

Steady-State Power System Security Analysis with PowerWorld Simulator



S12: Modeling GMD in PowerWorld Simulator



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GMD Concepts and Regulatory Environment

Overview

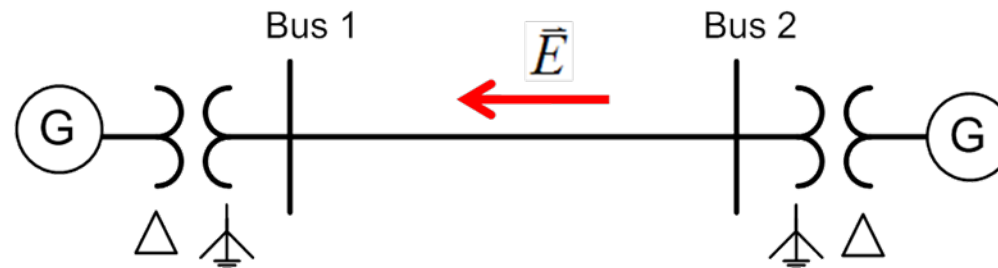


- The grid reliability is high, some events could cause large-scale, long duration blackouts
 - These include what NERC calls High-Impact, Low-Frequency Events (HILFs); others call them black swan events or black sky days
 - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) high altitude electromagnetics pulses (HEMPs)
 - Another could be volcanic eruptions
- PowerWorld Simulator has tools to analyze GMDs and some effects of HEMP (late time, E3)

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 high-voltage transmission lines, grounded transformers, and the Earth.



GIC Impact on Transformers



- 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

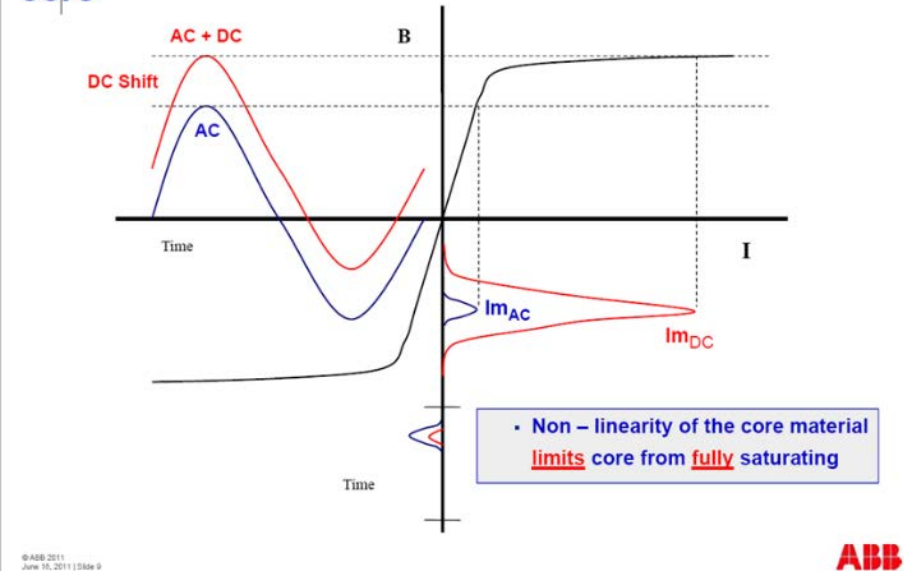


Image Source: Craig Stiegemeier, JASON Presentation, June 2011

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

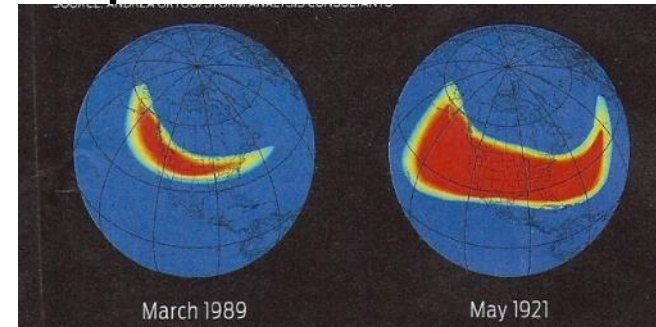


Image source: J. Kappenman, "A Perfect Storm of Planetary Proportions," *IEEE Spectrum*, Feb 2012, page 29

July 2012 GMD Near Miss



- In July 2014, NASA reported that a solar CME barely missed Earth in July of 2012
 - It would likely have caused the largest GMD that we have seen in the last 150 years
- There is still much uncertainty about how large a storm is reasonable to consider in electric utility planning

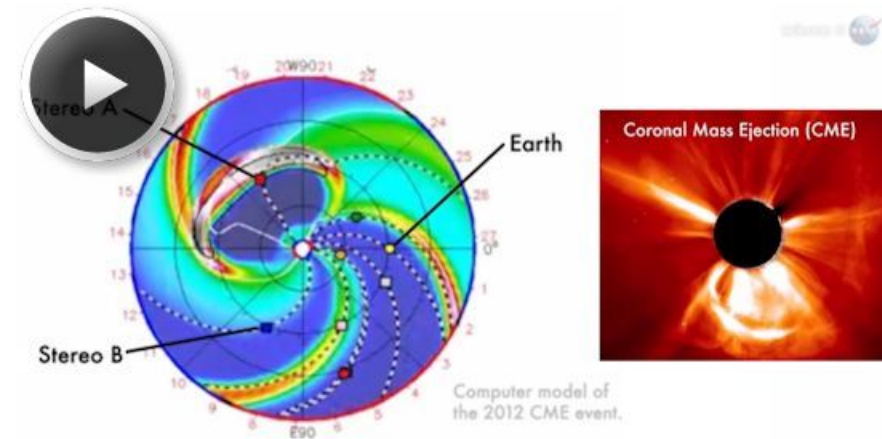


Image Source: science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/

Integrating GIC Analysis into Power System Planning

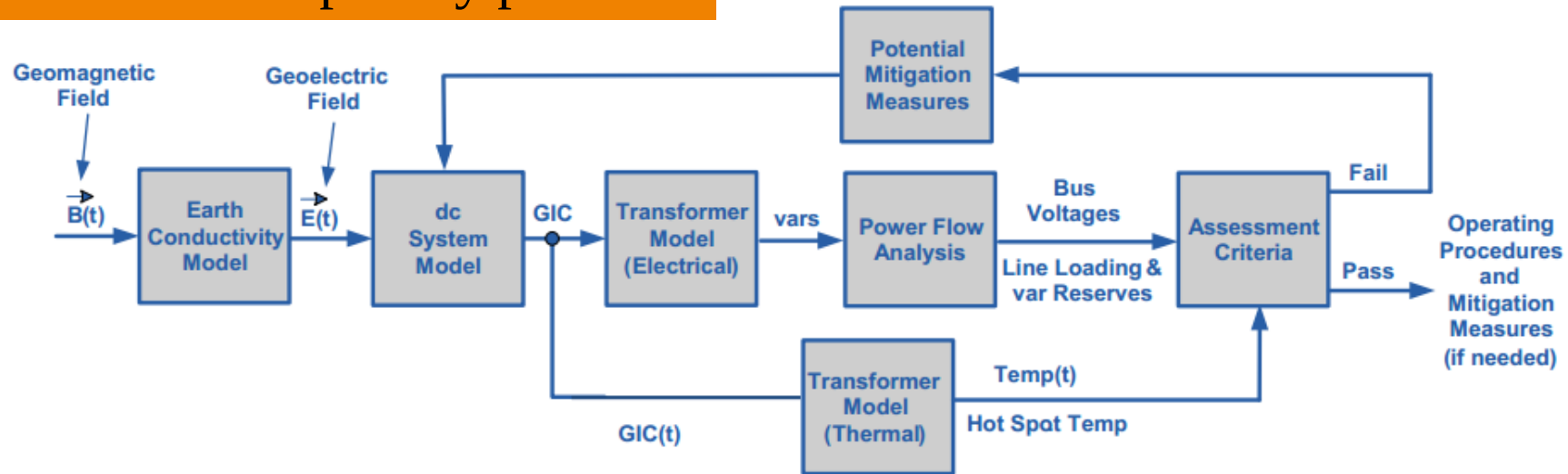


- A large GMD could substantially affect power system flows and voltages
- Studies allow for testing various mitigation strategies
 - Operational (short-term) changes include redispatching generation to avoid long distance power transfers and reducing transformer loading values, and strategically opening 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

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

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)

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 responded with TPL-007-2 and additional requirements including analysis of supplemental GMD event

NERC TPL-007-2



- Key Requirements
 - R2. Maintain AC system models and GIC system models
 - R3. Develop criteria for steady state voltage performance
 - R4. Complete a GMD Vulnerability Assessment every 5 years, based on **benchmark GMD event**
 - R7. Develop a Corrective Action Plan if needed
 - R8. Complete a GMD Vulnerability Assessment every 5 years, based on **supplemental GMD event**
 - R6 and R10. Transformer thermal assessments
 - R11 and R12. Obtain GIC monitor and GMD field data
- FERC NOPR (May 17, 2018) proposed to approve TPL-007-2
- 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)

Further Revisions



- TPL-007-3: Canadian Variance for alternative Benchmark and Supplemental Events
- FERC Order 851 approved TPL-007-2 on November 15, 2018, while directing a few modifications via NOPR
 - require corrective action plans (CAP) to mitigate supplemental GMD event vulnerabilities
 - corrective action plan time-extensions to be considered on a case by case basis
- TPL-007-4 affirmed by NERC voters November 2019
 - new R11 addresses supplemental event CAP
 - old R11 and R12 become R12 and R13, respectively

TPL-007-4 Timetable



- Adopted by NERC Board February 2020
- Compliance dates
 - R1, R2, R5, R9 (system models, GIC flow): upon effective date of the standard
 - R12 and R13 (monitor data): July 2021
 - R6 and R10 (thermal impact assessments): January 2022
 - R3, R4, R8 (voltage performance, vulnerability assessments): January 2023
 - R7 and R11 (corrective action plans): January 2024

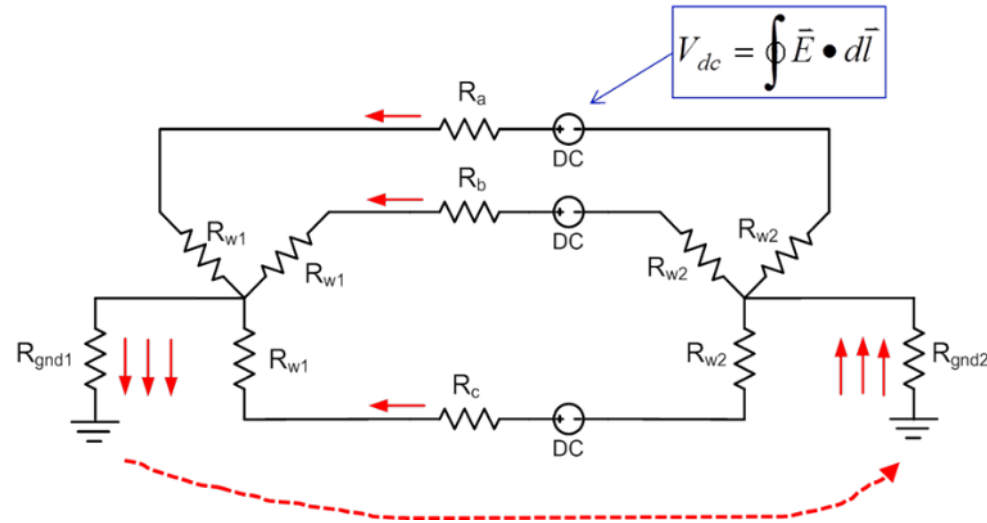


GIC Network Modeling Principles and Assumptions

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 input, consisting of a time-series geospatial grid of E-field magnitude and direction (available in Simulator 18)

