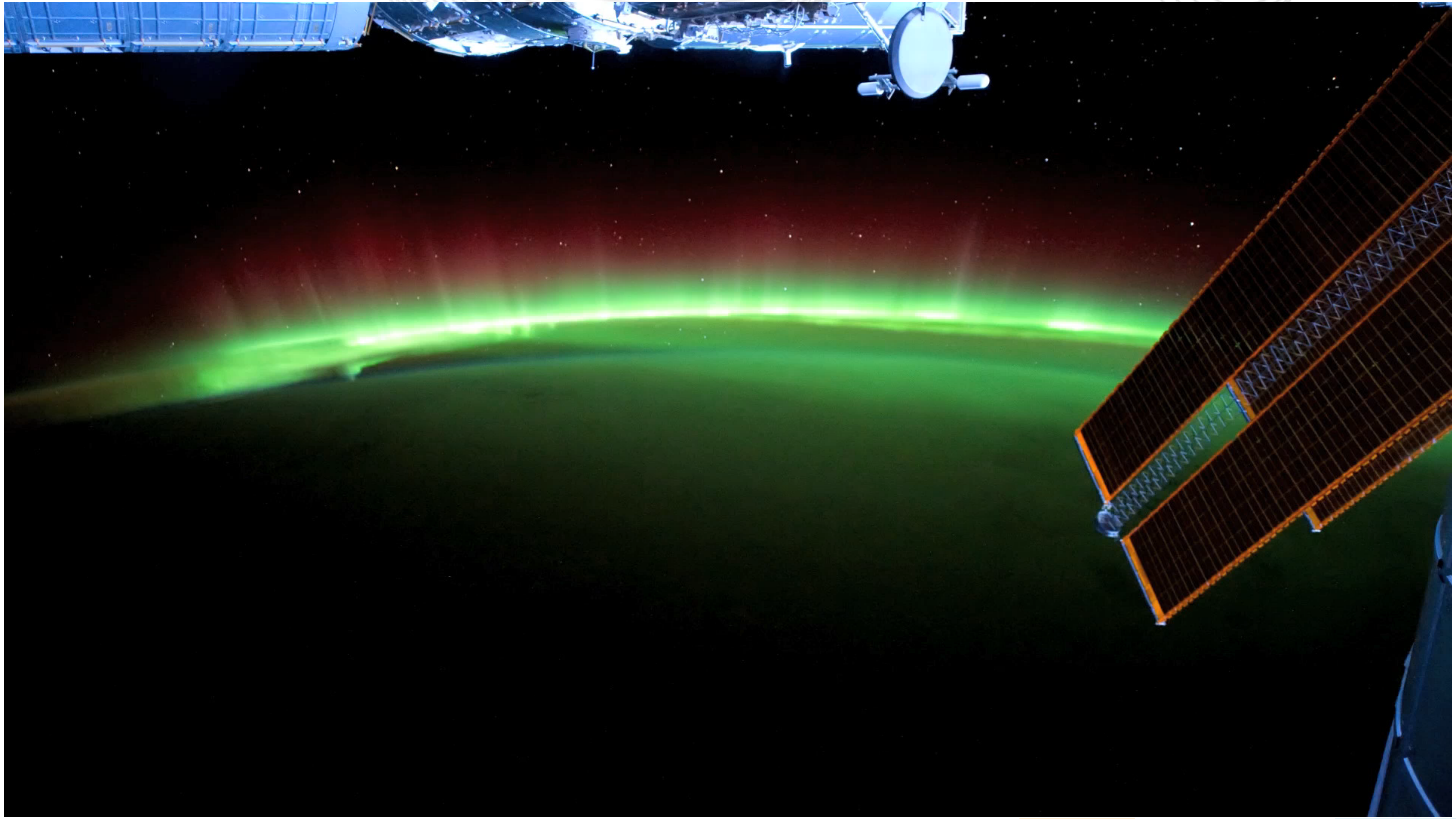
TPL-007-4
Transmission System Planned Performance for Geomagnetic Disturbance Events

Tarik Bensala
Sr. Engineer – PJM Transmission Planning

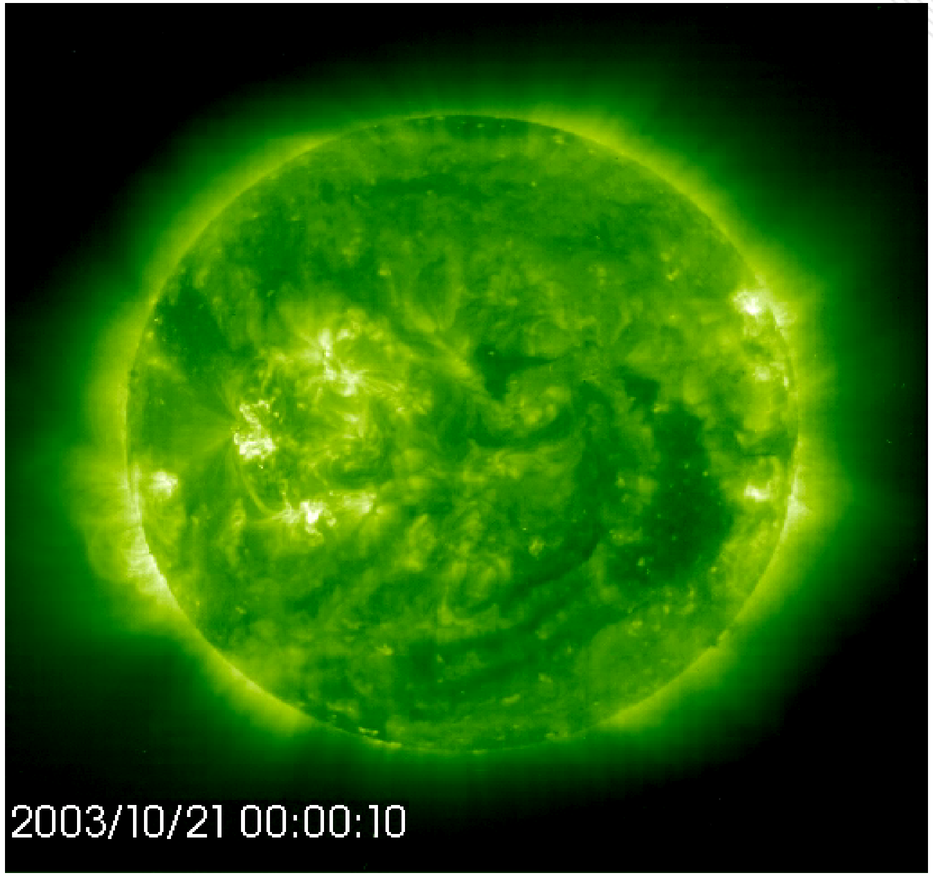
Justin Michlig
Sr. Manager – EPE Transmission Planning
(Consulting for PJM)

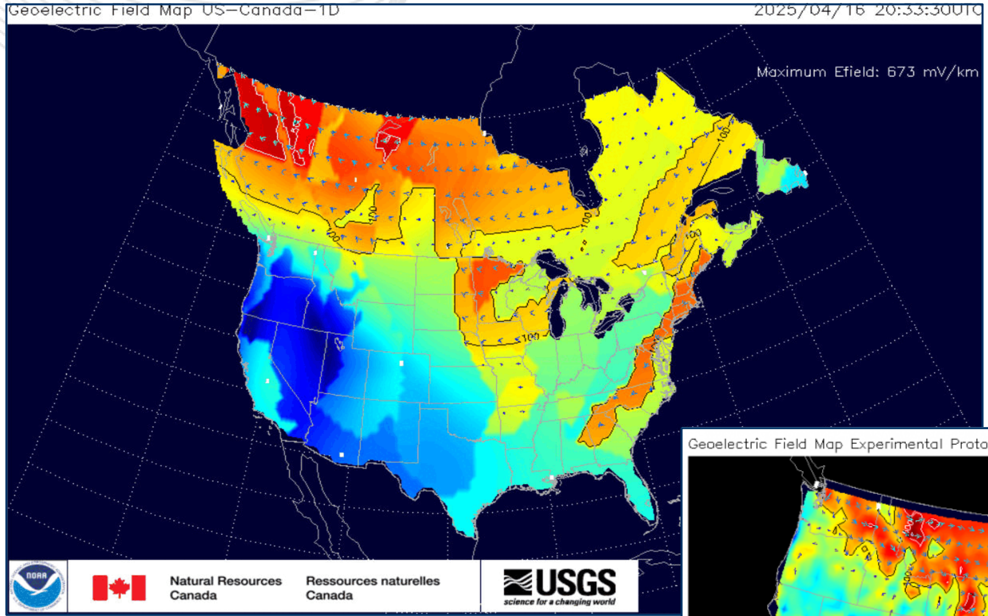
April 20, 2026

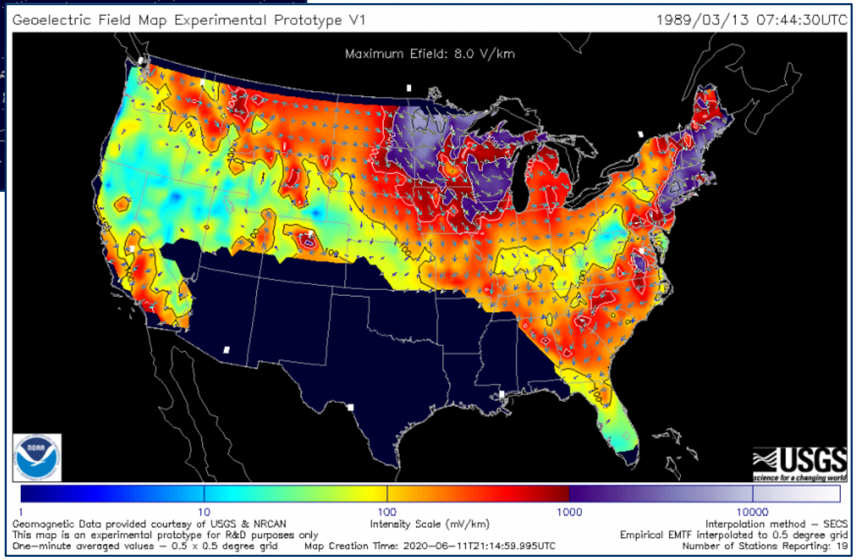
NASA footage of geomagnetic storm from International Space Station



CME from the sun to geophysical phenomenon







[Source: Geoelectric Field Map Upgrade to 3D Empirical Conductivity Model | NOAA / NWS Space Weather Prediction Center]

Project Contact Information

SMEs:
Stan Sliwa, Stanley.Sliwa@pjm.com
Tarik Bensala, tarik.bensala@pjm.com
Joshua Blume, Joshua.blume@pjm.com
Zachary Louis, Zachary.Louis@pjm.com

TPL-007-4: Transmission System Planned Performance for Geomagnetic Disturbance Events

Member Hotline
(610) 666 – 8980
(866) 400 – 8980
custsvc@pjm.com

Agenda

1 **Project Overview**

2 **NERC Compliance Requirements and GMD overview**

- TPL-007
- Agreements
- What do we need to do

3 **GMD impacts and analysis basics**

- What is GMD Analysis?
- What is Geomagnetic field, Geoelectric Field and GIC?
- Why GIC is impactful?
- Benchmark and Supplemental Events
- What is a Scaling factor and how we determine it?
- What is Benchmark and Supplemental Event?

4 **Data Collection and tutorial**

- Lines
- Substation
- Transformers
- Shunts
- Implicitly modeled devices

5 **Next steps and project timeline**

- Data collection
- Analytical process

Grouped Study Area	Requirement Pairing	Benchmark Requirement (R4)	Supplemental Requirement (R8)
System Modeling, Governance & Criteria Setup	R1 + R2 + R3	Define roles, maintain AC & GIC models, and set voltage performance criteria for GMD studies.	Same models and criteria used for supplemental studies.
GMD Vulnerability Assessment (System Performance Study)	Benchmark: R4 / Supplemental: R8	Perform 60-month benchmark study using benchmark GMD event, AC/DC models, on/off-peak cases, steady-state analysis, and required reporting.	Perform 60-month supplemental study using supplemental GMD event with same structure under more severe conditions.
CAP Trigger and Development	Benchmark CAP: R4 outcome/Supplemental CAP: R8 outcome	Develop CAP if benchmark study shows non-compliance; identify mitigation actions.	Develop supplemental CAP for non-compliance with expanded mitigation and stricter timelines.

Compliance Requirements

Grouped Study Area	Requirement Pairing	Benchmark Requirement (R4)	Supplemental Requirement (R8)
Thermal Impact Assessment (Transformer GIC Heating)	Benchmark: R6 (uses R5) / Supplemental: R10 (uses R9)	Perform thermal assessment when GIC ≥ 75 A/phase using R5 data; include assumptions and mitigation actions.	Perform thermal assessment when GIC ≥ 85 A/phase using R9 data under more severe conditions.
Data Provision & Monitoring Inputs	Benchmark inputs: R5, R12, R13 / Supplemental input: R9	Provide benchmark GIC flow information (R5) and implement processes for GIC monitoring (R12) and geomagnetic field data collection (R13) to support benchmark studies.	Same data framework extended using supplemental GIC flow information (R9) and enhanced data utilization for sensitivity and stress-case analysis.

Recommended Reading

- TPL-007 Standard: TPL-007-4
- TPL-007 technical rational: Project 2019-01 Draft 1 of Tech Rationale
- Benchmark Geomagnetic Disturbance Event Description: benchmark_gmd_event_aug27_clean.pdf
- Supplemental Geomagnetic Disturbance Event Description Report
- Application Guide – Computing Geomagnetically-Induced Current in the Bulk-Power System: NERC Report
- Geomagnetic Disturbance Planning Guide: Microsoft Word - GMD Planning Guide_approved
- Boteler, David & Pirjola, Risto. (2016). Modelling Geomagnetically Induced Currents: (PDF) Modelling Geomagnetically Induced Currents

PJM Current R1 Agreement Structure

Responsibility: PJM TO

Modeling & Data Collaboration

- PJM is responsible for System & GIC model maintenance
- It is done with PJM + members collaboration

- Transmission Owner data are submitted via a spreadsheet (PJM Excel template)
- Generator Owner data are submitted through Planning C[illegible]ter: Gen Model.

Steady-State Voltage Criteria

- Steady state voltage performance is assessed based on PJM Manuals (Ops, Planning, Nuclear)
- Voltage limits aligned with operations
- NPIR + TO-specific limits apply
- Cascading / collapse / islanding shall not occur.

GMD Event Stages

Voltage performance during GMD events are examined in three stages:

Stage 1: Initial Condition

- Pre-event adjustments
- Steady state voltage performance shall be consistent with Category P0 (No Contingency) per the TPL-001 standard.

Stage 2: GMD Event

- Reactive losses modeled
- Steady state voltage performance shall be consistent with Category P1 (Single Contingency) per the TPL-001 standard.)

Stage 3: GMD + Outages

- Facilities that are susceptible to harmonics are removed from service as a result of protection system operation/misoperation.
- Load Dump voltage limits used.

Assessments & Compliance

- Benchmark + supplemental assessments
- GIC flow info (as specified in R6 & R10 of TPL-007) will be provided to each TO and GO that owns BES Power Transformer.
- Assessment will be done at least once in every 60 months
- Based on models identified in requirement R2 of TPL-007
- Document assumptions & results
- Develop CAP if violations found

GIC Monitoring & Data

- PJM will obtain GIC monitor data from at least one GIC monitor located within the PJM footprint as per requirement R12 of TPL-007
- PJM uses ICCP (Inter-Control Center Communications Protocol) for data collection
- Trigger: Kp ≥ 7 events
- USGS (United States Geological Survey) magnetometer data is used.
- Future monitors based on studies

Geomagnetic impacts to the earth and power system

What is GMD Analysis?

What is Geomagnetic field, Geoelectric Field and GIC?

Why GIC is impactful?

