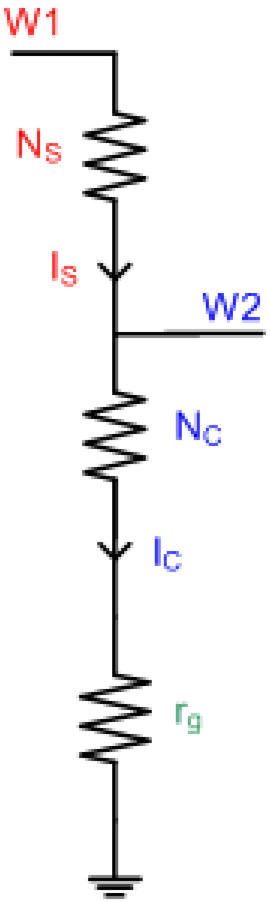


$$I_1 N_1 + I_2 N_2 = I_{eff} N_1$$

$$N = \frac{N_1}{N_2} = \frac{V_1}{V_2}$$

$$I_{eff} = \left| \frac{N I_1 + I_2}{N} \right|$$

Effective GIC
Two-winding auto transformer



$$I_S N_S + I_C N_C = I_{eff}(N_S + N_C)$$

$$N = \frac{N_S + N_C}{N_C} = \frac{V_1}{V_2}$$

$$I_{eff} = \left| \frac{(N-1)I_S + I_C}{N} \right|$$

GIC Calculations

8. Calculate Qlosses using K-factors

Mvar/Ampere Scaling Factor (K_{factor})

- One of the effects of the GICs flowing in transformer windings is that the transformer is subjected to half-cycle saturation resulting in increased reactive power (Mvar) losses in these equipment.

- Using GIC to Mvar scaling factors transformer reactive power losses are calculated.

- When a specific K_{factor} value is provided for a transformer:

$$Q = I_{eff} \times K_{factor}$$

- Using generic scaling factor value based on the transformer type:

$$Q = I_{eff} \times K_{factor} \times \frac{V_H}{500}$$

where V_H is Transformer Windings highest voltage in kV.

Generic Scaling Factors

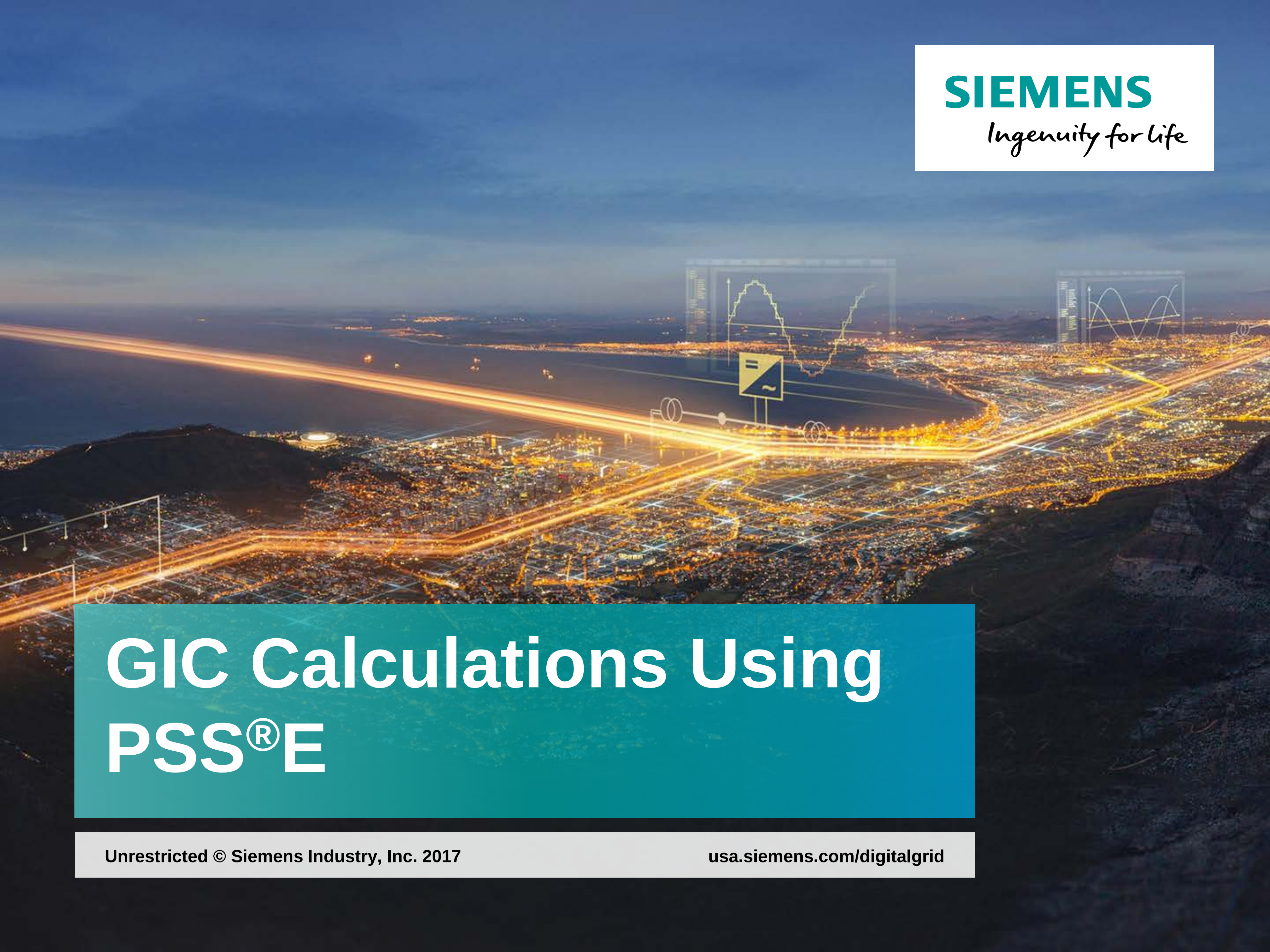
(a) K_{factor} determined based on transformer cores		
Core Design	Cores	K_{factor}
Three-phase, shell form	-1	0.33
Single-phase (three separate cores)	1	1.18
Three-phase, 3-legged, core form	3	0.29
Three-phase, 5-legged, core form	5	0.66
Three-phase, 7-legged, core form	7	0.66

(b) K_{factor} determined based on base kV of transformer windings	
Windings Highest Voltage	K_{factor}
Unknown core, <= 200 kV	0.6
Unknown core, > 200 kV and <= 400 kV	0.6
Unknown core, > 400 kV	1.1

Source: X. Dong, Y. Liu, J. G. Kappenman, "Comparative Analysis of Exciting Current Harmonics and Reactive Power Consumption from GIC Saturated Transformers", Proceedings IEEE, 2001, pages 318-322

GIC Calculations

- Repeat all the above steps for each electric field orientation
- Report Maximum Effective GIC for each transformer (Requirement R5)
- Computes GIC(t) for thermal impact assessment

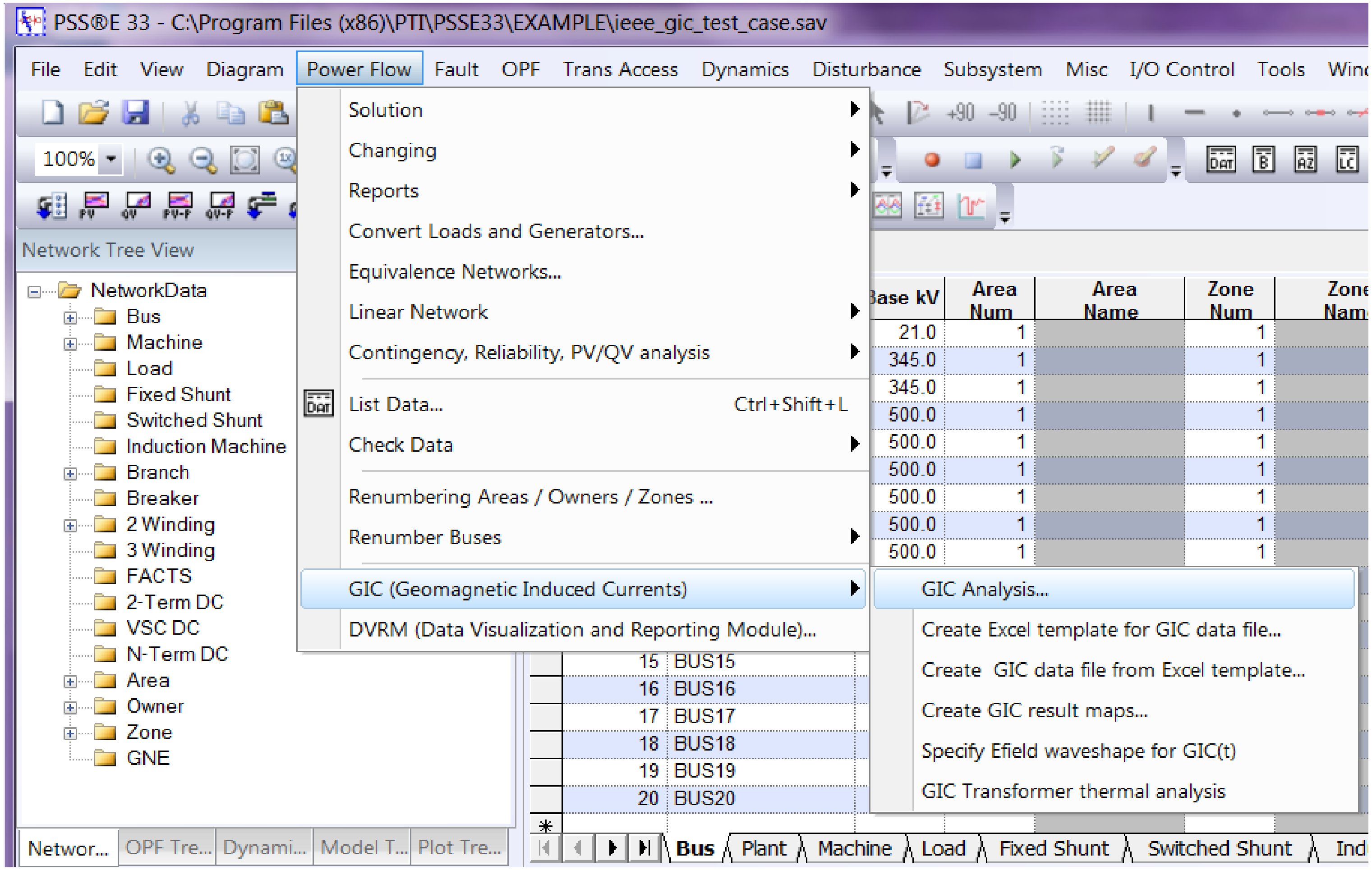


SIEMENS

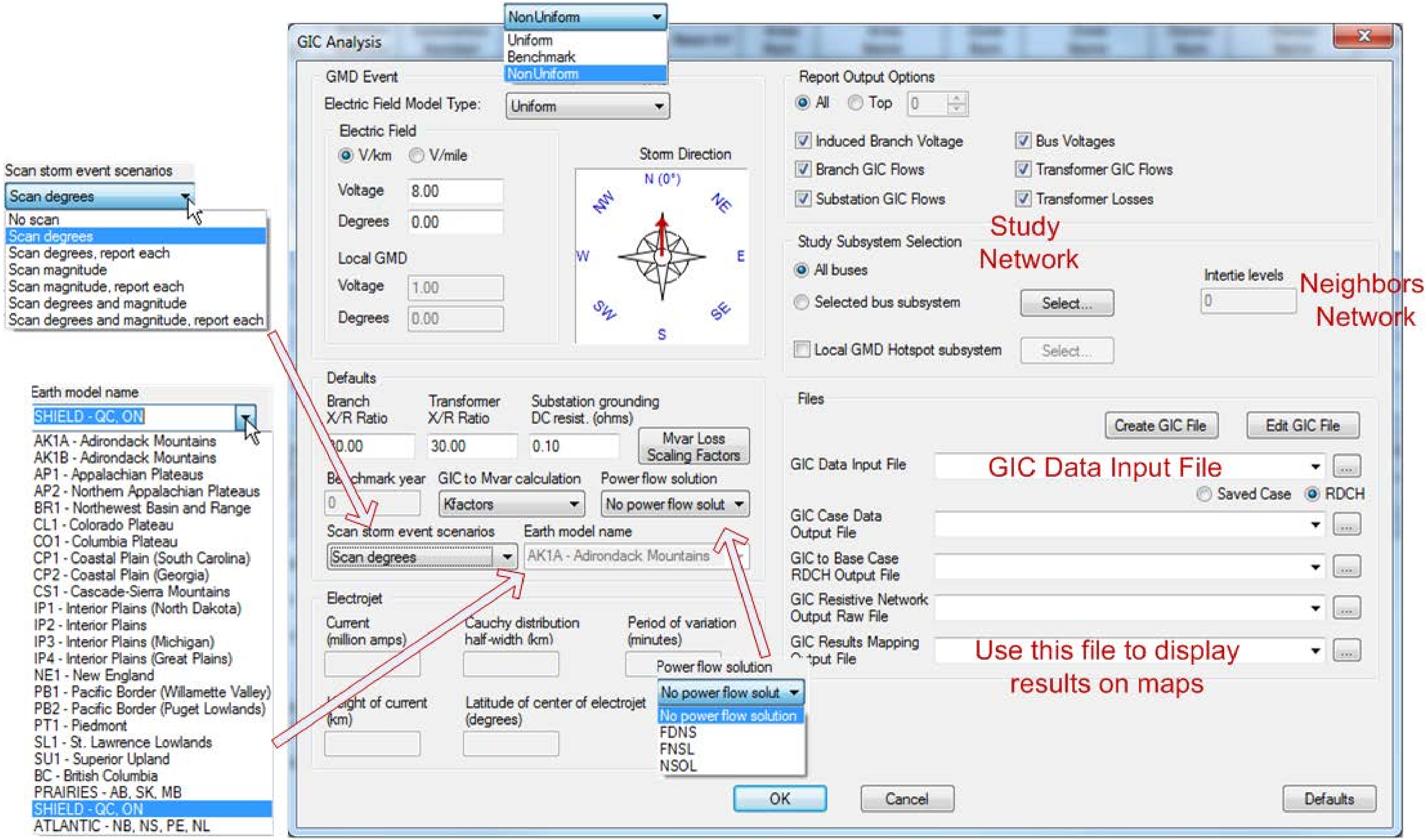
Ingenuity for life

GIC Calculations Using PSS®E

How to run GIC analysis in PSS®E?