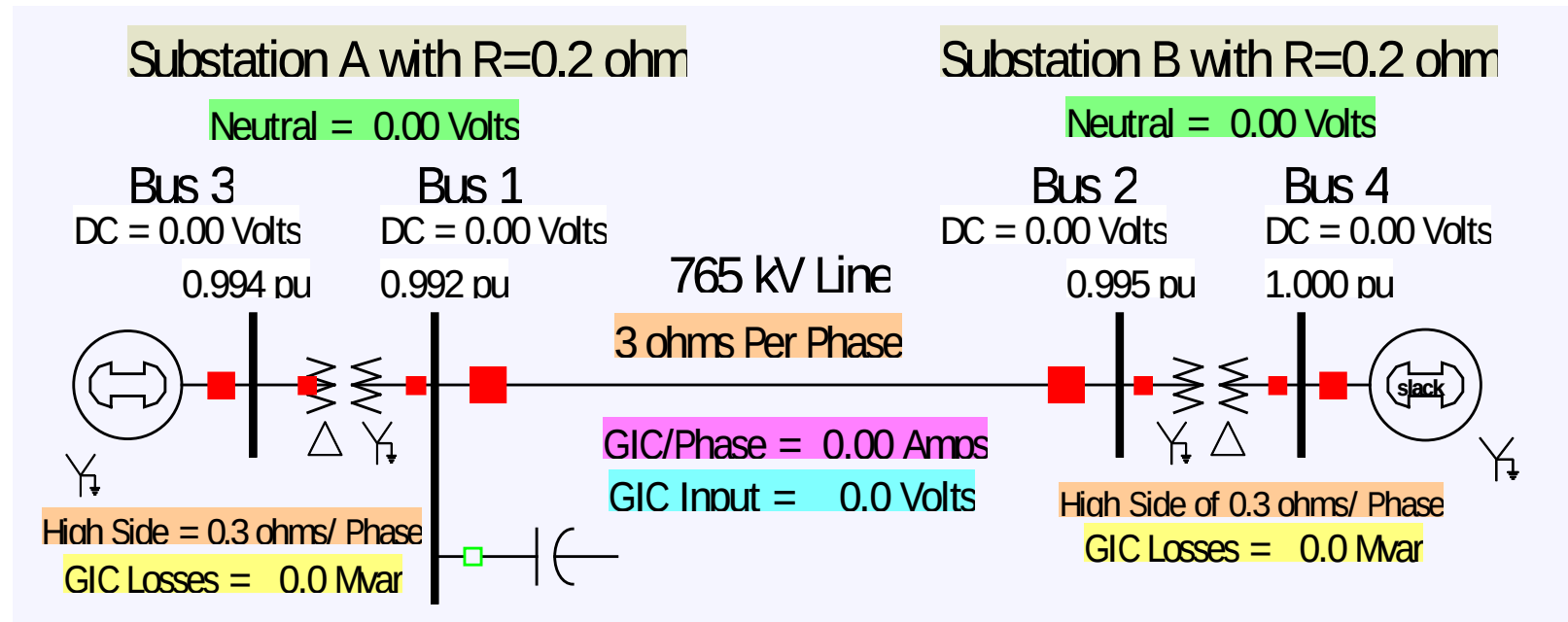
GIC Analysis Outputs and Results



- 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 'Calculation Mode' section has 'Single Snapshot' selected. The 'Update Line Voltages' checkbox is checked. The 'Select Step' list on the left has 'Tables and Results' selected. The 'Tables and Results' tab is active, showing a table with columns: Sub Num, Sub Name, Sub ID, GIC DC Neutral Voltage, GIC Amps to Neutral, Grounding Resistance (Ohms), GIC Used Grounding Resistance (Ohms), Latitude, Longitude, and Custom Ear Resistivity. Two substations are listed: Sub 1 and Sub 2, both with a grounding resistance of 0.20 Ohms. The table is as follows:

Sub Num	Sub Name	Sub ID	GIC DC Neutral Voltage	GIC Amps to Neutral	Grounding Resistance (Ohms)	GIC Used Grounding Resistance (Ohms)	Latitude	Longitude	Custom Ear Resistivity
1	Sub A	Sub1	0.00	0.00	0.20	0.20	40.0000	-89.0000	Using Region V
2	Sub B	Sub2	0.00	0.00	0.20	0.20	40.0000	-87.0000	Using Region V

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

Grounding resistance = 0.2Ω

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, approximate locations (e.g. within 100 km) are adequate for uniform field modeling

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 displays the 'GIC Analysis Form' window. The 'Transformers' tab is selected in the 'Tables and Results' section. The 'Calculation Mode' is set to 'Single Snapshot'. The 'Update Line Voltages' checkbox is checked. The 'Tables and Results' section shows a table with columns for Bus Name, Circuit, Coil Resistance, and Core Type. The table contains two rows of data for transformers connecting Bus 1 to Bus 2 and Bus 3 to Bus 4.

Bus Num High	Bus Name High	Bus Num Med	Bus Name Med	Bus Num Ter	Bus Name Ter	Circuit	Manually Enter Coil Resistance	Coil Resistance (Ohms) for High winding	Coil Resistance (Ohms) for Medium winding	Coil Resistance (Ohms) for Tertiary winding	XF Config High	XF Config Med	XF Config Ter	Assumed Transformer Grounding for GIC	Is Autotransformer	Assumed to be an AutoTransformer	Core Type
1	Bus 1	3	Bus 3	0		1	Yes	0.30000	0.10000		Gwye	Delta		GWye-Delta	No	NO	Single Phase
2	Bus 2	4	Bus 4	0		1	Yes	0.30000	0.10000		Gwye	Delta		GWye-Delta	No	NO	Single Phase

Four-Bus Inputs: Transformers



- Manually Enter Coil Resistance
 - “Yes”: user enters “Coil Resistance (Ohms) for High/Medium/Tertiary winding”
 - “No”: 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

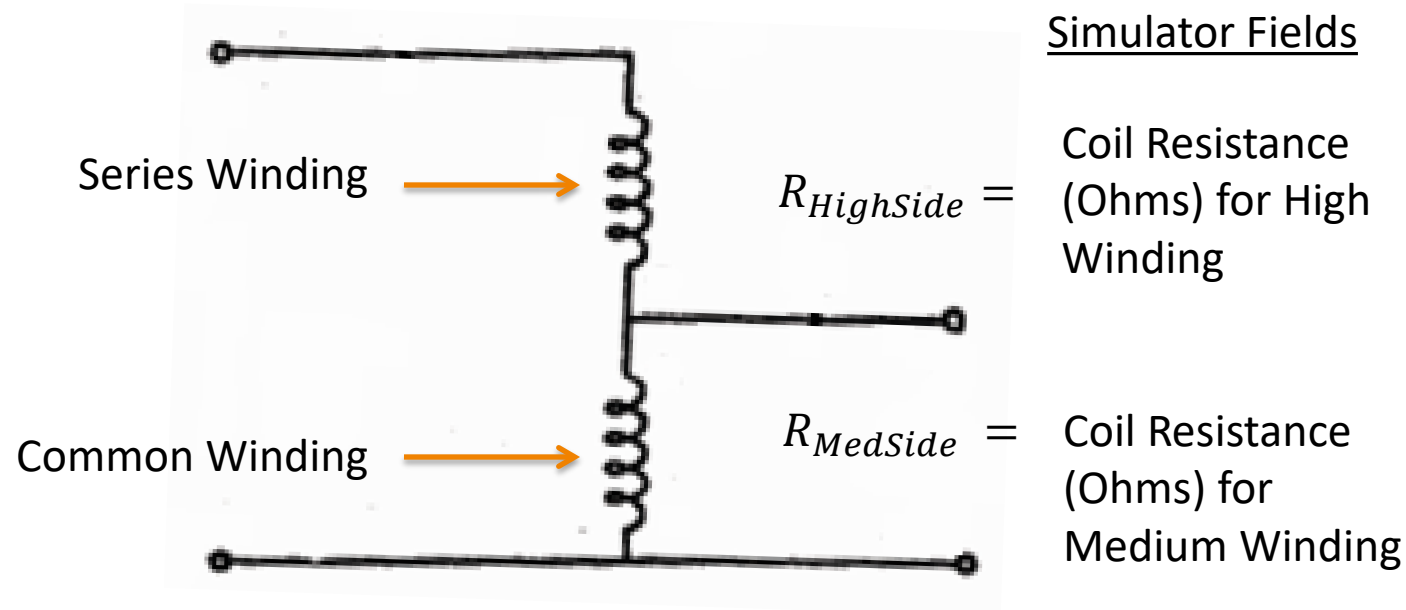


- It is always best to provide known quantities, especially for configuration and autotransformer fields
- If any transformer information is unknown, Simulator uses default values
- Coil Resistance
 - ohms per phase estimate based on positive-sequence AC per-unit series resistance and transformer impedance 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
 - Medium side nominal voltage is at least 50 kV
 - turns ratio is less than or equal to 4

DC Current Calculation AC Power Flow Model

Minimum Voltage Level to Include in Analysis (kV) 50.00

Maximum Assumed Line Segment for Nonuniform Fields (km) 8.05

Automatic Determination of Autotransformers

When to model as an Autotransformer when status is Unknown

Maximum Turns Ratio to Assume Autotransformer 4.00

Minimum Medium Voltage to Assume Autotransformer 50.00

If Low Medium, Minimum High Side Winding Voltage (kV) for Always GSU 300.00

Default Trans. Side Config Default Dist. Side Config

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 Medium Voltage 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)