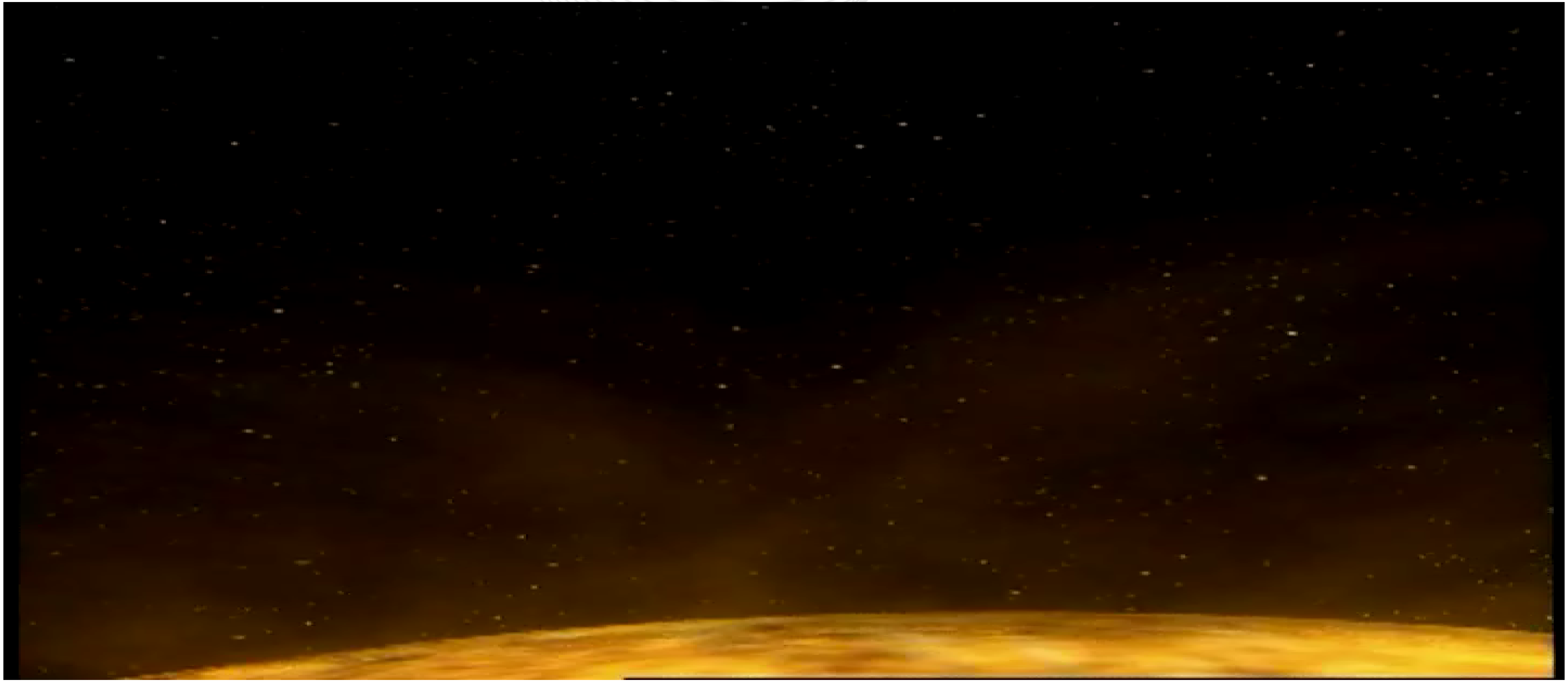
What is a Scaling factor and how we determine it?

What is Benchmark and Supplemental Event?

A geomagnetic disturbance **(GMD)** is a temporary disruption of Earth's magnetic field, usually caused by activity from the Sun.

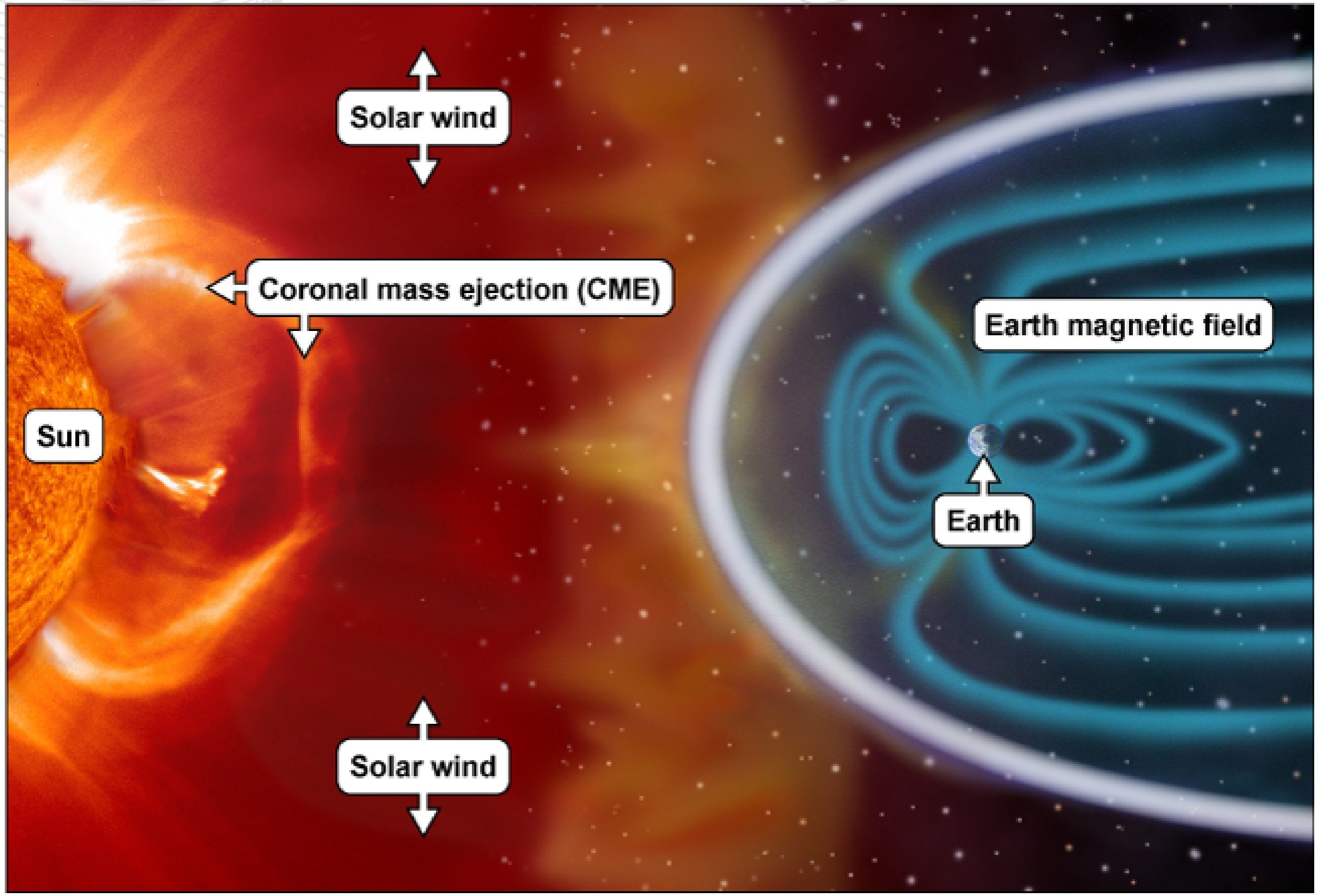
What causes it?	The main driver is space weather from the Sun, especially: • **Solar flares** – sudden bursts of energy • **Coronal Mass Ejections (CMEs)** – huge clouds of charged particles sent into space When these charged particles reach Earth, they interact with our planet's magnetic field (the magnetosphere), disturbing its normal structure.

How does it look like?



What happens during a geomagnetic disturbance?

- The magnetic field fluctuates and becomes unstable
- Electric currents form in the upper atmosphere
- Energy gets transferred into Earth's space environment



Source: National Aeronautics and Space Administration (illustration). | GAO-19-98

Effects on Earth

Bright auroras (Northern/Southern Lights), sometimes visible much farther south than usual

Disruptions to GPS and radio signals

Power grid failures in extreme cases (like during major solar storms)

How do we measure it?

Geomagnetic field "B" and its variation "dB/dt" describe the static and changing Earth's magnetic field at a specific location.

- B= magnetic field (measured in nanotesla, nT)
- dB/dt= how fast that field is changing (nT/s or nT/min)

What does this mean to me?

During a Geomagnetic Disturbance, solar activity disturbs the Magnetosphere, causing the magnetic field at Earth's surface to fluctuate, sometimes very rapidly.

It tells us:

- How rapid the magnetic field is changing
- Not just the strength, but the speed of variation

For example:

- Small dB/dt: gradual change → low impact
- Large dB/dt: sudden spike → high impact

Through Faraday's Law of Electromagnetic Induction, a changing magnetic field induces electric fields in the ground.

So:	• **High dB/dt** → strong induced electric field • **Strong electric field** → larger Geomagnetically Induced Currents
These currents:	• Create a voltage gradient across the crust of the earth • flow through transmission lines • stress transformers • May cause voltage instability or even blackout

More about GIC (Geomagnetically Induced Current)?

A Geomagnetically Induced Currents is an electric current that flows through long conductors on the Earth's surface, such as power lines, caused by changes in the Earth's magnetic field.

Key characteristics:

- **Low frequency / quasi-DC:** Usually very slow-changing compared to normal AC power.
- **Magnitude:** Can range from a few amperes to thousands of amperes during severe storms.
- **Path:** Follows the path of least resistance — along power grids.

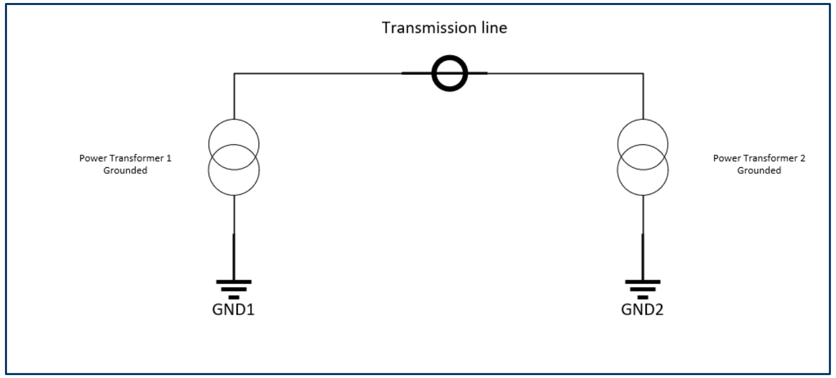
Transmission lines act like short-circuits across the earth

Transmission lines are:

- Long (100–1000 km)
- Grounded at substation transformers
- Made of conductive metal

When an electric field exists along the ground:

- It pushes voltage along the length of the line.
- Voltage = Electric field × distance



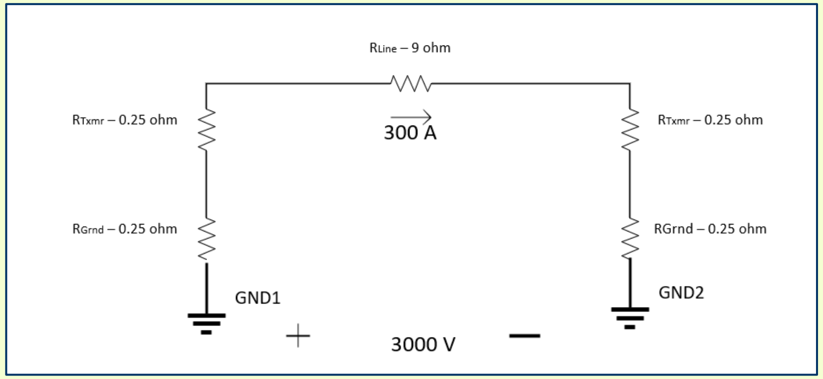
Example:

If: **Electric field = 10 V/km**
Line length = 300 km
Induced voltage = 3000 volts

That voltage drives current through:

- Transmission lines (assumed 9 ohm)
- Transformers (assumed .25 ohms)
- Grounding systems (assumed .5 ohm)

The induced quasi-DC current is called GIC (Geomagnetically Induced Current) and 300 A in this example



It's all about the transformers

Why GIC Is impactful?

GIC with transformers can:

- Push transformers into half-cycle saturation
- Drive Harmonics
- Audible noise
- Cause overheating
- Increase reactive power demand
- Trigger voltage instability

Let's consider the following scenario:	• **Transformer:** 500 MVA, 400 kV, Y-connected • **AC grid:** 60 Hz (one cycle = 16.67 ms) • **GIC:** 100 A (assumed) quasi-DC enters through the neutral • **Normal AC magnetizing current:** ~10 A RMS (for illustration)

Step 1: Entry of GIC

a. Quasi-DC GIC enters the transformer through the neutral and flows in the windings alongside the normal AC current.

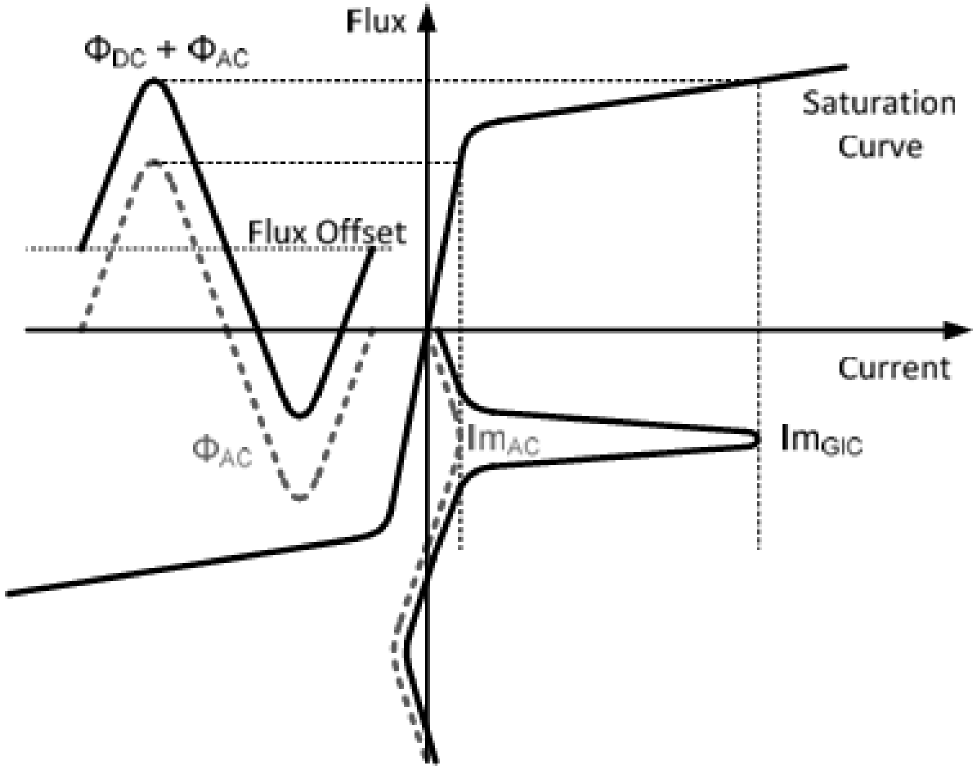
b. This DC current produces a steady magnetomotive force (MMF), creating a DC bias in the core flux.

c. This DC-biased flux shifts the AC flux waveform, driving the core into saturation during one half-cycle.