PSS®E GIC analysis GUI



GIC Analysis

GMD Event

Electric Field Model Type: Uniform

Electric Field: ● V/km ○ V/mile

Voltage 8.00

Degrees 0.00

Local GMD

Voltage 1.00

Degrees 0.00

Storm Direction

Report Output Options: ● All ○ Top 0

☑ Induced Branch Voltage ☑ Bus Voltages

☑ Branch GIC Flows ☑ Transformer GIC Flows

☑ Substation GIC Flows ☑ Transformer Losses

Study Subsystem Selection

● All buses

○ Selected bus subsystem

Intertie levels 0

☐ Local GMD Hotspot subsystem

Defaults

Branch X/R Ratio 0.00

Transformer X/R Ratio 30.00

Substation grounding DC resist. (ohms) 0.10

Benchmark year 0

GIC to Mvar calculation: Kfactors

Power flow solution: No power flow solut

Scan storm event scenarios: Scan degrees

Earth model name: AK1A - Adirondack Mountains

Electrojet

Current (million amps)

Cauchy distribution half-width (km)

Period of variation (minutes)

Height of current (km)

Latitude of center of electrojet (degrees)

Files

GIC Data Input File: ○ Saved Case ● RDCH

GIC Case Data Output File

GIC to Base Case RDCH Output File

GIC Resistive Network Output Raw File

GIC Results Mapping Output File

Scan storm event scenarios: Scan degrees

Earth model name: SHIELD - QC, ON

Study Network

Neighbors Network

GIC Data Input File

Use this file to display results on maps

GMD events modeled in PSS®E

Uniform Geoelectric Field E(t)

- Ignores effects of local earth conductivity and local geomagnetic latitude

Benchmark GMD Event E(t)

- E = 8 V/km
- Considers α, the scaling factor to account for local geomagnetic latitude, and β, the scaling factor to account for the local earth conductivity structure

Non-uniform Geoelectric Field E(t)

- Considers 1-D local earth conductivity models
- Calculates E(t) using Complex Image Method

Run GIC Analysis from Python™ Script

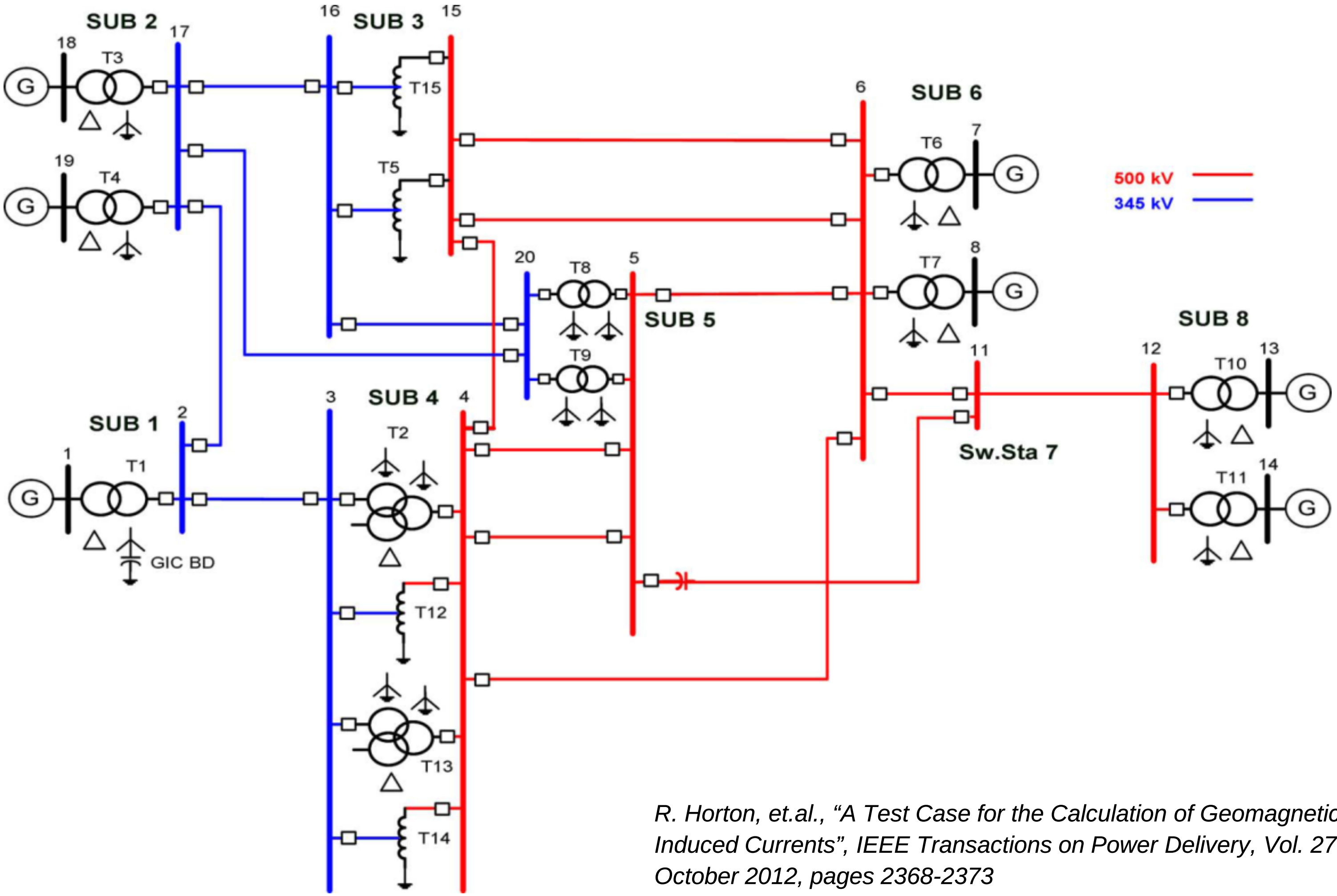
(A) Run GIC activity (gic_3) using psspy module

This runs GIC activity and produces GIC analysis results in PSS®E Text reports.

(B) Run GIC analysis and retrieve results in Python™ objects using arrbox.gic OR pssarrays modules

This runs GIC activity and returns GIC analysis results in Python™ objects.

Example
IEEE GIC Test Case Network



R. Horton, et.al., "A Test Case for the Calculation of Geomagnetically Induced Currents", IEEE Transactions on Power Delivery, Vol. 27, No. 4, October 2012, pages 2368-2373

IEEE GIC Test Case
Calculations with Activity GIC

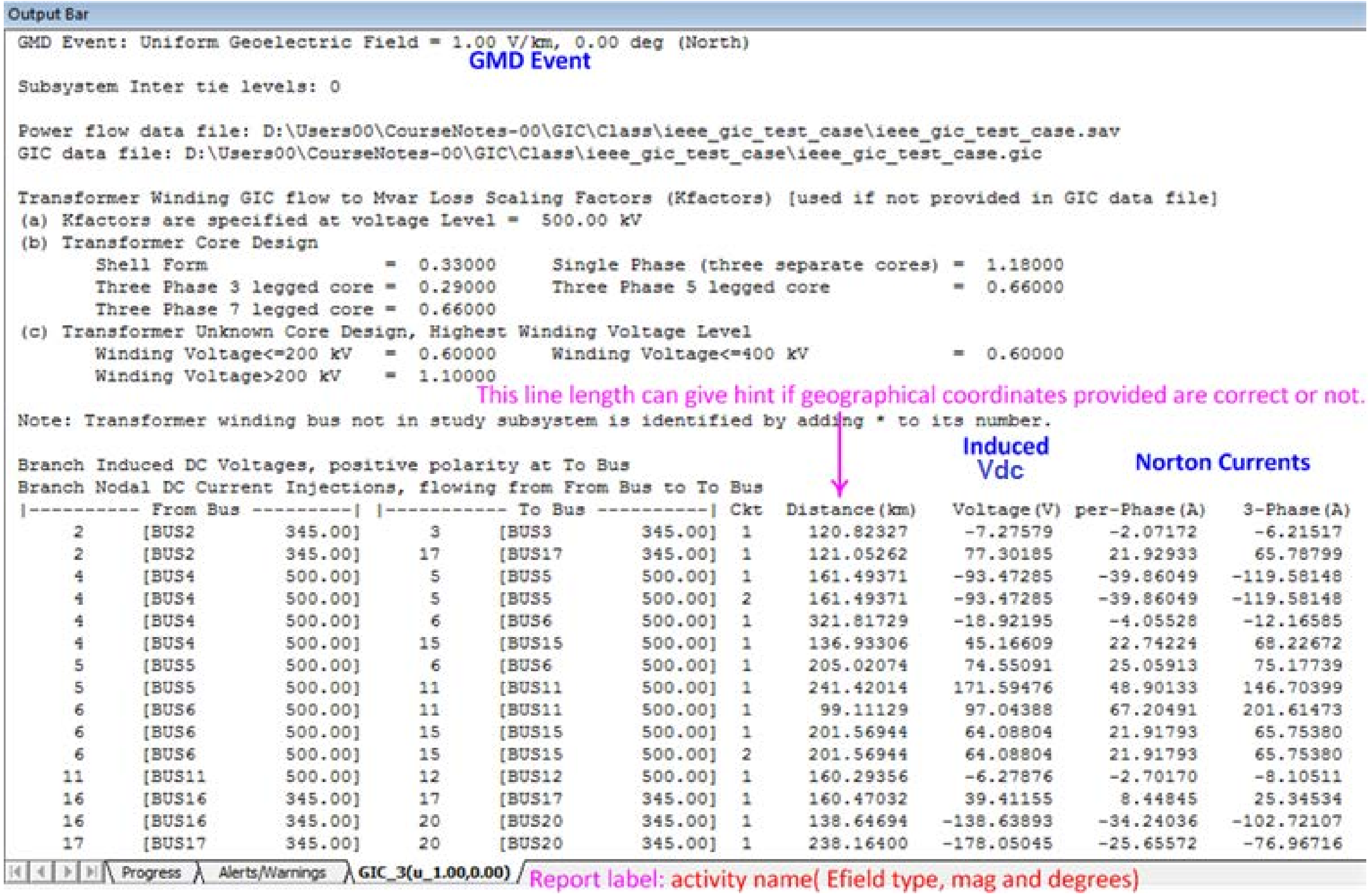
Refer files in folder ..\PTI\PSSExx\EXAMPLE