Options

DC Current Calculation AC Power Flow Model

Minimum Voltage Level to Include in Analysis (kV) 50.00

Maximum Assumed Line Segment for Nonuniform Fields (km) 8.05

Automatic Determination of Autotransformers

When to model as an Autotransformer when status is Unknown

Maximum Turns Ratio to Assume Autotransformer 4.00

Minimum Medium Voltage to Assume Autotransformer 50.00

If Low Medium, Minimum High Side Winding Voltage (kV) for Always GSU 300.00

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

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

K-Factor

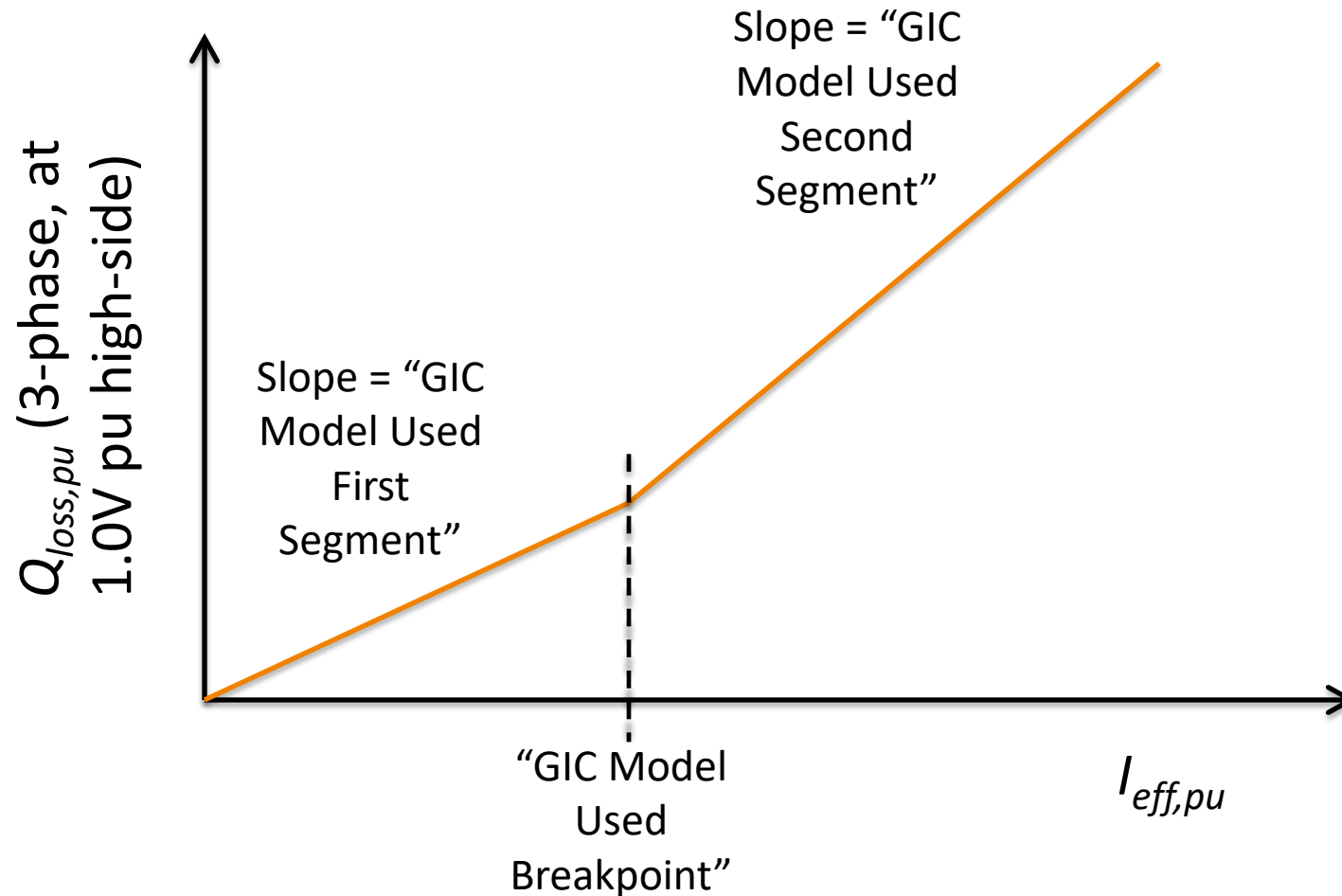


- *K-Factor* may be entered directly as a 2-step piecewise linear value with “GIC Model Type” set to **Piecewise Linear**
- Break point is $I_{eff,pu}$
- With “GIC Model Type” set to **Default**, K-Factor is based on Core Type and parameters at **Options** → **AC Power Flow Model**

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

User-specified values
 Values Used

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 Simulation
 Geomagnetic Latitude Scaling
 Earth Resistivity Scaling
 Time Varying Electric Field Input

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

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

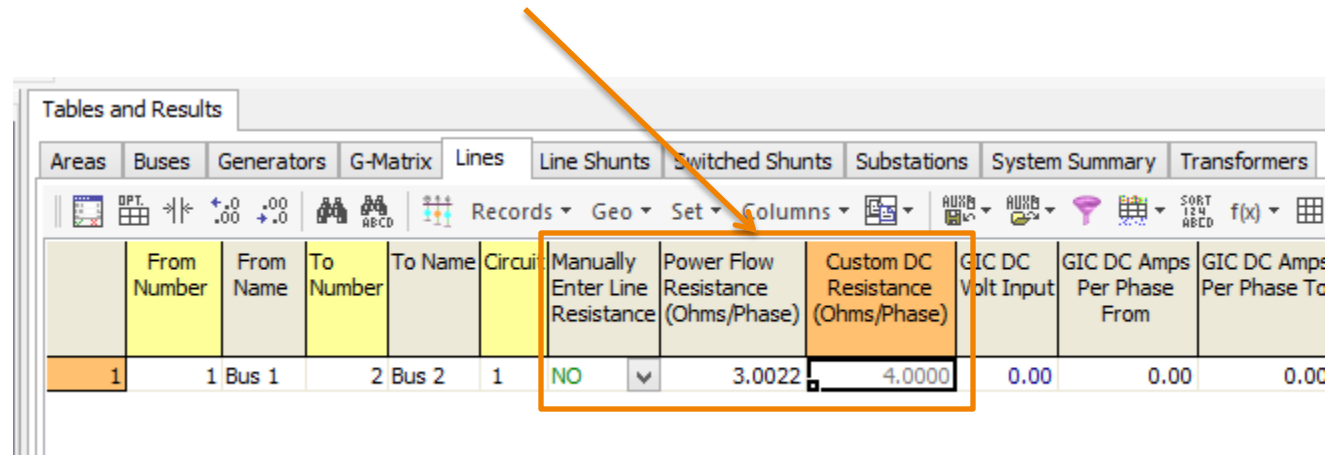


- **Options → DC Current Calculation**
 - Minimum Voltage Level to Include in Analysis (kV): transmission lines below this level are assumed to have zero GIC DC voltage input
 - Automatic Insertion of Substations for Buses without Substations
 - It is strongly recommended to assign all buses to substations 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)**



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	GIC DC Amps Per Phase To
1	1 Bus 1	2 Bus 2	1		NO	3.0022	4.0000	0.00	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

Buttons: 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

Buttons: 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

Records Set Columns

	Number (Name)	Name (Number)	Sub Sub A (1)	Sub Sub B (2)	Bus 1 (Bus 1)	Bus 2 (Bus 2)	Bus 3 (Bus 3)	Bus 4 (Bus 4)
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)

Field/Voltage Input

Voltage Input Parameters

Electric Field Model Parameters

Maximum Field 1.00 Volts/mile

Storm Direction 90.0 Degrees

☒ Also Calculate Maximum Direction Values

Restrict Lines to which to model DC Voltages

Minimum Line Length 1.00 mile

☐ Calculate Voltages for Equivalent Lines

☐ Calculate Voltages for Low R Lines

Units of Distance

☐ Kilometers

☒ Miles

Hotspot Modeling

☐ Include

Hotspot Field in V/Mile 20.00

Width of Hotspot in Miles 150.00

Height of Hotspot in Miles 150.00

Latitude of Center 45.000

Longitude of Center -90.000

☐ Scale Hotspot Value with Geomagnetic Latitude

☒ Scale Hotspot Value with Earth Resistivity

Earth Resistivity Scalar Value

☐ Region Scalar

☒ Region Hotspot Scalar

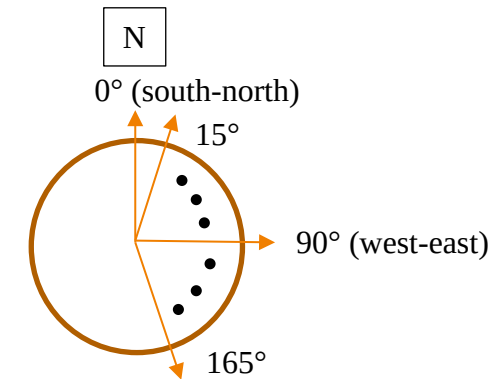
Geomagnetic Latitude Scaling Function No Scaling

Earth Resistivity Scaling Region Set No Resistivity Scaling

Modeling of Scaling and Hotspots

☐ Approximate with Substation Values

☒ Interpolate Along Line Path

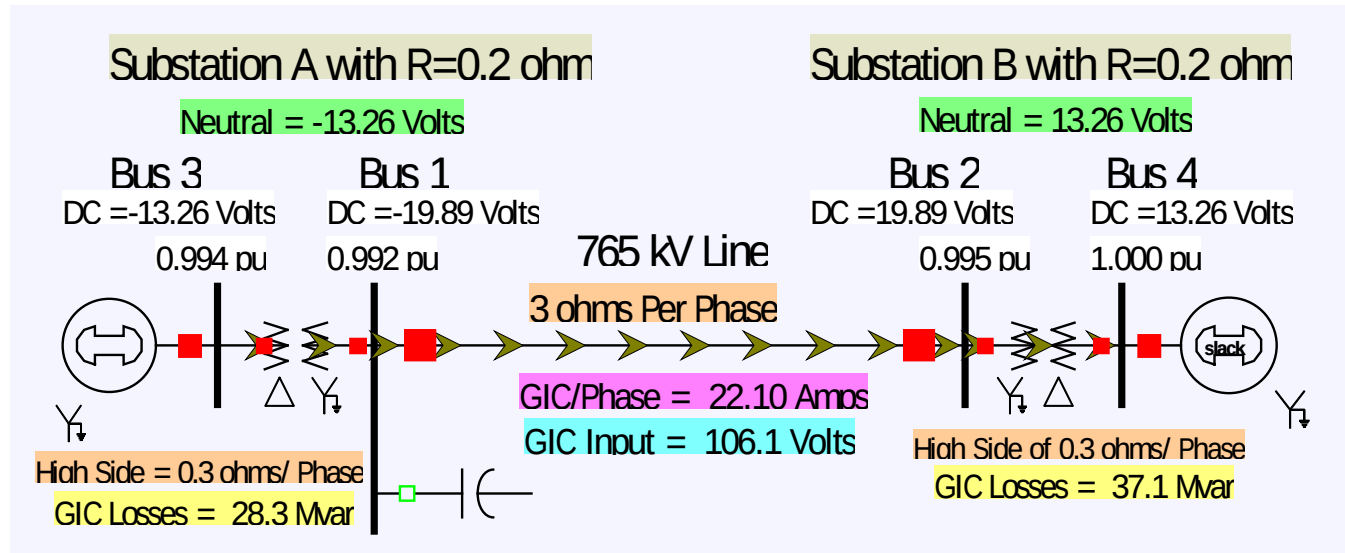


α and β scaling factors
for Benchmark Event

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 and Transient Stability**
- 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**) – or explicitly choose to Base Flow Scaling on *GIC Flows*