Step 2: Half-Cycle Saturation

- AC cycle: 0 → +V Peak → 0 → −V Peak → 0
- Positive half-cycle + DC flux → core hits saturation threshold.
- Negative half-cycle → core operates closer to the linear region
- This results in asymmetric magnetization (half-cycle saturation)

AC Phases	Core Status	Current Response
0 → +V Peak	Approaching saturation	Magnetizing current rises slightly
Near +V Peak	Saturation	Current **spikes rapidly** (50–200 A peak)
Falling back to 0	Leaving saturation	Current drops back
Negative half-cycle	Core in linear region	Current ~ normal AC (~10 A)



Step 3: Heating (Thermal Accumulation)

- **Saturated core** → increased eddy currents and hysteresis losses
- **Copper windings** → higher I^2R losses during magnetizing current spikes

Example Calculations	• Normal AC magnetizing loss: 1 MW • With GIC: half-cycle saturation adds 5–10 MW additional heating in short bursts • Over 1 hour: significant temperature rise in core and windings, stressing insulation

Step 4: Reactive Power Demand

AC system supplies magnetizing current, which is mostly reactive power.

Numbers Example:	• **Normal: 10 A RMS** → 2 MVAr reactive • **With 100 A GIC spikes**: effective current ~100–200 A for fractions of a second → reactive power rises to 20–30 MVAr • **This is extra load on generators trying to maintain 400 kV (assumed for example) line voltage**

Step 5: Voltage Instability

- **Grid sees higher reactive power demand + harmonics** → voltage starts to drop
- **Protective relays may detect abnormal conditions** → trip transformers or lines
- If multiple transformers are affected simultaneously (typical in wide-area GIC events), cascading effects can occur

Cascade Example:

- **Transformer A heating** → voltage drops
- Line connecting Transformer A to Grid trips
- **Transformer B now sees higher reactive demand** → more heating
- **Generators approach reactive power limits** → voltage collapse

Result: *blackout risk, even though the initial GIC was "only" 100 A.*

Effective GIC: net impact of GIC to the core of a transformer

a. 2 winding transformer

$$I_{eff} = \left|\frac{NI_1 + I_2}{N}\right|$$

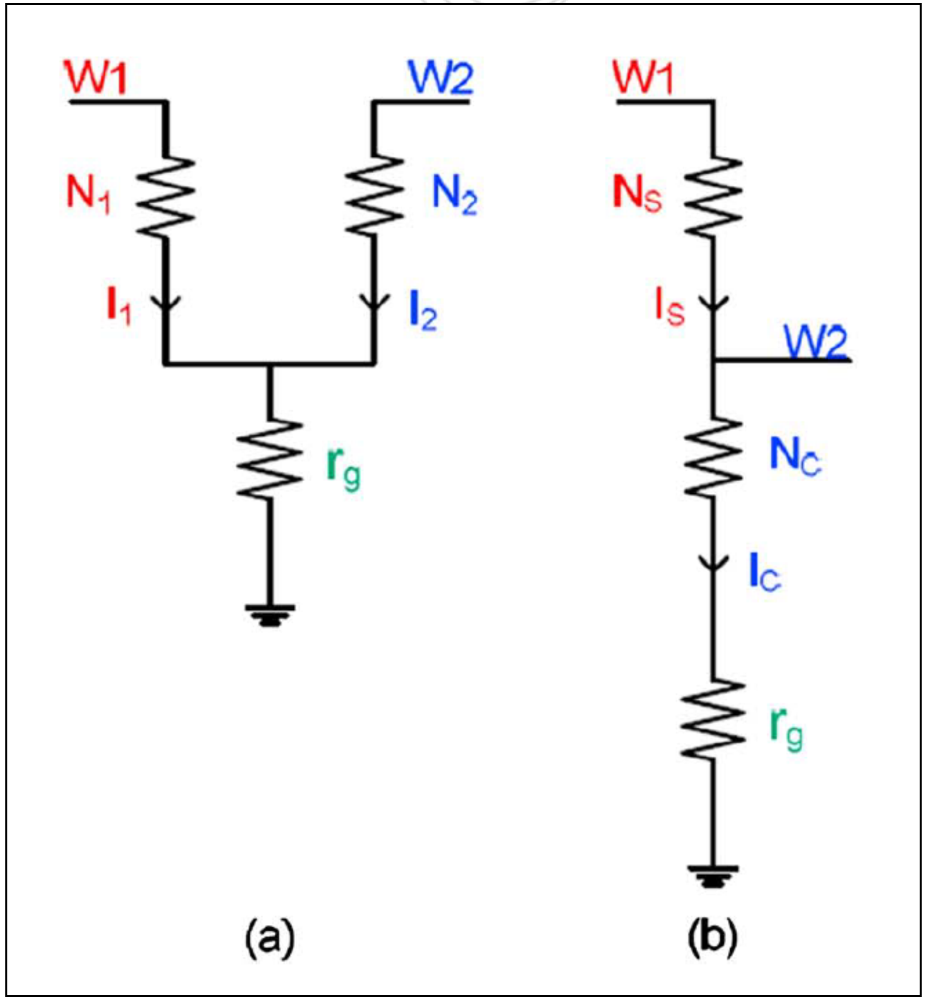
b. Auto Transformer

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

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

Auto transformer Example
Is = 50A V1 = 500
Ic = -50A V2 = 230

Answer
GIC effective = 0



Boteler, David & Pirjola, Risto. (2016). Modelling Geomagnetically Induced Currents. Space Weather. 15. 10.1002/2016SW001499.

What is K Factor and its Importance?

In GMD analysis, the **K-factor** is used as a linear sensitivity constant that relates *DC geomagnetically induced current* (GIC in amperes per phase) to *reactive power consumption increase* (MVAR) in a transformer.

K factor Represents:

$$K = \frac{\Delta Q}{I_{GIC}}$$

Where:

- ΔQ= increase in transformer reactive power consumption (MVAR)
- I_GIC= DC current flowing through transformer winding (A per phase)

Transformer Types vs K-factor

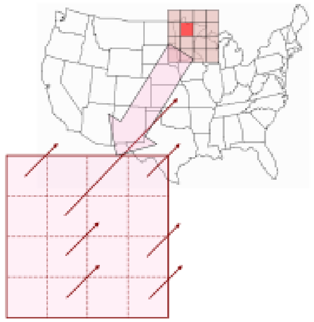
Transformer Type	Core / Electrical Characteristics	Relative K-factor Level	Engineering Interpretation in GMD Studies
3-leg core transformer (two-winding)	Single magnetic return path; common transmission design	High sensitivity	Strong tendency to saturate under GIC; produces relatively large increase in reactive power demand per unit of GIC
5-leg core transformer (two-winding)	Improved flux return path and magnetic balancing	Moderate sensitivity	Partial reduction in DC bias effects; lower reactive power increase compared to 3-leg designs
Shell-type transformer	Enclosed magnetic flux path with strong core containment	Low sensitivity	Best resistance to GIC-induced saturation; smallest reactive power increase per unit GIC
Autotransformer	Shared HV–LV winding with strong electrical coupling	High to very high sensitivity	Most sensitive class in many systems due to direct electrical coupling and voltage ratio effects; can amplify reactive power demand significantly
Generator step-up transformer (GSU)	Generator interface transformer, often grounded wye–delta	Moderate to high sensitivity	Behavior depends strongly on grounding and core design; can become significant reactive power source under high GIC conditions

Summary table of the Example

Effect	Mechanism	Example Numbers
Half-cycle saturation	DC bias + AC flux	Severe asymmetry in magnetization
Harmonics	Nonlinear + asymmetric waveform	Both even and odd harmonics
Heating	Eddy & hysteresis losses	+5–10 MW transient, core temp rises
Reactive power	Extra magnetizing current	+20–30 MVAr load on grid
Voltage instability	Reactive power shortage + harmonics	Voltage dips ⟶ relays trip ⟶ blackout risk

How do we calculate the impacts?

NERC uses a formal method in standards like TPL-007. Instead of calculating the storm itself, NERC:



Defines a worst-case reference event	**Converts** it into a geoelectric field	**Uses** that to calculate grid impact (GICs)

NERC defines 2 standard events: Benchmark and Supplemental GMD Events

Benchmark GMD event

- Base geoelectric field: 8 V/km
- Represents a wide-area severe storm
- Derived from historical data

Supplemental GMD event

- Base geoelectric field: 12 V/km
- Represents a more intense, localized effect
- Includes waveform enhancement (sharper spikes)

Scientific Approach vs NERC Approach

Scientific Approach	NERC Approach
Uses KP index (how disturbed Earth's magnetic field is globally), DST index (strength of the ring current around Earth) , real-time data	Uses **Benchmark event**
Describes what is happening	Designs for worst-case
Physics-focused	Grid reliability-focused

Scaling the storm impact for your location

8 V/KM or 12 V/km are generally stated to be used in GMD calculations, but cannot be applied directly.

Benchmark event formula: $E_{peak} = 8 \times \alpha \times \beta_b$

Supplemental event formula: $E_{peak} = 12 \times \alpha \times \beta_s$

It is scaled using α (alpha) → geomagnetic latitude
β (beta) → ground conductivity

Where:

- $\mathbf{E_{peak}}$ = peak geoelectric field (V/km)
- **α** = Latitude factor
- **β** = Conductivity factor
- **b / s** = benchmark or supplemental case

Benchmark Example:

$$\boldsymbol{E_{peak} = 8 \times \alpha \times \beta_b}$$

α = .9 (higher latitude like Ontario),
β = 1.2 (resistive ground)

Scaling the Benchmark event yields:
E_peak = 8×.9×1.2 = 8.64 V/km

Geoelectric Field latitude scaling

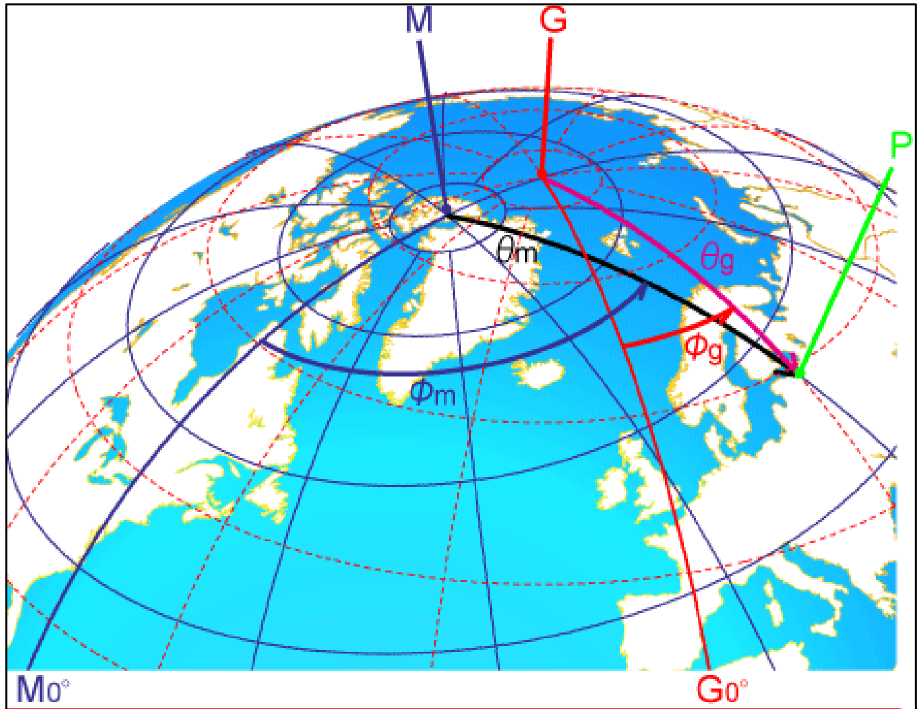
"α" is the geomagnetic latitude scaling factor used to adjust the GMD event from a reference location (60° latitude) to your actual location.

Since the benchmark event is defined at 60° geomagnetic latitude, α tells us: *"How strong is the disturbance at my latitude compared to 60°?"*

PJM Geophysical: 40.121, -75.418
PJM Geomagnetic: 49.13, -3.11

Redwood State Park physical: 40.290, -124.051
Redwood State Park mag: 45.43, -58.27

Reference: Transformation of Coordinate



G : Geographic pole M: Geomagnetic pole P: A point
θg: Geocentric colatitude (=90−Geocentric latitude)
Φg: Geographic longitude
θm: Geomagnetic colatitude (=90−Geomagnetic latitude)
Φm: Geomagnetic longitude

Two ways to get Latitude factor "α"

Method 1: Use the formula

$$\alpha = 0.001 \times e\hat{}((0.115 \times L)\ )$$

L = geomagnetic latitude (degrees)

α is limited to $0.1 \le \alpha \le 1.0$

Example: (Ontario-like latitude ~55°)

$$\alpha = 0.001 \times e^{(0.115 \times 55)}$$

$$\alpha \approx 0.001 \times e^{6.325} \approx 0.001 \times 556 \approx 0.56$$

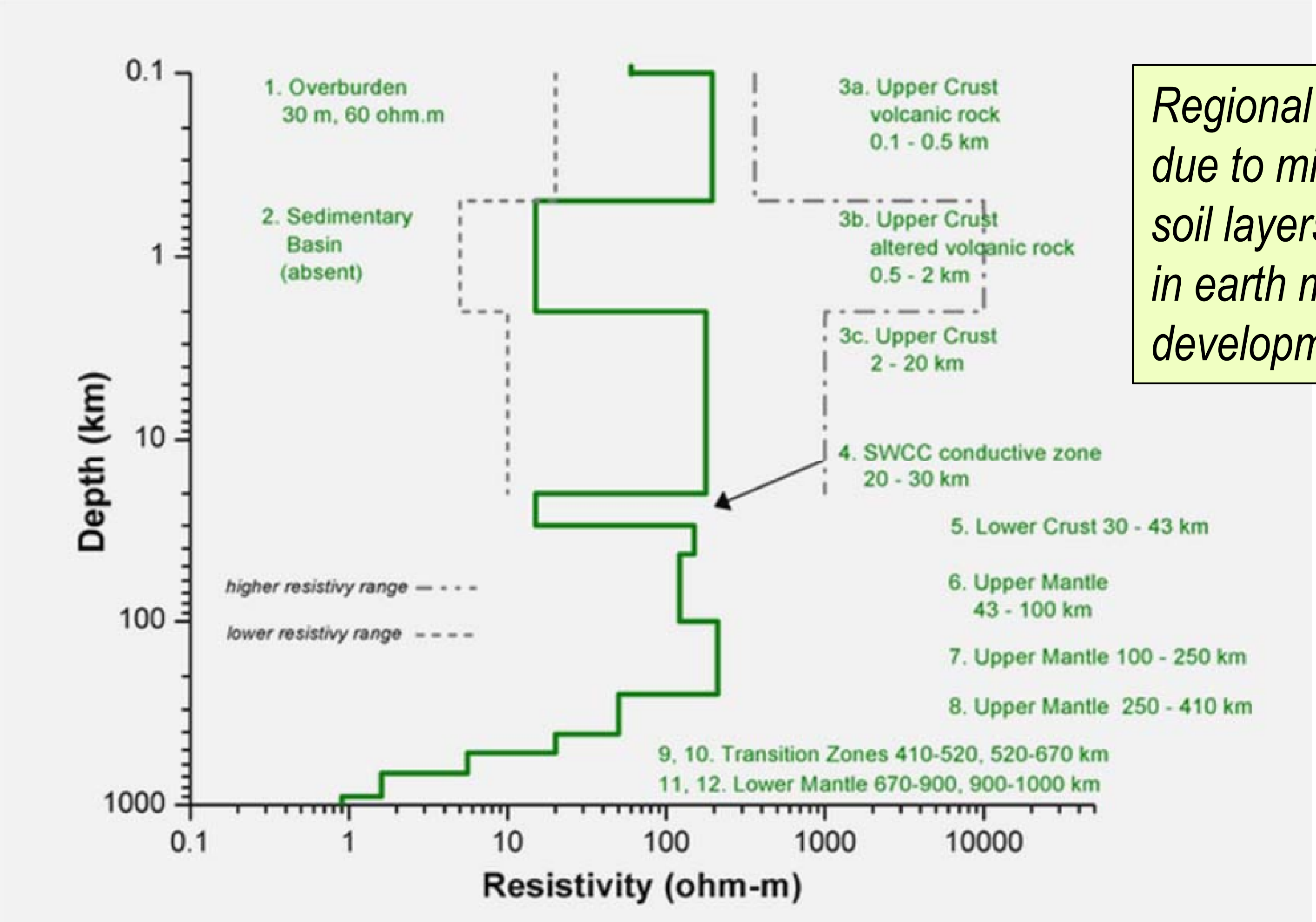
Method 2: Table lookup

Table 2: Geomagnetic Field Scaling Factors for the Benchmark and Supplemental GMD Events