ieee_gic_test_case.sav

ieee_gic_test_case.gic

ieee_gic_test_case.sld

GIC Calculations Report



```
GMD Event: Uniform Geoelectric Field = 1.00 V/km, 0.00 deg (North)

Subsystem Inter tie levels: 0

Power flow data file: D:\Users00\CourseNotes-00\GIC\Class\ieee_gic_test_case\ieee_gic_test_case.sav
GIC data file: D:\Users00\CourseNotes-00\GIC\Class\ieee_gic_test_case\ieee_gic_test_case.gic

Transformer Winding GIC flow to Mvar Loss Scaling Factors (Kfactors) [used if not provided in GIC data file]
(a) Kfactors are specified at voltage Level =  500.00 kV
(b) Transformer Core Design
      Shell Form                =  0.33000     Single Phase (three separate cores) =  1.18000
      Three Phase 3 legged core =  0.29000     Three Phase 5 legged core           =  0.66000
      Three Phase 7 legged core =  0.66000
(c) Transformer Unknown Core Design, Highest Winding Voltage Level
      Winding Voltage<=200 kV   =  0.60000     Winding Voltage<=400 kV             =  0.60000
      Winding Voltage>200 kV    =  1.10000

Note: Transformer winding bus not in study subsystem is identified by adding * to its number.

Branch Induced DC Voltages, positive polarity at To Bus
Branch Nodal DC Current Injections, flowing from From Bus to To Bus
|---------- From Bus ---------| |----------- To Bus ----------| Ckt  Distance(km)   Voltage(V) per-Phase(A)   3-Phase(A)
     2     [BUS2         345.00]     3     [BUS3         345.00]  1    120.82327     -7.27579     -2.07172     -6.21517
     2     [BUS2         345.00]    17     [BUS17        345.00]  1    121.05262     77.30185     21.92933     65.78799
     4     [BUS4         500.00]     5     [BUS5         500.00]  1    161.49371    -93.47285    -39.86049   -119.58148
     4     [BUS4         500.00]     5     [BUS5         500.00]  2    161.49371    -93.47285    -39.86049   -119.58148
     4     [BUS4         500.00]     6     [BUS6         500.00]  1    321.81729    -18.92195     -4.05528    -12.16585
     4     [BUS4         500.00]    15     [BUS15        500.00]  1    136.93306     45.16609     22.74224     68.22672
     5     [BUS5         500.00]     6     [BUS6         500.00]  1    205.02074     74.55091     25.05913     75.17739
     5     [BUS5         500.00]    11     [BUS11        500.00]  1    241.42014    171.59476     48.90133    146.70399
     6     [BUS6         500.00]    11     [BUS11        500.00]  1     99.11129     97.04388     67.20491    201.61473
     6     [BUS6         500.00]    15     [BUS15        500.00]  1    201.56944     64.08804     21.91793     65.75380
     6     [BUS6         500.00]    15     [BUS15        500.00]  2    201.56944     64.08804     21.91793     65.75380
    11     [BUS11        500.00]    12     [BUS12        500.00]  1    160.29356     -6.27876     -2.70170     -8.10511
    16     [BUS16        345.00]    17     [BUS17        345.00]  1    160.47032     39.41155      8.44845     25.34534
    16     [BUS16        345.00]    20     [BUS20        345.00]  1    138.64694   -138.63893    -34.24036   -102.72107
    17     [BUS17        345.00]    20     [BUS20        345.00]  1    238.16400   -178.05045    -25.65572    -76.96716
```

GMD Event

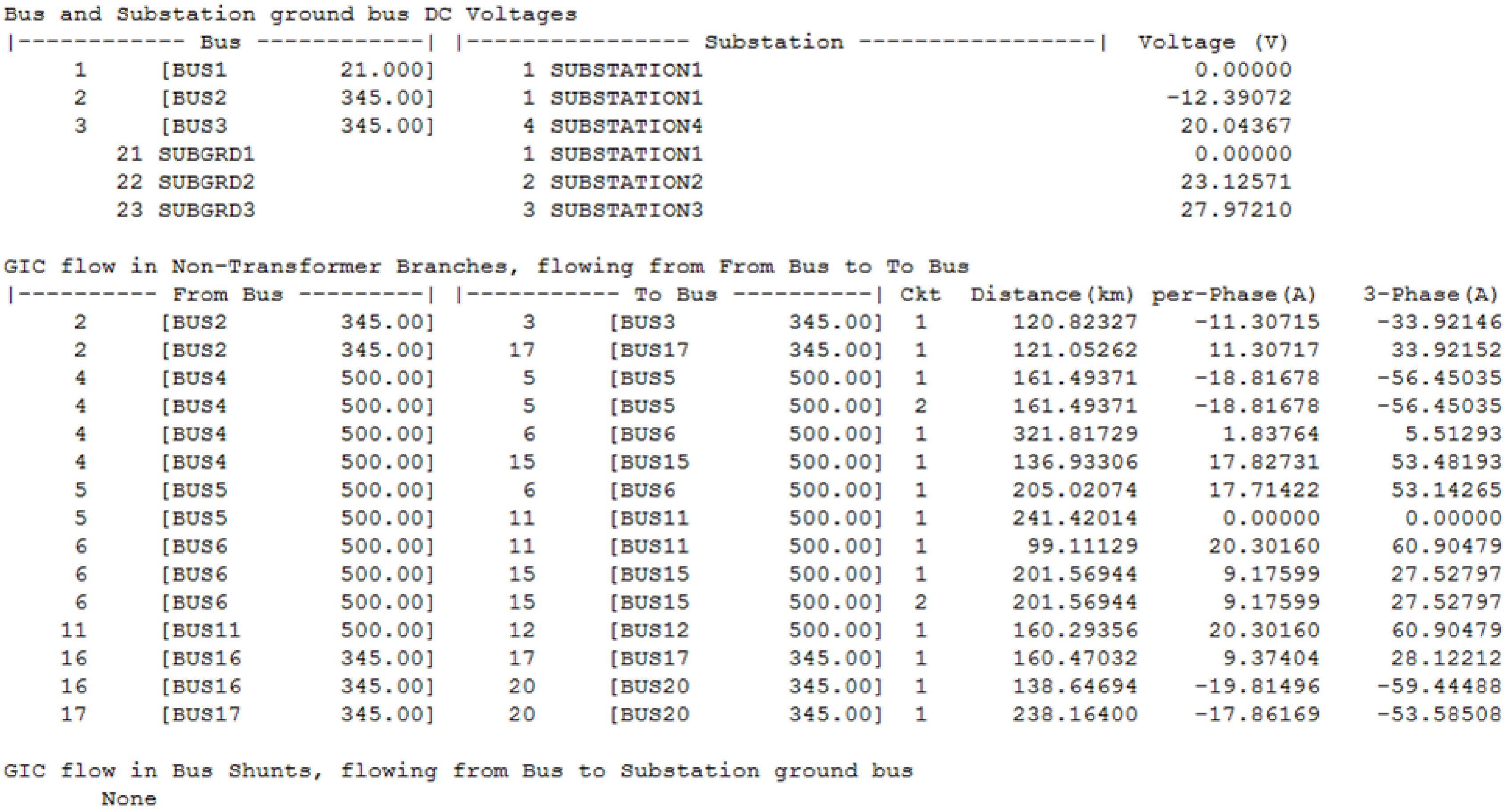
This line length can give hint if geographical coordinates provided are correct or not.

Induced Vdc

Norton Currents

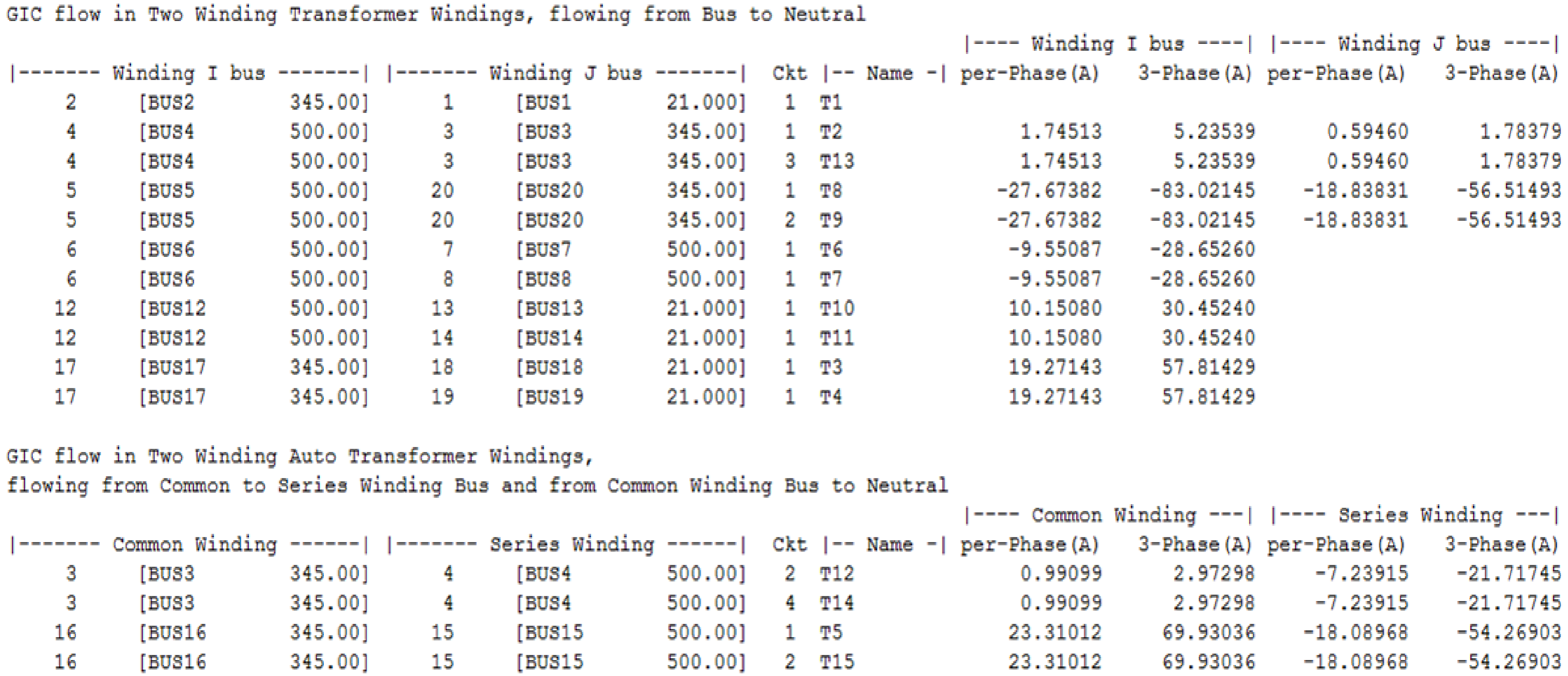
Report label: activity name(Efield type, mag and degrees)

GIC Calculations Report (continued)



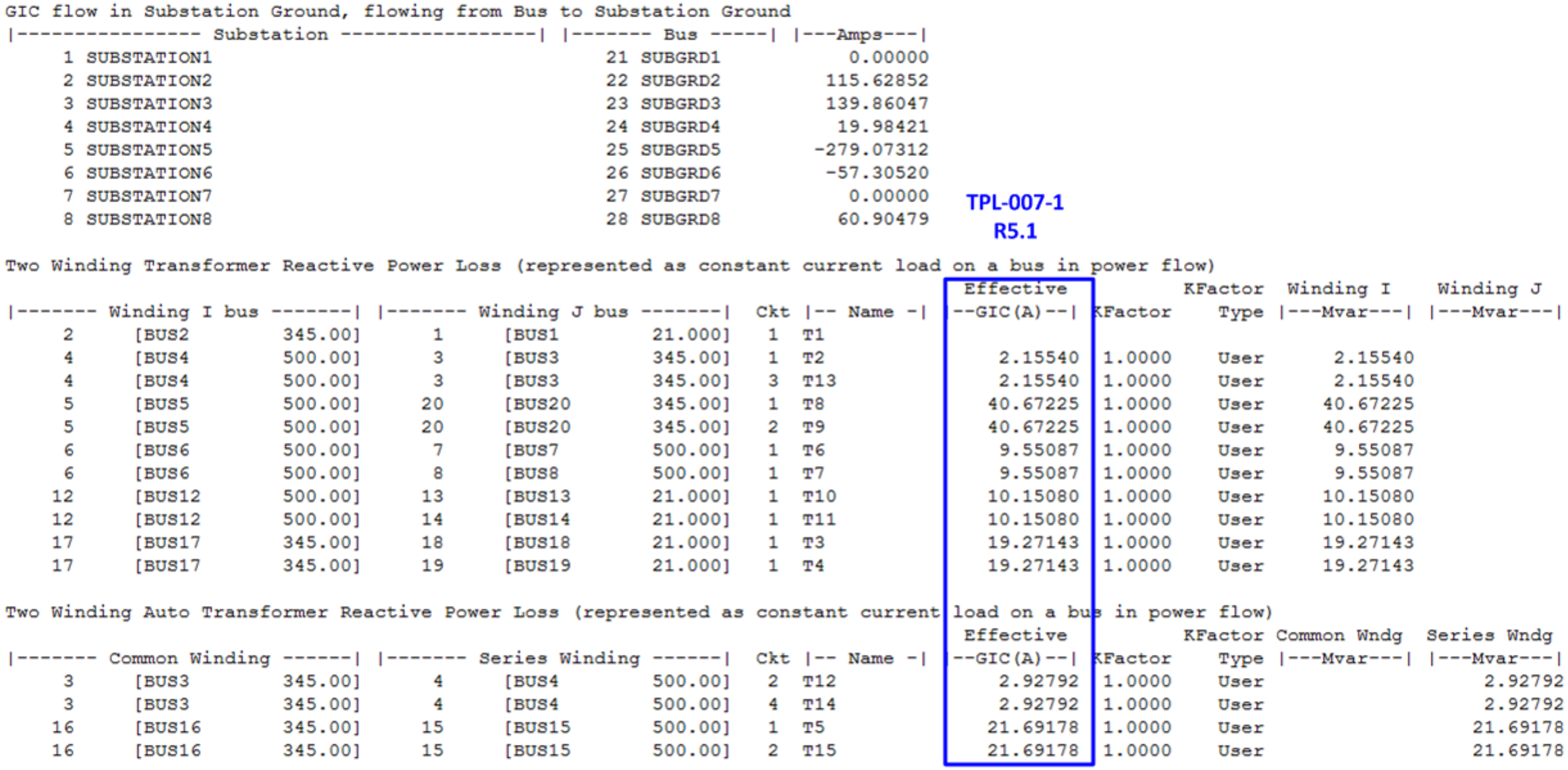
```
Bus and Substation ground bus DC Voltages
|------------ Bus ------------| |---------------- Substation -----------------|  Voltage (V)
     1     [BUS1        21.000]      1 SUBSTATION1                                    0.00000
     2     [BUS2        345.00]      1 SUBSTATION1                                  -12.39072
     3     [BUS3        345.00]      4 SUBSTATION4                                   20.04367
        21 SUBGRD1                   1 SUBSTATION1                                    0.00000
        22 SUBGRD2                   2 SUBSTATION2                                   23.12571
        23 SUBGRD3                   3 SUBSTATION3                                   27.97210

GIC flow in Non-Transformer Branches, flowing from From Bus to To Bus
|---------- From Bus ---------| |----------- To Bus ----------| Ckt  Distance(km) per-Phase(A)    3-Phase(A)
     2     [BUS2        345.00]      3     [BUS3        345.00]  1      120.82327    -11.30715     -33.92146
     2     [BUS2        345.00]     17     [BUS17       345.00]  1      121.05262     11.30717      33.92152
     4     [BUS4        500.00]      5     [BUS5        500.00]  1      161.49371    -18.81678     -56.45035
     4     [BUS4        500.00]      5     [BUS5        500.00]  2      161.49371    -18.81678     -56.45035
     4     [BUS4        500.00]      6     [BUS6        500.00]  1      321.81729      1.83764       5.51293
     4     [BUS4        500.00]     15     [BUS15       500.00]  1      136.93306     17.82731      53.48193
     5     [BUS5        500.00]      6     [BUS6        500.00]  1      205.02074     17.71422      53.14265
     5     [BUS5        500.00]     11     [BUS11       500.00]  1      241.42014      0.00000       0.00000
     6     [BUS6        500.00]     11     [BUS11       500.00]  1       99.11129     20.30160      60.90479
     6     [BUS6        500.00]     15     [BUS15       500.00]  1      201.56944      9.17599      27.52797
     6     [BUS6        500.00]     15     [BUS15       500.00]  2      201.56944      9.17599      27.52797
    11     [BUS11       500.00]     12     [BUS12       500.00]  1      160.29356     20.30160      60.90479
    16     [BUS16       345.00]     17     [BUS17       345.00]  1      160.47032      9.37404      28.12212
    16     [BUS16       345.00]     20     [BUS20       345.00]  1      138.64694    -19.81496     -59.44488
    17     [BUS17       345.00]     20     [BUS20       345.00]  1      238.16400    -17.86169     -53.58508

GIC flow in Bus Shunts, flowing from Bus to Substation ground bus
       None
```