Include GIC in Power Flow and Transient Stability



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

Message Log: B4GIC.pwb

Starting Solution using Rectangular Newton-Raphson

AC Power Flow Solution includes the modelling of additional Transformer Mvar losses caused by Geomagnetically Induced Currents

Number: 0	Max P: 1000.000 at bus	3	Max Q: 57.240 at bus	3
Number: 1	Max P: 61.347 at bus	3	Max Q: 155.355 at bus	3
Number: 2	Max P: 2.280 at bus	3	Max Q: 0.986 at bus	3
Number: 3	Max P: 0.000 at bus	3	Max Q: 0.001 at bus	3

Finished voltage control loop iteration: 1

Solution Finished in 0.001 Seconds

Simulation: Successful Power Flow Solution

Maximum Direction Values



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

Records Set Columns

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

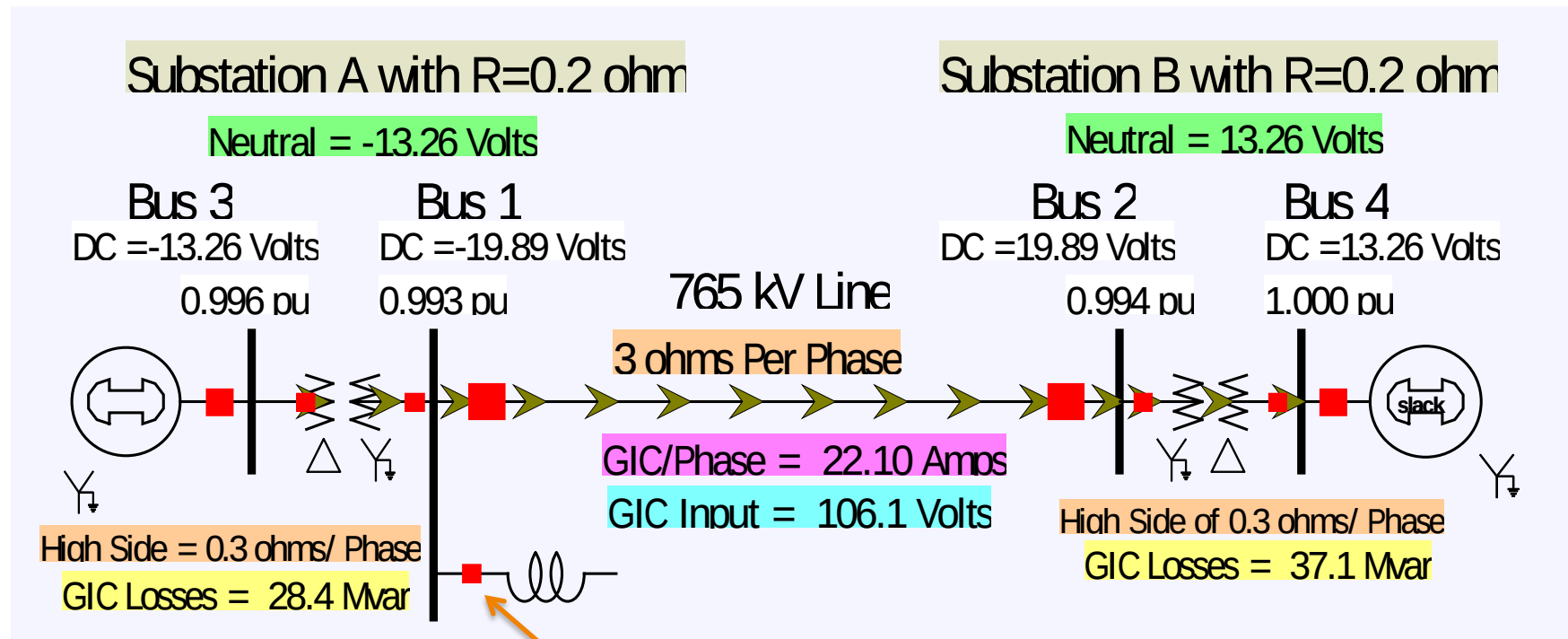
Note, maximum and minimum values are only computed for uniform direction fields

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 “Switched Shunt Information 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
Bus Name: Bus 1
Shunt ID: 1
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

Calculation Mode

☐ Single Snapshot ☐ Time Varying Electric Field Inputs ☒ Time Varying Series Voltage Inputs ☐ Spatially Uniform Time-Varying E-Field

Calculate GIC Values Clear GIC Values ☒ Include GIC in Power Flow and Transient Stability Validate Input Data for GIC

Current Time Offset from Reference (Seconds) 0.00 ☐ Calculate GIC on Time Change Clear All GIC Input and Values

Select Step

Field/Voltage Input Harmonic Analysis

AC Line Input Voltages Substation EField V/km (Display Only) Substation EField Direction Degrees (Display Only)

Branch ID	From Number	To Number	Circuit	From Latitude	To Latitude	From Longitude	To Longitude	Distance Between Substations (Miles)	Timepoint_1
1 Time in Seconds									0.000
2 Branch '1' '2' '1'	1	2	1	40.0000	40.0000	-89.0000	-87.0000	105.12	0.000
3 Branch '1' '3' '1'	1	3	1	40.0000	40.0000	-89.0000	-89.0000	0.00	0.000
4 Branch '2' '4' '1'	2	4	1	40.0000	40.0000	-87.0000	-87.0000	0.00	0.000

GMD

Input at Time (Seconds) 1.00 Add at Time Shift All by Seconds 60.00 Shift Time Delete at Time Delete All Delete All Existing Points and Load Timepoints Ee and En Values From File

Voltage Input Parameters

Electric Field Model Parameters

Maximum Field 0.00 Volts/mile

Storm Direction 90.0 Degrees

☒ Also Calculate Maximum Direction Values

Restrict Lines to which to model DC Voltages

Minimum Line Length 1.00 mile

☐ Calculate Voltages for Equivalent Lines

☐ Calculate Voltages for Low R Lines

Distance Units

☐ Kilometers ☒ Miles

Hotspot Modeling

☐ Include ☐ Scale Hotspot Value with Geomagnetic Latitude

Hotspot Field in V/Mile 20.00 ☒ Scale Hotspot Value with Earth Resistivity

Width of Hotspot in Miles 150.00 Earth Resistivity Scalar Value

Height of Hotspot in Miles 150.00 ☐ Region Scalar

Latitude of Center 45.000 ☒ Region Hotspot Scalar

Longitude of Center -90.000

Geomagnetic Latitude Scaling Function No Scaling

Earth Resistivity Scaling Region Set No Resistivity Scaling

Modeling of Scaling and Hotspots

☐ Approximate with Substation Values ☒ Interpolate Along Line Path

Save Setting to Aux Load AUX Supplemental File Options Clear All GIC Input Fields Close Help

Click Add at Time

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

	Branch ID	From Number	To Number	Circuit	From Latitude	To Latitude	From Longitude	To Longitude	Distance Between Substations (Miles)	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	106.12	0.000	106.123
3	Branch '1' '3' '1'	1	3	1	40.0000	40.0000	-89.0000	-89.0000	0.00	0.000	0.000
4	Branch '2' '4' '1'	2	4	1	40.0000	40.0000	-87.0000	-87.0000	0.00	0.000	0.000

GMD

Input at Time (Seconds) Shift All by Seconds

Voltage Input Parameters

Electric Field Model Parameters

Maximum Field Volts/mile

Storm Direction Degrees

☒ Also Calculate Maximum Direction Values

Restrict Lines to which to model DC Voltages

Minimum Line Length mile

☐ Calculate Voltages for Equivalent Lines

☐ Calculate Voltages for Low R Lines

Distance Units

☐ Kilometers

☒ Miles

Hotspot Modeling

☐ Include

☐ Scale Hotspot Value with Geo

Hotspot Field in V/Mile ☒ Scale Hotspot Value with Earth

Width of Hotspot in Miles

Height of Hotspot in Miles

Latitude of Center

Longitude of Center

Earth Resistivity Scalar Value

☐ Region Scalar

☒ Region Hotspot Scalar

Geomagnetic Latitude Scaling Function

Earth Resistivity Scaling Region Set

Modeling of Scaling and Hotspots

☐ Approximate with Substation Values

☒ Interpolate Along Line Path

Time-Varying Inputs



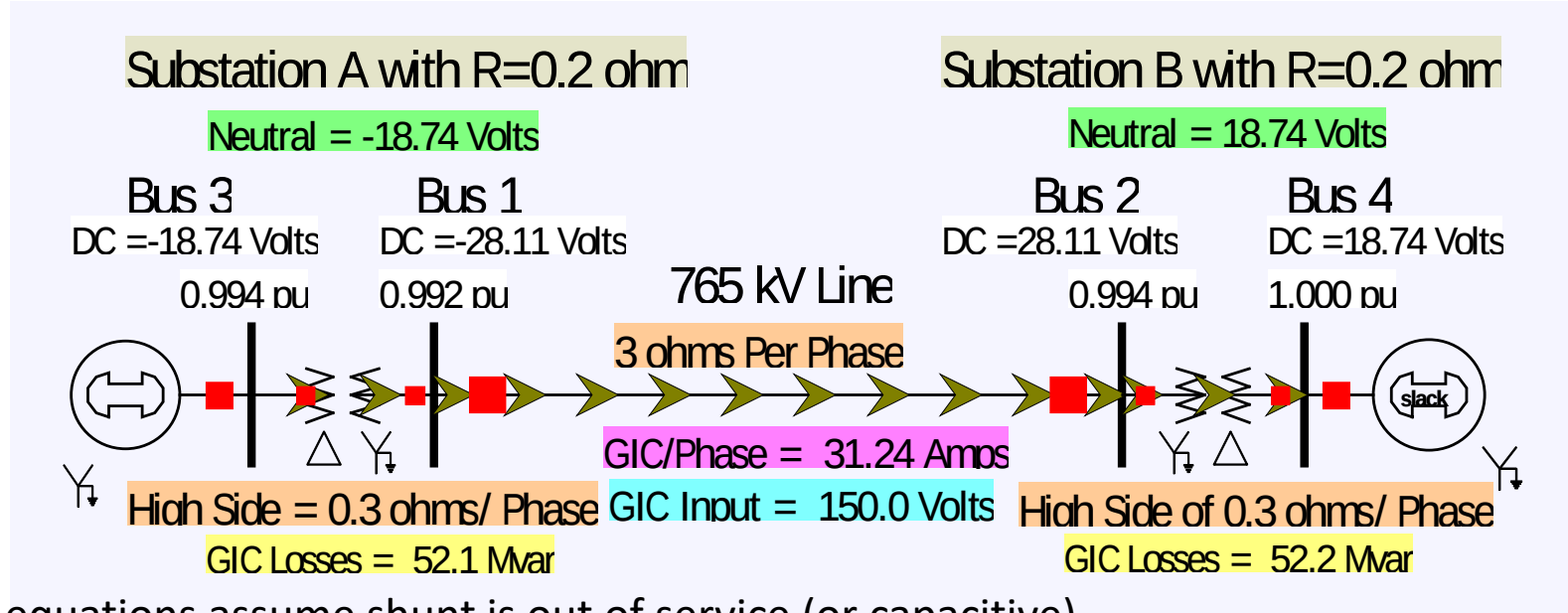
- Change “Current Time Offset from Reference” and click **Calculate GIC Values** or check “Calculate GIC on Time Change”
- Values are linearly interpolated between Timepoints for which inputs are provided
- You may also manually edit input voltages or timepoint values

