

Modeling GMD in PowerWorld Simulator



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Overview

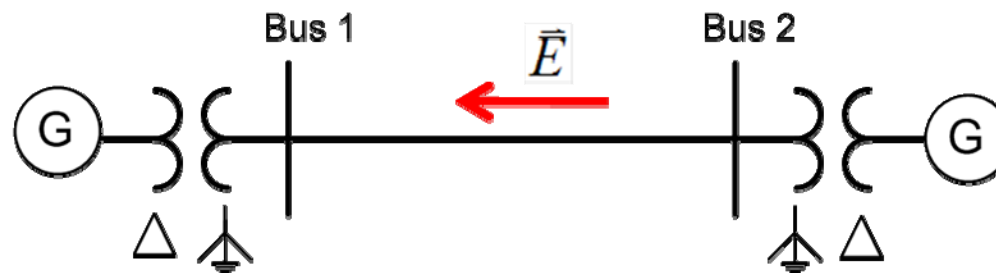


- The grid reliability is high, but there are some events that could cause large-scale, long duration blackouts
 - These include what NERC calls High-Impact, Low-Frequency Events (HILFs); others call them black swan events or black sky days
 - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) high altitude electromagnetics pulses (HEMPs)
 - Another could be volcanic eruptions
- Today's presentations focus primarily on GMDs, with a bit of HEMP

Geomagnetic Disturbances



- Geomagnetic disturbances (GMD) occur when particles discharged from the sun during solar storms interact with the earth's magnetic field.
- Power systems are vulnerable to geospatial variation in dc voltage caused by GMD.
- Geomagnetically induced currents (GIC) flow through circuits formed by the earth, a grounded transformer, a high-voltage transmission line, and a grounded transformer at the other end of the transmission line.



Power System Impacts of GICs



- The dc GICs are superimposed upon the ac currents. In transformers this can push the flux into saturation for part of the ac cycle
- This can cause large harmonics; in the positive sequence (e.g., power flow and transient stability) these harmonics can be represented by increased reactive power losses on the transformer.

DC causes Part – Cycle, Semi – Saturation of the core

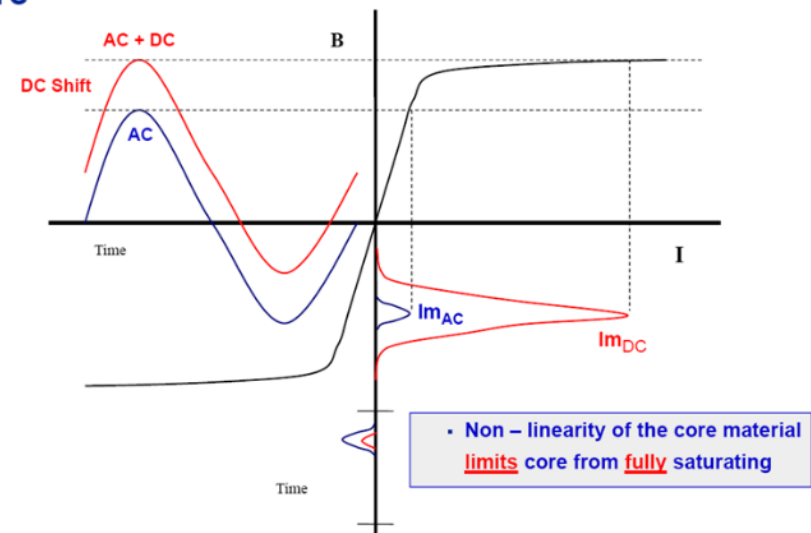


Image Source: Craig Stiegemeier, JASON Presentation, June 2011

Historic GMD Events



- A 1989 solar storm caused widespread outages on the Hydro Quebec system, but it was much smaller and less intense than a 1921 storm that occurred prior to widespread electrification.
- A similar storm could cause significant equipment damage and outages to modern interconnected power grids
- GMDs have the potential to severely disrupt operations of the electric grid
- PowerWorld Simulator GIC is a novel tool to help assess the impact of GMDs on interconnected power systems

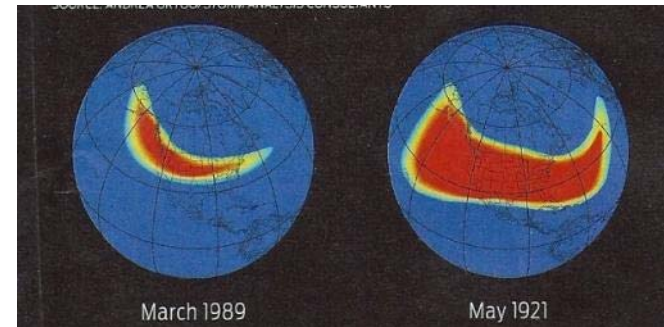


Image source: J. Kappenman, "A Perfect Storm of Planetary Proportions," *IEEE Spectrum*, Feb 2012, page 29

NERC Interim GMD Report



- On February 29, 2012 NERC issued an Interim GMD Report, <http://www.nerc.com/files/2012GMD.pdf>
- In section I.10 of the Executive Summary there are four high level recommended actions
 - Improved tools for industry planners to develop GMD mitigation strategies
 - Improved tools for system operators to manage GMD impacts
 - Develop education and information exchanges between researchers and industry
 - Review the need for enhanced NERC Reliability Standards

FERC Order 779



- *Reliability Standards for Geomagnetic Disturbances*, Issued May 16, 2013
- NERC must develop Reliability Standards that require power system owners and operators to:
 - develop and implement operational procedures to mitigate GMD (NERC EOP-010-1)
 - conduct initial and on-going assessments of the potential impact of **benchmark GMD events** (NERC TPL-007-1)
 - develop and implement a plan to prevent impacts of benchmark GMD events from causing instability, uncontrolled separation, or cascading failures (NERC TPL-007-1)

NERC TPL-007-1



- Key Requirements
 - R1. Maintain AC system models and GIC system models
 - R2. Complete a GMD Vulnerability Assessment every 5 years, based on **benchmark GMD event** – power system must remain stable
 - R3. Develop a Corrective Action Plan if needed
 - R7. Assess thermal impact of Gwye transformers at 200kV+
- More details at the NERC GMD Task Force page
[http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-\(GMDTF\)-2013.aspx](http://www.nerc.com/comm/PC/Pages/Geomagnetic-Disturbance-Task-Force-(GMDTF)-2013.aspx)

FERC Follow-up

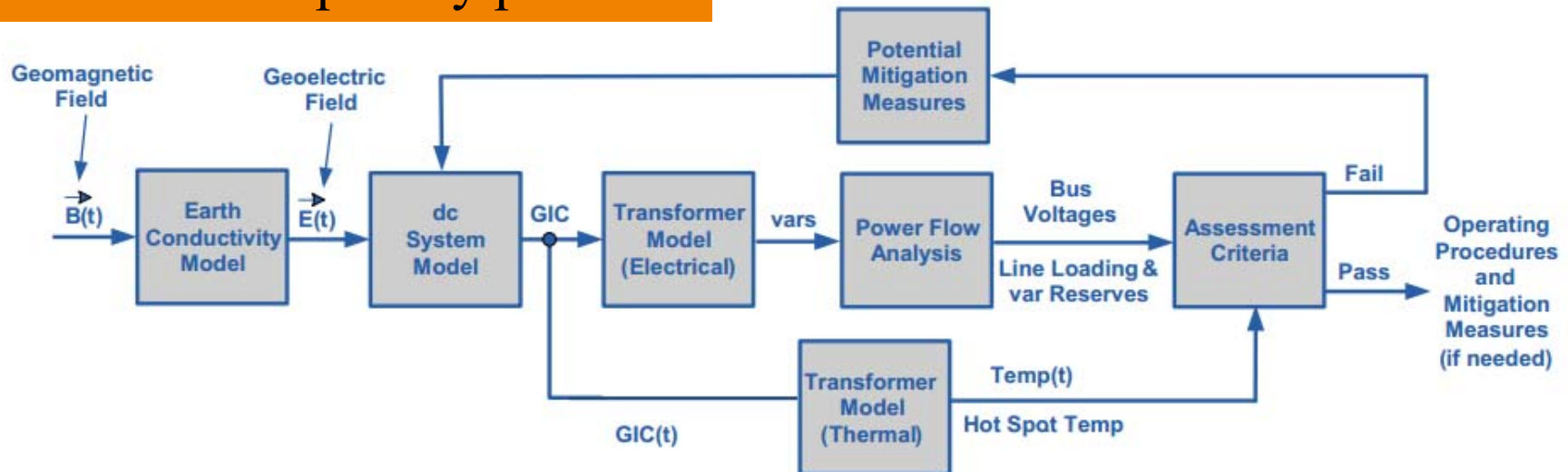


- FERC notice of proposed rulemaking (NOPR) to accept TPL-007-1 on May 14, 2015
- FERC Order 830 approved TPL-007-1 on September 22, 2016, while directing a few modifications
 - Benchmark Event shall not be based solely on spatially-averaged data
 - Collect and publicly share GIC monitoring and magnetometer data
 - Establish deadlines for corrective action plans and mitigation
- NERC GMD Task Force resumes meeting in February 2017

Overview of GMD Assessments



An interdisciplinary problem



The two key concerns from a big storm:

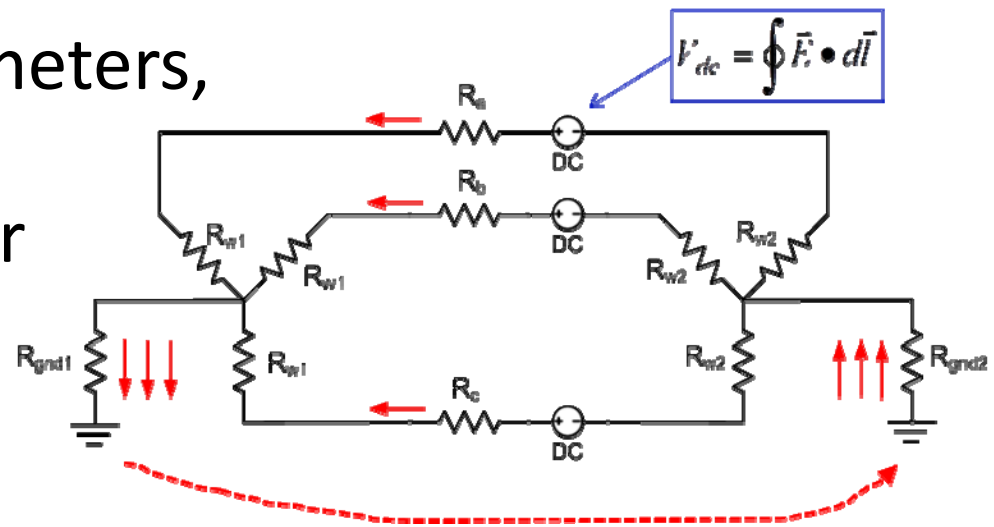
- 1) large-scale blackout due to voltage collapse,
- 2) permanent transformer damage due to overheating

Image Source: http://www.nerc.com/pa/Stand/WebinarLibrary/GMD_standards_update_june26_ec.pdf

GIC Modeling



- Modern methods model GIC as DC voltage sources in transmission lines
- With pertinent parameters, GIC computation is a straightforward linear calculation
- By integrating GIC calculations into PowerWorld Simulator, engineers can readily see the impact of GICs on their systems and consider mitigation options



GIC Analysis Inputs



- GIC calculations use some existing model parameters such as line resistance
- Some additional parameters are needed
 - Substation geo-coordinates and grounding resistance
 - Transformer grounding configuration, coil resistance, core type, whether auto-transformer, whether three-winding transformer
 - Generator step-up transformer parameters
- Transmission operators would be in the best position to provide these values, but all can be estimated when actual values are not available

Geographic Information



- The potentially time-varying GMD induced dc voltages depend on the storm strength and orientation and the latitude and longitude of the transmission lines
 - The electric field is integrated along the path of the transmission line
 - The geo-coordinates of the terminal substations are sufficient for uniform fields (path independence)
- Hence buses must be mapped to substations, and substations to their geo-coordinates
- Substation/geographic data can be supplied by PowerWorld for FERC 715 planning models
 - Buses mapped to substations
 - Latitude and longitude for substations

Mapping Transformer GICs to Transformer Reactive Power Losses



- Transformer specific, and varies with the core type: Single phase, shell, 3-legged, 5-legged
- Ideally this information would be supplied by the transformer owner
- Default data may be used for large system studies when nothing else is available.
- Simulator also supports a user-specified piecewise linear mapping
- Debate in the industry with respect to the magnitude of damage GICs would cause in transformers (from slightly age to permanently destroy)

GMD Storm Scenarios



- The starting point for GIC analysis in PowerWorld Simulator is an assumed storm scenario; this is used to determine the transmission line dc voltages
- Characterizing an actual storm can be complicated, and requires detailed knowledge of the associated geology
- February 2012 NERC report recommended a common approach for planning purposes
 - Uniform electric field model: all locations experience the same field; induced voltages in lines depend on assumed field direction
 - Maximum value in 1989 was 1.7 V/km (2.7 V/mile)
- Simulator can also use geospatially and time-varying electric field models
 - Direct user input of GIC DC voltage input on each transmission line
 - 3rd-party (AER, Inc.) input, consisting of a time-series geospatial grid of E-field magnitude and direction (available in Simulator 18)