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

Under NERC, we have two valid approaches to determine the peak geoelectric field:

Method 1: Physics-based calculation (more accurate)	**Method 2: Use predefined β (most common in practice)**
You directly compute the geoelectric field using: • Ground conductivity model (your region) • Reference geomagnetic field time series • A method like the "plane wave method" ***DO NOT USE BEFORE CONTACTING GMD TEAM***	Instead of physically modeling the ground, **Use β values from Table 3** (see next page from NERC TPL-007-4) Based on: • Regional geology • Conductivity maps (USGS / NRCan) Then combine with α (latitude scaling factor): ***Final formulas:*** Benchmark GMD event: $\mathbf{Epeak} = 8 \times \boldsymbol{\alpha} \times \boldsymbol{\beta}_{\boldsymbol{b}}$ Supplemental GMD event: $\mathbf{Epeak} = 12 \times \boldsymbol{\alpha} \times \boldsymbol{\beta}_{\boldsymbol{s}}$



Regional earth conductivity due to miles of rock and soil layers are considered in earth model development

Table 3: Geoelectric Field Scaling Factors

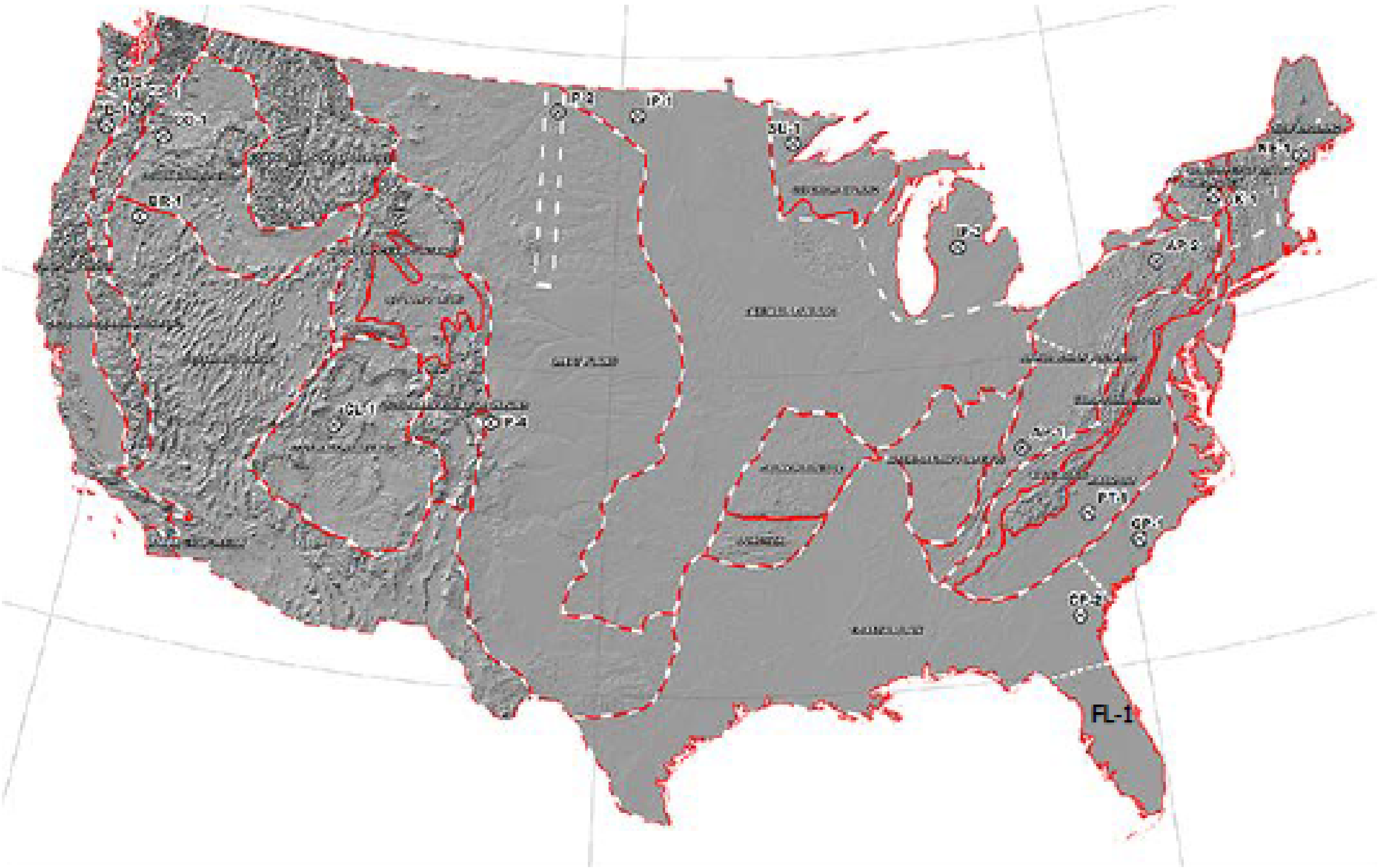
Earth model	Scaling Factor Benchmark Event (β_b)	Scaling Factor Supplemental Event (β_s)
AK1A	0.56	0.51
AK1B	0.56	0.51
AP1	0.33	0.30
AP2	0.82	0.78
BR1	0.22	0.22
CL1	0.76	0.73
CO1	0.27	0.25
CP1	0.81	0.77
CP2	0.95	0.86
FL1	0.76	0.73
CS1	0.41	0.37
IP1	0.94	0.90
IP2	0.28	0.25
IP3	0.93	0.90
IP4	0.41	0.35
NE1	0.81	0.77
PB1	0.62	0.55
PB2	0.46	0.39
PT1	1.17	1.19
SL1	0.53	0.49
SU1	0.93	0.90
BOU	0.28	0.24
FBK	0.56	0.56
PRU	0.21	0.22
BC	0.67	0.62
PRAIRIES	0.96	0.88
SHIELD	1.0	1.0
ATLANTIC	0.79	0.76

Supplemental GMD event (key difference)

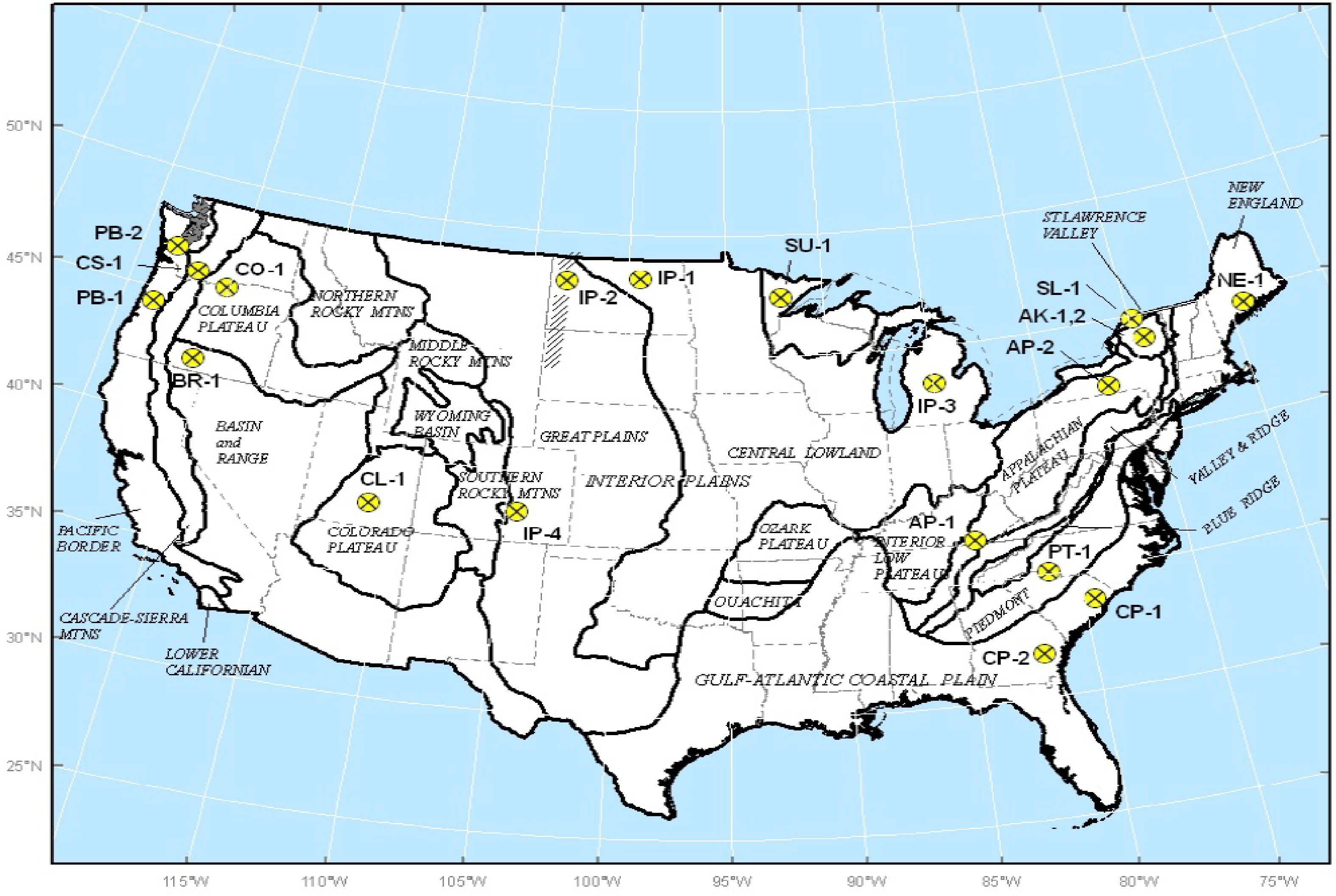
The supplemental event (12 V/km) is localized, not uniform. Planners have flexibility to apply it:

Simple, conservative:	• Apply 12 × α × β across the entire planning area
More realistic:	• Apply the high field only in a specific region, e.g.: • 100 km North-South • 500 km East-West • Use benchmark field (8 V/km) elsewhere
Hybrid/Custom modeling:	• Combine localized enhancements with benchmark elsewhere

Physiographic Regions of the Continental United States



Location of 1-D earth resistivity models with respect to physiographic regions of the contiguous United States



Benchmark Geomagnetic Field Waveform (GMD Event)

- Based on the March 13-14, 1989 geomagnetic storm measured at Ottawa by Natural Resources Canada
- Uses geomagnetic field components: Bn (Northward) and Be (Eastward)
- Sampled every 10 seconds
- Data scaled from 55° → 60° geomagnetic latitude

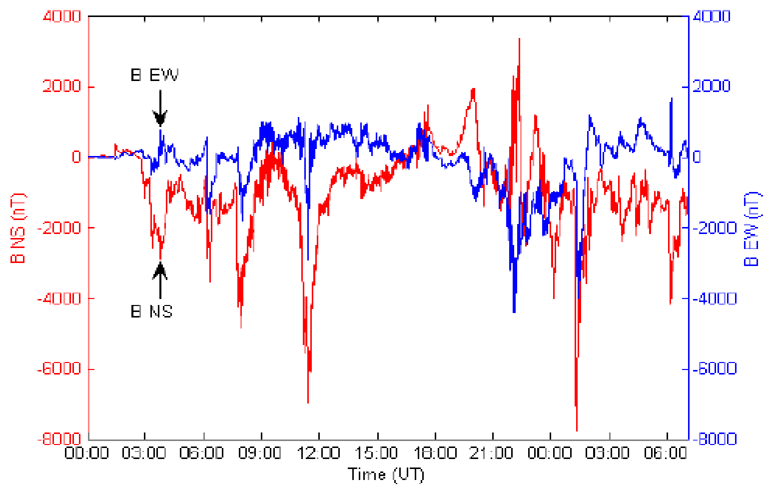


Figure 3: Benchmark Geomagnetic Field Waveform Red B_n (Northward), Blue B_e (Eastward)

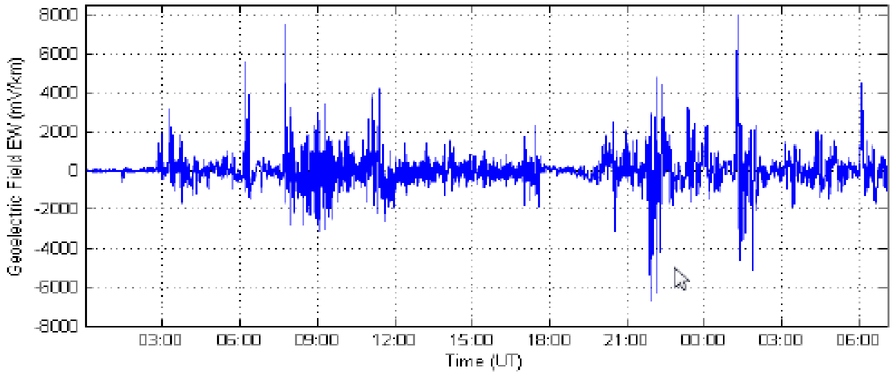
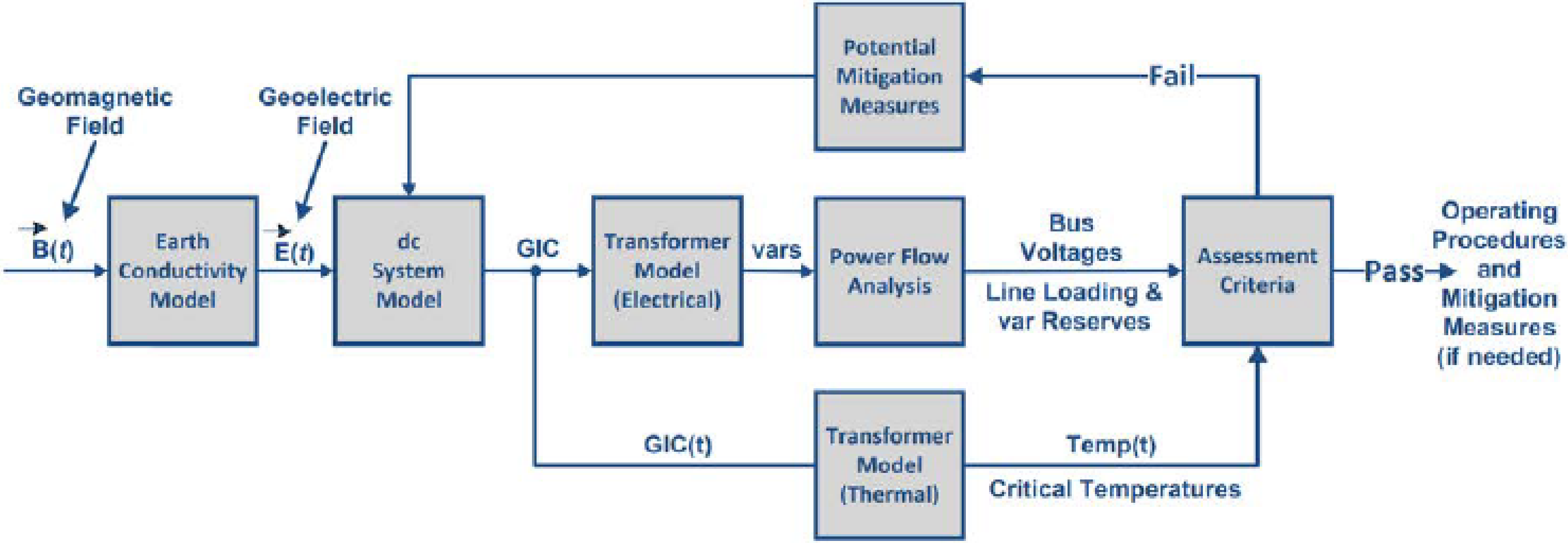