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



Data Interchange

Other Formats

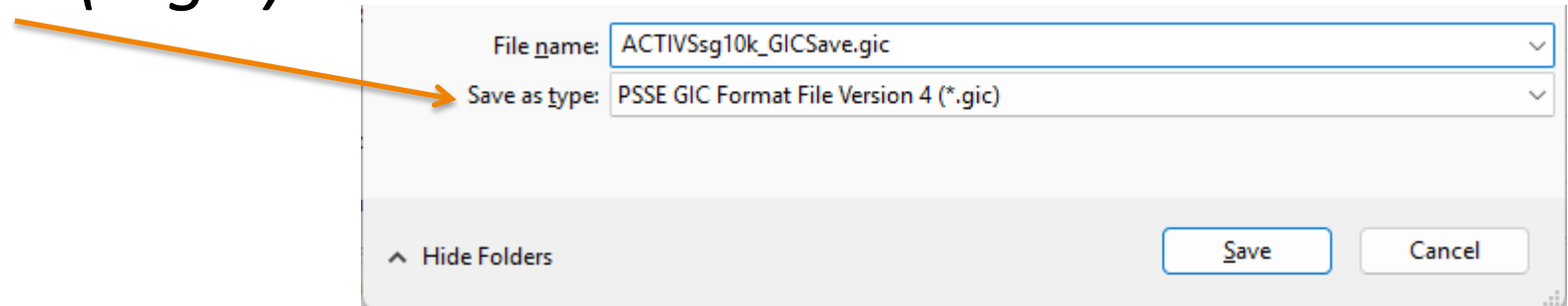


- Simulator can read and write GIC parameters in other industry text file formats
 - PSS/E *.gic
 - PSLF *.gmd
- Facilitates exchange of data between organizations

GIC File Example



- Open Case *ACTIVSg10k.pwb* and open the **GIC Dialog**
- Set all transformer Core Types to *Single Phase*
- Set all substation *Grounding Resistance (Ohms)* to 0.2
- Click the **Supplemental File Options** button, choose “Save supplemental file (*.gic, *.gmd)”, and save the file as *PSSE GIC Format File Version 4 (*.gic)*



GIC File Example



- Re-open Case *ACTIVSg10k.pwb*
- Switch to Edit Mode and delete all substations
- Switch to Run Mode and open the **GIC Dialog**
- Click the **Supplemental File Options** button, choose “Load supplemental file (*.gic, *.gmd)”, and load the just-created file
 - Substations are read with assigned buses and *Grounding Resistance (Ohms)* = 0.2
 - Transformers have *Core Type* = “Single Phase”, but it is grayed out because the piecewise linear K-Factors were explicitly stored in the gic file. (PSSE gic file format does not have Simulator-specific defaults by *Core Type*, but you could switch *GIC Model Type* to Default)



Earth Models

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

$$\text{Recalling } B(\omega) = -\mu_0 H(\omega)$$

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

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

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

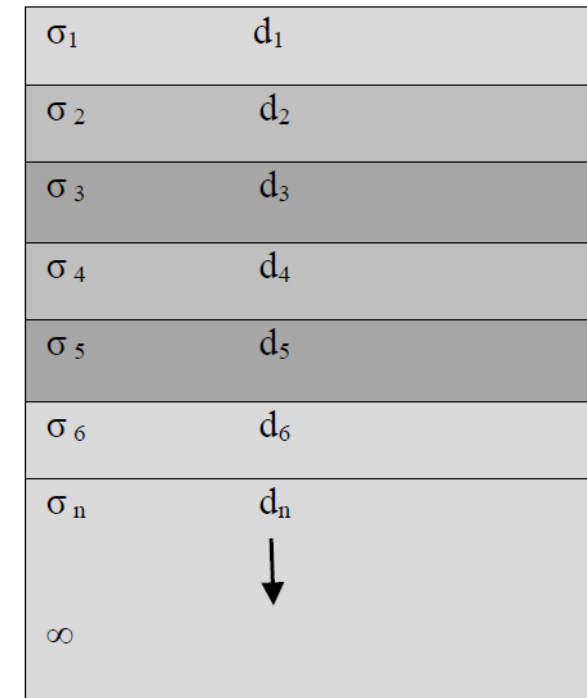


- With a 1-D model the earth is model as a series of conductivity layers of varying thickness
- The impedance at a particular frequency is calculated using a recursive approach, starting at the bottom, with each layer m having a propagation constant

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

- 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

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

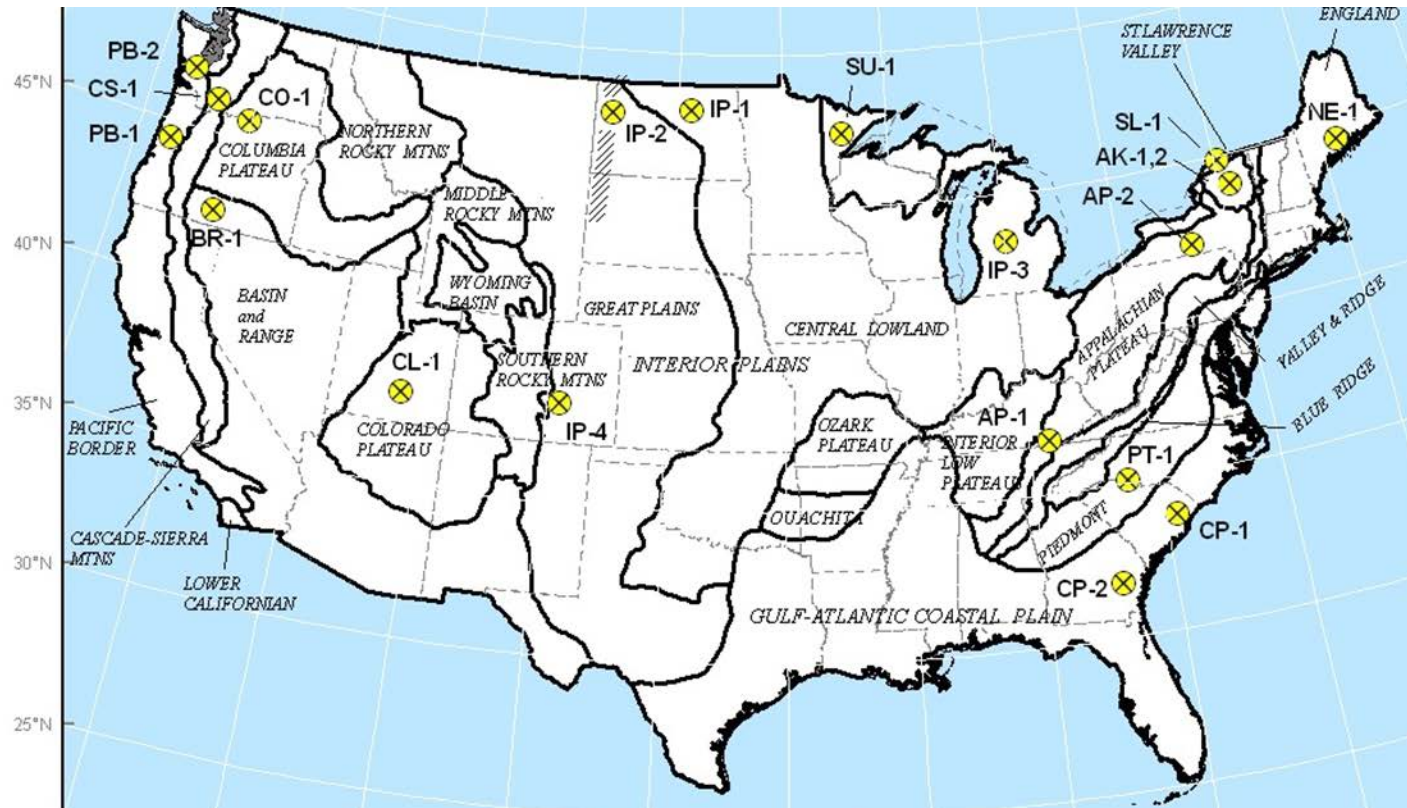
- With the impedance at the top of layer m given as

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

- 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



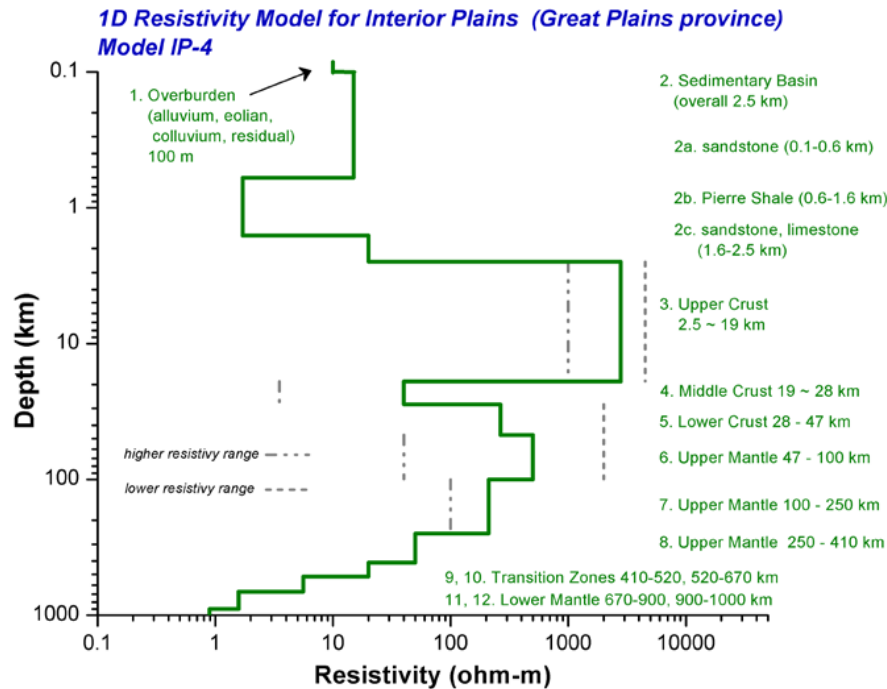
These region scalings are now being used for power flow GMD analysis