GIC Calculations Report (continued)



```
GIC flow in Two Winding Transformer Windings, flowing from Bus to Neutral
                                                                                   |---- Winding I bus ----| |---- Winding J bus ----|
|------- Winding I bus -------| |------- Winding J bus -------|  Ckt |-- Name -| per-Phase(A)   3-Phase(A) per-Phase(A)   3-Phase(A)
     2      [BUS2        345.00]     1      [BUS1        21.000]   1  T1
     4      [BUS4        500.00]     3      [BUS3        345.00]   1  T2                1.74513      5.23539      0.59460      1.78379
     4      [BUS4        500.00]     3      [BUS3        345.00]   3  T13               1.74513      5.23539      0.59460      1.78379
     5      [BUS5        500.00]    20      [BUS20       345.00]   1  T8              -27.67382    -83.02145    -18.83831    -56.51493
     5      [BUS5        500.00]    20      [BUS20       345.00]   2  T9              -27.67382    -83.02145    -18.83831    -56.51493
     6      [BUS6        500.00]     7      [BUS7        500.00]   1  T6               -9.55087    -28.65260
     6      [BUS6        500.00]     8      [BUS8        500.00]   1  T7               -9.55087    -28.65260
    12      [BUS12       500.00]    13      [BUS13       21.000]   1  T10              10.15080     30.45240
    12      [BUS12       500.00]    14      [BUS14       21.000]   1  T11              10.15080     30.45240
    17      [BUS17       345.00]    18      [BUS18       21.000]   1  T3               19.27143     57.81429
    17      [BUS17       345.00]    19      [BUS19       21.000]   1  T4               19.27143     57.81429

GIC flow in Two Winding Auto Transformer Windings,
flowing from Common to Series Winding Bus and from Common Winding Bus to Neutral
                                                                                   |---- Common Winding ---| |---- Series Winding ---|
|------- Common Winding ------| |------- Series Winding ------|  Ckt |-- Name -| per-Phase(A)   3-Phase(A) per-Phase(A)   3-Phase(A)
     3      [BUS3        345.00]     4      [BUS4        500.00]   2  T12               0.99099      2.97298     -7.23915    -21.71745
     3      [BUS3        345.00]     4      [BUS4        500.00]   4  T14               0.99099      2.97298     -7.23915    -21.71745
    16      [BUS16       345.00]    15      [BUS15       500.00]   1  T5               23.31012     69.93036    -18.08968    -54.26903
    16      [BUS16       345.00]    15      [BUS15       500.00]   2  T15              23.31012     69.93036    -18.08968    -54.26903
```

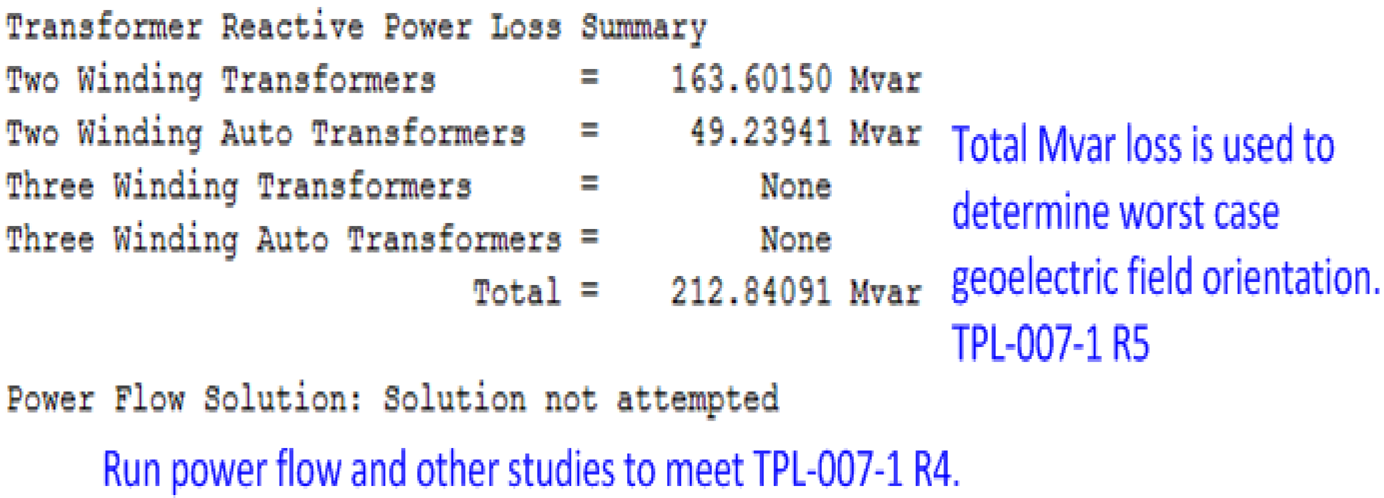
GIC Calculations Report (continued)



```
GIC flow in Substation Ground, flowing from Bus to Substation Ground
|---------------- Substation -----------------| |------- Bus -----| |---Amps---|
      1 SUBSTATION1                                   21 SUBGRD1          0.00000
      2 SUBSTATION2                                   22 SUBGRD2        115.62852
      3 SUBSTATION3                                   23 SUBGRD3        139.86047
      4 SUBSTATION4                                   24 SUBGRD4         19.98421
      5 SUBSTATION5                                   25 SUBGRD5       -279.07312
      6 SUBSTATION6                                   26 SUBGRD6        -57.30520
      7 SUBSTATION7                                   27 SUBGRD7          0.00000
      8 SUBSTATION8                                   28 SUBGRD8         60.90479

Two Winding Transformer Reactive Power Loss (represented as constant current load on a bus in power flow)
                                                                                Effective         KFactor  Winding I    Winding J
|------- Winding I bus -------| |------- Winding J bus -------|  Ckt  |-- Name -| |--GIC(A)--| KFactor    Type  |---Mvar---| |---Mvar---|
      2    [BUS2         345.00]      1    [BUS1         21.000]   1   T1
      4    [BUS4         500.00]      3    [BUS3         345.00]   1   T2               2.15540  1.0000     User     2.15540
      4    [BUS4         500.00]      3    [BUS3         345.00]   3   T13              2.15540  1.0000     User     2.15540
      5    [BUS5         500.00]     20    [BUS20        345.00]   1   T8              40.67225  1.0000     User    40.67225
      5    [BUS5         500.00]     20    [BUS20        345.00]   2   T9              40.67225  1.0000     User    40.67225
      6    [BUS6         500.00]      7    [BUS7         500.00]   1   T6               9.55087  1.0000     User     9.55087
      6    [BUS6         500.00]      8    [BUS8         500.00]   1   T7               9.55087  1.0000     User     9.55087
     12    [BUS12        500.00]     13    [BUS13        21.000]   1   T10             10.15080  1.0000     User    10.15080
     12    [BUS12        500.00]     14    [BUS14        21.000]   1   T11             10.15080  1.0000     User    10.15080
     17    [BUS17        345.00]     18    [BUS18        21.000]   1   T3              19.27143  1.0000     User    19.27143
     17    [BUS17        345.00]     19    [BUS19        21.000]   1   T4              19.27143  1.0000     User    19.27143

Two Winding Auto Transformer Reactive Power Loss (represented as constant current load on a bus in power flow)
                                                                                Effective         KFactor Common Wndg  Series Wndg
|------- Common Winding ------| |------- Series Winding ------|  Ckt  |-- Name -| |--GIC(A)--| KFactor    Type  |---Mvar---| |---Mvar---|
      3    [BUS3         345.00]      4    [BUS4         500.00]   2   T12              2.92792  1.0000     User                   2.92792
      3    [BUS3         345.00]      4    [BUS4         500.00]   4   T14              2.92792  1.0000     User                   2.92792
     16    [BUS16        345.00]     15    [BUS15        500.00]   1   T5              21.69178  1.0000     User                  21.69178
     16    [BUS16        345.00]     15    [BUS15        500.00]   2   T15             21.69178  1.0000     User                  21.69178
```

TPL-007-1
R5.1

GIC Calculations Report (continued)

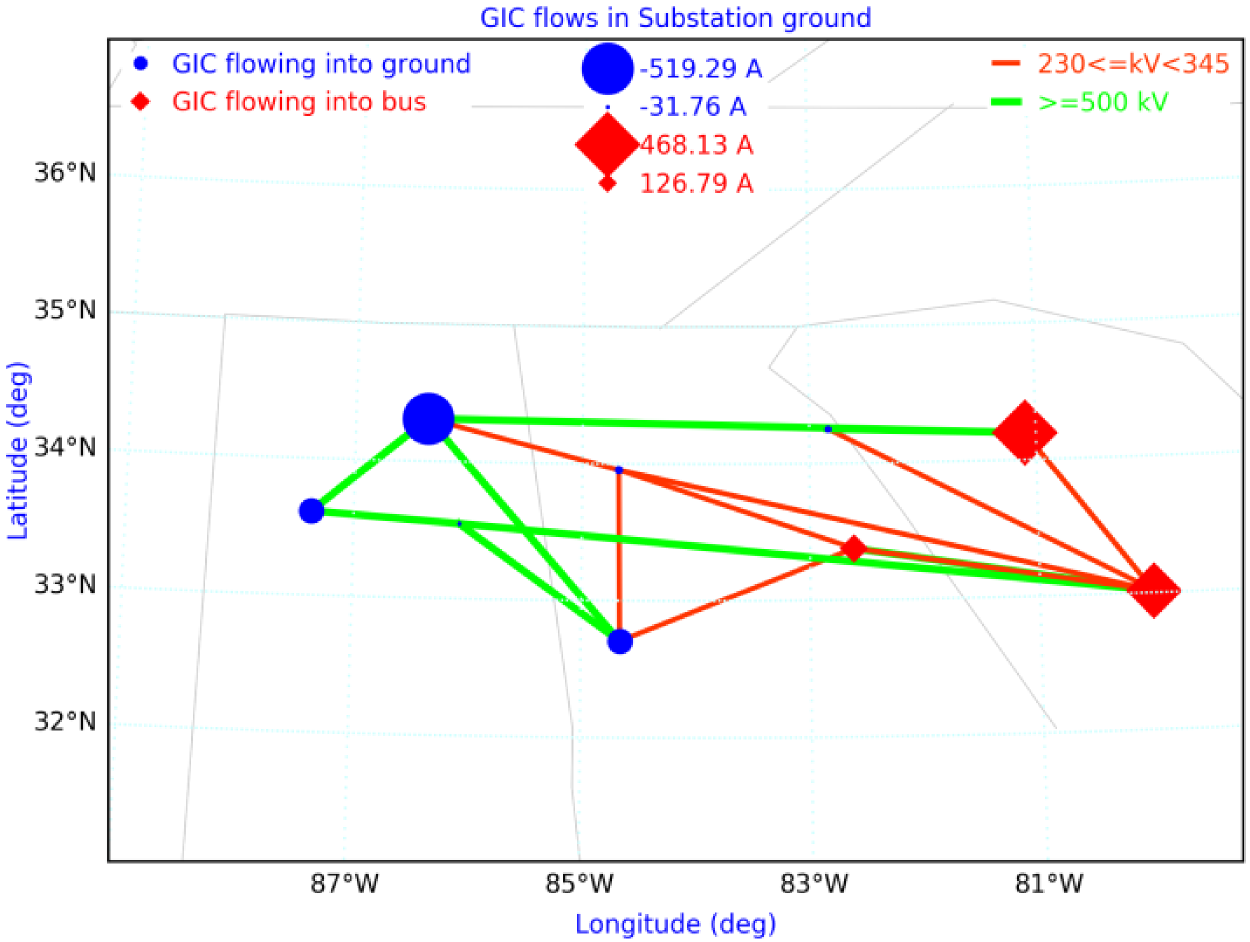


```
Transformer Reactive Power Loss Summary
Two Winding Transformers         =    163.60150 Mvar
Two Winding Auto Transformers    =     49.23941 Mvar
Three Winding Transformers       =         None
Three Winding Auto Transformers  =         None
                           Total =    212.84091 Mvar

Power Flow Solution: Solution not attempted
```