Figure 4: Benchmark Geoelectric Field Waveform E_E (Eastward)

GMD Vulnerability Assessment Process

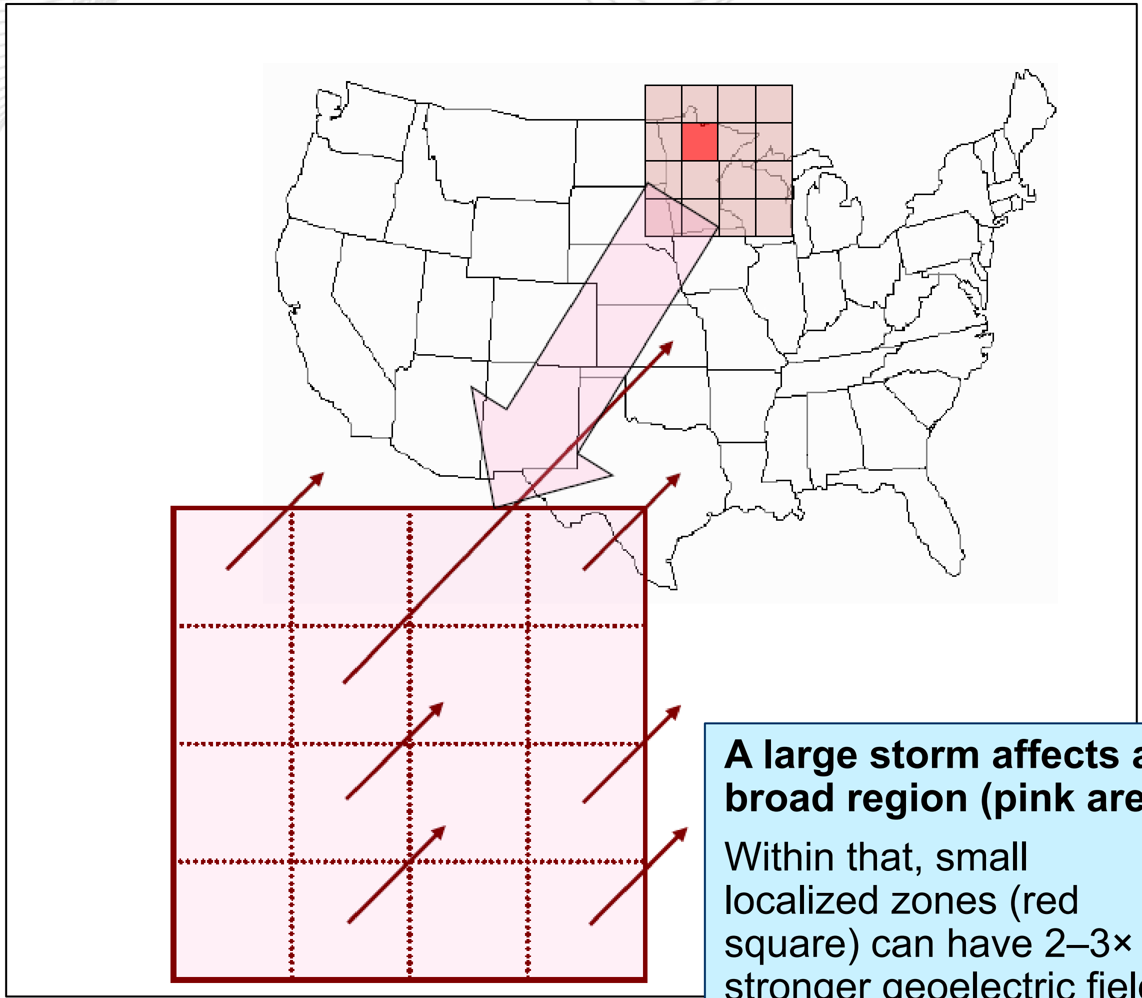


Spatial Complexity

Spatial complexity means that during a geomagnetic storm, the geoelectric field is not uniform across space—it varies in strength and direction from one location to another, sometimes very sharply over short distances.

Key distinction:

- These are externally driven localized enhancements (from space weather).
- NOT due to Ground conductivity variations (e.g., coastal effects)



A large storm affects a broad region (pink area).

Within that, small localized zones (red square) can have 2–3× stronger geoelectric fields than nearby areas.

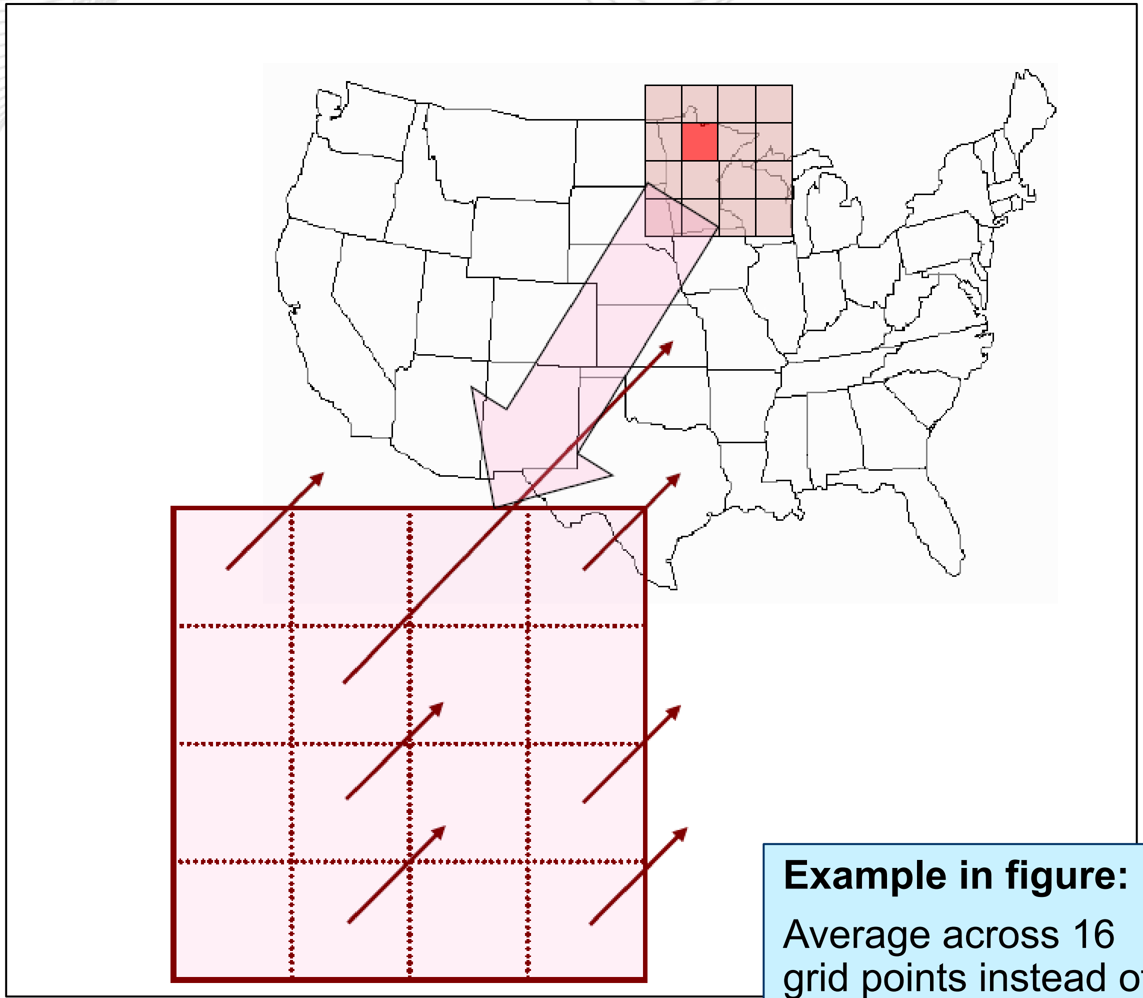
Why Spatial Averaging Matters?

Earlier studies focused on single measurement stations and captured localized extremes, **not** system-wide behavior.

This can overestimate risk when applied to large power grids.

Solution: Use spatial averaging over regions (~500 km scale)

This produces a more realistic regional field strength and avoids overly pessimistic assumptions about cascading failures



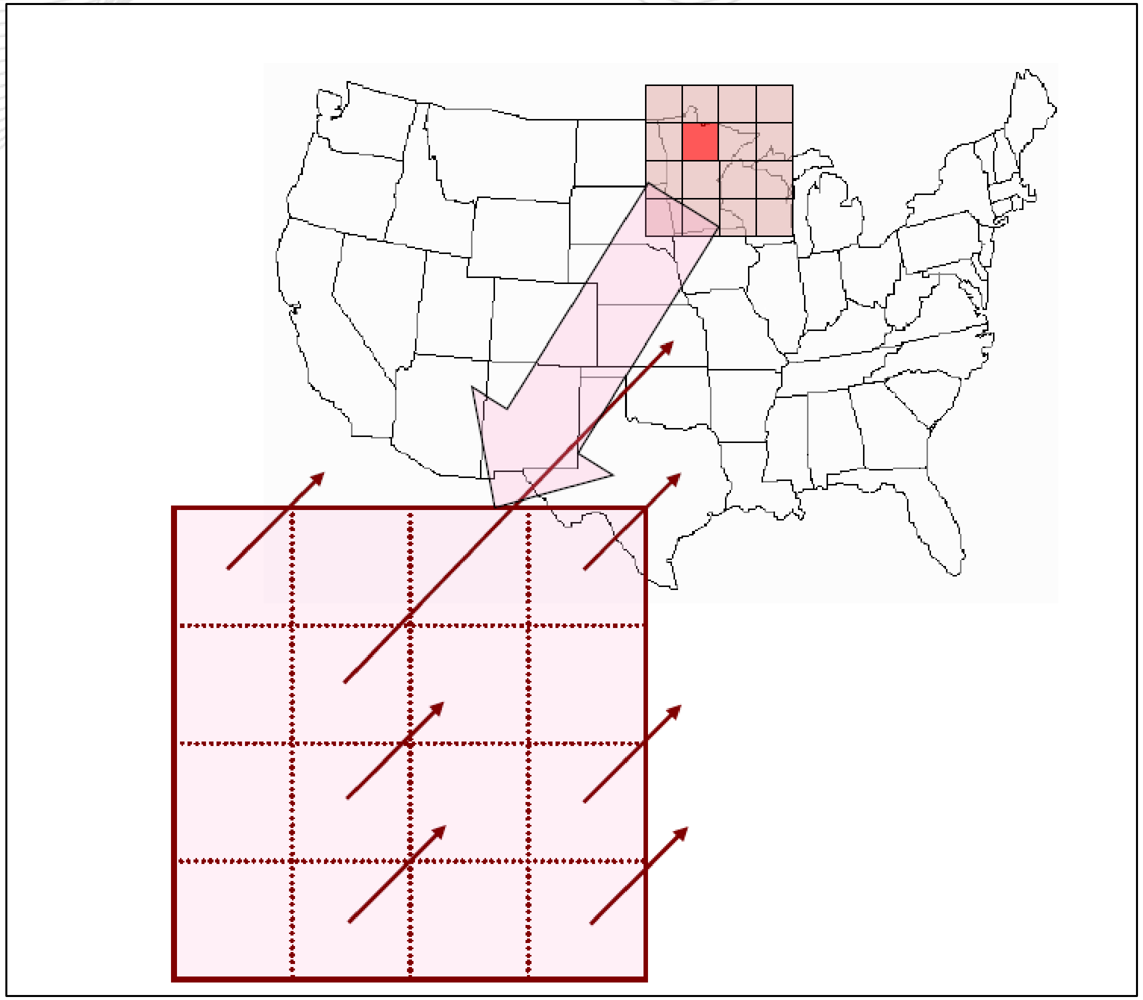
Example in figure:

Average across 16 grid points instead of one hotspot

The benchmark GMD event is designed to evaluate wide-area grid impacts, such as

- Increased reactive power (VAR) demand
- Voltage depressions
- Risk of voltage collapse

Without spatial averaging, models could be skewed by small extreme hotspots, leading to overdesign or incorrect risk assessment




STOP

Modeling GIC

To calculate GIC, we need a DC network model of the power system.

However, Real Systems are:

- 3-phase AC
- Full of Complex Equipment

So, we simplify everything into: Resistances + current sources + grounding paths

Category	Source	Details / What It Provides
Existing AC Models	Power flow / short circuit models	Network topology, transmission lines, transformers
Equipment Data	Test reports & specifications	Transformer test reports, conductor specs, grounding measurements
Geographic Data	Substation coordinates	Latitude/longitude needed for geoelectric field calculations (GIC dependence on Earth field)

What gets modeled (and How)

Component	Model Representation	Key Details / Rules	Notes
Transmission Lines	Resistance	$R = \frac{1}{3} \times$ phase resistance	Divide by 3 because GIC uses single-phase equivalent
Transformers	Resistance (critical component)	Only grounded windings are modeled	Main path for GIC into the grid
Grounded Wye Transformer	Resistance	Use measured DC winding resistance, **adjust to 75°C**, divide by 3	Most important transformer type for GIC
Autotransformer	Separate resistances	Model **series winding** and **common winding** separately	Requires careful handling
Transmission Lines	Resistance	$R = \frac{1}{3} \times$ phase resistance	Divide by 3 because GIC uses single-phase equivalent

What gets modeled (and How)

Component	Model Representation	Key Details / Rules	Notes
Shunt Reactors	Resistance to ground	Similar to transformer winding modeling	Provides ground path
Substation Ground Grid	Ground resistance	Use measured (preferred) or calculated values	Includes soil, rods, shield wires
Generators	Not modeled	Ignored in DC model	DC-isolated → no GIC flow
Blocking Devices	Variable resistance	Resistor = actual value; Capacitor ≈ very high resistance (~1 MGenerators Ω); Solid ground ≈ very low resistance (~100 μΩ)	Used to control GIC
Series Capacitors	State-dependent resistance	Bypassed = very low resistance; Inserted = very high resistance	DC cannot pass through capacitors

GIC Data in PSSE V34 vs V35

When reading Version 4 in PSSE V35:

System will:

- Add “single bus” substation configuration
- Convert non-node-breaker → node-breaker model

Constraint:

Version 4 can only be loaded if:

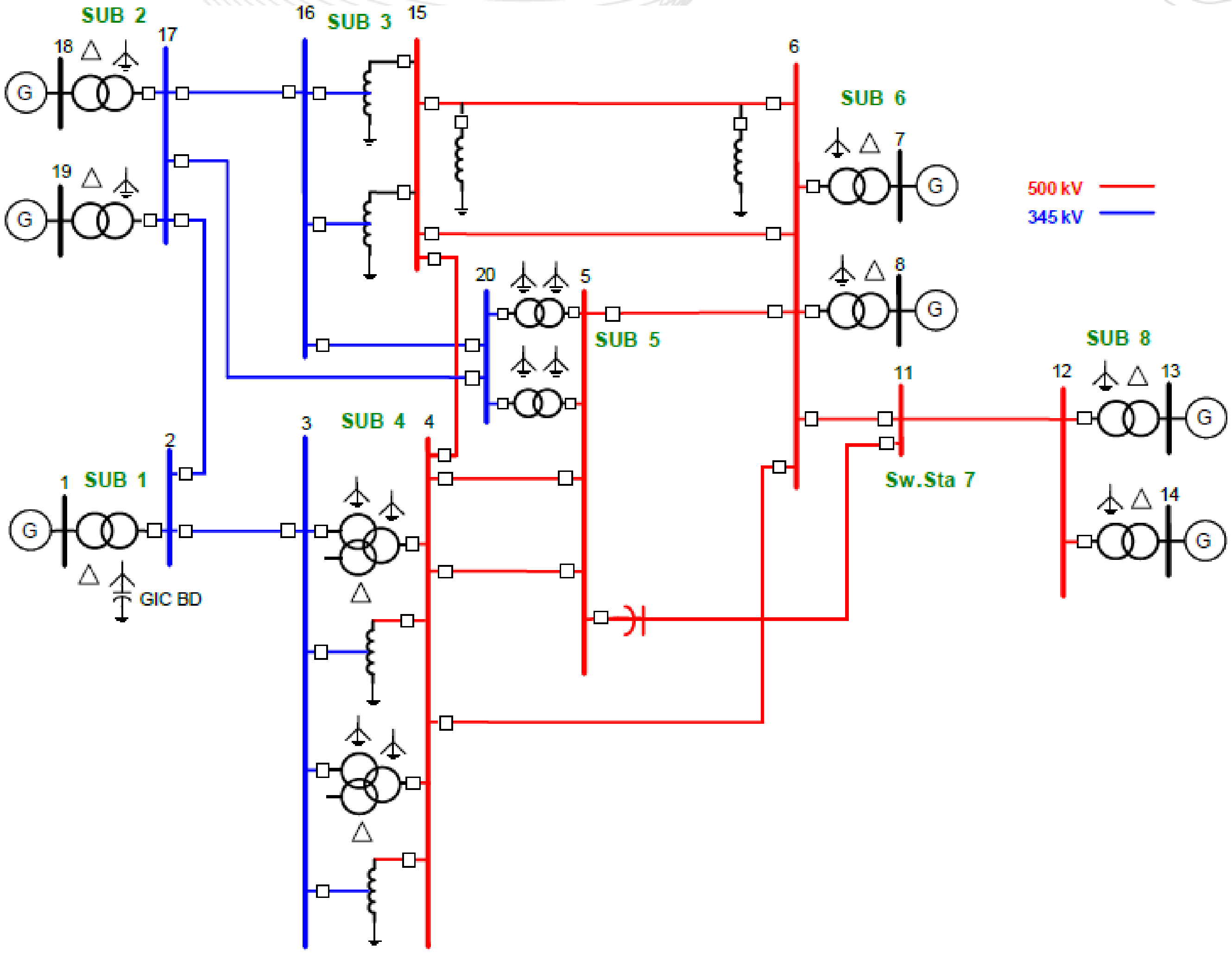
- Base case has NO node-breaker model

The idea is to avoid duplicate/conflicting data.