GIC Analysis Outputs and Results

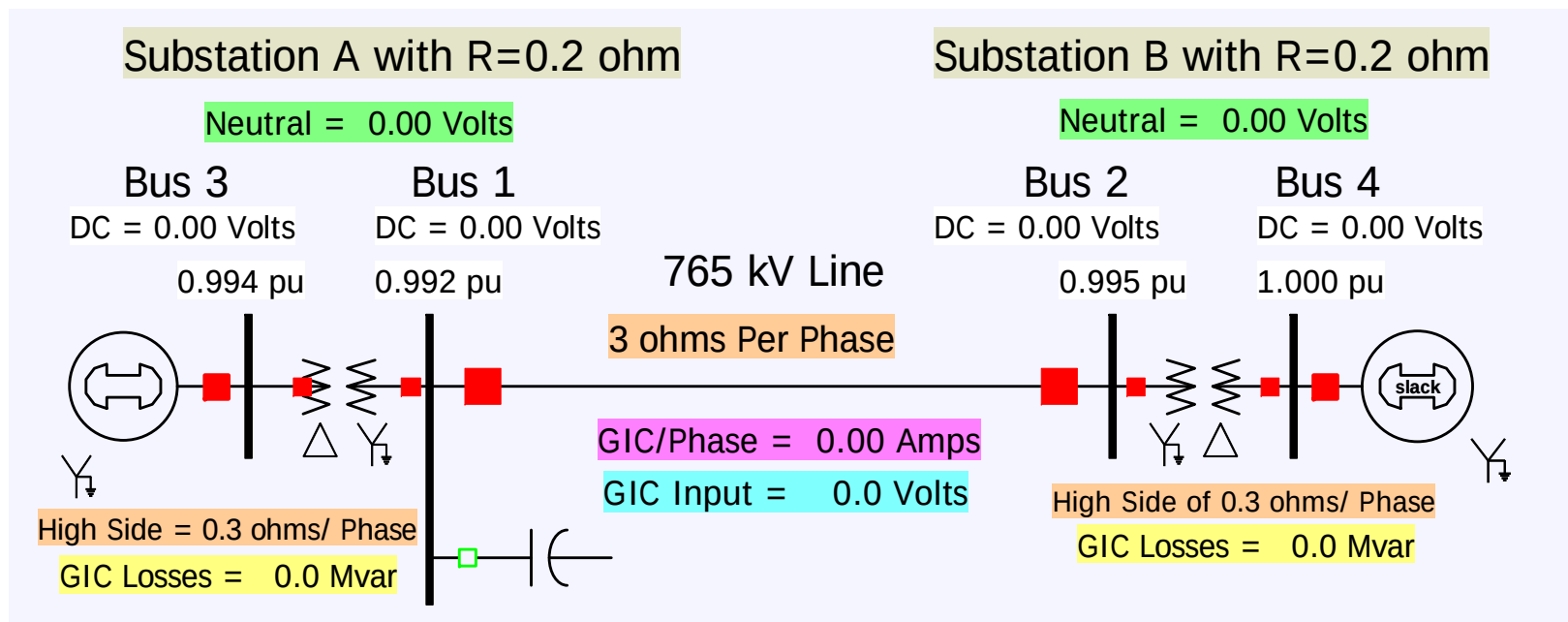


- GIC studies involve the traditional power system results (voltages, flows, etc.) and GIC-specific quantities, such as
 - Substation neutral dc voltages
 - Bus dc voltages
 - Transformer neutral amps
 - Transformer Mvar losses
 - Transmission line dc amps
- Providing easy access to the data and results is a key objective in PowerWorld Simulator, as is good wide-area visualization

Four-Bus Example



- Simple topology with one 765-kV transmission line with a grounded wye-delta transformer at either end



Four-Bus Inputs: Substations



- To open the **GIC Analysis Form** dialog, choose **Add-Ons → GIC...**
- Select the **Substations** page from **Tables and Results**
- Key inputs are the grounding resistance and geo-location (latitude and longitude)

The screenshot shows the 'GIC Analysis Form' dialog box. The 'Tables and Results' tab is active, and the 'Substations' sub-tab is selected. The table below shows the input data for two substations:

Sub Num	Sub Name	Sub ID	GIC DC Neutral Voltage	GIC Amps to Neutral	Grounding Resistance (Ohms)	GIC Used Grounding Resistance (Ohms)	Latitude	Longitude
1	Sub A	Sub1	0.00	0.00	0.20	0.20	40.000	-89.000
2	Sub B	Sub2	0.00	0.00	0.20	0.20	40.000	-87.000

2 substations along an east-west line, with the same latitude

Grounding resistance = 0.2 Ω

Grounding Resistance



- Substation grounding resistance is the resistance in ohms between the substation neutral and earth ground (zero-potential reference)
- An actual “fall of potential” test is the best way to determine this resistance
- Simulator provides defaults based on number of buses and highest nominal kV, but research has shown this to be a poor substitute for actual measurements
 - Simulator defaults range from 0.1 to 2.0 Ω
 - Substations with more buses and higher nominal kV are assumed to have lower grounding resistance
- Grounding resistance is not necessary for substations that have no transformer or switched shunt connections to ground

Substation Coordinates



- Longitude and latitude should be provided for all substations that contain terminals of lines for which a GIC equivalent DC voltage is applied
 - Generally this includes all lines greater than minimum length and nominal kV specified on GIC Analysis Form
 - Series compensated line terminals may be disregarded, if there are no other lines that meet above criteria
- The need for coordinates applies regardless of whether the substation contains grounded transformers
- If there are no grounded transformers, the location may be approximate (e.g. within 100 km)

Four-Bus Inputs: Transformers



- Key inputs
 - Coil resistance (DC ohms)
 - Grounding configuration
 - Autotransformer? (Yes/No)
 - Core Type
- } Most essential parameters; these determine the basic topology of the GIC network

The screenshot shows the 'GIC Analysis Form' window. On the left is a tree view with 'Tables and Results' expanded, showing 'Transformers' selected. The main area displays a table with the following data:

Bus Num High	Bus Name High	Bus Num Med	Bus Name Med	Bus Num Ter	Bus Name Ter	Circuit	Manually Enter Coil Resistance	High Side Ohms per Phase	Medium Side Ohms per Phase	XF Config High	XF Config Med	XF Config Ter	Assumed XF Config	Is Autotrans	Assumed to be an AutoTrans	Core Type
1	Bus 1	3	Bus 3	0	1	1	Yes, User Set	0.30000	0.10000	Gwye	Delta		GWye-Delta	No	NO	Single Phase
2	Bus 2	4	Bus 4	0	1	1	Yes, User Set	0.30000	0.10000	Gwye	Delta		GWye-Delta	No	NO	Single Phase

Four-Bus Inputs: Transformers



- Manually Enter Coil Resistance
 - “Yes, User Set”: user enters “High Side Ohms per Phase” and “Medium Side Ohms per Phase”
 - “No, Auto Default”: Simulator estimates values
- XF Config High and XF Config Med: most common options are “Gwye” and “Delta”
 - Tertiary windings are assumed Delta
- Is Autotransformer: “Yes”, “No”, or “Unknown”
- Core Type

Simulator Assumptions

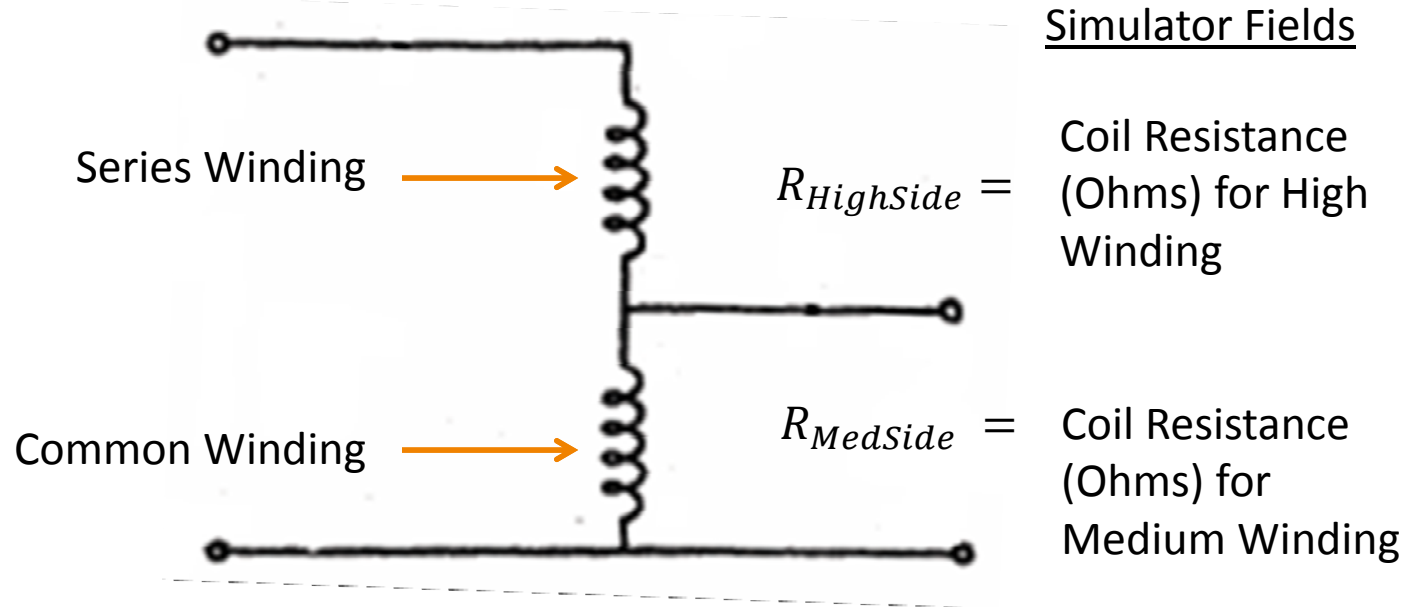


- It is always best to provide known quantities, especially for configuration and autotransformer fields
- If any transformer information is unknown, Simulator uses default values
- Coil Resistance
 - ohms per phase estimate based on positive-sequence AC per-unit series resistance and transformer impedance base
 - Assumed split between each winding:

$$R_{pu} * R_{Base,HighSide} = R_{HighSide} + a_t^2 R_{MedSide}$$

$$R_{HighSide} = a_t^2 R_{MedSide}$$

Coil Resistance: Autotransformers

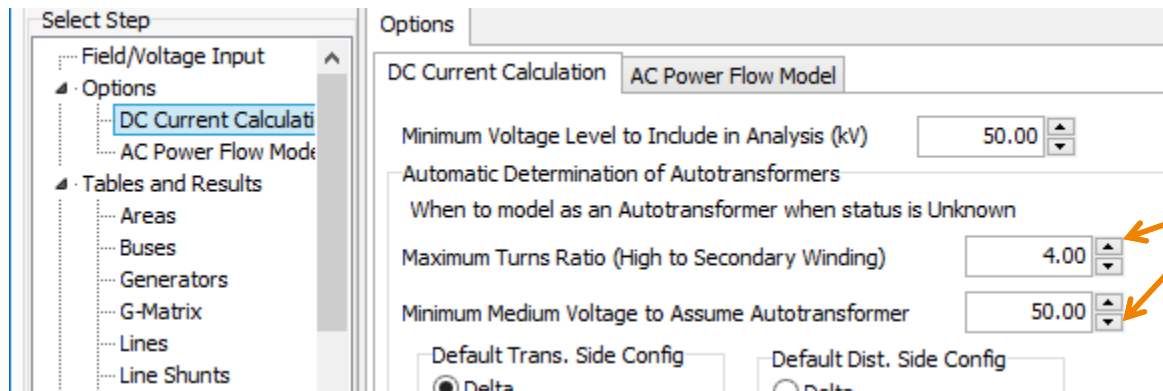


- Tertiary Windings are assumed delta connected and coil resistance is not normally populated

Simulator Assumptions: Autotransformers



- Some parameters for assumptions applied to unknown transformers are at **Options → DC Current Calculation**
- Units are assumed to be autotransformers if all of the following criteria are met
 - unit is not a phase-shifting transformer
 - high side and low side are at different nominal voltages
 - high side nominal voltage is at least 50 kV
 - turns ratio is less than or equal to 4

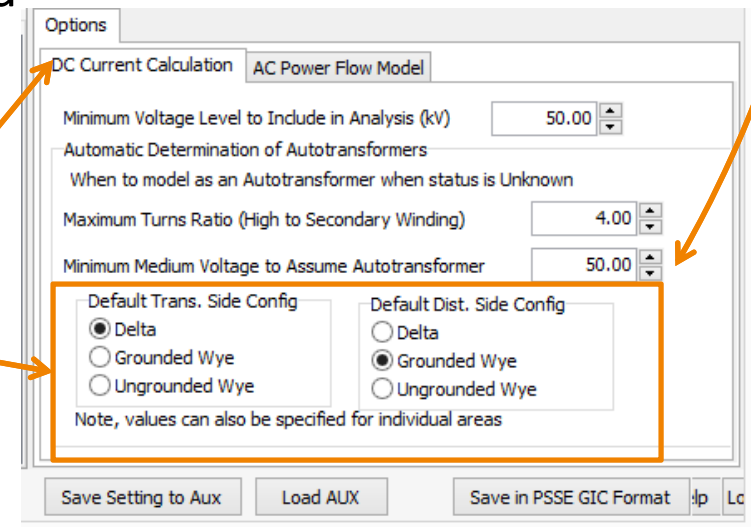


These parameters may be adjusted at **Options → DC Current Calculation**

Simulator Assumptions: Transformer Configuration



- “Unknown” windings are assumed either Delta, Grounded Wye, or Ungrounded Wye
- Autotransformer Minimum High Side Winding Voltage (kV) is also the assumed delineation between transmission and distribution voltages (default 50 kV, referred to as kV_{min} hereafter on this slide)
- If high side $> kV_{min}$ and low side is connected to a radial generator OR if high side ≥ 300 kV and low side $< kV_{min}$, unit is assumed a GSU with high side Gwye and low side Delta
- If both sides $> kV_{min}$ OR both sides $< kV_{min}$, both are assumed Gwye
- Otherwise, if high side $> kV_{min}$ and low side $< kV_{min}$ or has radial load, use *Default Trans. Side Config* and *Default Dist. Side Config* on **Options** → **DC Current Calculation** (or as specified by area)



Simulator Assumptions



- I_{Eff} is per-phase “effective GIC”, computed from GIC in high and low side windings and turns ratio (a_t)

$$I_{Eff,pu} = \left| \frac{a_t I_H + I_L}{a_t I_{base}} \right|$$

- *K-Factor* relates transformer’s effective GIC (I_{GIC}) to 3-phase reactive power loss at nominal voltage

$$Q_{loss,pu} = V_{pu} K_{pu} I_{Eff,pu}$$

- This looks like a constant current MVar load at the transformer’s high-side bus