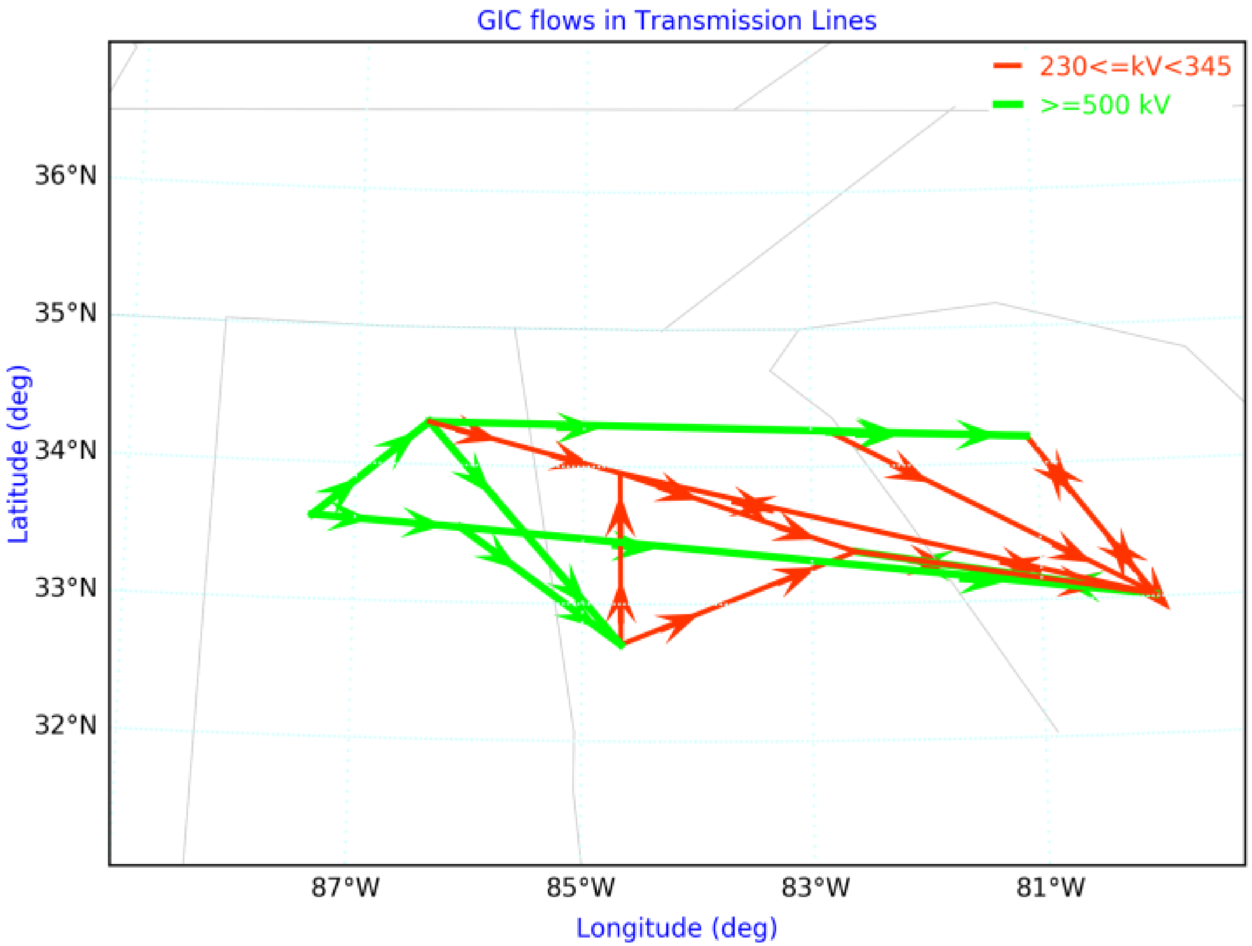
Total Mvar loss is used to determine worst case geoelectric field orientation. TPL-007-1 R5

Run power flow and other studies to meet TPL-007-1 R4.

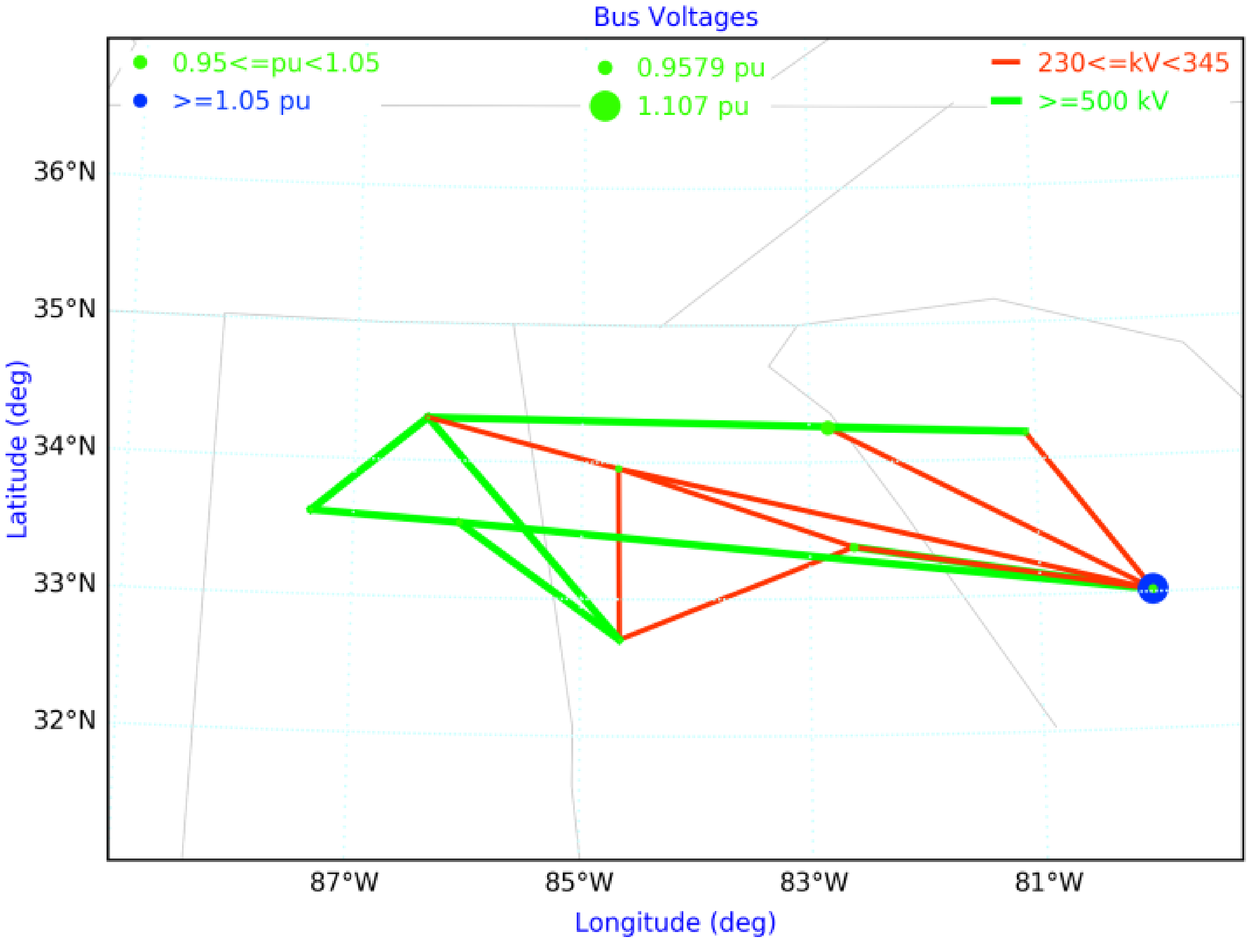
GIC Results on Network Maps



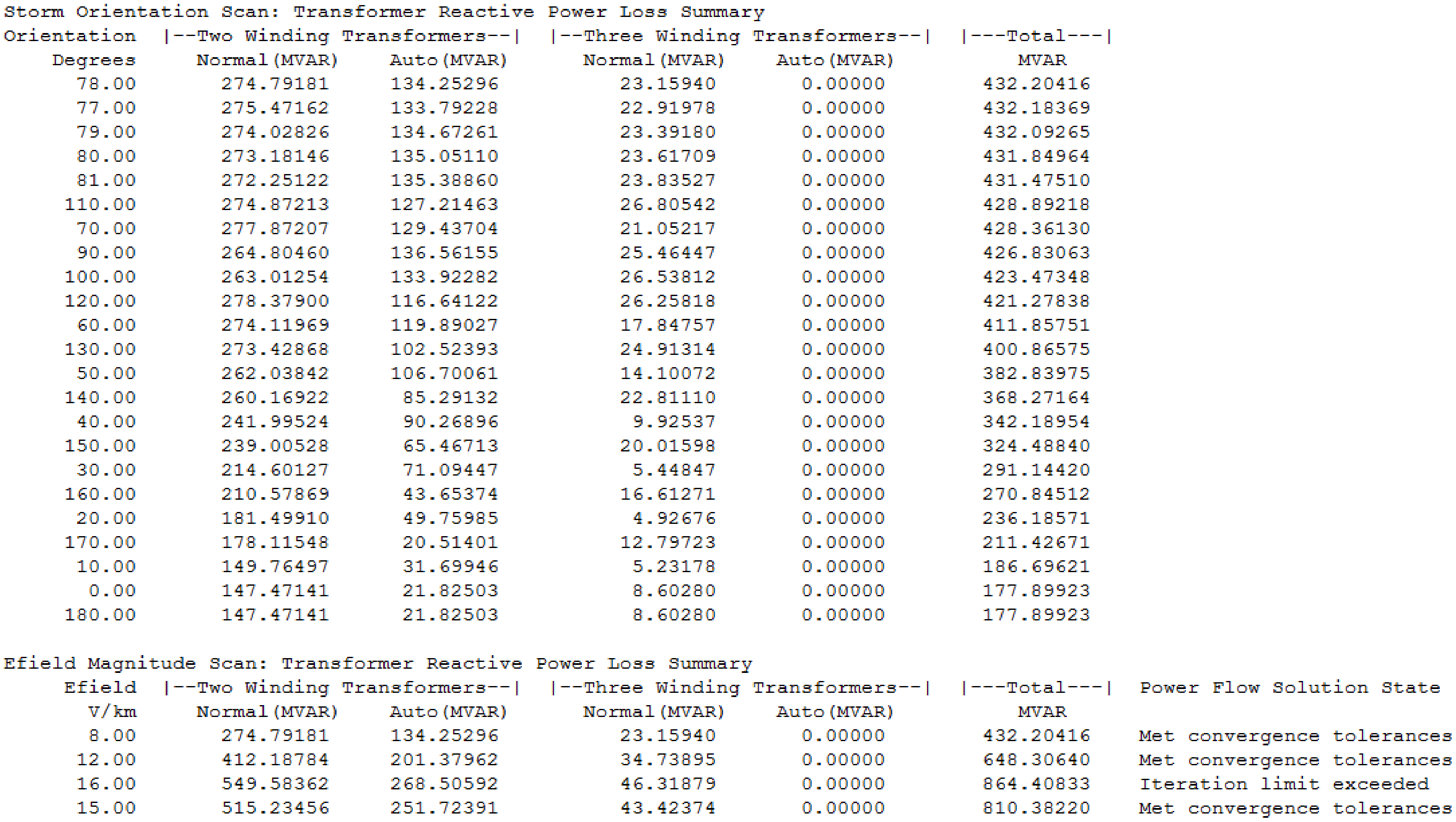
GIC Results on Network Maps (continued)