- Key Differences in BUS Substation Data

GIC File Version 4	GIC File Version 5
You must explicitly define which bus belongs to which substation. • BUSNUM, SUBNUM This is a separate “Bus Substation Data” group	• This mapping is completely removed from the GIC file. • Bus–substation relationships are now defined in the base case (power flow data) • GIC file no longer controls topology relationships.

Single-line diagram of example power system used to demonstrate the various components that require dc models



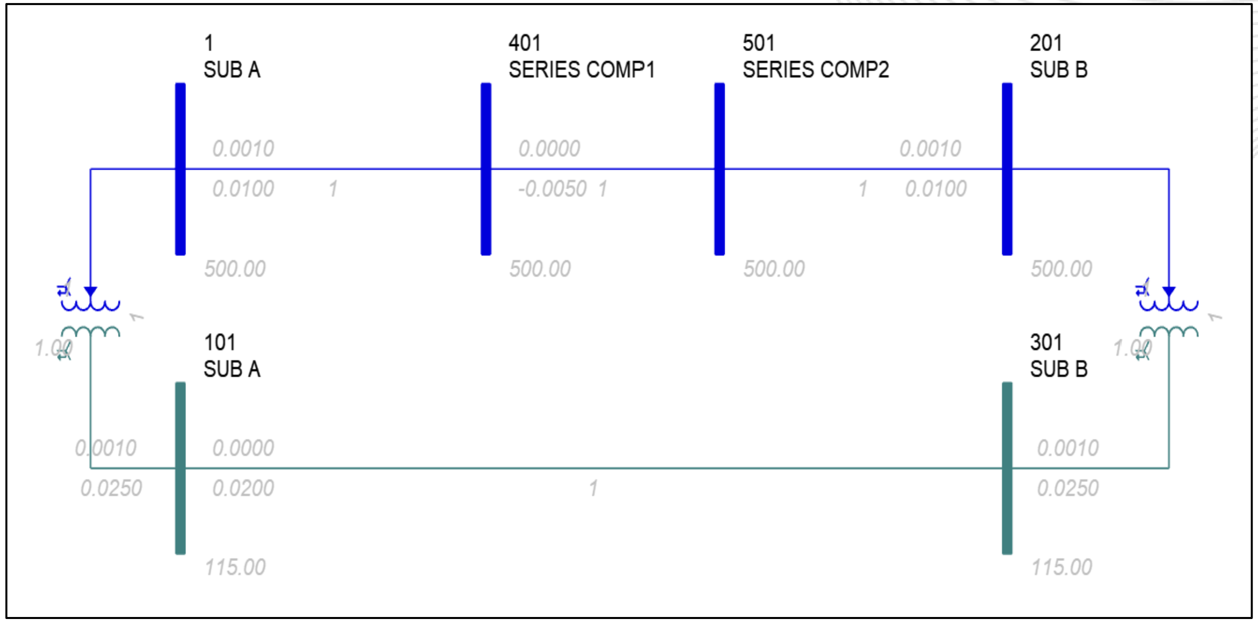
Data Requirement Spreadsheet

- *Data request will be submitted via a spreadsheet*
- *Official request posted on PJM model building SharePoint*
- *Request will be submitted to area transmission rep*
- *Responses due: June 1*
- *Prepopulated with previously supplied date where existing*

Microsoft Excel Worksheet

GO data will be collected through GenModel if not currently submitted

Scope of inclusions



TPL-007 requires all 200+ kV equipment be modeled and evaluated. Additional inclusions are recommended:
Lower kV parallel circuits to series compensated lines

Lower kV grounded equipment in close proximity to a 200+ kV autotransformers

Transformer Data

Review of information collected

Sr. No.	Transformer Type	From Bus Number	From Bus Name	Blocking device Present	To Bus Number	To Bus Name	Blocking device Present	Last Bus Number	Last Bus Name	Blocking device Present	Id	From winding resistance (ohms/ phase)	To winding resistance (ohms/ phase)	Last winding resistance (ohms/ phase)	Vector Group	Cores	K Factor	RGRD1 (ohms)	RGRD2 (ohms)	RGRD3 (ohms)	DC Network Model	Data Status	Additional Comments
1																							
2																							
3																							

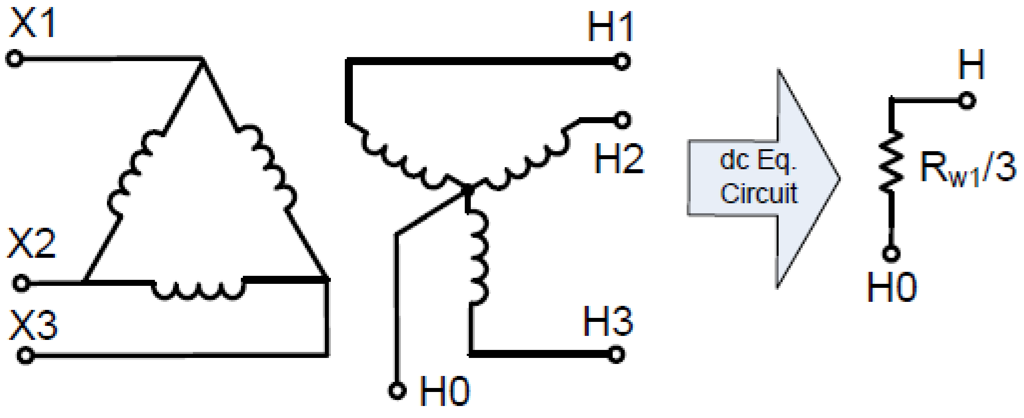
Common types of transformers will have the information above collected.

Data Color Key: Mandatory data; Mandatory with a three winding; Data is an either/or selection process; Existing data

If you have phase shifting transformers and need assistance, please reach out to the project team.

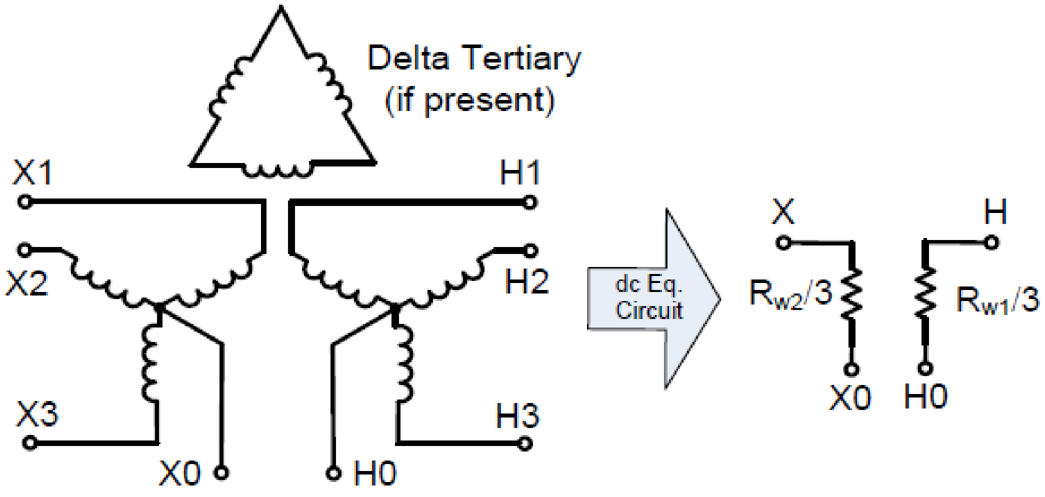
Transformer Type: Typical GSU (Generator Step-Up)

Component	Included in DC Model?	How It's Modeled	Key Notes
Grounded wye winding	Yes	Resistance $R_{w1}/3$	Main path for GIC to ground
Delta winding	No	Not modeled	No DC path (closed loop)
Neutral (H0)	Yes	Connected to ground (or via blocking device)	Entry/exit point for GIC
Blocking device	Optional	Inserted between H0 and ground	Limits GIC flow
Resistance source	Use measured	From test report (preferred)	Can estimate if unavailable



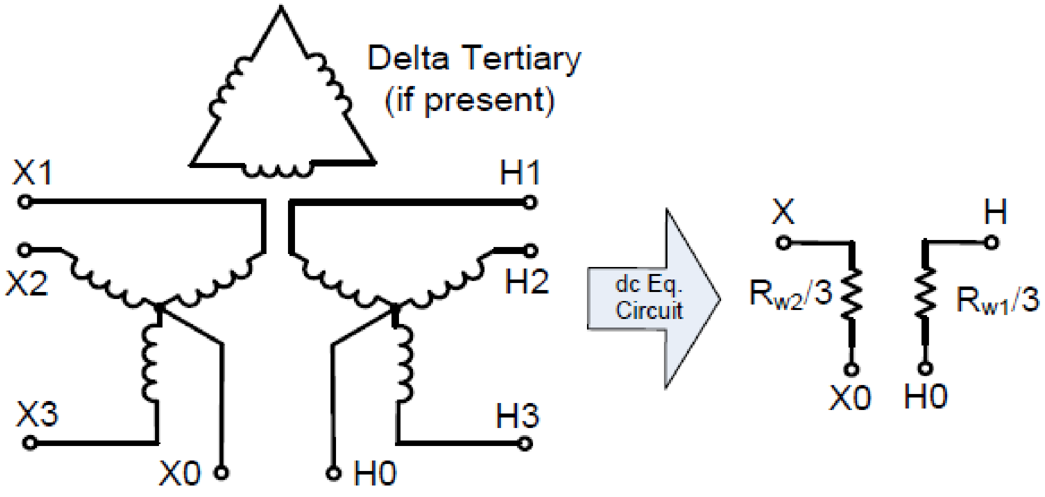
Transformer Type: Two Winding Transformer

Component	Included in DC Model?	How It's Modeled	Key Notes
HV winding (H)	Yes (if grounded)	$R_{w1}/3$	Must be grounded to carry GIC
LV winding (X)	Yes (if grounded)	$R_{w2}/3$	Same rule as HV
Delta tertiary	No	Not modeled	No steady-state DC path
Neutral points (H0, X0)	Yes	Connected to ground or left floating	Determines GIC path
Ungrounded wye	No	Not modeled	No return path to Earth



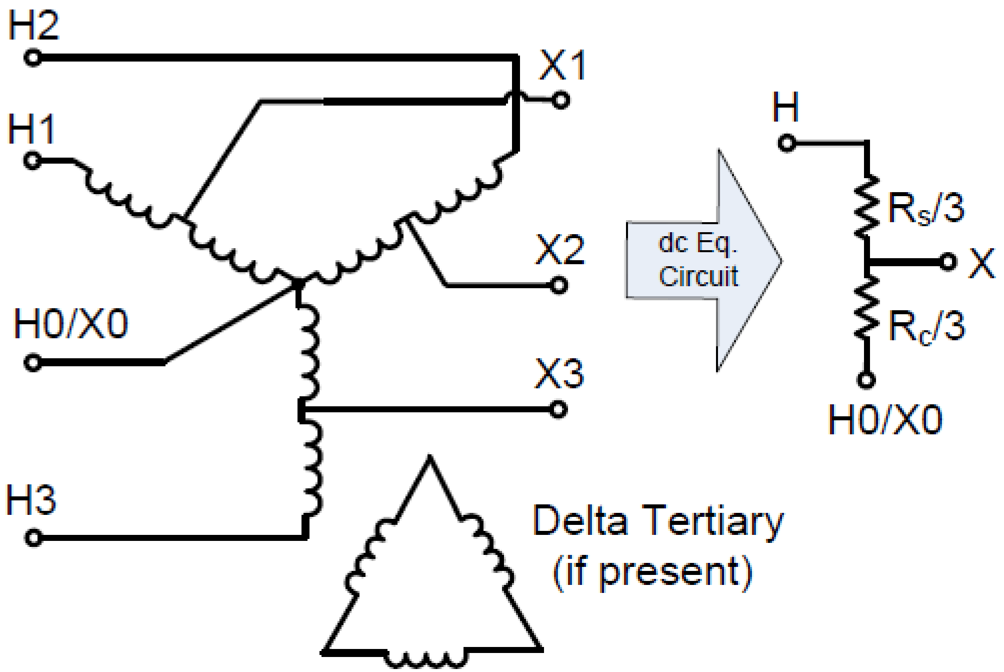
Transformer Type: Three Winding Y-Y grounded Transformer

Component	Included in DC Model?	How It's Modeled	Key Notes
HV, MV, LV windings	Yes (if grounded)	Each as resistance /3	Modeled individually
Delta winding	No	Not modeled	Same reasoning (no DC path)
Neutral points	Yes	Explicit nodes in model	Critical for GIC flow



Transformer Type: Autotransformer

Component	Included in DC Model?	How It's Modeled	Key Notes
Series winding	Yes	$R_s/3$	
Common winding	Yes	$R_c/3$	
Shared neutral (H0/X0)	Yes	Connected to ground	Major GIC path
Delta tertiary	No	Not modeled	No DC path



Reading the Transformer Test Report

TRANSFORMER CERTIFIED TEST REPORT

[redacted] TRANSFORMERS

CUSTOMER: [redacted] F.P. S/O.: [redacted]
CUSTOMER ORDER NO.: [redacted] DATE OF TEST: 92/6/10
kV(10000 TYPE: ONAN 60 HZ 3 PHASE
VOLTS: 44000-13200 INSULATING FLUID: OIL
TEMPERATURE RISE: 65 C POLARITY: SEE DIAGRAM NAMEPLATE