K-Factor

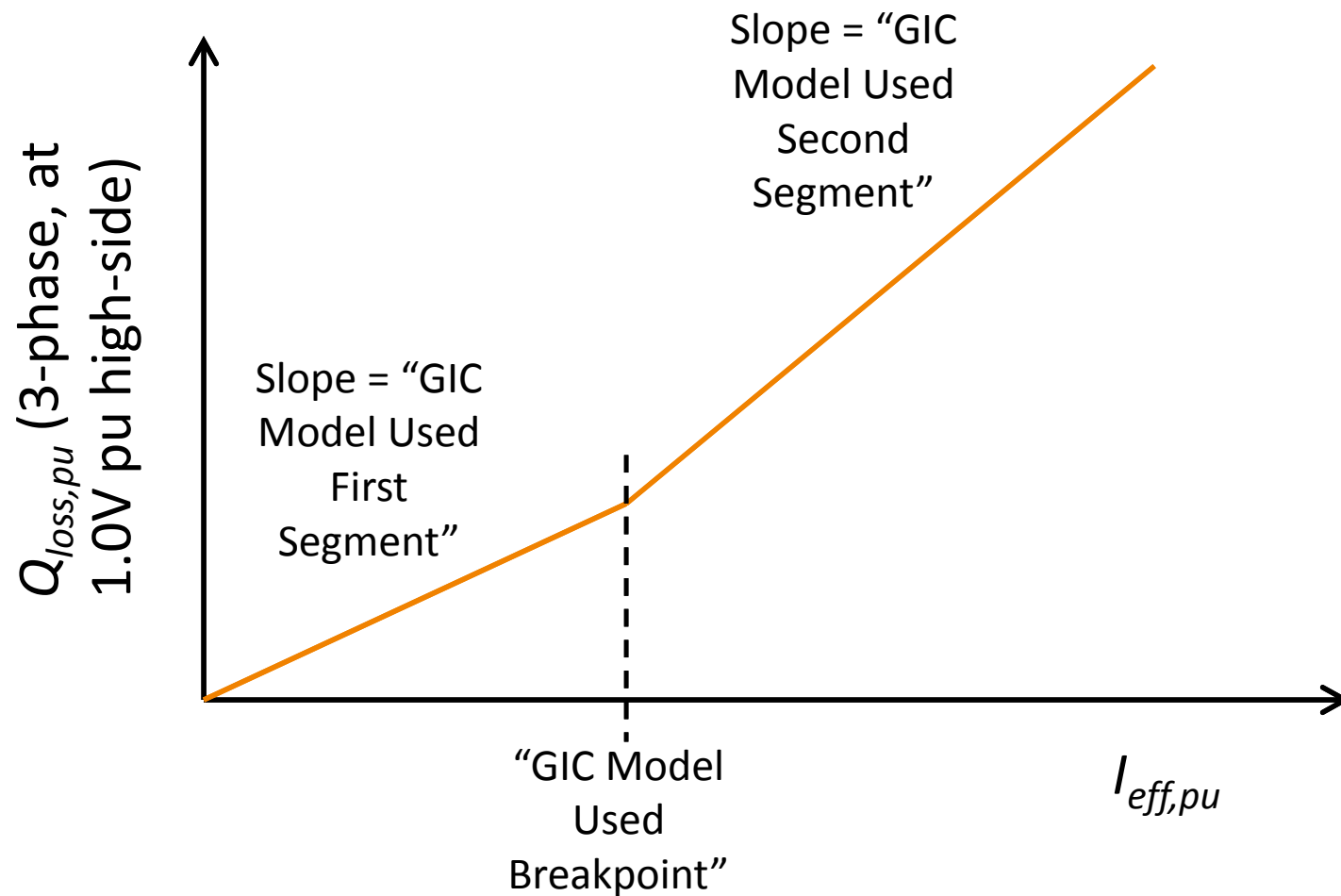


- *K-Factor* may be entered directly as a 2-step piecewise linear value with “GIC Model Type” set to **Piecewise Linear**

Core Type	GIC Model Type	GIC Model First Segment Slope	GIC Model Param Break Point	GIC Model Param Second Segment Slope	GIC Model Used First Segment	GIC Model Used Break Point	GIC Model Used Second Segment
Single Phase	Piecewise Linear	1.000	0.050	1.500	1.000	0.050	1.500
Single Phase	Default	0.000	0.000	0.000	1.800	0.000	1.800

- Break point is $I_{eff,pu}$
- With “GIC Model Type” set to **Default**, K-Factor is based on Core Type and parameters at **Options → AC Power Flow Model**

K-Factor



K-Factor Defaults



- **Options → AC Power Flow Model** (values used where “GIC Model Type” = **Default**)

Field/Voltage Input
Options
DC Current Calculation
AC Power Flow Model
Tables and Results
Areas
Buses
Generators
G-Matrix
Lines
Line Shunts
Switched Shunts
Substations
System Summary
Transformers
Sensitivity Analysis
Non-Uniform Electric Field Scaling
Geomagnetic Latitude Scaling
Earth Resistivity Scaling
Time Varying Electric Field Scaling

DC Current Calculation AC Power Flow Model

Default Transformer Core Type Effective GIC to Mvar Loss Scalings

Core Type	First Segment Per Unit Value	Per Unit Break Point	Second Segment Per Unit Value
Single Phase (Three Separate Cores)	1.80	0.000	1.80
Three Phase, Shell Form Generic	1.45	0.000	1.45
Three Phase, Core Form Generic	1.50	0.000	1.50
Three Phase, 3-Legged	0.00	0.038	1.75
Three Phase, 5-Legged	1.50	0.000	1.50
Three Phase, 7-Legged	1.20	0.000	1.20
Unknown Core, > 400 kV	1.80	0.000	1.80
Unknown Core, > 200 kV	1.50	0.000	1.50
Unknown Core, <= 200 kV	1.50	0.000	1.50

Reset All Scalings to Default Values

If the core type is known, then the core-type specific fields are used. Otherwise the "Unknown Core" values are used, based on the highest nominal voltage. Values are only used if the GIC Model Type field is "Default."

Transformer reactive power losses are modeled as a function of Ieffective using a two segment piecewise linear model. Values are in per unit using the peak current for the transformer as a base. That is, $I_{base} = S_{base} * 1000 * \sqrt{2} / (V_{base} * \sqrt{3})$; for example with $S_{base} = 100\text{MVA}$, $V_{base} = 500\text{kV}$, $I_{base} = 163.3\text{ A}$.

Save Setting to Aux Load AUX Save in PSSE GIC Format Load in PSSE GIC Format Clear All GIC Input Fields Close Help

Other Modeling Assumptions



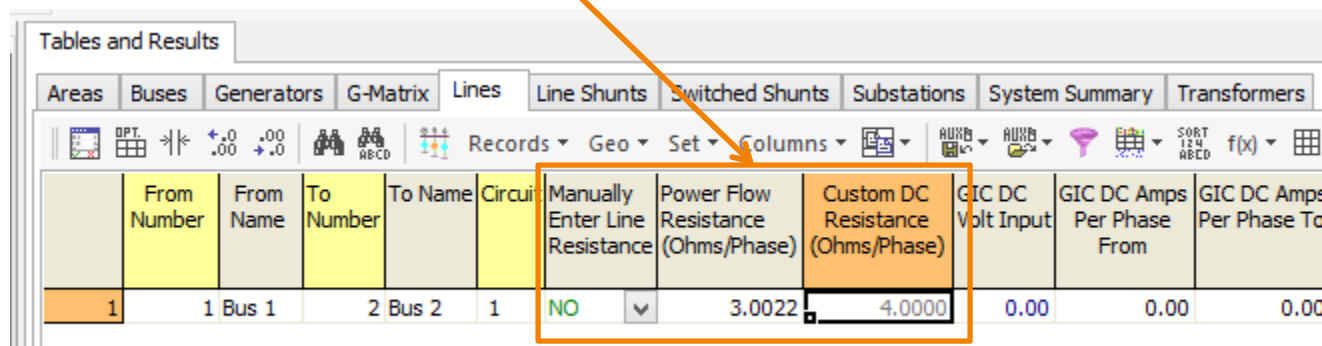
- **Options → DC Current Calculation**

- Minimum Voltage Level to Include in Analysis (kV):
transmission lines below this level are assumed to have zero GIC DC voltage input
- Automatic Insertion of Substations for Buses without Substations
 - It is strongly recommended to assign all buses to substations and all substations to latitude/longitude locations, at least within the GIC study footprint
 - Default assumption is to model unlocated facilities as ungrounded
 - Lines that terminate in unlocated substations do not have GIC DC input voltage

Four Bus Inputs: Transmission Lines



- DC resistance is derived from AC per-unit resistance and the impedance base by default (assumes skin effect is negligible at 60 Hz)
- You may also specify DC resistance
 - **Manually Enter Line Resistance = YES**
 - Provide value in **Custom DC Resistance (Ohms/Phase)**



Tables and Results										
Areas Buses Generators G-Matrix Lines Line Shunts Switched Shunts Substations System Summary Transformers										
Records Geo Set Columns										
	From Number	From Name	To Number	To Name	Circuit	Manually Enter Line Resistance	Power Flow Resistance (Ohms/Phase)	Custom DC Resistance (Ohms/Phase)	GIC DC Volt Input	GIC DC Amps Per Phase From
1	1	Bus 1	2	Bus 2	1	NO	3.0022	4.0000	0.00	0.00

Area Inputs



- Ignore GIC Losses: If YES, area transformers are assumed to have no reactive power loss
- Ignore GIC DC Volts: If YES, area transmission lines have zero GIC DC voltage input

GIC Analysis Form

Calculation Mode
☒ Single Snapshot
☐ Time Varying Series Voltage Inputs
☐ Time Varying Electric Field Inputs

Calculate GIC Values Clear GIC Values ☐ Include GIC in Power Flow Validate Input Data for GIC

Select Step

- Field/Voltage Input
 - Options
 - DC Current Calculation
 - AC Power Flow Model
 - Tables and Results
 - Areas
 - Buses
 - Generators
 - G-Matrix
 - Lines
 - Substations
 - Transformers

Tables and Results

Areas Buses Generators G-Matrix Lines Substations Transformers

Area Num	Area Name	Ignore GIC Losses	Mvar Losses	Ignore GIC DC Volts	Use Case Default Trans/Dist Voltage	Minimum Trans. kV	Default Trans. Side XF Config	Default Dist. Side XF Config
1	1 Home	NO	74.22	NO	YES	100.0	Case Default	Case Default

Save Setting to Aux Load AUX Close Help

Area Inputs



- These settings override the global options on **Options → DC Current Calculation**
 - *Use Case Default Trans/Dist Voltage*: set to NO to allow the area to have a different delineation between transmission and distribution voltage
 - *Default Trans. Side XF Config*
 - *Default Dist. Side XF Config*

G-Matrix



- Diagonal terms are the sum of the 3-phase conductance of all incident devices
- Off-diagonal terms are the negative of the 3-phase conductance between the nodes

Tables and Results

Areas		Buses	Generators	G-Matrix	Lines	Line Shunts	Switched Shunts	Substations	System Summary	Transfo
1	Sub 1 (Sub A)	Sub Sub A (1)	15.0000		-10.0000		-0.0000			
2	Sub 2 (Sub B)	Sub Sub B (2)		15.0000		-10.0000		-0.0000		
3	Bus 1 (Bus 1)	Bus Bus 1 (1)	-10.0000		10.9993	-0.9993	0.0000			
4	Bus 2 (Bus 2)	Bus Bus 2 (2)		-10.0000	-0.9993	10.9993		0.0000		
5	Bus 3 (Bus 3)	Bus Bus 3 (3)	-0.0000		0.0000		0.0000			
6	Bus 4 (Bus 4)	Bus Bus 4 (4)		-0.0000		0.0000		0.0000		

G-Matrix

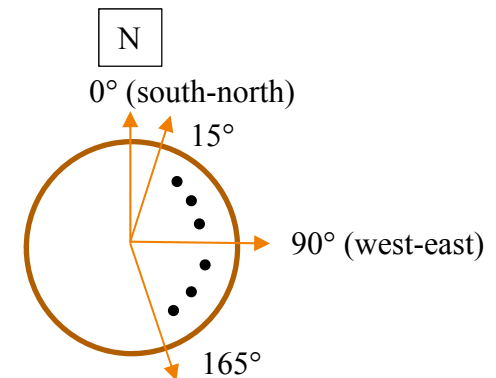


- Each bus and each substation neutral is a node in the DC network
- Bus and substation neutral DC Voltages (vector $\mathbf{V}$) are solved with $\mathbf{V}=\mathbf{G}^{-1}\mathbf{I}$, where
 - $\mathbf{G}$ is the 3-phase conductance matrix
 - $\mathbf{I}$ is a vector of Norton equivalent DC current injections from the GMD-induced electric fields
- Similar in form to the power flow admittance matrix, except with only real conductance
- Equation is linear and may be solved in a single step without iteration

Uniform Electric Field Modeling



- **Calculation Mode** = “Single Snapshot”
- **Field/Voltage Input**
 - Electric-Field Magnitude (V/mile or V/km)
 - Storm Direction (0 to 360 degrees)

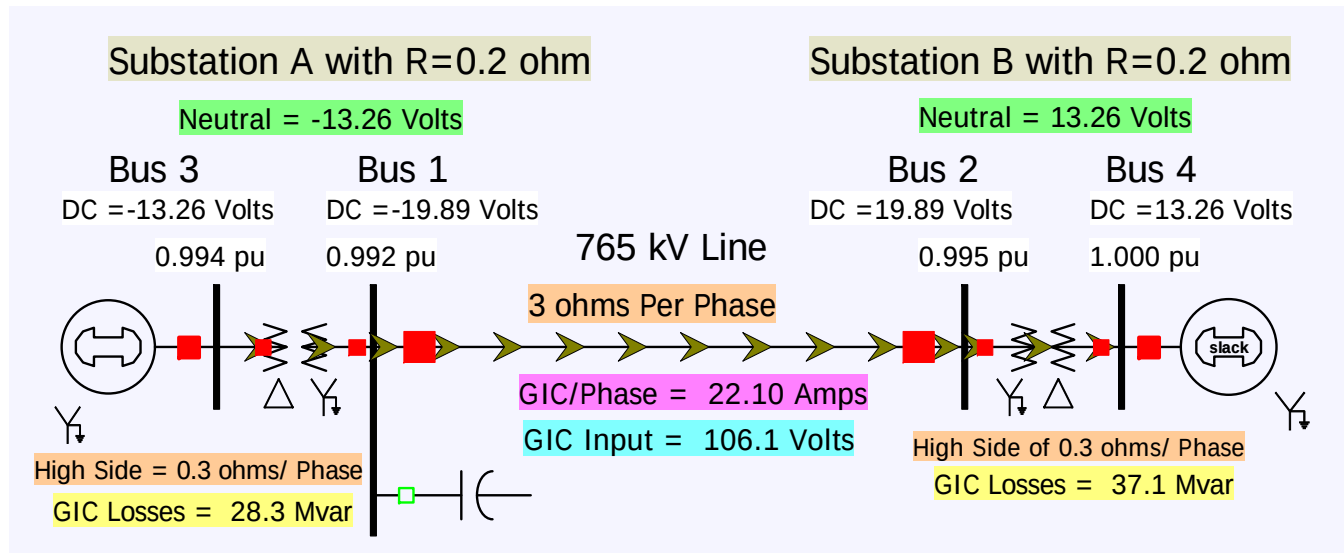


α and β scaling factors
for Benchmark Event

Uniform Electric Field Modeling



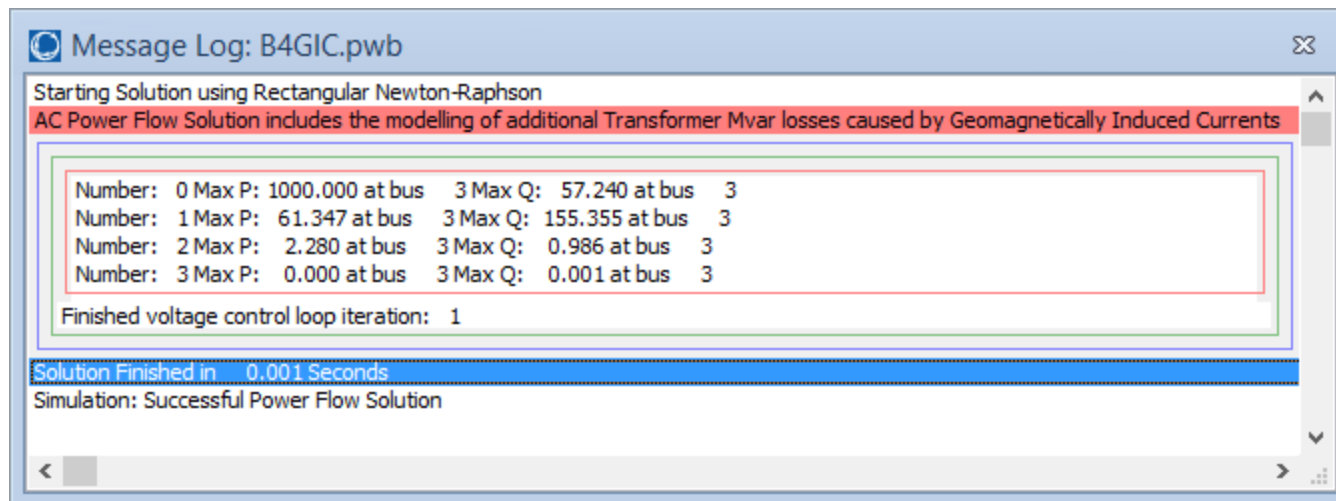
- Enter **Maximum Field** = 1 V/mile; **Storm Direction** = 90 degrees (eastward)
- Check **Also Calculate Maximum Direction Values** and **Include GIC in Power Flow**
- Click **Calculate GIC Values**
- Simulator computes DC voltages, GIC, and reactive losses
- Animated flows show GIC from *Custom Float 1* field (**Online Display Options** → **Animated Flows**)