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

1-D Earth Models

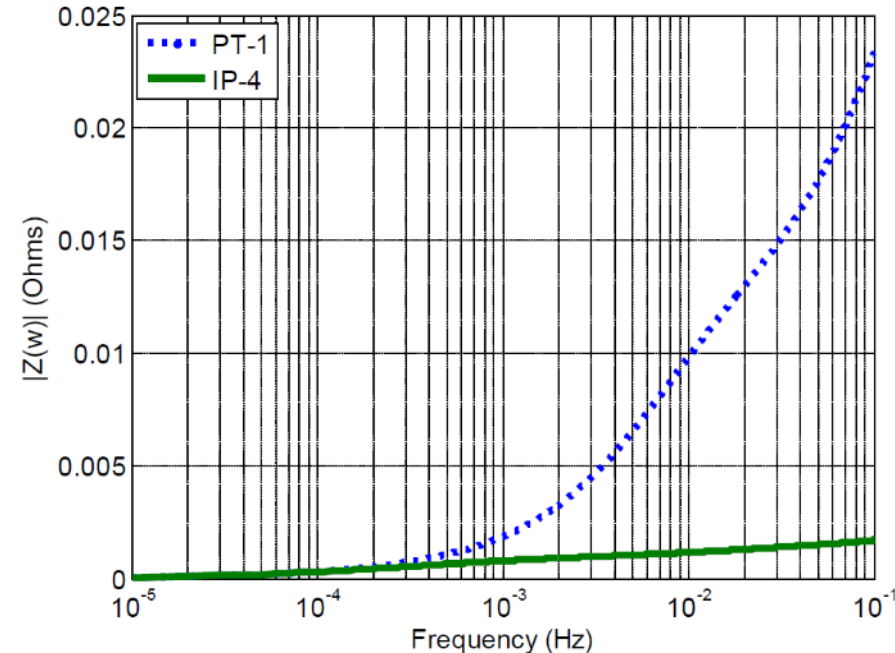


- Image on left shows an example 1-D model, whereas image on right shows the $Z(\omega)$ variation for two models



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.



3-D Earth Models



- 3-D Earth Models produce more complex and realistic non-uniform surface E-field behavior
 - Earthscope
 - US Magnetotelluric (MT) Array
- Research ongoing at EarthScope, Oregon State University, Incorporated Research Institutions for Seismology (IRIS), and NOAA
- Data gaps still exist, most notably in Southwest
- PowerWorld Simulator's time-varying E-field Calculation Mode can make use of these inputs as researchers and industry develop them



TPL-007 Benchmark and Supplemental GMD Events

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 *TX2000.pwb*
- Solve power flow and **Set Present Case as Base Case in Difference Flows**
- Benchmark GMD Event
 - Load *NERC_USGS_2017_Regions.aux* for Earth Resistivity β factors
 - Enter GIC Electric Field of 8 V/km at 0 degrees, “Single Snapshot” calculation 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 and Transient Stability, Validate Input, ☒ Update Line Voltages (Should be True Unless Explicitly Entered), Load Time-Varying Inp

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 S
Earth Resistivity Scaling
Earth Resistivity Scaling

Options

DC Current Calculation | AC Power Flow Model

Minimum Voltage Level to Include in Analysis (kV) **200.00**

Maximum Assumed Line Segment for Nonuniform Fields (km) 8.05

Automatic Determination of Autotransformers
When to model as an Autotransformer when status is Unknown

Maximum Turns Ratio to Assume Autotransformer 4.00

Minimum Medium Voltage to Assume Autotransformer 100.00

If Low Medium, Minimum High Side Winding Voltage (kV) for Always GSU 300.00

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

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

☐ Also insert substations for buses without latitude/ longitude coordinates

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, ☐ PSSE Save and Load Using AreaZone Filters

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 Flow
☒ Update Line Voltages (Should be True Unless 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 Scaling
 - Geomagnetic Latitude Scaling
 - Earth Resistivity Scaling
 - Earth Resistivity Scaling

Tables and Results

Line Shunts Switched Shunts Substations System Summary Transforms

System Summary

Total Mvar Losses in Specified Direction	994.5
Total Mvar Losses in Maximum Direction	1156.7
Maximum Direction, Degrees	93
Total Mvar Losses in Minimum Direction	975.7
Minimum Direction, Degrees	156

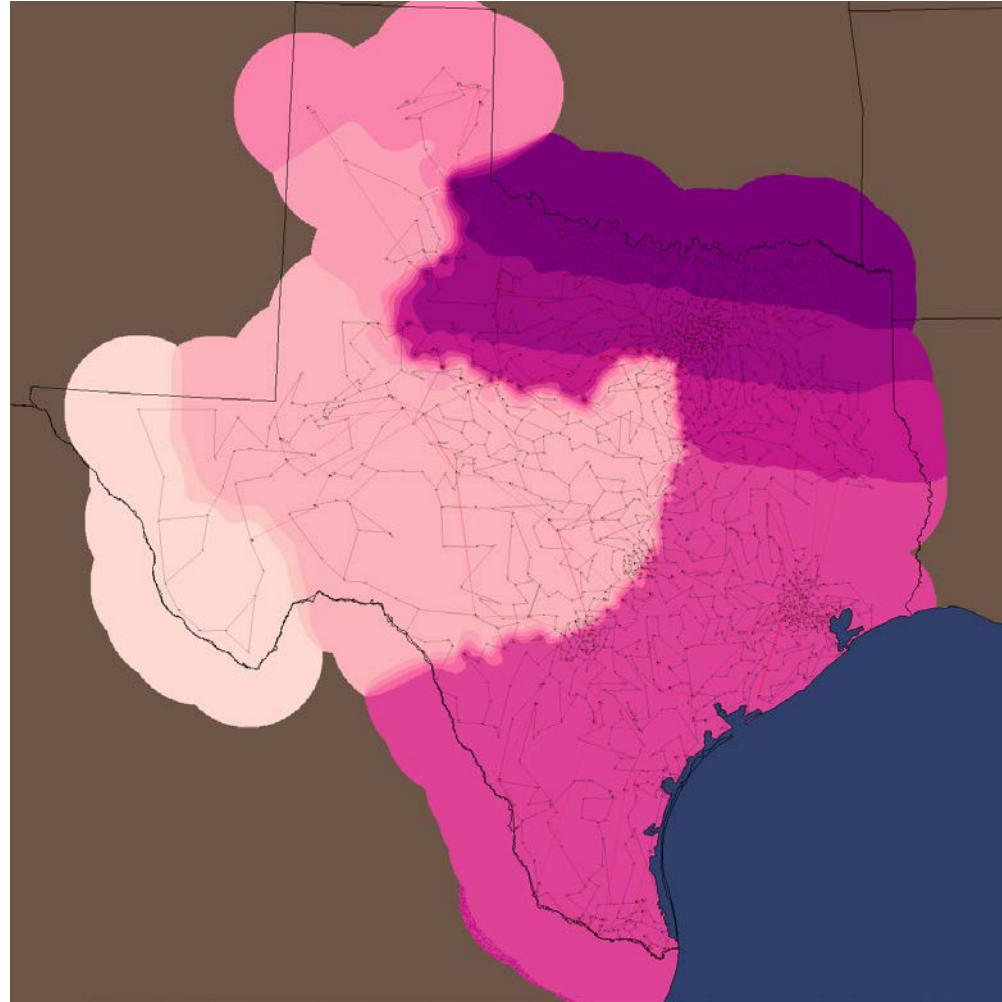
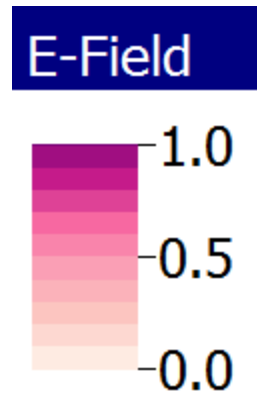
Note, maximum and minimum values are only computed for uniform direction fields

Save Setting to Aux Load AUX Save in PSSE GIC Format

Benchmark GMD Event



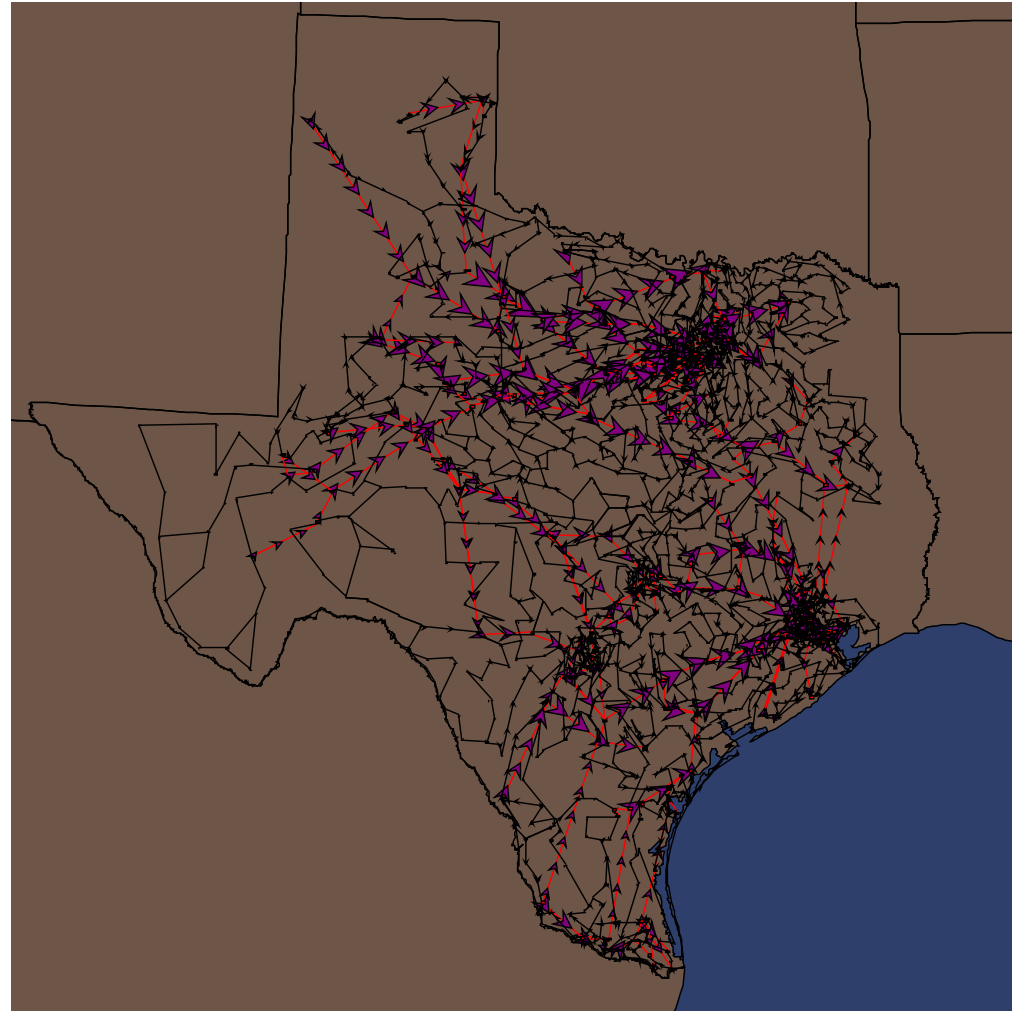
- E-field Contour (V/km)