SERIAL NUMBER	% EXCITING CURRENT @ 100% RATED VOLTAGE	NO LOAD LOSS WATTS @ 100% RATED VOLTAGE	44000 VOLTS TO 13200 VOLTS @ 10000 KVA LOAD LOSS: WATTS @ 85 C	44000 VOLTS TO 13200 VOLTS @ 10000 KVA % IMP. @ 85 C	41800 VOLTS TO 13200 VOLTS @ 10000 KVA LOAD LOSS: WATTS @ 85 C	41800 VOLTS TO 13200 VOLTS @ 10000 KVA % IMP. @ 85 C	TOTAL LOSS ON RATED CONN. WATTS @ 85 C
GUAR.	1	8900	40600	5.5			49500
1568401002	0.12	8112	38053	5.33	38466	5.26	46165
1568401003	0.14	8172	37482	5.17	37888	5.09	45654
AVERAGES	0.13	8142	37767	5.25	38177	5.17	45909

RESISTANCES FOR THREE PHASE TRANSFORMERS = 3 TIMES THE RESISTANCE PER PHASE

SERIAL NUMBER	RESISTANCE IN OHMS @ 85 C X	RESISTANCE IN OHMS @ 85 C H	% REGULATION @ 85 C 100 % P.F.	% REGULATION @ 85 C 80 %P.F.	% DISSIPATION FACTOR H-LG	% DISSIPATION FACTOR L-HG	% DISSIPATION FACTOR HL-G	FLUID DIELECTRIC TEST (KV)
[redacted]	.076136	2.88	0.52	3.58	.24	.31	.35	54
	.075840	2.85	0.51	3.47	.32	.32	.33	61

DIELECTRIC TESTS

APPLIED POTENTIAL TESTS	INSULATION CLASS RATING IN KV	TEST VOLTAGE: APPLIED IN KV	DURATION OF TEST IN SECONDS
APPLIED VOLTAGE BETWEEN EACH WINDING WITH ALL OTHER WINDINGS & CORE CONNECTED TO GROUND	HV 44	95	60
	LV 13.2	34	60

INDUCED POTENTIAL TEST: 2 TIMES RATED VOLTS ACROSS FULL WINDING FOR 7200 CYCLES

NOTES: ALL TEMPERATURES IN DEGREES CELSIUS

HEAT RUN RESULTS

	ONAN: N RISE	RISE
GUAR. C	65	N
TOP LIQ.	54.7	
AVE(H) C	52.8	
AVE(X) C	53.7	

SERIAL #: [redacted]
HEAT RUN ON MIN. TAP
CONN. AT 100% OUTPUT

BY/FOR: [redacted] DATE 92/6/10 SPEC. P.O. [redacted]

PROFESSIONAL ENGINEERS PROVINCE OF ONTARIO [redacted]

[redacted] [redacted]

Test Report – TR 26.0732

7. Winding Resistance Measurements

IEEE Std C57.12.90-2021, Clause 5

Measuring Instrument: WR50-12, Raytech

Date: 02.15.2026

Results: Satisfactory

Top Oil Temp.: 24.7 ºC Bottom Oil Temp.: 22.0 ºC Avg. Oil Temp.: 23.35 ºC

HV Winding

Tap Position	H1-H0 R (mΩ)	H2-H0 R (mΩ)	H3-H0 R (mΩ)	Rmean (mΩ)	Rmean @ 85 ºC (mΩ)
16R	655.55	654.40	656.20	655.38	812.08
15R	650.60	649.50	651.30	650.47	805.99
14R	646.55	645.40	647.30	646.42	800.97
13R	641.60	640.55	642.30	641.48	794.86
12R	636.65	635.45	637.40	636.50	788.68
11R	631.65	630.70	632.35	631.57	782.57
10R	627.75	626.45	628.35	627.52	777.55
9R	622.70	621.75	623.40	622.62	771.48
8R	617.80	616.75	618.50	617.68	765.37
7R	612.75	611.75	613.45	612.65	759.13
6R	607.90	606.60	608.50	607.67	752.96
5R	602.85	601.85	603.60	602.77	746.88
4R	598.00	596.65	598.60	597.75	740.67
3R	593.00	591.80	593.65	592.82	734.55
2R	589.35	587.70	589.75	588.93	729.74
1R	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
N	577.80	576.45	577.95	577.40	715.45
1L	586.60	584.65	587.70	586.32	726.50
2L	590.70	588.30	591.25	590.08	731.17
3L	595.70	593.45	596.15	595.10	737.38
4L	600.45	598.18	601.00	599.88	743.30
5L	605.25	603.20	605.90	604.78	749.38
6L	609.40	606.90	609.80	608.70	754.24
7L	614.30	612.10	614.75	613.72	760.45
8L	619.30	616.80	619.65	618.58	766.48
9L	624.00	621.90	624.55	623.48	772.55
10L	629.15	626.70	629.50	628.45	778.71
11L	633.90	631.85	634.45	633.40	784.84
12L	639.05	636.70	639.40	638.38	791.02
13L	643.80	641.80	644.55	643.38	797.21
14L	648.00	645.85	648.60	647.48	802.29
15L	652.65	650.95	653.45	652.35	808.32
16L	658.40	656.10	659.30	657.93	815.24

[redacted]

Scaling of DC Resistance in Transformers

Transformer DC resistance likely requires scaling to meet event calculation expectations of a 75˚C.

Requires some computation based on tested values.

Temperature correction to 75 °C

If the resistance is measured at temperature T_m, convert it to 75 °C:

$$R_{75} = R_{measured} \times \frac{234.5 + 75}{234.5 + T_m}$$

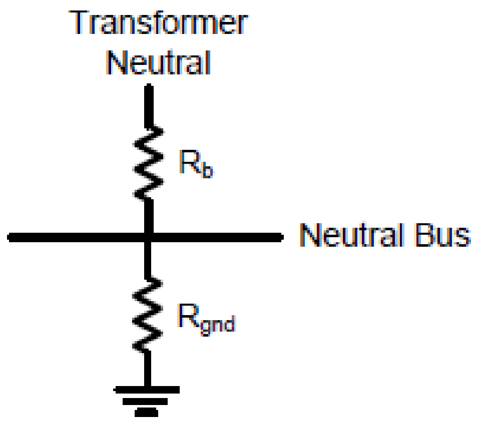
Where:

- $R_{measured}$: measured DC resistance
- T_m: measurement temperature in °C
- 234.5 is the constant for copper (use 225 for aluminum)

GIC Blocking Device Modeling

Device Type	Modeled As	Resistance Value	Behavior
Solidly grounded	Resistor	~100 μΩ (0.1 mΩ)	Allows full GIC flow
Resistive grounding	Resistor	Actual resistance value	Limits GIC
Capacitive blocking device	High resistance	~1 MΩ	Blocks GIC (acts open circuit)

Electrical model of GIC blocking device between transformer neutral and substation ground grid as used in GIC calculations



From and To Bus for winding order matters

Recommended steps:

1. Export the case raw data file
2. Ensure the winding order lines up with this
3. Do not change the order of the GIC data file
4. Data request will be in the order of the raw data representation (windings matching)

Recommend using the built-in tools to ensure that vector groups are matching expectations

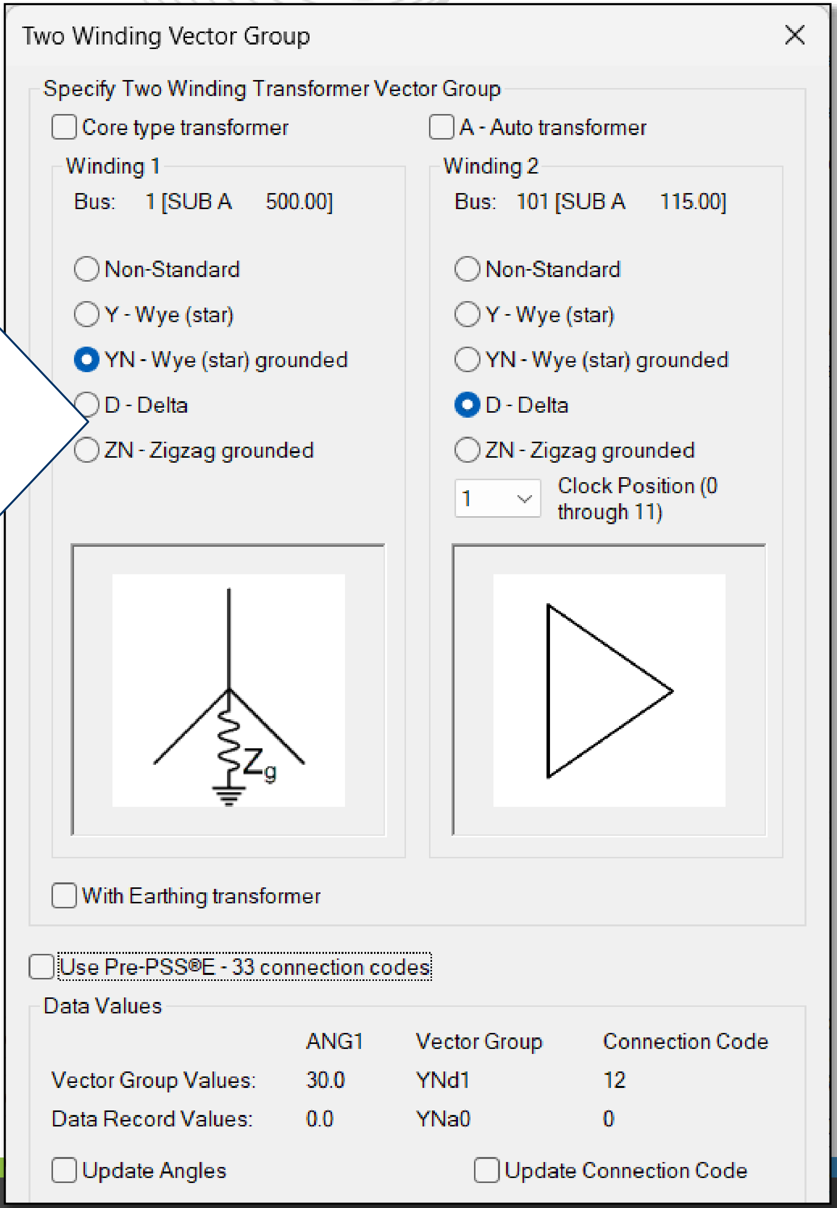
GIC File
202, 102, 0, '1', 1, 0.5,,

Raw data file
Case 1
102, 202, 0,'1 ',

≠

GIC File
202, 102, 0, '1', 1, 0.5,,

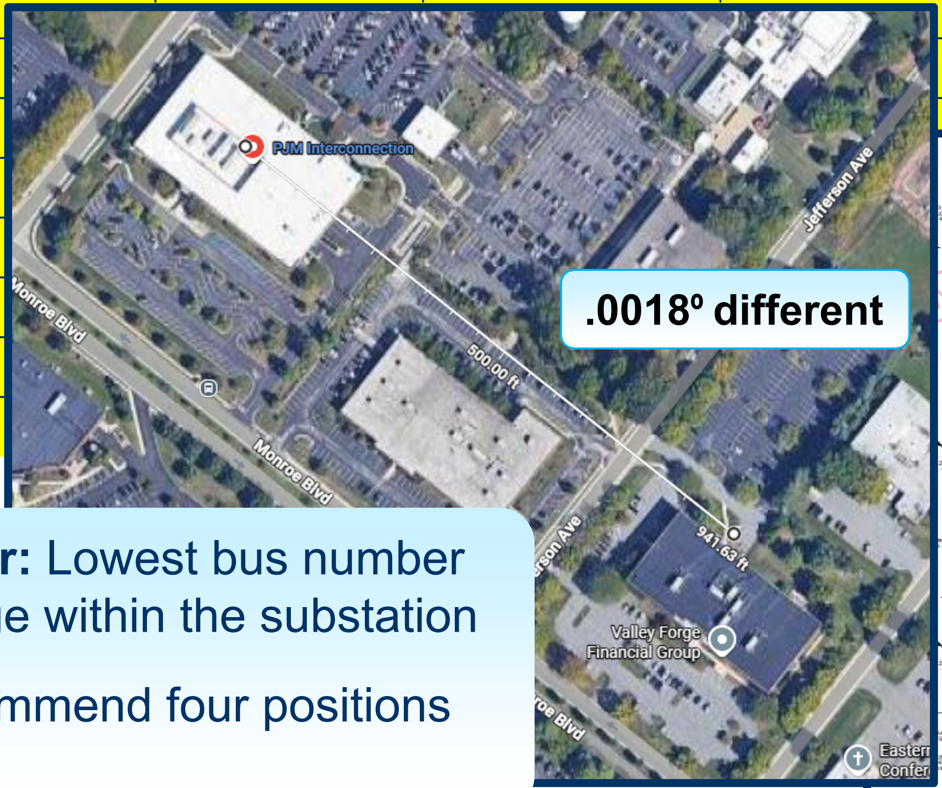
Raw data file
Case 1
202, 102, 0,'1 ',

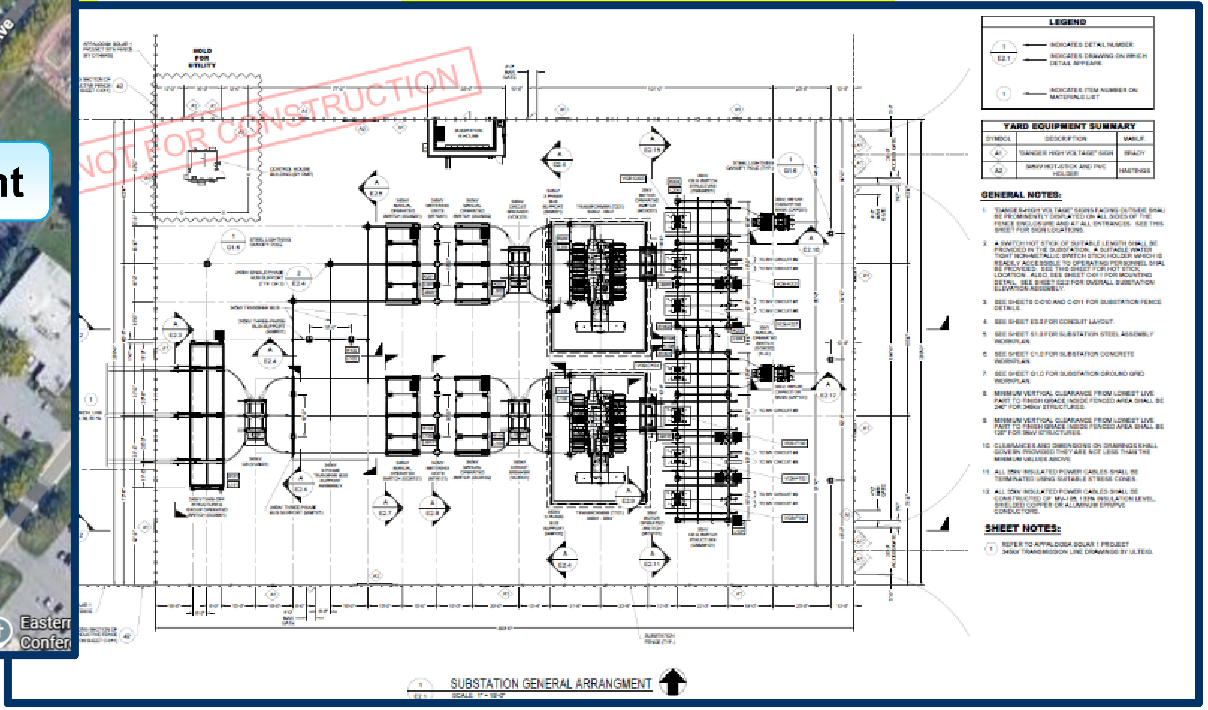


Pause for xfmr questions and PSSE hints

Substation Data Collection

Sr. No.	Targeted Model	Substation Number	Substation Name	Bus Number	Summer grounding resistance (ohms)	Earth Model to be applied	Grounding resistance method	Latitude of Substation	Longitude of Substation	Data Status	Additional Comments
1		1	First Sub	1,2,3,4,5,6	.5	AP2		40.1211	-75.4181		
2											
3											
4											
5											
6											
7											
8											
9											
10											