Include GIC in Power Flow



- Checkbox on GIC Analysis Form
- Subsequent solutions of AC power flow include transformer GIC reactive power losses



Maximum Direction Values



- Indicate Storm Direction that results in maximum (and sometimes minimum) values for various quantities, and the resulting quantities
- Transformers: MVar Losses and Neutral Current
- Areas: MVar Losses
- System Summary: MVar Losses

Maximum Direction Values



- In this case, maximum direction aligns with the only transmission line (90 degrees)
- Minimum direction is orthogonal to the line (0 degrees)

Tables and Results

Areas	Buses	Generators	G-Matrix	Lines	Line Shunts	Switched Shunts	Substations	System Summary	Transformers
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System Summary

Total Mvar Losses in Specified Direction	65.7
Total Mvar Losses in Maximum Direction	65.7
Maximum Direction, Degrees	90
Total Mvar Losses in Minimum Direction	0.0
Minimum Direction, Degrees	0

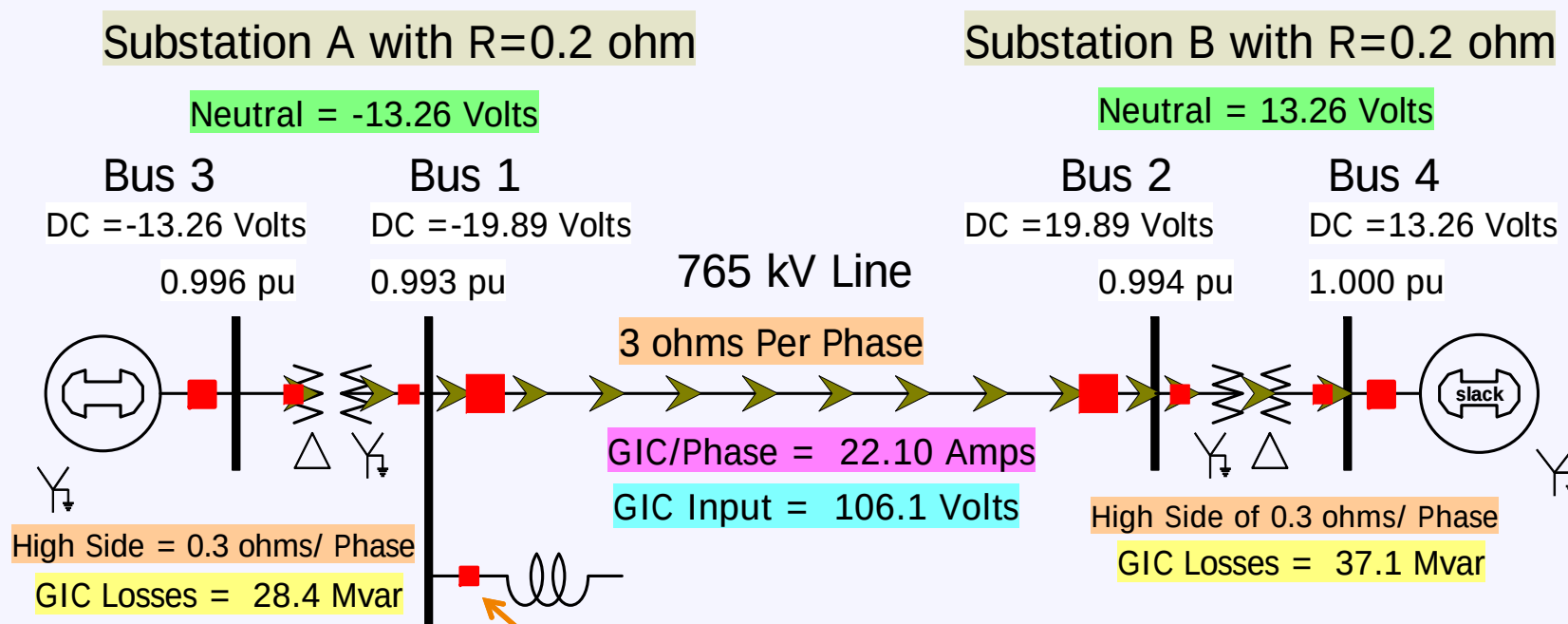
Note, maximum and minimum values are only computed for uniform direction fields

Switched Shunts



- Shunts operating as inductors can also provide a conducting path for GIC
- Simulator assumes shunts have infinite resistance by default, but resistances may be provided by the user
- Inductors are assumed to have non-magnetic core designs and thus not subject to saturation and MVar losses as in transformers (i.e. $K=0$)
- Shunts operating as capacitors always have infinite resistance

Switched Shunt Example



Close this

Switched Shunt Example



- Right click on the shunt, choose “Show Dialog” and the *GIC* tab
- Set the “Per-Phase Reactor GIC Grounding Resistance” to 0.5 ohms
- Optionally “Scale Conductance for Reactors with Multiple Blocks”
 - The provided resistance applies when all inductive blocks are in service
 - If half of the available blocks are in service, the resistance is twice as much
- Optional neutral resistance (3-phase)
- Click OK to close the dialog

Switched Shunt Information for Current Case

Bus Number: 1 Find By Number
 Bus Name: Bus 1 Find By Name
 Shunt ID: 1 Find ...
 Labels: no labels

Status:
☐ Open
☒ Closed
 Energized:
☐ NO (Offline)
☒ YES (Online)

Parameters Control Options Fault Information Owners, Area, Zone Custom Stability GIC

GIC Input Fields
 Per Phase Reactor GIC Grounding Resistance (in Ohms, Zero is Treated as Infinite) 0.500
☒ Scale Conductance for Reactors with Multiple Blocks
 Neutral Resistance (in Ohms) 0.000

Note: The resistance should be the value per phase. Hence the total resistance for all three phases is one third this value. The resistance is ignored when the switched shunt value is capacitive. If the Scale Conductance box is checked, with conductance value is scaled based on the percentage of reactors that are actually connected. The resistance field then gives the minimum resistance (maximum conductance). The Neutral Resistance models any extra resistance in the switched shunt neutral; hence it is in series with the three phase resistance of the reactor.

GIC Results
 DC Voltage (Volts) -19.889 Substation DC Voltage (Volts) -13.259
 Neutral Flow (Amps) -39.778
 Used total three phase conductance (Siemens) 6.000

OK Cancel Save ? Help Print

Time-Varying Series Voltage Inputs



- Allows direct entry of GIC DC input voltage on each transmission line
- At time zero, enter E-field of zero

Calculation mode

Time and Field input

Click **Add at Time**

The screenshot shows the 'GIC Analysis Form' window. The 'Calculation Mode' section has three radio buttons: 'Single Snapshot', 'Time Varying Series Voltage Inputs' (selected), and 'Time Varying Electric Field Inputs'. The 'Current Time' is set to 0.00. The 'Field/Voltage Input' section has a tab 'AC Line Input Voltages' with a table of input voltages. The table has columns: Object ID, From Number, To Number, Circuit, From Latitude, To Latitude, From Longitude, To Longitude, and Timepoint_1. The table contains four rows of data. The 'Input at Time (Seconds)' is set to 0.00. The 'Add at Time' button is highlighted with an orange arrow and the text 'Click Add at Time'.

Object ID	From Number	To Number	Circuit	From Latitude	To Latitude	From Longitude	To Longitude	Timepoint_1
1 Time in Seconds								0.000
2 Branch '1' '2' '1'	1	2	1	40.0000	40.0000	-89.0000	-87.0000	0.000
3 Branch '1' '3' '1'	1	3	1	40.0000	40.0000	-89.0000	-89.0000	0.000
4 Branch '2' '4' '1'	2	4	1	40.0000	40.0000	-87.0000	-87.0000	0.000

Time-Varying Inputs



- At time = 1 sec, add 1 volt/mile at 90 degrees
- For each **Add at Time**, a column of DC Input Voltages is added

GIC Analysis Form

Calculation Mode
☐ Single Snapshot
☒ Time Varying Series Voltage Inputs
☐ Time Varying Electric Field Inputs

Calculate GIC Values Clear GIC Values ☐ Include GIC in Power Flow Validate Input Data for GIC

Current Time 0.00 ☐ Calculate GIC on Time Change

Select Step
Field/Voltage Input
Options
DC Current Calculation
AC Power Flow Model
Tables and Results
Areas
Buses
Generators
G-Matrix
Lines
Substations
Transformers
Sensitivity Analysis
Non-Uniform Electric Field Scaling
Geomagnetic Latitude Scaling
Earth Resistivity Scaling
Time Varying Electric Field Inputs

Field/Voltage Input

AC Line Input Voltages

Object ID	From Number	To Number	Circuit	From Latitude	To Latitude	From Longitude	To Longitude	Timepoint_1	Timepoint_2
1 Time in Seconds								0.000	1.000
2 Branch '1' '2' '1'	1	2	1	40.0000	40.0000	-89.0000	-87.0000	0.000	106.123
3 Branch '1' '3' '1'	1	3	1	40.0000	40.0000	-89.0000	-89.0000	0.000	0.000
4 Branch '2' '4' '1'	2	4	1	40.0000	40.0000	-87.0000	-87.0000	0.000	0.000

Input at Time (Seconds) 1.00 Add at Time Delete at Time Delete All

Voltage Input Parameters

Electric Field Model Parameters
Maximum Field 1.00 Volts/mile
Storm Direction 90.0 Degrees

Restrict Lines to which to model DC Voltages
Minimum Line Length 1.00 mile
☐ Calculate Voltages for Equivalent Lines

Units of Distance
☐ Kilometers
☒ Miles

Geomagnetic Latitude Scaling Function No Scaling
Earth Resistivity Scaling Region Set No Resistivity Scaling

Save Setting to Aux Load AUX Close Help

Time-Varying Inputs



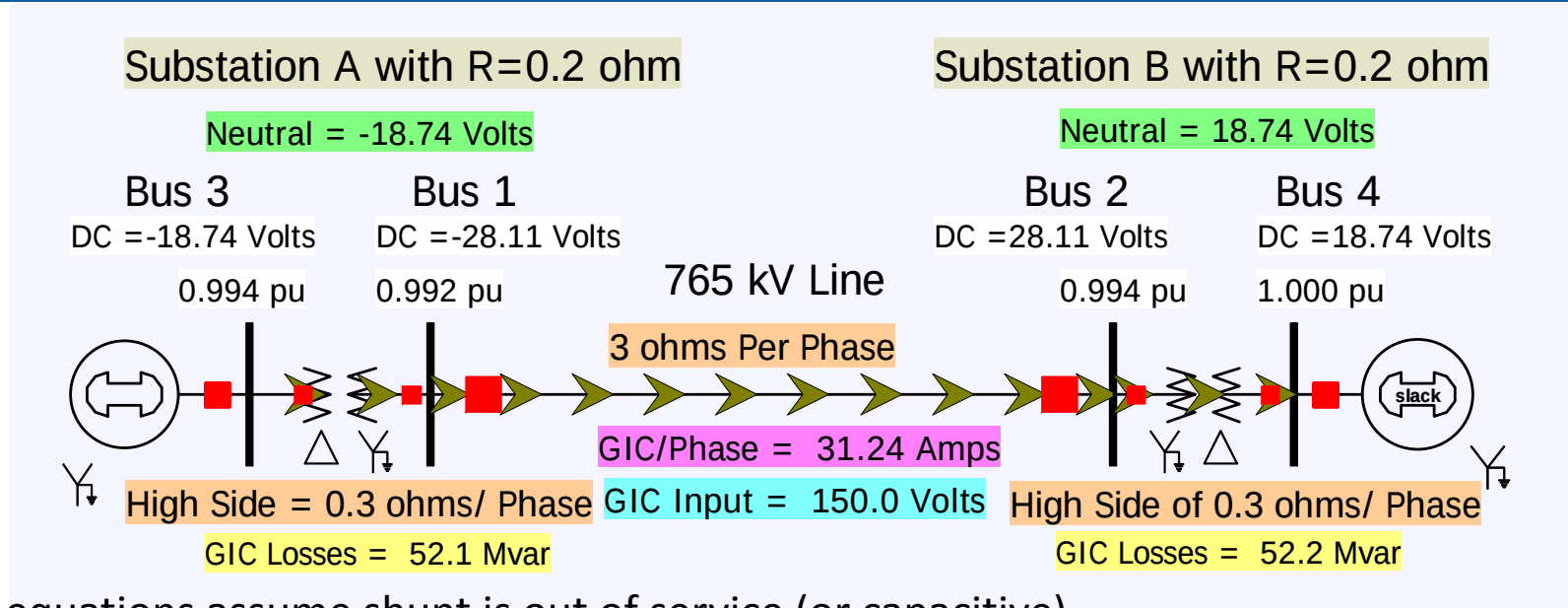
- Change “Current Time” and click **Calculate GIC Values** or check “Calculate GIC on Time Change” box
- Values are linearly interpolated between Timepoints for which inputs are provided
- You may also manually edit input voltages or timepoint values

AC Line Input Voltages

Object ID	From Number	To Number	Circuit	From Latitude	To Latitude	From Longitude	To Longitude	Timepoint_1	Timepoint_2
1 Time in Seconds								0.000	1.000
2 Branch '1' '2' '1'	1	2	1	40.0000	40.0000	-89.0000	-87.0000	0.000	150.000
3 Branch '1' '3' '1'	1	3	1	40.0000	40.0000	-89.0000	-89.0000	0.000	0.000
4 Branch '2' '4' '1'	2	4	1	40.0000	40.0000	-87.0000	-87.0000	0.000	0.000

GIC DC Volt
Input
changed to
150 V

GIC DC Volt Input = 150 V



Note: equations assume shunt is out of service (or capacitive)

$$I_{GIC,3Phase} = \frac{150 \text{ volts}}{(1 + 0.1 + 0.1 + 0.2 + 0.2) \Omega} = 93.75 \text{ amps or } 31.25 \text{ amps/phase}$$

Line series resistance: 0.000513 pu at Z_{base} of 5852.25 Ω = 3 Ω /phase or 1 Ω , 3-phase

Transformer high side 0.3 Ω /phase or 0.1 Ω each, 3-phase

Substation grounding resistance 0.2 Ω each, 3-phase

Impact of Earth Models



- The magnitude of the induced electric field depends upon the rate of change in the magnetic field, and deep earth (potentially 100s of km) conductivity
- The relationship between changing magnetic fields and electric fields are given by the Maxwell-Faraday Equation

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (\text{the } \nabla \times \text{ is the curl operator})$$

$$\oint_{\partial \Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S} \quad \text{Faraday's law is } V = -\frac{d\lambda}{dt}$$

Background on Relationship Between dB/dT and E



- The magnetic field variation in the atmosphere induces currents in the earth that somewhat cancel the magnetic field variation
 - Lenz's law says the direction of any induced current is always such that it will oppose the change that produced it
- The induced fields tend to cancel the magnetic field variation, leading to decreased fields. This gives rise to a frequency dependent skin depth

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

where f is the B field variation in Hz

μ is the magnetic permeability ($4\pi \times 10^{-7}$ H/m here)

σ is the conductivity in S/m

As an example,
at 0.01 Hz and
conductivity of
0.01 S/m the skin
depth is 50.3 km

Frequency Domain Analysis With Uniform Conductance



- If the earth is assumed to have a single conductance, σ , then

$$Z(\omega) = \frac{j\omega\mu_0}{\sqrt{j\omega\mu_0\sigma}} = \sqrt{\frac{j\omega\mu_0}{\sigma}}$$

- The magnitude relationship is then

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

$$|E(\omega)| = |Z(\omega) H(\omega)|$$

$$= \left| \sqrt{\frac{j\omega\mu_0}{\sigma}} \frac{B(\omega)}{\mu_0} \right|$$

For example, assume

σ of 0.001 S/m and

a 500nT/minute maximum

variation at 0.002 Hz.