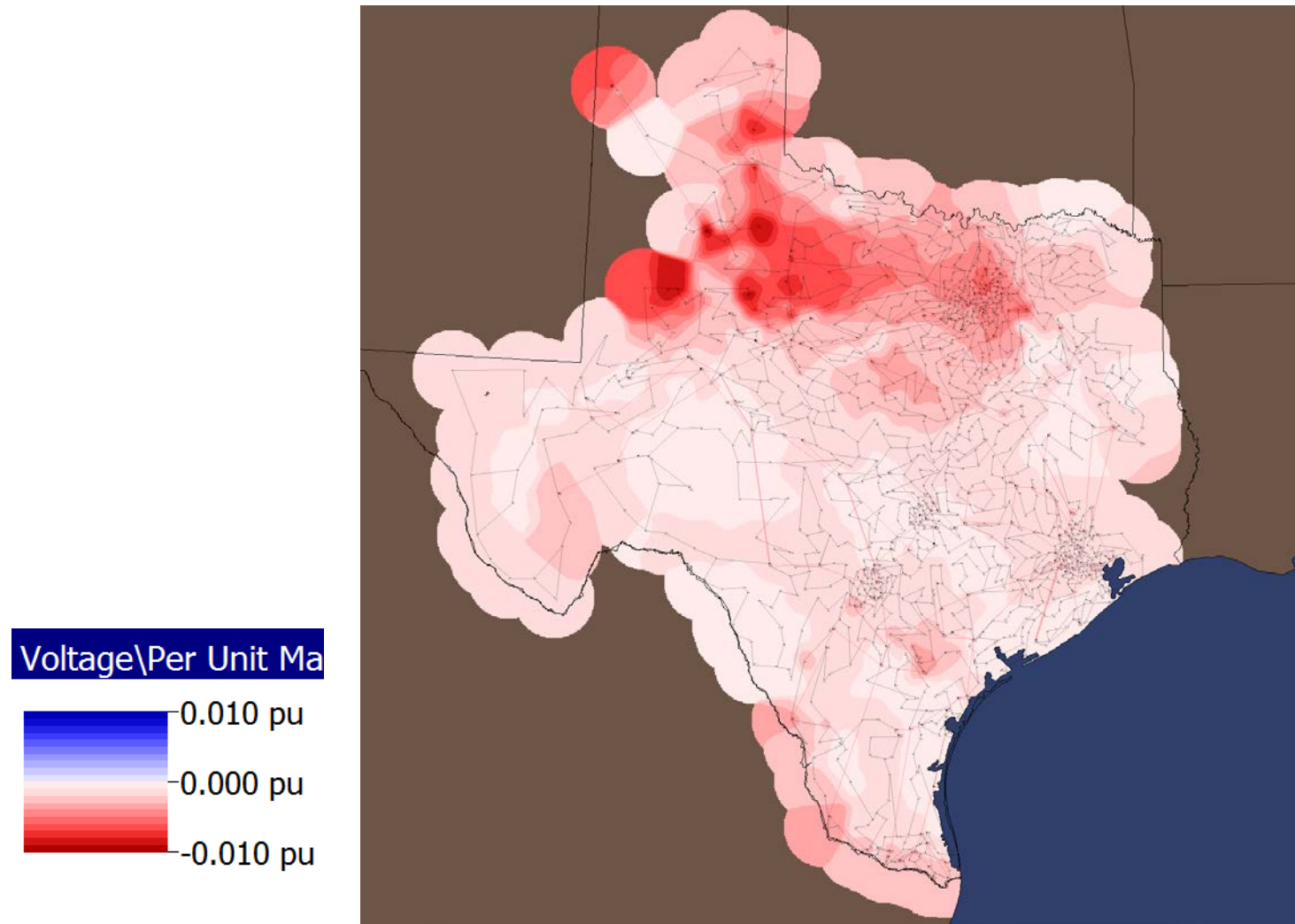
Benchmark GMD Event Example



- Show Custom Float 1 in Animated Flows



Difference Flows: Voltage Contour



Benchmark Event Time Series



- Simulator 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



- Check **Tables and Results** → **Transformers**
- Edit *Display/Column Options* to show the field *Maximum IEffective*
- Apply an advanced filter for transformers with maximum GIC ≥ 25 A
- Change **Calculation Mode** to “Spatially Uniform Time-Varying E-Field”

Benchmark Event Time Series



- Set Time-Varying Input File to *NERC_GMDBenchmarkEventTimeSeries.csv*
- Set Output File to *TexasGICt.csv*
- Click “Calculate Transformer Ieffective”

Field/Voltage Input

Spatially Uniform time-Varying E-Field Options

Time-Varying Input File

File: C:\Training Cases\S12_GMD\NERC_GMDBenchmarkEventTimeSeries.csv Browse...

Save Output File

File: C:\Training Cases\S12_GMD\TexasGICt.csv Browse...

☐ Also output the EPRI Thermal Transformer Model (ETTM) GIC Signature (*.txt) file format for a single transformer.

NOTE: ETTM supports GIC signature files for individual transformers. This option will only create an output file if the Tables and Results: Transformers display is filtered to show a single transformer.

Save ETTM Format Output File

File: C:\Training Cases\S12_GMD\TexasGICt.txt Browse...

Calculate Transformer Ieffective

Benchmark Event Time Series



- When the process is complete, open the output file in Excel
- Resulting time-series may then be input into thermal calculations
 - An example is in *GICXfrHotSpotTempCalcs.xlsx*
 - Help is provided in cell comments
 - Copy one transformer's time series at a time into column G of the sheet *XfrTimeSeries*
 - EPRI also provides a thermal calculator (ETTM)

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)	1802 (Throckmorton 345) [HIGH] ; 447 (Throckmorton 115) [MED] CKT 1	1866 (Wac)	1900 (Nor)	1990 (Mer)	1993 (Terrell)
2	0	0	0	0	0	0	0	0
3	10	0.019	0.038	0.069	0.172	0.085	0.096	0.077
4	20	0.015	0.05	0.06	0.209	0.075	0.137	0.12
5	30	0.028	0.014	0.093	0.095	0.108	0.007	0.017
6	40	0.022	-0.032	0.06	0.089	0.065	0.129	0.145
7	50	0.014	0.015	0.048	0.076	0.057	0.028	0.015
8	60	0.01	0.018	0.037	0.084	0.045	0.044	0.034
9	70	0.027	-0.008	0.084	0.008	0.095	0.062	0.084
10	80	0.003	0.012	0.012	0.05	0.015	0.035	0.031
11	90	0.019	0.013	0.062	0.074	0.073	0.014	0.002
12	100	0.018	0.008	0.057	0.056	0.067	0.002	0.013
13	110	0.031	0.006	0.1	0.069	0.116	0.022	0.049
14	120	0.006	0.024	0.024	0.1	0.031	0.07	0.063
15	130	0.002	0.001	0.007	0.005	0.008	0.001	0.003
16	140	0.004	0.017	0.018	0.071	0.023	0.049	0.044
17	150	0.005	-0.003	0.014	0.005	0.016	0.016	0.02
18	160	0.005	0.034	0.023	0.136	0.032	0.102	0.095
19	170	0.005	0.011	0.017	0.047	0.022	0.028	0.023
20	180	0.005	-0.015	0.011	0.051	0.01	0.055	0.057
21	190	0.004	-0.01	0.011	0.032	0.012	0.038	0.041

Supplemental GMD Event



- The NERC-TPL-007-2 Supplemental GMD Event may be included in Simulator with Hotspot Modeling

Include Hotspot

Hotspot characteristics
(e.g. over Dallas, TX)

Apply scale factors

Apply supplemental Earth
resistivity factor inside the Hotspot

Hotspot Modeling

☒ Include

Hotspot Field in V/km 12.00

Width of Hotspot in Kilometers 500.00

Height of Hotspot in Kilometers 100.00

Latitude of Center 32.777

Longitude of Center -96.797

☒ Scale Hotspot Value with Geomagnetic Latitude

☒ Scale Hotspot Value with Earth Resistivity

Earth Resistivity Scalar Value

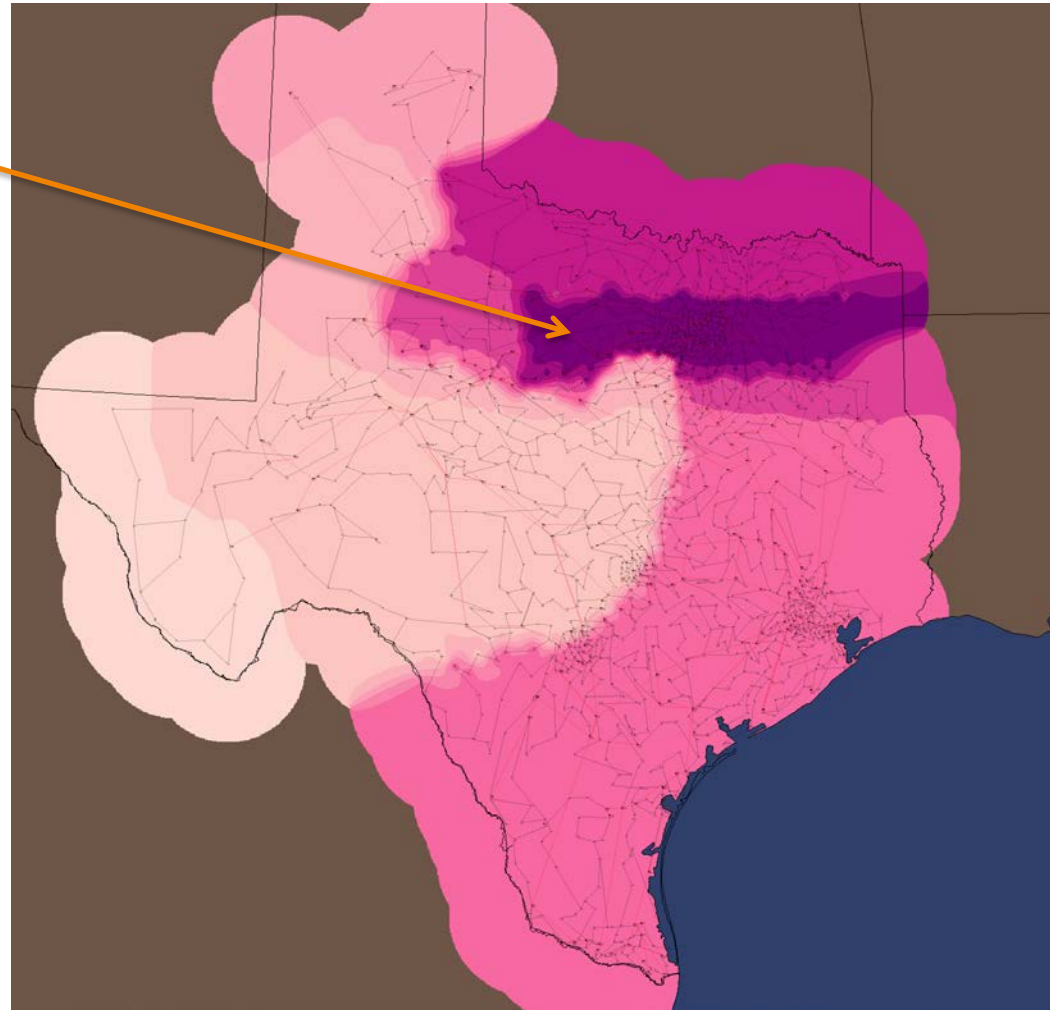
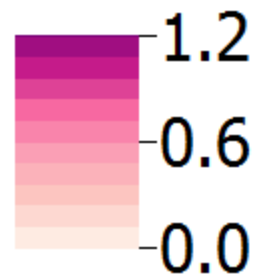
☐ Region Scalar ☒ Region Hotspot Scalar