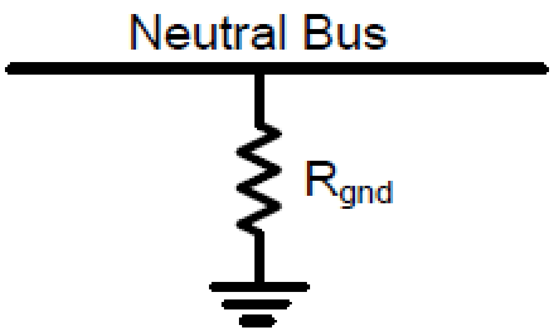
Substation Number: Lowest bus number of the highest voltage within the substation

Geolocation: Recommend four positions past the decimal

Substation Ground Grid Modeling

Component	Included in DC Model?	How It's Modeled	Typical Values	Key Notes
Ground Grid (Rgnd)	Yes	Resistance to remote earth	Measured or calculated	One value per substation
Neutral Bus	Yes	Common connection node	—	Connects all grounded transformer neutrals
Connections to Neutral Bus	Yes	Based on number of grounded windings	—	More grounded transformers → more paths
Shield wires / grounding paths	Yes (indirectly)	Included in Rgnd	—	Not modeled separately

Electrical model of substation ground grid to remote earth for use in GIC calculations



Transmission Line Data Collection

Sr. No.	From Bus Number	From Bus Name	To Bus Number	To Bus Name	Id	Resistance (ohms/phase)	Induced Vp (volts)	Induced Vq (volts)	From DC resistance (ohms/phase)	To DC resistance (ohms/phase)	Data Status	Additional Comments
1	111011											
2												
3												
4												
5												
6												
7												
8												

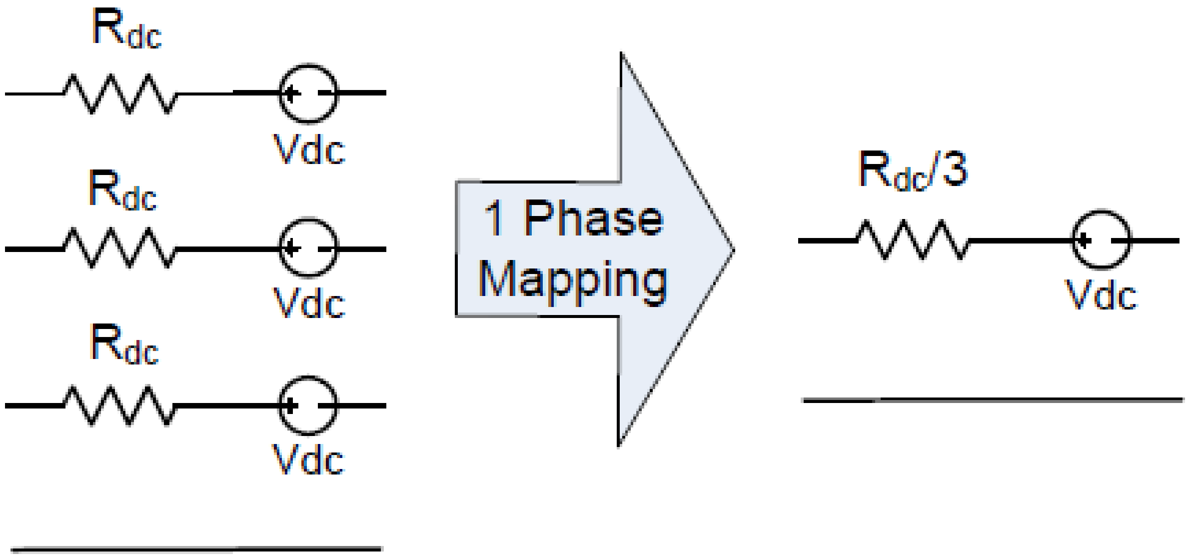
No transmission line data will be required, for most transmission lines, as the AC→DC conversion is close. Implicitly modeled shut reactors and blocking devices will need to be entered.

Indicates a Mandatory Field | While the entries could use one or more of the magenta data fields

If a series capacitor is not explicitly modeled in the power flow as a negative reactance, *please include the line segment in this table with a comment indicating that a series capacitor is present.*

Transmission Line GIC Model

Component	Included in DC Model?	How It's Modeled	Key Formula
Line resistance (Rdc)	Yes	Series resistance	R = $\frac{1}{3}$ x phase resistance
Induced voltage (Vdc)	Yes	DC voltage source	V = $\int E.dl$
Geoelectric field (E)	Yes	Driving source of GIC	Depends on geomagnetic activity



Blocking GIC in Transmission Lines (Series Capacitors)

Component	Included in DC Model?	How It's Modeled	Typical Value	Key Effect
Series capacitor (inserted)	Yes	Very large resistance in series	~1 MΩ	Blocks GIC (acts like open circuit)
Series capacitor (bypassed)	Yes	Very small resistance	~100 μΩ	Allows GIC flow
Alternative modeling	Yes	Remove line entirely	—	Equivalent to fully blocking GIC

Shunt Data Collection

Switched Shunt Data

Sr. No.	From Bus Number	From Bus Name	ID	Resistance (DC Ohms/Phase)	Grounding Resistor Present	Grounding Resistance (in Ohms)	Block Number	Block Size	Step Number	Data Status	Additional Comments
1											
2											
3											
4											

Fixed Shunt Data

Sr. No.	From Bus Number	From Bus Name	ID	Resistance (DC Ohms/Phase)	Grounding Resistor Present	Grounding Resistance (in Ohms)	Data Status	Additional Comments			
1											
2											
3											
4											

Only reactors will need to be modeled within the GMD assessment. These provide a resistive path to ground. Capacitors are blocks to these currents.

Data Color Key: (yellow) Necessary data (green) Data may be present

Shunt Devices in GIC Modeling

Device Type	Included in DC Model?	How It's Modeled	Reason
Shunt capacitor	No	Not modeled	Blocks DC (very high impedance)
Shunt reactor (grounded wye)	Yes	Resistance to ground	Provides GIC path

Implicit Device Modeling

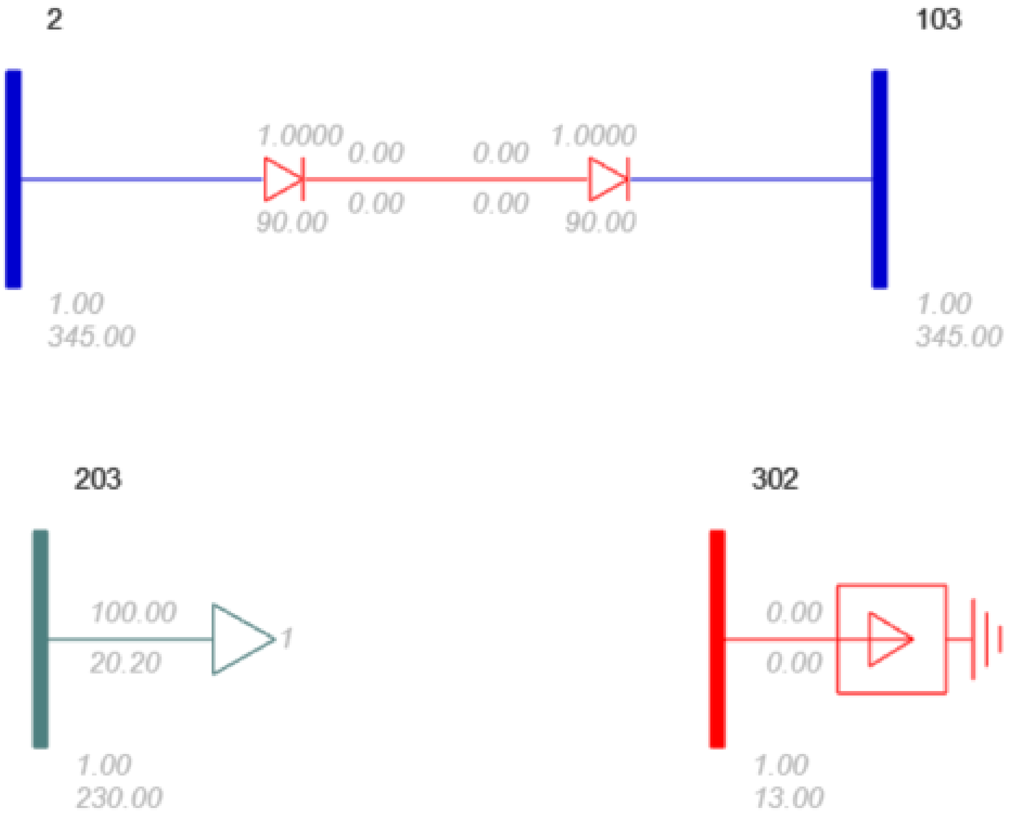
Sr. No.	Device	From Bus Number	From Bus Name	ID	Resistance (DC Ohms/ Phase)	Grounding Resistor Present	Grounding Resistance (in Ohms)	Transformer Core Construction	K Factor (If known)	Data Status	Additional Comments
1	Load										
2	DC Line Data										
3	VSC										
4	FACTS										
5	Other										

Many devices in our powerflow model can alter GIC flows on the system but have "hidden" attributes. These are implicitly modeled devices. The transformer information needs to be included through this portion of the data request.

Data Color Key: Yellow = Necessary data; Green = Data may be present; Pink = Data is an either/or selection process

Examples of Implicit Equipment Modeling

Not all components clearly state their path to ground. Loads, HVDC and FACTS devices are a set of equipment which may require data entries.



Source: Bing and Google maps inclusions

Modeling neighboring power systems

Method	Description	Model Components	Accuracy	Advantages	Disadvantages	When to Use
1. Ignore Neighboring Network (Open Circuit)	Treat the boundary as disconnected	No connection (open circuit)	**Lowest**	Simplest- Requires no external data	Largest error- Blocks GIC flow between systems	Preliminary or rough estimates only
2. First Line + Substation Grounding	Model only the first transmission line and grounding at the neighboring substation	Line resistance Substation grounding resistance	**Moderate**	More realistic than open circuit- Limited data needed	Still simplified- May miss broader network effects	When limited data is available
3. Thevenin Equivalent (Preferred)	Replace neighboring network with an equivalent voltage source and resistance	$V_{th} = V_L$(induced voltage) $R_{th} = R_L$(line resistance)	**Highest (practical)**	Best balance of accuracy and simplicity- Captures GIC flow properly	Requires estimation of induced voltage	Recommended for most GIC studies

Start next steps and project schedule

- Transmission Owners data request will be available at the conclusion of this meeting on the PJM modeling SharePoint site
- Generator Owners will submit the data through GenModel portal if it is not already present
- Submissions will be due: 6/1/2026

Technical Workflow Steps for GMD Assessment

R2 – GIC System Modeling	**R4 –** Benchmark GMD Assessment	**R5 –** Benchmark GIC Results	**R6 –** Transformer Thermal Assessment
Develop **DC GIC system model** of the network	Perform **steady-state power flow with GIC effects**	Simulate and provide **GIC values** for benchmark event	Assess **thermal impact of GIC on transformers**
Include **≥200 kV grounded-wye transformers**	Follow defined performance criteria	Used for **thermal assessment input**	*Focus on:* **≥200 kV grounded-wye units**
Used to calculate **Geomagnetically Induced Current flow**	*Include:* **On-peak load case** **Off-peak load case**	*Reference threshold:* **~75 A per phase** (low risk level)	Repeat/update assessment during each study cycle
Supports: • Reactive power loss calculation • Transformer thermal studies	Based on models from R2	Can convert to **GIC(t)** for time-series analysis	Critical for **system reliability**

Technical Workflow Steps for GMD Assessment

R7 – Corrective Action Plans (Benchmark)	**R8 –** Supplemental GMD Assessment	**R9 –** Supplemental GIC Results	**R10 –** Supplemental Thermal Assessment
Develop **mitigation plans** for identified issues	Same as R4 but for **supplemental GMD event**	Provide **GIC values for supplemental event**	Perform transformer thermal evaluation using: • Simulation models • Manufacturer curves • Screening methods
Examples: • Operational changes • Equipment upgrades	Includes **localized severe condition**	*Higher severity:* **~85 A per phase threshold**	Repeat/update with each assessment cycle
Timeline approvals handled case-by-case	Must include: On-peak and off-peak cases	Used for **advanced thermal assessment**	
		Supports **time-series GIC(t)** conversion	

Technical Workflow Steps for GMD Assessment

R11 – Corrective Action Plans (Supplemental)	**R12 –** GIC Monitoring	**R13 –** Geomagnetic Field Monitoring
Mandatory **mitigation plans for supplemental vulnerabilities**	Collect **real GIC measurements**	Collect **geomagnetic field data**
Focus on: Severe/localized risks	*Typically, via:* Neutral current sensors (Hall effect)	*Sources:* • Observatories (e.g., *Natural Resources Canada*) • Magnetometers
Based on **Federal Energy Regulatory Commission directives**	*Used for:* • Model validation • Situational awareness	*Supports:* • Model accuracy • GMD event analysis

Flow of PJM TPL analysis efforts

GMD Workshop and TPL-007 Procedure review and drafting
April 2026

Data Collection from TO/GO (Completion Target)
June 2026

Data Validation and Cleanup
July 2026

Update system models, GIC system models and validation
September 2026

GIC flow calculations: Benchmark & Supplemental
September 2026

Steady state performance criteria

TO and GO thermal assessment
October 2026

Steady state analysis of harmonically-sensitive equipment outages
September 2027

Create corrective action plans
October 2027

Assumptions for GIC Simulations

Sr. #	Parameter	Assumption (Benchmark Event)
1	**Electric Field Model Type**	Benchmark: 8V/km (uniform)
2	**Scan Storm Event Step Size**	1 Degree for Benchmark up to 180 degrees
3	**Branch X/R ratio**	30 (Assumed)
4	**Transformer X/R ratio**	30 (Assumed)
5	**Substation grounding DC resistance**	0.1 (Assumed)
6	**AC to DC resistance conversion factors**	1 for both Branch and Transformer
7	**Benchmark Year**	N/A
8	**Scan Storm Event Scenario**	Scan Degree
9	**Earth Model**	Upon validating, preference will be given to the data received from TO/GOs else EPE (in coordination with PJM) will decide this.
10	**Scan options**	As we are using uniform field, Mag scan step will be 0.
11	**Study subsystem selection**	Choose "Selected bus subsystem". The selected subsystem will be defined by the python script.

Sr. #	Parameter	Assumption (Supplemental Event)
1	**Electric Field Model Type**	Supplemental: 12V/km (Uniform)
2	**Scan Storm Event Step Size**	15 degrees for Supplemental event up to 360 degrees.
3	**Branch X/R ratio**	30 (Assumed)
4	**Transformer X/R ratio**	30 (Assumed)
5	**Substation grounding DC resistance**	0.1 (Assumed)
6	**AC to DC resistance conversion factors**	1 for both Branch and Transformer
7	**Benchmark Year**	N/A
8	**Scan Storm Event Scenario**	Scan Degree
9	**Earth Model**	Upon validating, preference will be given to the data received from TO/GOs else EPE (in coordination with PJM) will decide this.
10	**Scan options**	As we are using uniform field, Mag scan step will be 0.
11	**Study subsystem selection**	Choose "Selected bus subsystem". The selected subsystem will be defined by the python script.
12	**Box Dimension**	100km x 100km
13	**Field inside the Box** **Field outside the Box**	12V/km (Uniform) 8V/km (Uniform)

- TOs to submit GIC data to PJM no later than June 1, 2026
- GO Data Request window will open May 1, 2026 and be open for 45 days
- PJM to provide periodic updates at PC

Questions?


PROTECT THE POWER GRID
THINK BEFORE YOU CLICK!
pjm
BE ALERT TO MALICIOUS PHISHING EMAILS
Report suspicious email activity to PJM.
Call (610) 666-2244 or email it_ops_ctr_shift@pjm.com