Then $B(\omega) = 660 \times 10^{-9}$ T and

$$E(\omega) = \sqrt{\frac{2\pi \times 0.002 \times \mu_0}{0.001}} \frac{660 \times 10^{-9} \text{ T}}{\mu_0}$$

$$E(\omega) = 0.00397 \times 0.525 = 2.1 \text{ V/km}$$

1-D Earth Models

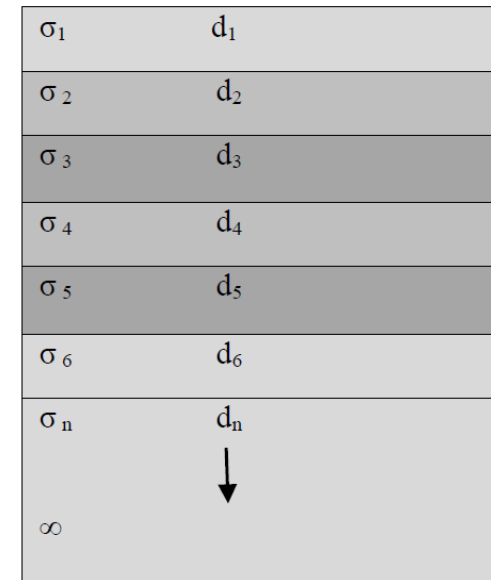


- With a 1-D model the earth is model as a series of conductivity layers of varying thickness
- The impedance at a particular frequency is calculated using a recursive approach, starting at the bottom, with each layer m having a propagation constant

$$k_m = \sqrt{j\omega\mu_0\sigma_m}$$

- At the bottom level n

$$Z_n = \frac{j\omega\mu_0}{k_n}$$



1-D Layers

Image: Figure 3.1 from NERC Application Guide: Computing Geomagnetically-Induced Current in the Bulk-Power System, December 2013

1-D Earth Models



- Above the bottom layer, each layer m , has a reflection coefficient associated with the layer below

$$r_m = \frac{(1 - k_m) \frac{Z_{m+1}}{j\omega\mu_0}}{(1 + k_m) \frac{Z_{m+1}}{j\omega\mu_0}}$$

- With the impedance at the top of layer m given as

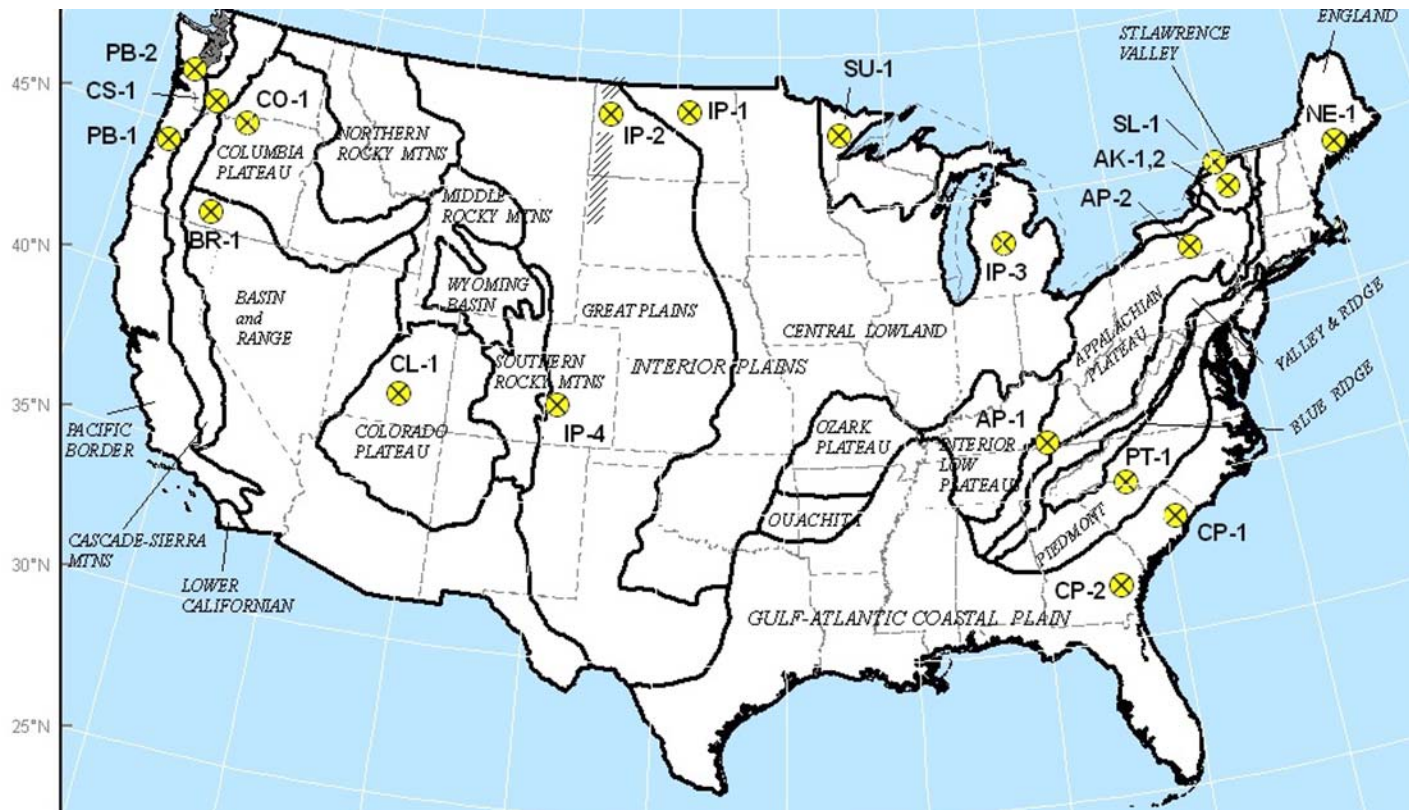
$$Z_m = j\omega\mu_0 \left(\frac{1 - r_m e^{-2k_m d_m}}{k_m (1 + r_m e^{-2k_m d_m})} \right)$$

- Recursion is applied up to the surface layer

USGS 1-D Conductivity Regions



- The USGS has broken the continental US into about 20 conductivity (resistivity) regions



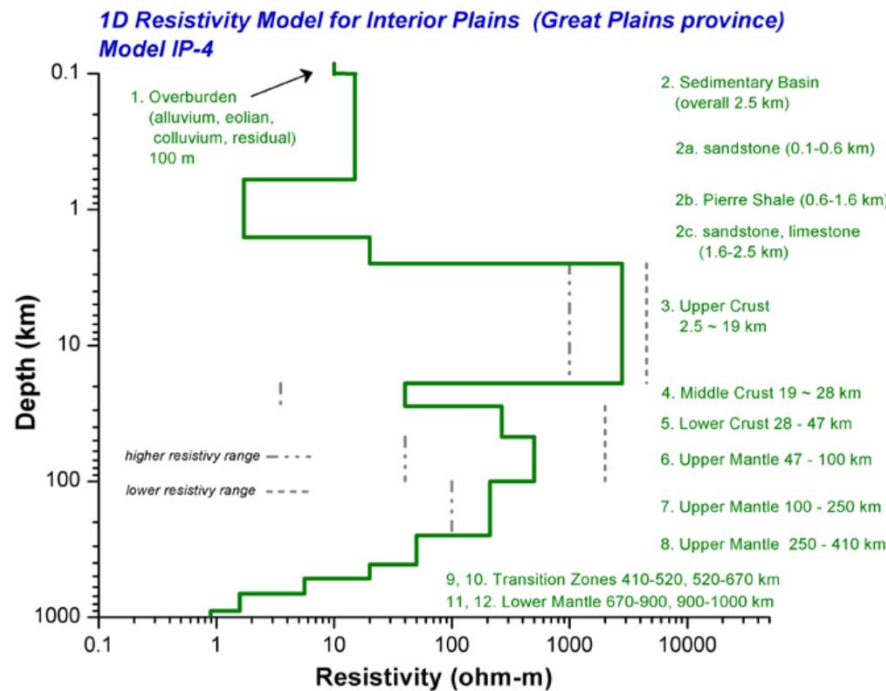
These region scalings are now being used for power flow GMD analysis

Image from the NERC report; data is available at <http://geomag.usgs.gov/conductivity/>

1-D Earth Models

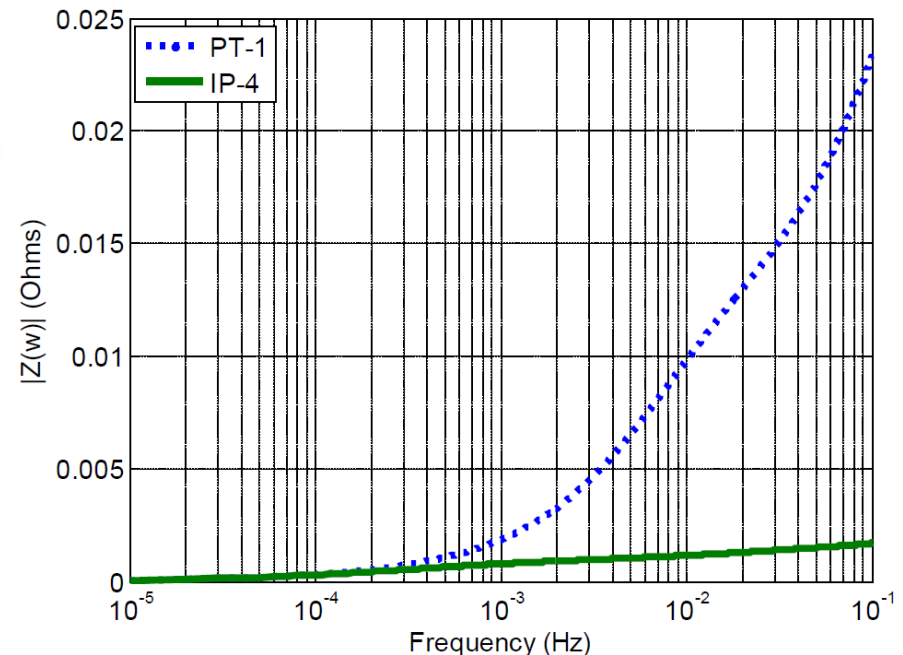


- Image on left shows an example 1-D model, whereas image on right shows the $Z(w)$ variation for two models



Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure 9: Frequency response of two layered Earth conductivity models.



Benchmark GMD Event



- Waveshape based on March 1989 Quebec event, with 10-second sampling and amplitude scaled to a statistically estimated 1-in-100 year event
- Peak surface electric field magnitude is 8 V/km at a reference location in Quebec at 60°N geomagnetic latitude
- Scaling for other locations is based on local geomagnetic latitude and earth resistivity

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

$$\alpha = 0.001e^{0.115L}$$

Where β is a scaling factor for earth resistivity
and L is geomagnetic latitude in degrees

Benchmark GMD Event Example



- Open *Texas2000.pwb*
- Solve power flow and **Set Present Case as Base Case in Difference Flows**
- Benchmark GMD Event
 - Load *NERC_USGS_2014_Regions.aux* for Earth Resistivity β factors
 - Enter GIC Electric Field of 8 V/km at 0 degrees, Single Snapshot mode
- Leave default transformer and substation parameters
- Disable voltage controllers globally in Simulator Options

Benchmark GMD Event Example



Include GIC in Power Flow

Calculate
Max
Direction

$$E_{\text{peak}} = 8 \text{ V/km}$$

β based on USGS earth resistivity
models loaded from aux

α calculated from
Equation II-1 in
NERC Guide

Benchmark GMD Event Example



GIC Analysis Form

Calculation Mode
☒ Single Snapshot
☐ Time Varying Series Voltage Inputs
☐ Time Varying Electric Field Inputs

Buttons: Calculate GIC Values, Clear GIC Values, ☒ Include GIC in Power Flow, Validate Input Data for GIC

☒ Update Line Voltages (Show be True Unelss Explicitly Entered)

Select Step

- Field/Voltage Input
- Options
 - DC Current Calculation**
 - AC Power Flow Model
- Tables and Results
 - Areas
 - Buses
 - Generators
 - G-Matrix
 - Lines
 - Line Shunts
 - Switched Shunts
 - Substations
 - System Summary
 - Transformers
- Sensitivity Analysis
- Non-Uniform Electric Field Sc
 - Geomagnetic Latitude Sc
 - Earth Resistivity Scaling
 - Earth Resistivity Scaling
 - Time Varying Electric Field Ir

Options

DC Current Calculation AC Power Flow Model

Minimum Voltage Level to Include in Analysis (kV) 200.00

Automatic Determination of Autotransformers

When to model as an Autotransformer when status is Unknown

Maximum Turns Ratio (High to Secondary Winding) 4.00

Minimum Medium Voltage to Assume Autotransformer 50.00

Default Trans. Side Config
☒ Delta
☐ Grounded Wye
☐ Ungrounded Wye

Default Dist. Side Config
☐ Delta
☒ Grounded Wye
☐ Ungrounded Wye

Note, values can also be specified for individual areas

Automatic Insertion of Substations for Buses without Substations

Where to Add a Substation
☐ Group buses with the same latitude/longitude
☐ Make one substation per bus
☒ Do not add substations - Model Bus Device Neutrals as Ungrounded

☐ Also insert substations for buses without latitude/ longitude coordinates

Buttons: Insert Substations, Delete Automatically Inserted Substations, Substation Geographic Consistency Check

Note: Substations should be defined to properly model the common grounding of all bus neutrals at a substation. If substations do not exist they will be automatically created when performing the GIC DC current calculation.