GIC Results on Network Maps (continued)



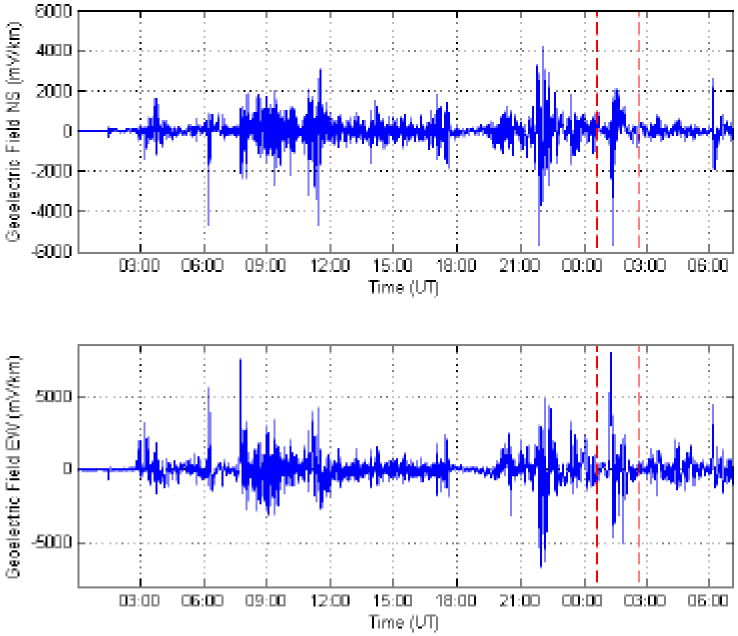
Scan degrees & magnitude Option - Results

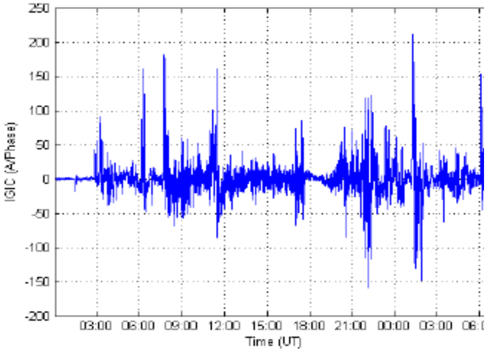


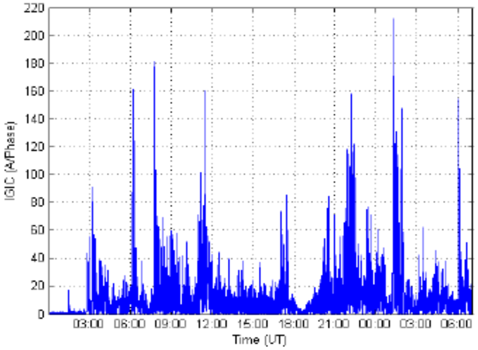
```
Storm Orientation Scan: Transformer Reactive Power Loss Summary
Orientation  |--Two Winding Transformers--|  |--Three Winding Transformers--|  |---Total---|
    Degrees      Normal(MVAR)    Auto(MVAR)      Normal(MVAR)    Auto(MVAR)        MVAR
      78.00        274.79181     134.25296          23.15940       0.00000      432.20416
      77.00        275.47162     133.79228          22.91978       0.00000      432.18369
      79.00        274.02826     134.67261          23.39180       0.00000      432.09265
      80.00        273.18146     135.05110          23.61709       0.00000      431.84964
      81.00        272.25122     135.38860          23.83527       0.00000      431.47510
     110.00        274.87213     127.21463          26.80542       0.00000      428.89218
      70.00        277.87207     129.43704          21.05217       0.00000      428.36130
      90.00        264.80460     136.56155          25.46447       0.00000      426.83063
     100.00        263.01254     133.92282          26.53812       0.00000      423.47348
     120.00        278.37900     116.64122          26.25818       0.00000      421.27838
      60.00        274.11969     119.89027          17.84757       0.00000      411.85751
     130.00        273.42868     102.52393          24.91314       0.00000      400.86575
      50.00        262.03842     106.70061          14.10072       0.00000      382.83975
     140.00        260.16922      85.29132          22.81110       0.00000      368.27164
      40.00        241.99524      90.26896           9.92537       0.00000      342.18954
     150.00        239.00528      65.46713          20.01598       0.00000      324.48840
      30.00        214.60127      71.09447           5.44847       0.00000      291.14420
     160.00        210.57869      43.65374          16.61271       0.00000      270.84512
      20.00        181.49910      49.75985           4.92676       0.00000      236.18571
     170.00        178.11548      20.51401          12.79723       0.00000      211.42671
      10.00        149.76497      31.69946           5.23178       0.00000      186.69621
       0.00        147.47141      21.82503           8.60280       0.00000      177.89923
     180.00        147.47141      21.82503           8.60280       0.00000      177.89923

Efield Magnitude Scan: Transformer Reactive Power Loss Summary
     Efield  |--Two Winding Transformers--|  |--Three Winding Transformers--|  |---Total---|  Power Flow Solution State
       V/km      Normal(MVAR)    Auto(MVAR)      Normal(MVAR)    Auto(MVAR)        MVAR
       8.00        274.79181     134.25296          23.15940       0.00000      432.20416    Met convergence tolerances
      12.00        412.18784     201.37962          34.73895       0.00000      648.30640    Met convergence tolerances
      16.00        549.58362     268.50592          46.31879       0.00000      864.40833    Iteration limit exceeded
      15.00        515.23456     251.72391          43.42374       0.00000      810.38220    Met convergence tolerances
```

GIC(t) Waveform for Thermal Impact Assessment

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







Review GIC Calculation Results

- Run GIC Module for Benchmark GMD event

- After running GIC, review results to identify any length related errors in the data. Rerun GIC module with corrected data.

- If transformers are identified as meeting the criteria of maximum effective GIC >= 75 A for thermal impact analysis, then review the GIC input data file if any assumed data was used at that transformer and nearby buses based on GIC flows. If data is assumed but not measured or actual data then, try to get actual data, rerun GIC module with measured/actual data.

- The calculated GICs depend on the topology of the system. If the topology changes, the GIC values need to be recalculated.

GIC Calculation – Possible Sensitivity Studies

- Consider the following sensitivity studies just to understand impacts on GIC and the worst orientation of electric field on your system:
    - Including lower kV facilities (100 kV and above)
    - Include neighboring system (1-4 levels) - pay attention to the substation numbering
    - Bypassing any series capacitors

GMD Vulnerability Assessment

usa.siemens.com/digitalgrid

NERC TPL-007-1
GMD Vulnerability Assessment Process

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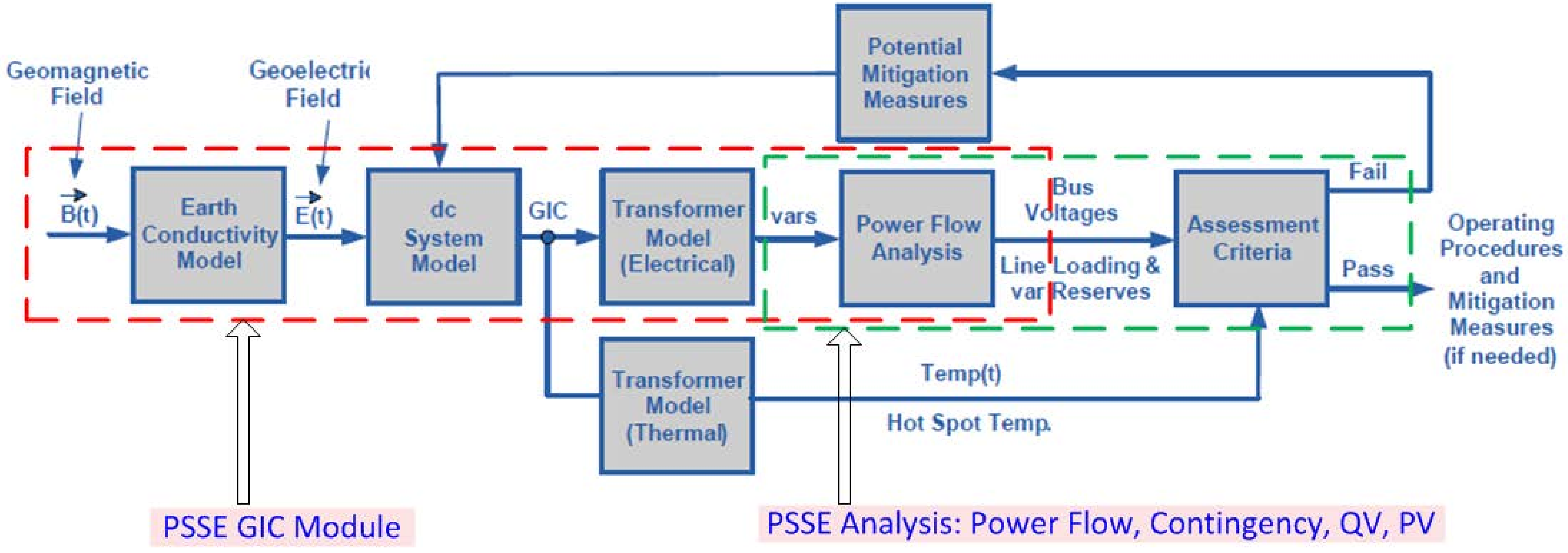
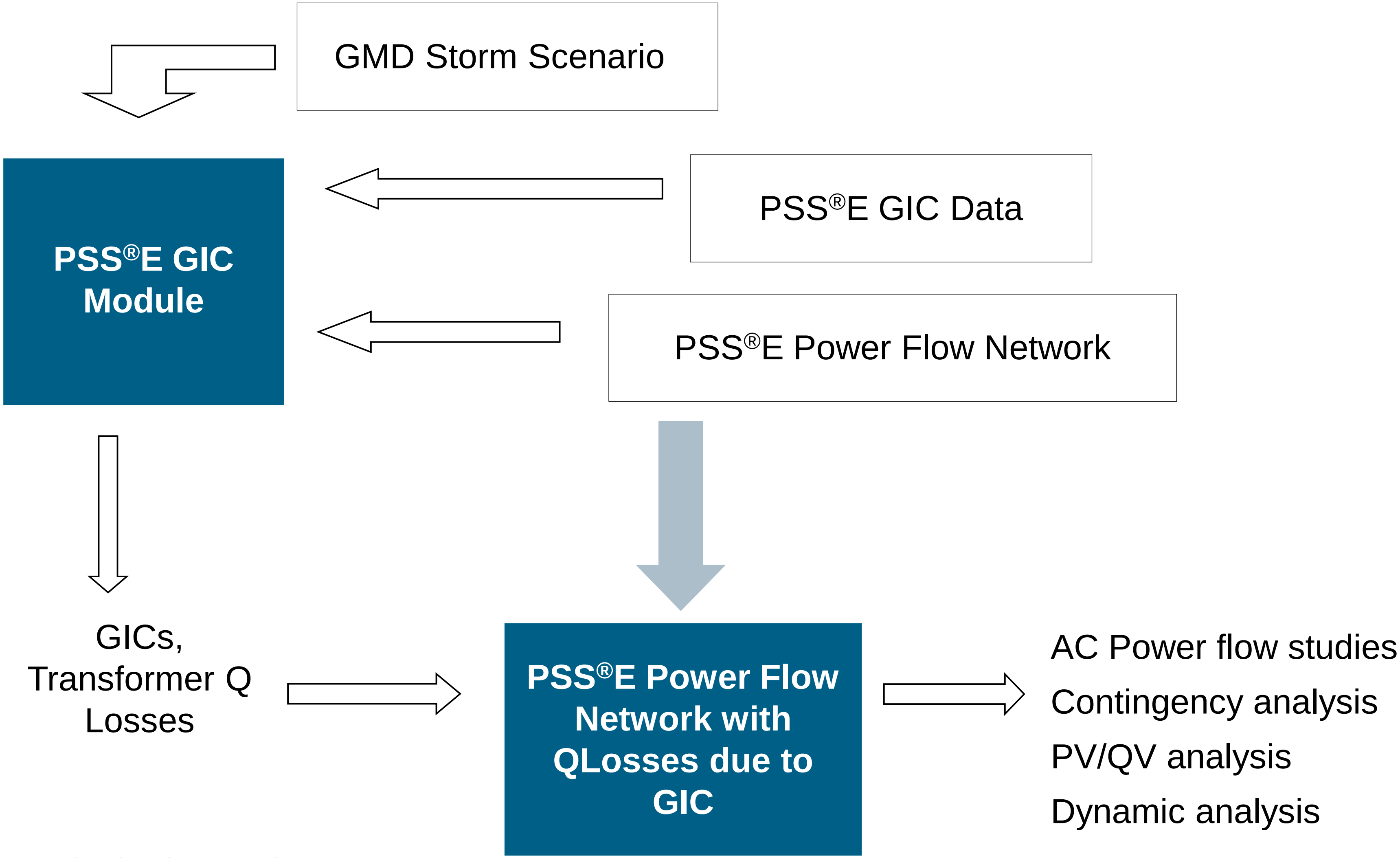


Source: NERC GMD Task Force Documents

PSS®E GIC Calculations



GMD Storm Scenario

PSS®E GIC Data

PSS®E Power Flow Network

PSS®E GIC Module

GICs, Transformer Q Losses

PSS®E Power Flow Network with QLosses due to GIC

AC Power flow studies

Contingency analysis

PV/QV analysis

Dynamic analysis

GMD Vulnerability Assessment (R4)

- Assess the behavior of the system in terms of voltage limits, potential voltage collapse, and cascading outages due to Benchmark GMD event by taking into account transformer var absorption caused by half-cycle saturation.