Buttons: Save Setting to Aux, Load AUX, Save in PSSE GIC Format, Load in PSSE GIC Format, Clear All GIC I

Calculate GIC DC
input voltages on
lines at 200 kV
and above

Benchmark GMD Event Example



- Calculate GIC Values
- Check **Tables and Results** → **System Summary**
- Maximum MVar Losses Occur with 93 degree direction
- Change Storm Direction to 93 degrees and recalculate GIC Values

GIC Analysis Form

Calculation Mode
☒ Single Snapshot
☐ Time Varying Series Voltage Inputs
☐ Time Varying Electric Field Inputs

Calculate GIC Values Clear GIC Values ☒ Include GIC in Power F

☒ Update Line Voltages (Show be True Unelss Explicitly Entered)

Select Step

- Field/Voltage Input
 - Options
 - DC Current Calculation
 - AC Power Flow Model
 - Tables and Results
 - Areas
 - Buses
 - Generators
 - G-Matrix
 - Lines
 - Line Shunts
 - Switched Shunts
 - Substations
 - System Summary
 - Transformers
 - Sensitivity Analysis
 - Non-Uniform Electric Field Sc
 - Geomagnetic Latitude Sc
 - Earth Resistivity Scaling
 - Earth Resistivity Scaling
 - Time Varying Electric Field Ir

Tables and Results

Areas Buses Generators G-Matrix Lines Line Shunts Switched Shun

Records Set Columns

System Summary

Total Mvar Losses in Specified Direction	1005.8
Total Mvar Losses in Maximum Direction	1174.8
Maximum Direction, Degrees	93
Total Mvar Losses in Minimum Direction	986.9
Minimum Direction, Degrees	156

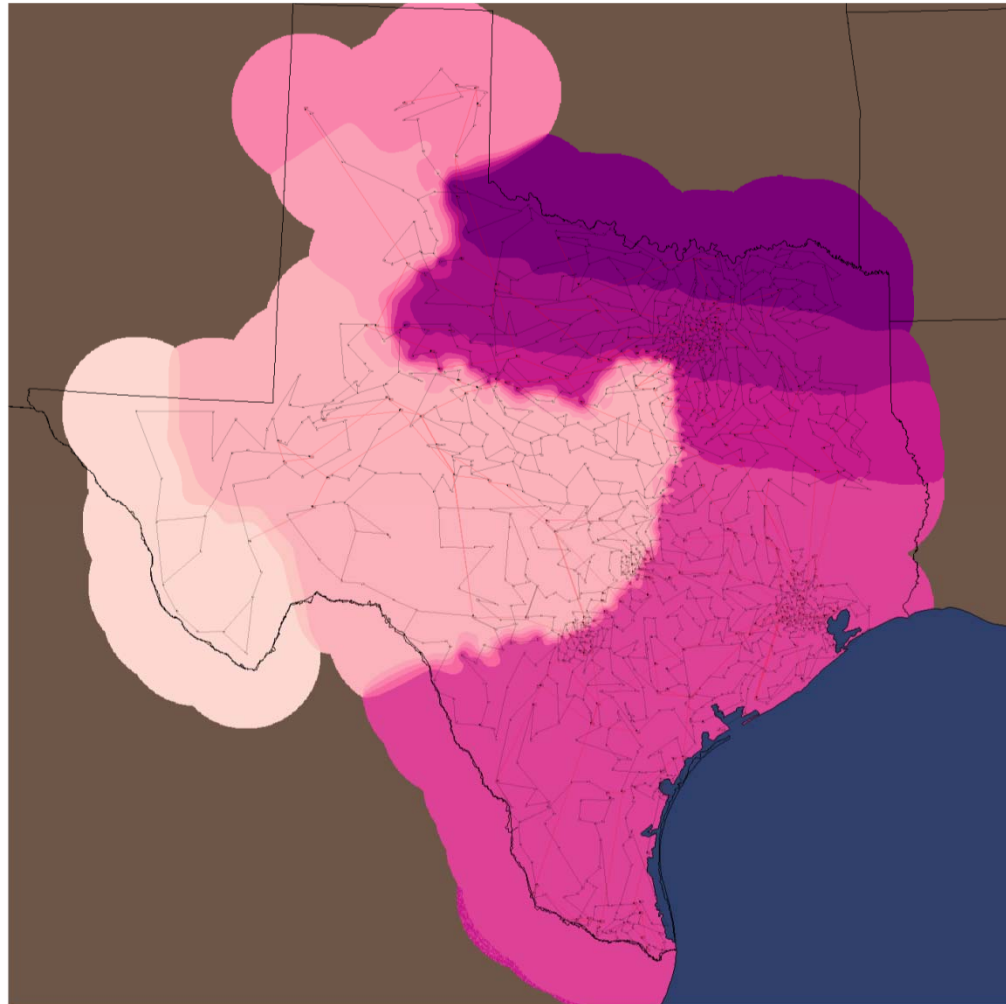
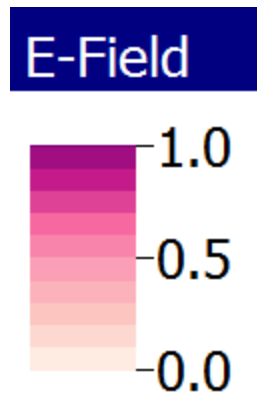
Note, maximum and minimum values are only computed for uniform direction fields

Save Setting to Aux Load AUX Save in PSSE GIC Format help

Benchmark GMD Event



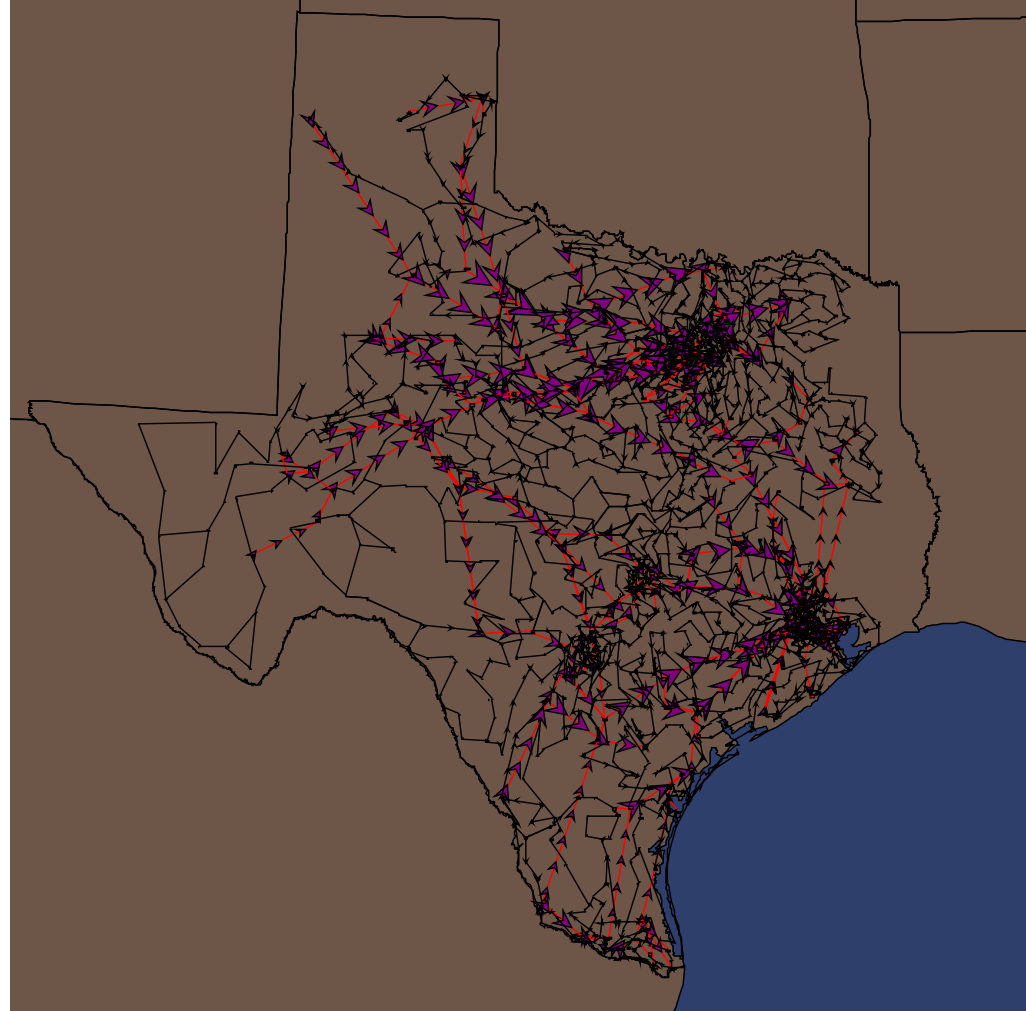
- E-field Contour (V/km)



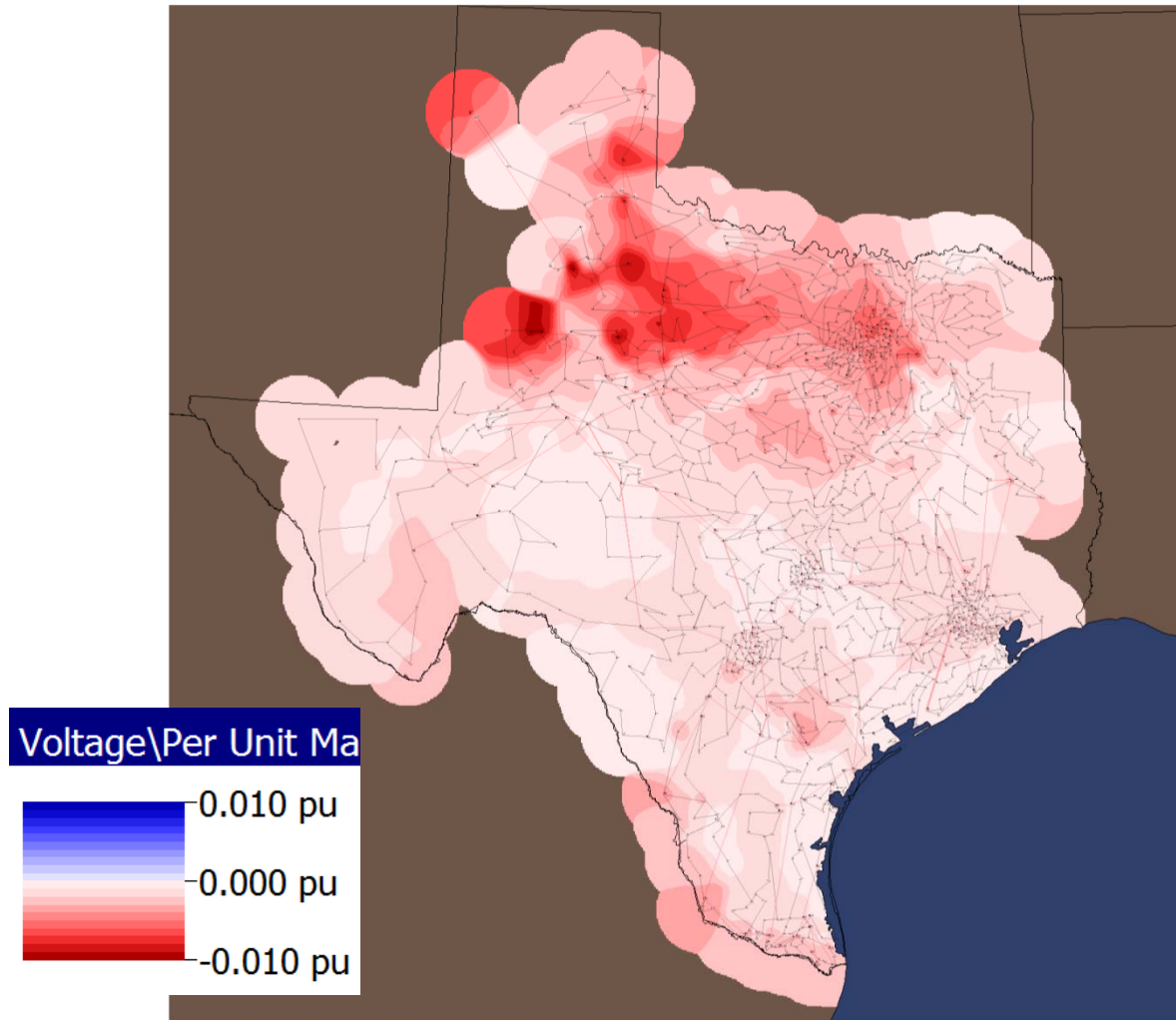
Benchmark GMD Event Example



- Show Custom Float 1 in Animated Flows



Difference Flows: Voltage Contour



Benchmark Event Time Series



- Simulator (version 20) can automatically generate a csv file of GIC(t) time series for a uniform time-varying $E(t)$ field
- Sample input file
NERC_GMDBenchmarkEventTimeSeries.csv
 - 10-second samples matching **Figures 2 and 3** in the NERC *Benchmark Geomagnetic Disturbance Event Description*
 - fields are time, eastward $E(t)$, and northward $E(t)$ in V/km
- Output is GIC(t) for all transformers on the GIC Transformers display
 - it usually makes sense to filter this list (e.g. transformers with Maximum per-phase Effective GIC $\geq 75A$)

Benchmark Event Time Series



- From the Texas2000.pwb case, set Geomagnetic Latitude Scaling Function to “No Scaling”
- Leave other parameters unchanged
- Re-calculate GIC Values

GIC Analysis Form

Calculation Mode
☒ Single Snapshot
☐ Time Varying Series Voltage Inputs
☐ Time Varying Electric Field Inputs

Buttons: Calculate GIC Values, Clear GIC Values, ☐ Include GIC in Power Flow, Validate Input Data for GIC

☒ Update Line Voltages (Show be True Unless Explicitly Entered)

Load Time-Varying Input and Calculate Transformer IEffective

Select Step
 Field/Voltage Input

Field/Voltage Input

Voltage Input Parameters

Electric Field Model Parameters
 Maximum Field: 8.00 Volts/km
 Storm Direction: 0.0 Degrees
☒ Also Calculate Maximum Direction Values

Restrict Lines to which to model DC Voltages
 Minimum Line Length: 1.61 km
☐ Calculate Voltages for Equivalent Lines
☐ Calculate Voltages for Low R Lines