- The system must perform within applicable limits under various contingencies – such as forced outage of a shunt capacitor bank or static var compensator (SVC)

- System performance is evaluated based on.
  - Steady state voltage performance criteria established by the planning entity.
  - Table 1 of TPL-007-1

GMD Vulnerability Assessment (R4) – Performance Criteria

The vulnerability Assessment Studies shall meet following performance criteria.
(Table 1 of TPL-007-1)

- Voltage collapse, cascading and uncontrolled islanding shall not occur.
- Generation loss is acceptable as a consequence of the planning event.
- Planned System adjustments such as Transmission configuration changes and re-dispatch of generation are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings.

TPL-007-1
R4 – Performance Criteria

The vulnerability Assessment Studies shall meet following performance criteria.
(Table 1 of TPL-007-1)

- Initial Condition:
  - The System condition for GMD planning may include adjustments to posture the System that are executable in response to space weather information.
  - The GMD conditions for the planning event (Benchmark GMD event) are described Attachment 1.

- Event:
- Reactive Power Compensation Devices and other Transmission Facilities removed as a result of Protection System operation or mis-operation due to harmonics during the GMD event
  - Load loss and/or curtailment of firm transmission service may be used to meet BES performance requirements but the likelihood and magnitude should be minimized.

GMD Vulnerability Assessment (R4)

- Based on your system knowledge, include new contingencies for loss of reactor power devices and transmission facilities.

- Better approach for identify those contingencies by performing Harmonic analysis and reviewing the performance of protection and control (P&C) systems

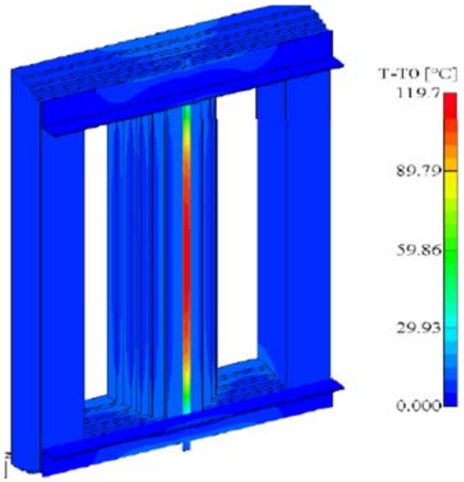
- Include additional contingencies that were agreed upon by Planning Coordinator and Transmission Planner

Thermal Impact Assessments (Requirement R6)

- Transmission Owners and Generator Owners conduct thermal impact assessment of power transformers (Wye grounded on high side at 230 kV or higher) if the maximum effective GIC value provided in Requirement R5.1 is **75 A per phase or greater**.

- Hot spot heating of transformers due to GIC during a GMD event is a primary concern since automatic protection systems are not likely to operate on this basis.

- A thermal assessment, which uses the most conservative thermal models known to date indicates that a GIC of 75A will not result in peak metallic hot spot temperatures above 172°C.



Thermal Impact Assessments- IEEE C57.163-2015

- Lists procedures for calculating the thermal response of windings and structural parts to a GIC profile.

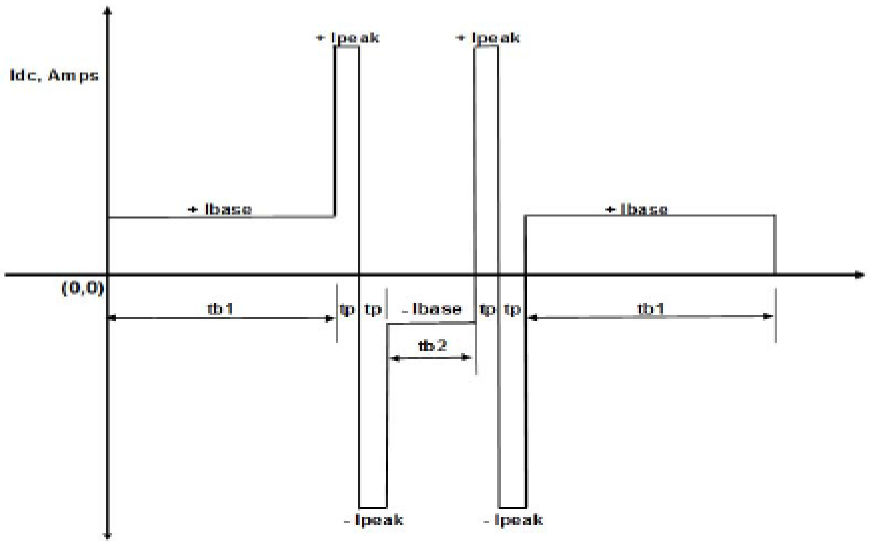


Figure 24—Recommended simplified GIC signature

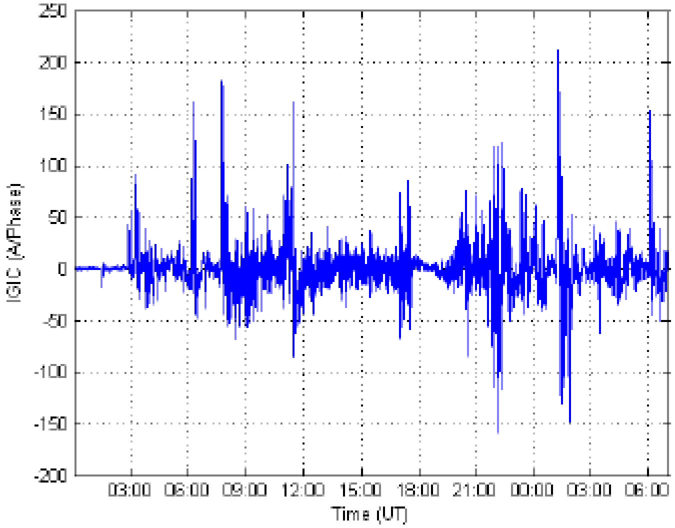


Table 3—Recommended hot-spot temperature limits for GIC

Component	GIC type		
	Base GIC	Short duration GIC events	
	IEEE/IEC	IEEE	IEC
Cellulose insulation	140 °C	180 °C	160 °C
Structural parts	160 °C	200 °C	180 °C

NERC – Transformer Thermal Impact White Paper

- Outlines the process for performing Transformer Thermal Impact Assessment using GIC flow time series, GIC(t) and Transformer Thermal Capability Curves to determine if the transformer will be able to withstand the thermal transient effects associated with the Benchmark GMD event

- A transformer GMD impact assessment must consider GIC amplitude, duration, and transformer physical characteristics such as design and condition (e.g., age, gas content, and moisture in the oil)

- Winding and metallic part hot spot heating have different thermal time constants, and their temperature rise will be different if the GIC currents are sustained for 2, 10, or 30 minutes for a given GIC peak amplitude

NERC – Transformer Thermal Impact White Paper

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- A **simplified thermal assessment** may be performed based on **Table 1**, which provides the peak metallic hot spot temperatures that can be reached using conservative thermal models.

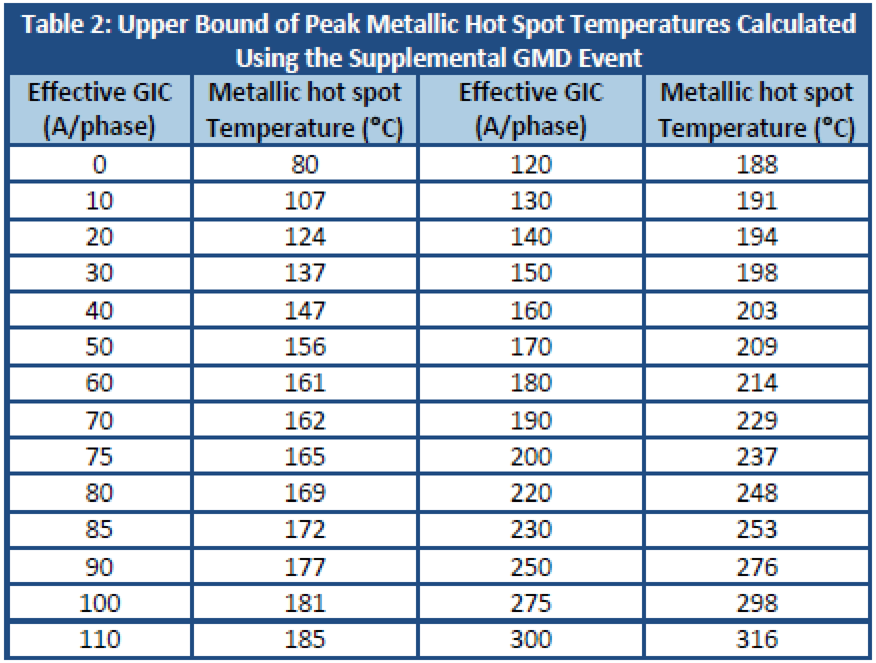


Table 2: Upper Bound of Peak Metallic Hot Spot Temperatures Calculated Using the Supplemental GMD Event

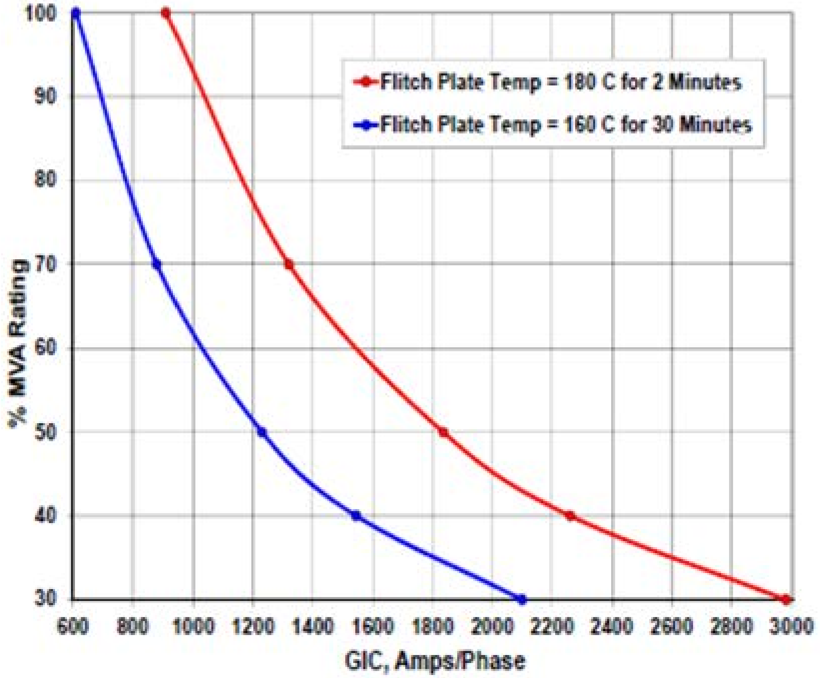
Effective GIC (A/phase)	Metallic hot spot Temperature (°C)	Effective GIC (A/phase)	Metallic hot spot Temperature (°C)
0	80	120	188
10	107	130	191
20	124	140	194
30	137	150	198
40	147	160	203
50	156	170	209
60	161	180	214
70	162	190	229
75	165	200	237
80	169	220	248
85	172	230	253
90	177	250	276
100	181	275	298
110	185	300	316

NERC – Transformer Thermal Impact White Paper

- If the effective GIC results in higher than threshold temperatures, then use a **detailed thermal assessment** using two different ways given below:
  - Transformer manufacturer GIC capability curves
  - Thermal response simulation

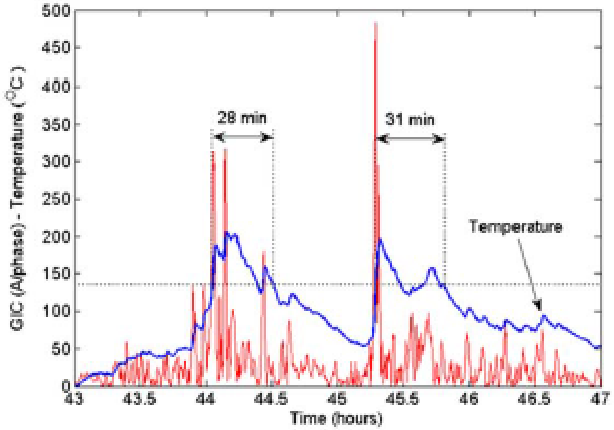
NERC – Transformer Thermal Impact White Paper

- Transformer manufacturer GIC capability curves
  - These curves relate permissible peak GIC (obtained by the user from a steady-state GIC calculation and loading, for a specific transformer).