Units of Distance
☒ Kilometers
☐ Miles

Hotspot Modeling
☐ Include
 Scaling of Hotspot Magnitude
☒ Use Specified Value
☐ Scalar of Maximum Field

Hotspot Field in V/km: 12.43
 Width of Hotspot in Kilometers: 241.40
 Latitude of Center: 45.000
 Longitude of Center: -90.000

Modeling of Scaling and Hotspots
☐ Approximate with Substation Values
☒ Interpolate Along Line Path

Geomagnetic Latitude Scaling Function: No Scaling
 Earth Resistivity Scaling Region Set: NERC_USGS_2014

Scale Hotspot Value with Geomagnetic Latitude: ☐
 Scale Hotspot Value with Earth Resistivity: ☒

Buttons: Save Setting to Aux, Load AUX, Save in PSSE GIC Format, ☐ PSSE Save and Load Using AreaZone Filters, Load in PSSE GIC Format, Clear All GIC Input F

Benchmark Event Time Series



- Check **Tables and Results** → **Transformers**
- Load *Maximumleff.aux* to insert a field for the per-phase GIC at maximum direction
- Apply an advanced filter for transformers with maximum GIC ≥ 75 A
- Click “Load Time-Varying Input and Calculate Transformer Ieffective”

Benchmark Event Time Series



- Click “Load Time-Varying Input and Calculate Transformer Ieffective”

GIC Analysis Form

Calculation Mode
☒ Single Snapshot
☐ Time Varying Series Voltage Inputs
☐ Time Varying Electric Field Inputs

Buttons: Calculate GIC Values, Clear GIC Values, ☐ Include GIC in Power Flow, Validate Input Data for GIC

☒ Update Line Voltages (Show be True Unless Explicitly Entered)

Load Time-Varying Input and Calculate Transformer Ieffective

Select Step
 Field/Voltage Input
 Options
 DC Current Calculation
 AC Power Flow Model
 Tables and Results
 Areas
 Buses
 Generators
 G-Matrix
 Lines
 Line Shunts
 Switched Shunts
 Substations
 System Summary
 Transformers
 Sensitivity Analysis
 Non-Uniform Electric Field Simulation
 Geomagnetic Latitude Scaling
 Earth Resistivity Scaling

Tables and Results

Bus Num Med	Bus Name Med	Bus Num Ter	Bus Name Ter	Circuit	Transformer Per Phase Effective GIC, Amps	Transformer Per Unit Effective GIC	GIC Mvar Losses	Maximum Mvar Losses	Maximum Losses Direction (Degrees)	Maximum Phase E GIC, An	Ne (A)
1	1593 Wadsworth 2 G0	0		1	301.99	1.2760	199.0592	212.70	20.6323	322.68708	
2	87 Terrell 2 115	0		1	197.93	0.8363	126.0179	155.10	144.3380	243.61107	
3	290 North Richland Hills 115	0		1	28.37	0.1199	17.6714	149.35	83.2046	239.74708	
4	921 Lytle 115	0		1	65.69	0.2776	42.3000	146.59	106.7715	227.64141	
5	638 Houston 12 115	0		1	149.49	0.6317	95.0261	142.92	48.3278	224.84331	
6	421 De Leon 115	0		1	113.99	0.4817	74.3854	136.94	122.9016	209.85157	
7	1095 Lopeno 115	0		1	99.63	0.4210	65.4419	136.06	61.2507	207.13916	
8	447 Throckmorton 115	0		1	9.77	0.0413	6.3758	135.06	87.2943	206.99579	
9	1290 Memphis 115	0		1	189.55	0.8009	122.7865	133.21	157.1802	205.64316	
10	918 Laredo 5 115	0		1	169.85	0.7177	110.2239	126.25	29.1798	194.53389	
11	1676 Cooper G0	0		1	92.28	0.3899	60.8248	124.44	60.7394	188.78881	
12	115 Dallas 18 115	0		1	21.88	0.0924	13.6457	115.47	96.7869	185.10543	
13	742 Katy 115	0		1	179.91	0.7602	114.0466	116.85	12.5860	184.33756	
14	13 Plano 115	0		1	104.96	0.4435	65.7978	111.42	53.8040	177.73380	
15	883 Tivoli 3 115	0		1	58.08	0.2454	38.2020	116.83	70.9147	177.61802	
16	14 Plano 2 115	0		1	110.75	0.4680	69.2791	110.61	51.2208	176.82668	
17	942 Beeville 115	0		1	59.18	0.2501	38.8620	107.52	111.1883	163.73356	

Buttons: Save Setting to Aux, Load AUX, Save in PSSE GIC Format, ☐ PSSE Save and Load Using AreaZone Filters, Load in PSSE GIC Format, Clear All GIC Input Field

Benchmark Event Time Series



- Open the input file
NERC_GMDBenchmarkEventTimeSeries.csv
- Name an output csv file
- When the process is complete, open the output file in Excel
- Resulting time-series can then be input into thermal calculations
 - An example is in *GLCXfrHotSpotTempCalcs.xlsx*
 - Help is provided in cell comments
 - Copy one transformer's time series at a time into column G of the sheet *XfrTimeSeries*

Output CSV File



- First three columns are echoed from the input file: time, eastward $E(t)$, and northward $E(t)$ in V/km
- Transformer time series begin in Column D

	A	B	C	D	E	F	G	H
1	Time (Sec)	E_EW (V/km)	E_NS (V/km)	1786 (Dallas 10 345) [HIGH] ; 107 (Dallas 10 115) [MED] CKT 1	1788 (Coo	1788 (Coo	1788 (Coo	1796 (H
2	10	0.019	0.038	0.241	0.347	0.347	0.838	0.4
3	20	0.015	0.05	0.177	0.367	0.367	0.887	0.5
4	30	0.028	0.014	0.389	0.31	0.31	0.75	0.3
5	40	0.022	-0.032	0.329	0.033	0.033	0.08	0
6	50	0.014	0.015	0.186	0.19	0.19	0.459	0
7	60	0.01	0.018	0.131	0.175	0.175	0.423	0.1
8	70	0.027	-0.008	0.391	0.194	0.194	0.47	0.1
9	80	0.003	0.012	0.03	0.081	0.081	0.196	0.1
10	90	0.019	0.013	0.257	0.221	0.221	0.534	0.1
11	100	0.018	0.008	0.242	0.189	0.189	0.458	
12	110	0.031	0.006	0.438	0.298	0.298	0.72	0.1
13	120	0.006	0.024	0.062	0.165	0.165	0.399	0.1
14	130	0.002	0.001	0.028	0.02	0.02	0.049	0
15	140	0.004	0.017	0.048	0.119	0.119	0.287	0.1
16	150	0.005	-0.003	0.07	0.026	0.026	0.064	0
17	160	0.005	0.034	0.042	0.205	0.205	0.495	0.1
18	170	0.005	0.011	0.059	0.092	0.092	0.222	0.1

Thermal Calculation Spreadsheet



- Transformer Properties on *Parameters* sheet
- Paste GIC(t) time series for a transformer starting in column G of *XfrTimeSeries*
- Temperature graphs on *TimeSeriesChart*

The screenshot shows the 'XfrTimeSeries' sheet in Excel. The formula bar displays '0.241' for cell G3. The table below represents the data in the spreadsheet:

	A	B	C	D	E	F	G
1	Time	BusNum3W	BusNum3W:1	BusNum3W:2	BusNum3W:3	LineCircuit	GICXEffective1
2	0						0
3	10	5	6	0	0	1	0.241
4	20	5	6	0	0	1	0.177
5	30	5	6	0	0	1	0.389
6	40	5	6	0	0	1	0.329
7	50	5	6	0	0	1	0.186
8	60	5	6	0	0	1	0.131
9	70	5	6	0	0	1	0.391
10	80	5	6	0	0	1	0.03
11	90	5	6	0	0	1	0.257
12	100	5	6	0	0	1	0.242
13	110	5	6	0	0	1	0.438
14	120	5	6	0	0	1	0.062
15	130	5	6	0	0	1	0.028
16	140	5	6	0	0	1	0.048
17	150	5	6	0	0	1	0.07
18	160	5	6	0	0	1	0.042
19	170	5	6	0	0	1	0.059

The status bar at the bottom shows: AVERAGE: 6.8886925 COUNT: 11200 SUM: 77153.356

Benchmark Event Resources



- PowerWorld's Knowledge Base has several resources for GIC modeling

<https://www.powerworld.com/knowledge-base?term20=gic&submit=Go>

- Complete time series for NERC Benchmark GMD Event
- Spreadsheet for transformer thermal response modeling
- Earth Resistivity Models

Sensitivity Analysis



- “Transformer $I_{\text{effective}}$ GIC Sensitivity” can identify transmission lines with greatest effect on transformer GIC current
- Sort transformers by $I_{\text{effective}}$
- Include Throckmorton 345/115 kV in Sensitivity Calculation
- Click **Recalculate Sensitivities**
- $dI_{\text{effective}}/dE_{\text{field}}$ indicates change in $I_{\text{effective}}$ for a 1 V/km variation in E-field on the line in question

Options

- DC Current Calculation
- AC Power Flow Model

Tables and Results

- Areas
- Buses
- Generators
- G-Matrix
- Lines
- Line Shunts
- Switched Shunts
- Substations
- System Summary
- Transformers
- Sensitivity Analysis

Sensitivity Analysis

☐ Line Amp Input Sensitivity

☒ Transformer Effective GIC Sensitivity

Sensitivity Options

Assumed Direction (Degrees, 0 to 360)

0.00

Assumed Field Direction

☒ Parallel to Line

☐ Specified Direction

Recalculate Sensitivities

Calculate Sub Driving Point Values

	Bus Num High	Bus Name High	Bus Num Med	Bus Name Med	Bus Num Ter	Bus Name Ter	Circuit	Include in Sensitivity Calculation	Transformer Phase Effect GIC, Amps
1	1900	North Richland Hills 1 345	290	North Richland Hills 1	0	1	1	NO	29.389
2	1802	Throckmorton 345	447	Throckmorton 115	0	1	1	YES	25.653
3	2006	Dallas 18 345	115	Dallas 18 115	0	1	1	NO	23.290
4	1882	Lytle 345	921	Lytle 115	0	1	1	NO	22.110
5	1788	Cooper 345	1676	Cooper G0	0	1	1	NO	20.816
6	2007	De Leon 345	421	De Leon 115	0	1	1	NO	20.778
7	1993	Terrell 2 345	87	Terrell 2 115	0	1	1	NO	19.109
8	1959	Garland 3 345	23	Garland 3 115	0	1	1	NO	17.927
9	2003	Lopeno 345	1095	Lopeno 115	0	1	1	NO	17.614
10	1924	Plano 1 345	13	Plano 115	0	1	1	NO	17.366

Lines

	From Number	From Name	To Number	To Name	Circuit	$dI_{\text{effective}}/dE_{\text{field}}$	$dI_{\text{effective}}/dV_{\text{line}}$	Distance Between Substations (km)	Compass Angle Between Substations
1	1802	Throckmorton 345	1845	Knox City 345	1	8.557	0.140	61.14	296.29
2	1801	Gordon 345	1802	Throckmorton 345	1	7.512	-0.068	109.66	307.37
3	1801	Gordon 345	1802	Throckmorton 345	2	7.512	-0.068	109.66	307.37
4	1802	Throckmorton 345	1842	Floydada 1 345	1	7.333	0.062	119.13	299.14
5	1802	Throckmorton 345	1860	Jacksboro 2 345	1	7.122	0.084	85.22	93.22
6	1949	Loving 345	1802	Throckmorton 345	1	6.752	-0.093	72.53	259.21
7	1949	Loving 345	1802	Throckmorton 345	2	6.752	-0.093	72.53	259.21
8	434	Loving 115	447	Throckmorton 115	1	2.176	0.030	72.53	259.21
9	1942	Muenster 1 345	1949	Loving 345	1	1.452	-0.013	111.75	248.33

345 kV lines into Throckmorton are responsible for most GIC

Sensitivity Analysis



- “Line Amp Input Sensitivity” shows the sensitivity of GIC quantities (currents, DC bus voltages) to a GIC injection on the selected transmission line
- Following the use of “Line Amp Input Sensitivity”, you must click **Calculate GIC Values** again to restore the GIC quantities for the simulated GMD event

Assumed GIC injection on line

Selected Line

Sensitivity Analysis

Type of Sensitivity Calculation

☒ Line Amp Input Sensitivity

☐ Transformer Ineffective GIC Sensitivity

Sensitivity Options

Assumed Line Injection (Amps) 1.00

Assumed Field Direction

☒ Parallel to Line

☐ Specified Direction

Choose the Transmission Line (for input sensitivities) or Transformer (for Ineffective Sensitivities)

Sort by ☐ Name ☒ Number

Filter Advanced Branch

☒ Use Area/Zone Filters Quick Define Remove

1842

Search For Near Bus

Select Far Bus, CKT

1838 (Manor 1 345) [345.0 kV]

1839 (Austin 17 345) [345.0 kV]

1840 (Austin 22 345) [345.0 kV]

1841 (Wheeler 345) [345.0 kV]

1842 (Floydada 1 345) [345.0 kV]

1843 (Odonnell 345) [345.0 kV]

1844 (Clyde 345) [345.0 kV]

1845 (Knox City 345) [345.0 kV]

1846 (O'Brien 345) [345.0 kV]

1847 (Ahilene 5 345) [345.0 kV]

1286 (Floydada 115) [115.0 kV] CKT 1

1770 (Floydada 1 GO) [13.80 kV] CKT 1

1802 (Throckmorton 345) [345.0 kV] CKT 1

1954 (Tell 345) [345.0 kV] CKT 1

Recalculate Sensitivities

Calculate Sub Driving Point Values

Buses	Lines	Substations	Transformers					
From Number	From Name	To Number	To Name	Circuit	Neutral Current (Amps)	Transformer Phase Effect GIC, Amps	Transformer Per Unit Effective GIC	Effective/d
1	1286 Floydada 115	1842 Floydada 1 345	1	0.308	0.125	0.00053		
2	1770 Floydada 1 GO	1842 Floydada 1 345	1	0.259	0.086	0.00036		
3	447 Throckmorton	1802 Throckmorton 3 1		-0.198	0.074	0.00031		
4	1697 Throckmorton	1802 Throckmorton 3 1		-0.117	0.039	0.00016		
5	1297 Tell 115	1954 Tell 345	1	0.096	0.034	0.00014		
6	434 Loving 115	1949 Loving 345	1	-0.062	0.016	0.00007		
7	1442 Jacksboro 2 1	1860 Jacksboro 2 345	1	-0.042	0.015	0.00006		
8	1607 Mcadoo 2 GO	1464 Mcadoo 2 115	1	0.035	0.012	0.00002		
9	1473 Olive 2 115	1872 Olive 2 345	1	-0.028	0.010	0.00004		

Substation Resistance Sensitivity



- Recent research has indicated that the GICs can be quite sensitive to the assumed grounding resistance; hence measured values are recommended
- The relative importance of a particular substation grounding resistance can be determined by comparing its value to the driving point resistance seen looking into the network at that location; these values can be computed quickly using sparse vector methods

$$\mathfrak{R}_i := \frac{R_i}{R_i + R_{TH,i}}$$

Substation Resistance Sensitivity Example



- Click **Calculate Sub Driving Point Values**
- Relative sensitivities for substations with high neutral GIC currents

Lines		Substations									
	Sub Num	Sub Name	Sub ID	GIC DC Neutral Voltage	GIC Amp Neutral	Grounding Resistance (Ohms)	GIC Used Grounding Resistance (Ohms)	Thevenin Resistance (Ohms)	Thevenin Voltage (Volts)	GIC Thevenin Ratio	Lat
1	446	Throckmorton	446	-26.33	-132.74	0.000	0.198	0.161	-47.705	0.552	33
2	135	Cooper	135	26.66	120.23	0.000	0.222	0.347	68.388	0.390	33
3	106	Dallas 10	106	16.91	93.41	0.000	0.181	0.077	24.097	0.702	32
4	1424	Baytown 4	1424	14.17	90.39	0.000	0.157	0.071	20.567	0.689	29
5	388	Electra	388	-14.98	-89.35	0.000	0.168	0.446	-54.780	0.273	33
6	86	Terrell 2	86	21.57	84.23	0.000	0.256	0.193	37.831	0.570	32
7	427	Gordon	427	-18.35	-82.75	0.000	0.222	0.088	-25.624	0.716	32
8	22	Garland 3	22	20.52	80.15	0.000	0.256	0.060	25.328	0.810	32
9	1418	Pasadena 4	1418	10.43	74.34	0.000	0.140	0.065	15.251	0.684	29
10	1324	Knox City	1324	-13.98	-70.47	0.000	0.198	0.148	-24.390	0.573	33

Capacitive Neutral Blocking



- Sort by Transformer Neutral Current, absolute value (hold shift key, click column header)
- Toggle “GIC Blocked for Transformer Neutral” = YES for Cooper GSU and recalculate GIC
- Cooper GSU GIC goes to zero, but GIC increases in Cooper autotransformers and a few other locations

Tables and Results																	
Areas Buses Generators G-Matrix Lines Line Shunts Switched Shunts Substations System Summary Transformers																	
Records Set Columns Options																	
	Bus Num High	Bus Name High	Bus Num Med	Bus Name Med	Bus Num Ter	Bus Name Ter	Circuit	Transformer Per Phase Effective GIC, Amps	Transformer Per Unit Effective GIC	GIC Mvar Losses	Maximum Mvar Losses	Maximum Losses Direction (Degrees)	Neutral Current (Amps)	Maximum Neutral Amps	Maximum Neutral Current Degrees	Ignore GIC Losses	GIC Blocked for Transformer Neutral
1	1802	Throckmorton 345	447	Throckmorton 115	0		1	24.624	0.104	16.07	16.16	86.7	-96.473	97.23	85.8	NO	NO
2	1993	Terrell 2 345	87	Terrell 2 115	0		1	19.200	0.081	12.22	18.70	142.2	84.227	95.71	121.4	NO	NO
3	1959	Garland 3 345	23	Garland 3 115	0		1	10.986	0.046	6.83	7.16	110.3	80.149	80.15	93.0	NO	NO
4	1786	Dallas 10 345	107	Dallas 10 115	0		1	14.664	0.062	9.09	9.25	103.5	72.758	79.81	117.3	NO	NO
5	1788	Cooper 345	1676	Cooper G0	0		1	22.393	0.095	14.76	17.47	60.7	67.179	79.49	60.7	NO	YES
6	1785	Plano 5 345	48	Plano 5 115	0		1	7.261	0.031	4.58	4.99	69.5	57.978	62.64	70.8	NO	NO
7	1943	Laredo 5 345	918	Laredo 5 115	0		1	10.865	0.046	7.05	13.17	35.4	-56.571	77.18	50.1	NO	NO
8	1921	Allen 1 345	3	Allen 115	0		1	1.381	0.006	0.87	1.61	35.7	54.450	65.41	59.3	NO	NO
9	1900	North Richland Hills	290	North Richland Hills 1	0		1	27.076	0.114	16.87	17.03	85.0	52.037	61.83	60.3	NO	NO
10	1882	Lytle 345	921	Lytle 115	0		1	19.482	0.082	12.55	12.98	107.9	-51.069	51.72	83.9	NO	NO
11	1816	Baytown 3 345	788	Baytown 3 115	0		1	13.103	0.055	8.47	8.60	83.1	50.992	51.01	91.3	NO	NO

Capacitive Neutral Blocking



- Toggle “GIC Blocked for Transformer Neutral” = YES for Cooper Autotransformers and recalculate GIC
- The Cooper neutral current goes to zero, but some GIC still flows through the series windings

Tables and Results																	
Areas		Buses	Generators	G-Matrix	Lines	Line Shunts	Switched Shunts	Substations	System Summary	Transformers							
DPT																	

GIC by Bus: Quick Power Flow List



Quick Power Flow List for Current Case

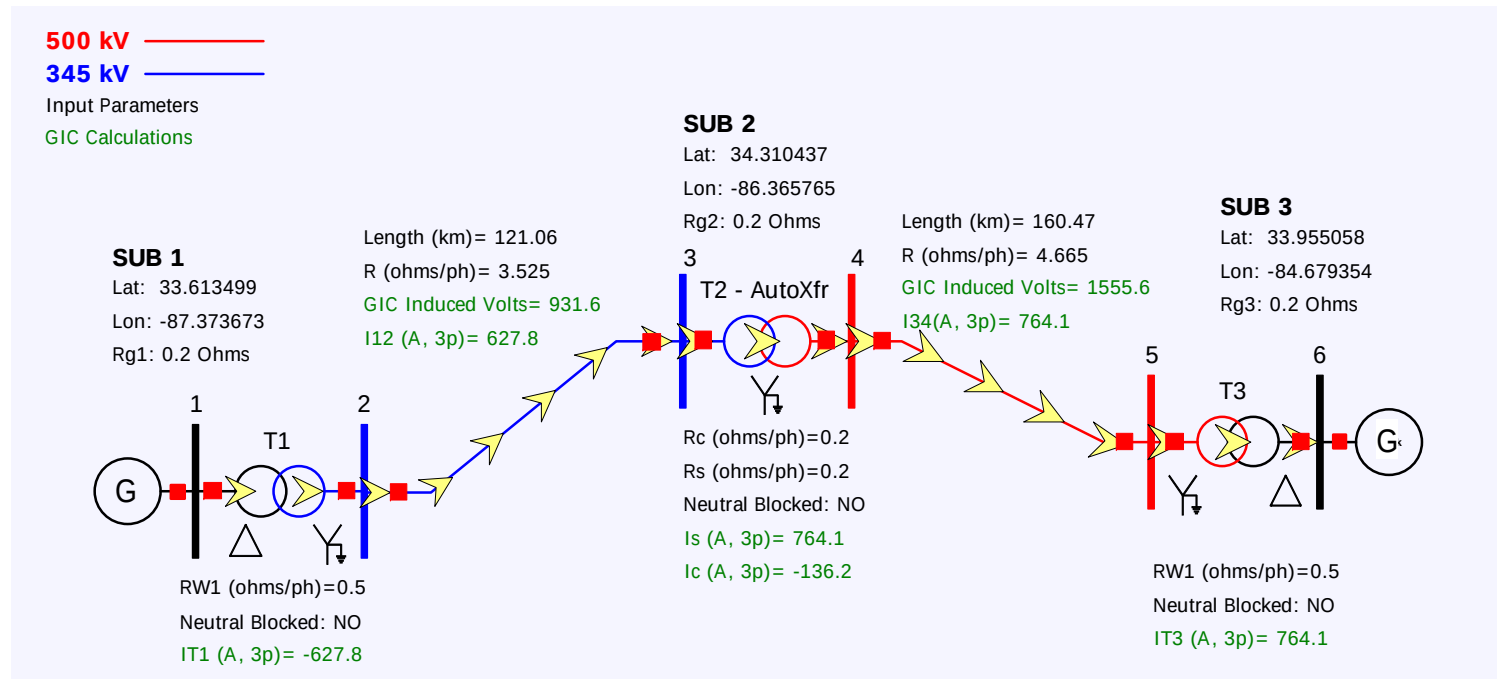
Bus Number: 1788 Show Buses Clear List Print Close

BUS	1788	Cooper	345	345.0	MW	Mvar	MVA	%	GIC Amps	1.0292	-3.51	1	NCENT
GIC DC Volt = 68.79 Sub DC Neutral Volt = 0.00													
TO	136	Cooper	115	1	236.39	23.48	237.6	24	5.9A	1.0000NT	0.0		
TO	136	Cooper	115	2	236.39	23.48	237.6	24	5.9A	1.0000NT	0.0		
TO	1676	Cooper	G0	1	-1648.91	-163.94	1657.0	71	0.0N	1.0000NT	0.0		
TO	1920	Mckinney	1 345	1	592.82	55.56	595.4	45	-10.2				
TO	1993	Terrell	2 345	1	583.31	61.41	586.5	39	-1.5				

NERC 6-Bus Example



- Described in the NERC Application Guide, Appendix II*
- 2 gweye-delta GSUs, 1 gweye-gweye autotransformer, 2 transmission lines



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

GIC in Transient Stability



- It often makes sense to analyze GIC in the transient stability domain, especially for time-varying surface electric fields
- High-Altitude EMP disturbances have faster rise times than typical GMD, but may last only several minutes
- Useful for generating transformer I_{eff} time series for inputs to thermal models

Transient Stability Example



- Open *GIC Analysis Form* and select the **Calculation Mode** “Time Varying Series Voltage Inputs”
- Insert 3 time points to create a 5 second rise from 0 V/km to 15V/km at 90 degrees and a 5 second decline to 0 V/km
- Open *Transient Stability Analysis Form*

GIC in Transient Stability



- **Options → Power System Model → Common**
- Check “Include GIC Effects”
- More details on using Simulator’s Transient Stability Tool are provided in a separate course

Options

Note: Changes made to option entries are saved immediately and will be applied during the next transient stability run.

General Power System Model Result Options Generic Limit Monitors User Defined Models Distributed Computing

Common Compatibility Options

Power System Values

Nominal System Frequency (Hz) 60.0

Initial System Frequency (Hz) 60.000

System MVA Base 100.00

Network Equations Solution Options

Solution Tolerance (MVA) 0.10000

Maximum Iterations 25

Force Network Equation Update 0.00

☒ Use Voltage Extrapolation

Inner Loop Mismatch Scalar 1.0

Infinite Bus Modeling

☐ No infinite buses (recommended setting)

☒ Model the power flow slack buses as infinite buses

Handling of Initial Limit Violations

☒ Modify Limits and Run

☐ Abort

☐ Run without Changing Limits

Load Modeling

Default Load Model

☐ Constant Impedance

☐ ZIP Model from Power Flow Model

☒ Constant Current

☐ Constant Current P, Impedance Q

Minimum Per Unit Voltages for

Constant Power Models 0.700

Constant Current Models 0.500

Change

Minimum Load P for Complex Load Models (MW) 0.500

Minimum Load P/Q Ratio for Complex Load Models 0.25

Integration Method

☐ Second Order Runge-Kutta

☒ Euler

☒ Include GIC Effects

GIC XF Time Constant (Sec) 0.0

Bus Frequency Measurement Time Constant (Sec.) 0.02

GIC in Transient Stability

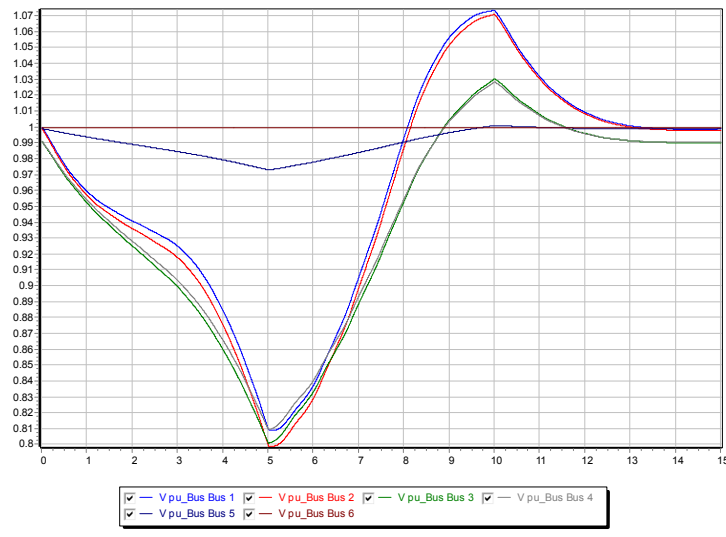


- Run Transient Stability Simulation for 15 seconds
- Time-series plots are generated for generator rotor angle, bus frequency, bus voltage, transformer I_{eff} , transformer GIC MVar losses (by substation), generator MVar output, and generator field current

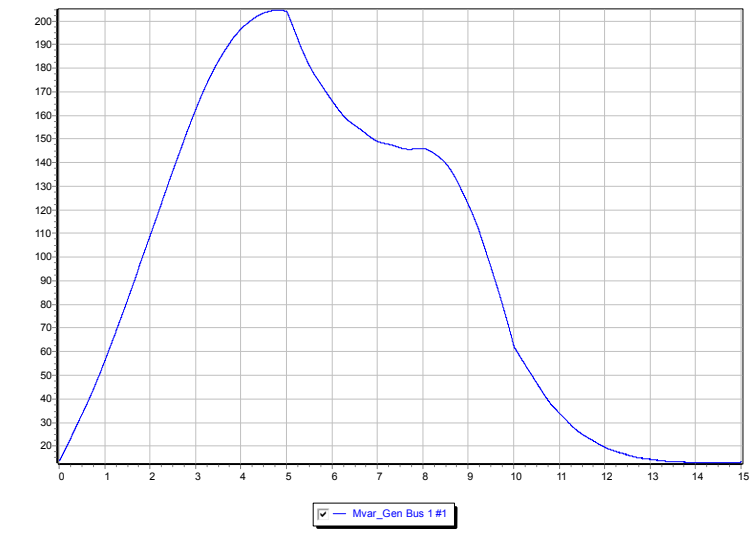
Transient Stability Plots



- Bus Voltages



- Generator MVar



- Note generator at bus 1 exceeds its power flow limit of 50 MVar for several seconds
- Simulation in power flow leads to collapse at $t=4.2$
- Increasing peak field strength beyond 20 V/km leads to collapse in transient stability simulation

Summary:

Integrating GIC Calculations into Power System Planning



- A large GMD could substantially affect power system flows and voltages
- Studies allow for testing various mitigation strategies
 - Operational (short-term) changes include redispatching generation to avoid long distance power transfers and reducing transformer loading values, and strategically opening devices to limit GIC flows
 - Longer-term mitigation actions include the installation of GIC blocking devices on the transformer neutrals (such as capacitors) and/or increased series capacitor compensation on long transmission lines
- Determining relay settings – when to trip the transformer