Sample GIC Manufacturer Capability Curve of a Large Single-Phase Transformer Design using the Flitch Plate Temperature Criteria

- Thermal response simulation
  - The input to this type of simulation is the time series or waveshape of effective GIC flowing through a transformer and the result of the simulation is the hot spot temperature (winding or metallic part) time sequence for a given transformer.



Sample Tie Plate Temperature Calculation

Blue trace is incremental temperature and red trace is the magnitude of the GIC/phase

- In the absence of manufacturer specific information, use the temperature limits for safe transformer operation such as those suggested in the **IEEE Std C57.91-2011** standard (Establishing Power Transformer Capability while under Geomagnetic Disturbances) for hot spot heating during short-term emergency operation.

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CAP

Corrective Action Plan (CAP)

- TPL-007 requires a CAP when system performance requirements are not met in the Benchmark GMD Vulnerability Assessment.

- Requirement R7 lists examples of such actions:
  - Operating procedures
  - Hardening the system
  - Installing monitors
  - Protection system review and special protection systems
  - New technologies or other initiatives

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Corrective Action Plan (CAP)

- **Operating procedures (Non-hardware mitigation)**
  - Specify how long they will be needed as part of CAP
  - Identify Reactive Reserve Zones based on studies and monitor those
  - Turn on additional units - more Reactive Power (Q) margin on online units
  - Postpone outages, bring facilities back in service so the in service facilities are not operated in stressed conditions
  - Reconfiguration of the transmission system
  - Load rejection

Corrective Action Plan (CAP)

- **Other options (Hardware mitigation)**
  - Series Compensating Lines
  - GIC Blocking Devices – Capacitor blocking
  - GIC Reduction Devices – Resistive blocking
  - GIC Monitoring devices on transformers – Hall-effect CTs

Corrective Action Plan (CAP)

- **New or Improved technologies**
  - GIC-safe Transformers
    - Siemens manufactures GIC-safe transformers for up to 200 A extra DC capability, use non-magnetic steel inserts to reduce high saturation levels at extreme DC levels, lowers eddy current losses and prevents overheating due to lower losses.
  - New Tools for Operators
    - Real-time on-line/offline GMD assessment tool that take EMS case with scheduled outages on the system, takes Space weather forecast and runs GIC study, evaluates system performance and identifies mitigation options based on those results.

Corrective Action Plan (CAP) - Hydro-Québec

- Following the March 1989 storm, Hydro-Québec took a number of measures, including
  - Reviewed protective relaying and concluded that the replacement of electromechanical relays with IEDs has practically eliminated the impact of GIC on reliability and security of the protection schemes used in Hydro One.
    - Desensitization of the protection of SVCs to amplification of the voltage wave asymmetry and harmonics

  - Addition of series compensation on the entire 735 kV network (North - South)

  - Addition of blocking capacitors in the neutral of the most vulnerable high power transformers

Corrective Action Plan (CAP) - Hydro-Québec

  - In southern Québec, installed an automatic load shedding scheme to counter slow voltage collapse in 2004

  - Installed real-time asymmetry monitoring at several substations to complement K-index forecast.

- These following were in their proposed plan for solar cycle 24:

  - Estimate in real time the GIC flowing through the transformer from
    - SCADA measurements of reactive power loss
    - Harmonic currents measured with modern relays (IEDs)

  - Measure in real time the rate of change of dissolved gasses in selected transformers to establish correlations with the estimated hot spot heating.

Other GMD-related Studies

- PV Analysis
- Transient Stability
- Harmonic Analysis
- QV Analysis

PV Analysis

- If the study system has known voltage stability constrained interfaces, perform voltage stability with the power flow model that has the GIC impact superimposed (i.e. Qlosses added as load) to identify if the existing limits can be maintained.

- Along with significant line outages, consider contingencies involving loss of reactive power resources in the study area.

Transient Stability Analysis

- Using the powerflow model with GIC impacts (transformer reactive power losses) added, perform transient stability analysis to identify the impact of additional reactive power losses due to the GIC

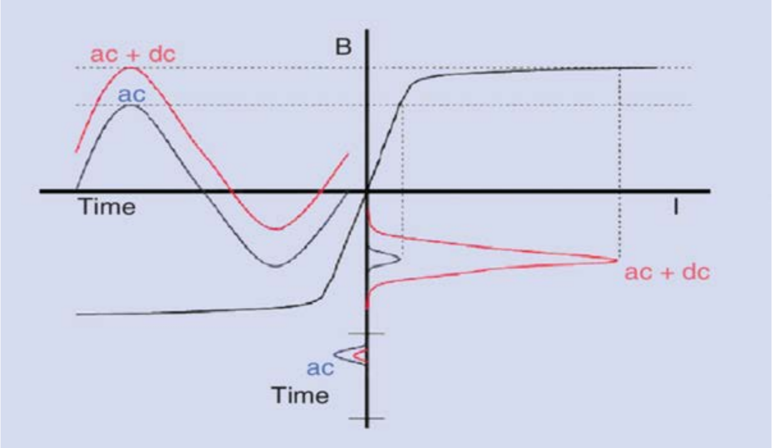
- Consider new faults involving loss of reactive devices

Harmonic Analysis

- Half-cycle saturation of transformer increases magnetizing current and creates harmonics.

- Impacts of harmonics:
  - Heating effects
  - Voltage asymmetry
  - Noise
  - Protection system mis-operation

- Magnetizing current wave is not symmetric and is non-sinusoidal, contains significant amount of even and odd harmonic components. Fourier analysis is used to find these components.



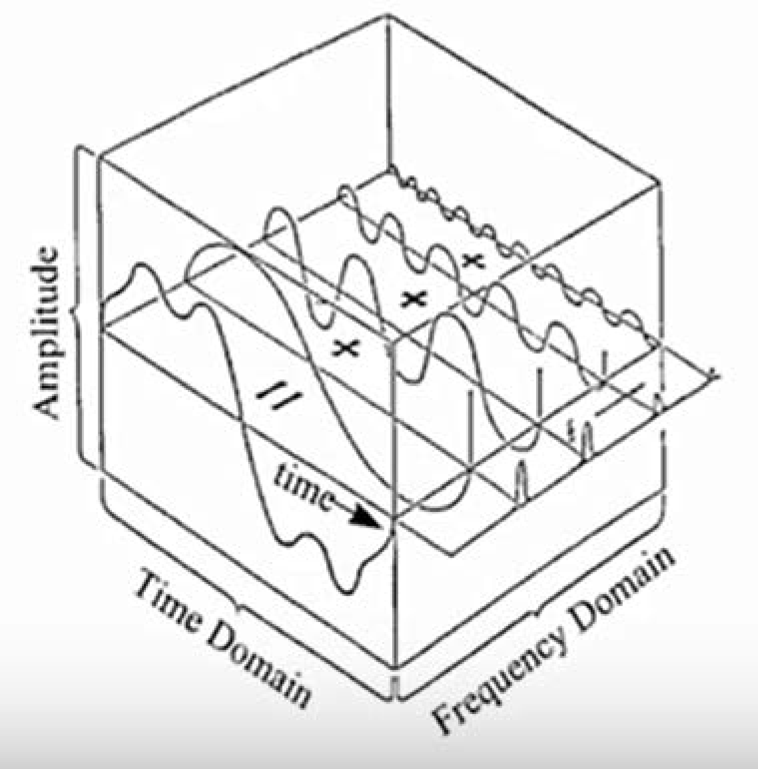
Harmonic Analysis

- Harmonics – Integer multiples of fundamental
  - Even - 120 Hz (2nd order), 240 Hz (4th order)..
  - Odd - 180 Hz (3rd order), 300 Hz (5th order)..

- Fourier Analysis
  - Process of decomposition for any distorted pe waveshape into a fundamental wave and a se harmonics.

- Harmonic impact on transformer:
  - EMTP modeling and simulation (PSCAD…)
    - Detailed Transformer magnetic models are available

- Harmonic component analysis: MATLAB numerical analysis to identify harmonic components



Source: Webinar on Power and Harmonic Analysis on Distorted Waveforms – Yokogawa Test & Measurement

Harmonic Analysis

- Existing tools have limitations
  - Don’t have ability to combine impact from multiple harmonic sources for system-wide assessment
  - Need detailed transformer magnetic models

- Harmonics analysis capabilities are part of NERC and EPRI’s GMD research work plan, which is a multi-year effort that is getting underway this year. One aspect of the research is to develop guidance and tools to aid in system-wide assessment of GMD-related harmonics.

- EPRI has started work on a harmonic analysis tool this year. This work will be concluded under the GMD research work plan with a beta delivery at the end of 2018.

Meeting TPL-007-1 Requirements

TPL-007-1 Requirements		How to meet?
R1	Identify individual or entity	Policy document
R2	Maintain System models and GIC System (DC) models	**Power flow Case (PSS®E, PLSF …) and GIC data files (Text, excel)**
R3	Have acceptable voltage criteria	Policy document
R4	GMD Vulnerability Assessment studies	**GIC Module (PSS®E, Powerworld, PSLF…) and other Power flow activities**
R5	1) Provide GIC flow information for worst case Geoelectric field orientation 2) Effective GIC time series, GIC(t)	**GIC Module output (PSS®E …)**
R6	Conduct a thermal impact assessment with I_{eff}/phase > 75 Amps	Using GIC(t) and transformer thermal response capability data
R7	Develop corrective action plan	a) Company policy: based on grid knowledge develop this **b) implement in Power flow Case and GIC data files**

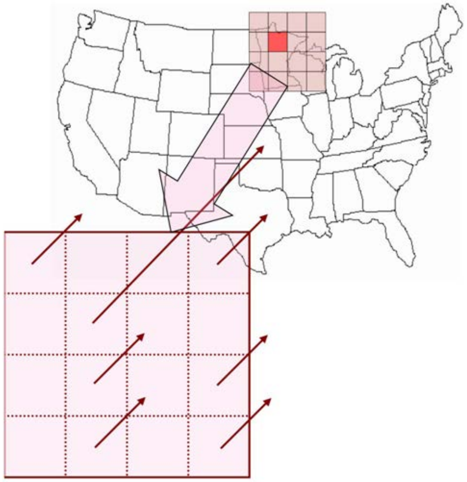
TPL-007-2 – Draft - Additional Requirements

Per FERC 830 Directives – TPL-007-2 – Draft Version

- The revised standard will be submitted to the Board of Trustees for adoption and then filed with the FERC

- Supplemental GMD event added to address local enhancements

- Phenomenon
  - Electric field amplitudes are fairly well understood
  - Geographical extent is not well known



- Initial review of data from several significant events

- Observations
  - Waveform similarities - local intense peak (2-5 minutes in duration)
  - Longitudinal extent: ~300-500 km; Latitudinal extent; ~100 km
  - Amplitude increase: ~ factor of two

Additional Requirements R8-R12

R8 - R10 – Supplemental GMD Vulnerability Assessment

- Geoelectric field of **12 V/km** and updated Geoelectric field scaling factors
- GIC(t) waveform scaled up for 12 V/km
- Transformer thermal impact analysis criteria: 85 A

R11 – GIC Monitors

R11. Each responsible entity, as determined in Requirement R1, shall implement a process to obtain GIC monitor data from at least one GIC monitor located in the Planning Coordinator's planning area or other part of the system included in the Planning Coordinator's GIC System model.

R12 – Magnetometers

R12. Each responsible entity, as determined in Requirement R1, shall implement a process to obtain geomagnetic field data for its Planning Coordinator’s planning area.

Revisions To Requirements R1 - R7

- Requirements R1, R2, R3 revised to include reference to supplemental and to obtain GIC measurement data

- **Requirement R7 revised**
  - Develop CAP within one year from completion of GMD vulnerability assessment
  - CAP implementation deadlines
    - Two years – non-hardware mitigation
    - Four years – hardware mitigation

- Requirements R4, R5 and R6 related to Benchmark GMD Assessment – No changes

Resources

Resources

- NERC Standard TPL-007-1: Transmission System Planned Performance for Geomagnetic Disturbance Events
- NERC Geomagnetic Disturbance Planning Guide, Dec 2013
- NERC Application Guide for Computing GIC in the Bulk Power System, Dec 2013
- NERC 2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System, Feb 2012
- NERC Transformer Thermal Impact Assessment White Paper
- Project 2013-03 Geomagnetic Disturbance Mitigation
- IEEE Publications

Conclusion

Summary

- GMD and its impact on Power System

- NERC TPL-007-1 requirements and how to meet those requirements

- TPL-007-2 – Revised standard with additional requirements

- Get involved in the future NERC GMD efforts

Thank You!

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