Supplemental GMD Event



Hotspot Region

E-Field



Supplemental Event Time Series



- Sample input file *NERC_GMDSupplementalEventTimeSeries.csv*
 - 10-second samples matching the NERC *Supplemental 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 $\geq 85A$)

Supplemental Event Time Series



- Check **Tables and Results** → **Transformers**
- Edit *Display/Column Options* to show the field *Maximum IEffective*
- Apply an advanced filter for transformers with maximum GIC ≥ 30 A
- Change **Calculation Mode** to “Spatially Uniform Time-Varying E-Field”

Apply Hotspot Scalar for Time Series



- Go to **Non-Uniform Electric Field Scaling Functions → Earth Resistivity Scaling Regions**
- Set “Scalar” equal to Hotspot Scalar
(Local Menu → Set/Toggle/Columns → Set All Values to Field)

Non-Uniform Electric Field Scaling Functions						
Geomagnetic Latitude Scaling		Earth Resistivity Scaling Regions		Earth Resistivity Scaling Region Sets		
	Name	Scalar	Hotspot Scalar	Description	Number of Boundary Points	Region's Set is Active
1	AK-1	0.5100	0.5100	Adirondack Mountains	16	YES
2	AP-1	0.3000	0.3000	Appalachian Plateaus	38	YES
3	AP-2	0.7800	0.7800	Northern Appalachian Plateaus	30	YES
4	BR-1	0.2200	0.2200	Northwest Basin and Range	101	YES
5	CL-1	0.7300	0.7300	Colorado Plateau	32	YES
6	CO-1	0.2500	0.2500	Columbia Plateau	40	YES
7	CP-1	0.7700	0.7700	Coastal Plain (South Carolina)	23	YES
8	CP-2	0.8600	0.8600	Coastal Plain (Georgia)	76	YES
9	FL-1	0.7300	0.7300	Florida Peninsula	14	YES
10	CS-1	0.3700	0.3700	Cascade-Sierra Mountains	65	YES
11	IP-1	0.9000	0.9000	Interior Plains (North Dakota)	125	YES
12	IP-2	0.2500	0.2500	Interior Plains (North American)	13	YES
13	IP-3	0.9000	0.9000	Interior Plains (Michigan)	23	YES
14	IP-4	0.3500	0.3500	Interior Plains (Great Plains)	124	YES
15	NE-1	0.7700	0.7700	New England	23	YES
16	PB-1	0.5500	0.5500	Pacific Border (Willamette Valle	67	YES
17	PB-2	0.3900	0.3900	Pacific Border (Puget Lowlands	19	YES
18	PT-1	1.1900	1.1900	Piedmont	42	YES
19	SL-1	0.4900	0.4900	St. Lawrence Lowlands	33	YES
20	SU-1	0.9000	0.9000	Superior Upland	17	YES
21	BC	0.6200	0.6200	British Columbia (Canada)	14	YES
22	PRAIRIES	0.8800	0.8800	Prairies (Canada)	11	YES
23	ATLANTIC	0.7600	0.7600	Atlantic (Canada)	15	YES
24	MIDATL	0.7700	0.7700	Mid-Atlantic	15	YES
25	OZARK	0.8600	0.8600	Ozark	63	YES
26	RM	0.7300	0.7300	Rocky Mountain	93	YES
27	LC	0.5500	0.5500	Lower Californian	14	YES

Supplemental Event Time Series



- Set Time-Varying Input File to NERC_GMDSupplementalEventTimeSeries.csv
- Set Output File to TexasGICtSupp.csv
- Clear option
Hotspot
Modeling
“Include”
- Click “Calculate Transformer IEffective”
- Following time series calculation, reload *NERC_USGS_2017_Regions.aux* to reapply normal scalars

Field/Voltage Input

Spatially Uniform time-Varying E-Field Options

Time-Varying Input File
File: G:\pw\version.210\Training\Training Cases\NERC_GMDSupplementalEventTir Browse...

Save Output File
File: G:\pw\version.210\Training\Training Cases\TexasGICtSupp.csv Browse...

☐ Also output the EPRI Thermal Transformer Model (ETTM) GIC Signature (*.txt) file format for a single transformer.
NOTE: ETTM supports GIC signature files for individual transformers. This option will only create an output file if the Tables and Results Transformers display is filtered to show a single transformer.

Save ETTM Format Output File
File: Browse...

Calculate Transformer IEffective

Voltage Input Parameters

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

Geomagnetic Latitude Scaling Function NERC Draft March 2014 E
Earth Resistivity Scaling Region Set NERC_USGS_2017

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

Hotspot Modeling
☐ Include
Hotspot Field in V/km 12.00
Width of Hotspot in Kilometers 500.00
Height of Hotspot in Kilometers 100.00
Latitude of Center 32.777
Longitude of Center -96.797
☒ Scale Hotspot Value with Geomagnetic Latitude
☒ Scale Hotspot Value with Earth Resistivity
Earth Resistivity Scalar Value
☐ Region Scalar ☒ Region Hotspot Scalar

Capacitive Neutral Blocking



- Sort by Transformer Maximum Neutral Amps
- Toggle “GIC Blocked for Transformer Neutral” = YES for Wadsworth and Cooper GSUs 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 DC Lines Lines Line Shunts Loads Switched Shunts Substations Transformers System Summary G-Matrix Multi-Terminal DC Lines VSC DC Lines																		
	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	Maxim IEffec	Transformer Per Unit Effective GIC	GIC Mvar Losses	Maximum Mvar Losses	Maximum IEffec Direction (Degrees)	Neutral Current (Amps)	Maximum Neutral Amps	Maximum Neutral Current Degrees	Ignore GIC Losses	GIC Blocked for Transformer Neutral
1	1900	North Richland Hills 1 345	290	North Richland Hills 115	0	1	1	41.245	41.6314	0.174	25.69	25.93	83.2	47.754	47.78	89.1	NO	NO
2	1993	Terrell 2 345	87	Terrell 2 115	0	1	1	24.306	40.2374	0.103	15.48	25.62	143.8	63.745	95.43	139.1	NO	NO
3	1802	Throckmorton 345	447	Throckmorton 115	0	1	1	37.445	37.4516	0.158	24.43	24.44	92.0	-102.505	102.58	93.2	NO	NO
4	1866	Wadsworth 2 345	1593	Wadsworth 2 G0	0	1	1	10.859	32.2693	0.046	7.16	21.27	20.6	-32.577	96.81	20.6	NO	YES
5	2006	Dallas 18 345	115	Dallas 18 115	0	1	1	31.633	31.7901	0.134	19.73	19.83	96.7	49.784	50.05	85.1	NO	NO
6	1924	Plano 1 345	13	Plano 115	0	1	1	24.346	30.3973	0.103	15.26	19.06	54.2	44.349	47.42	70.2	NO	NO
7	1885	Plano 2 345	14	Plano 2 115	0	1	1	23.205	29.9620	0.098	14.52	18.74	51.7	40.375	43.23	70.0	NO	NO
8	1788	Cooper 345	1676	Cooper G0	0	1	1	24.600	28.6816	0.104	16.21	18.91	60.0	73.799	86.04	60.0	NO	YES
9	1990	Memphis 345	1290	Memphis 115	0	1	1	11.704	28.1834	0.049	7.58	18.26	156.4	-30.297	75.57	157.3	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	DC Lines	Lines	Line Shunts	Loads	Switched Shunts	Substations	Transformers	System Summary		G-Matrix	Multi-Terminal DC Lines	VSC DC Lines			
		BPT																

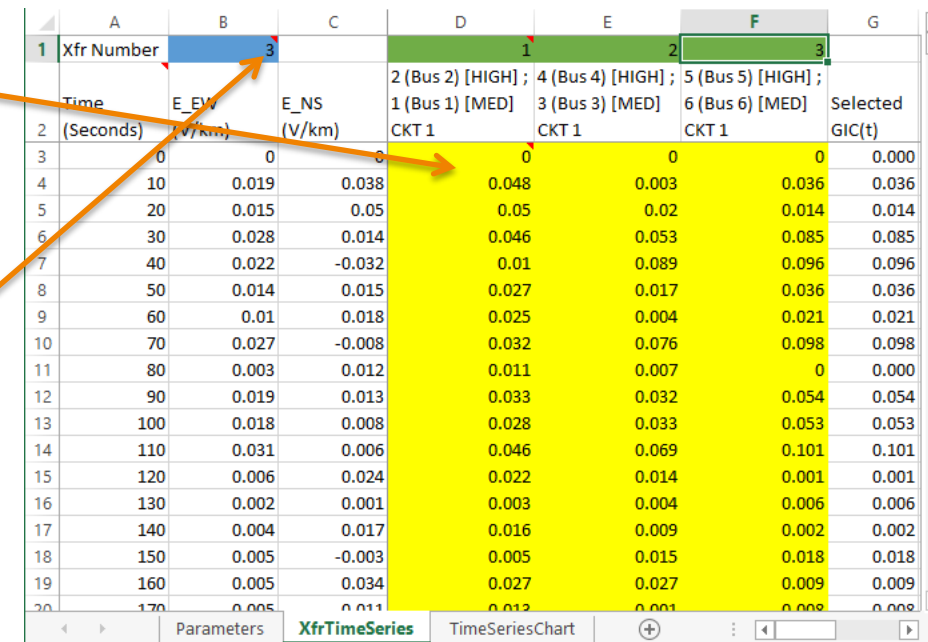
Modeling Resources



- 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 and Supplemental GMD Events
 - Spreadsheet for transformer thermal response modeling
 - Earth Resistivity Models
 - Aux Export Format

Thermal Calculation Spreadsheet

- Transformer Properties on *Parameters* sheet
- Paste GIC(t) time series for a transformer starting in column D of *XfrTimeSeries* (3 columns provided, but insert more if needed)
- Enter the column number of the transformer to apply thermal calculations
- Temperature graphs on *TimeSeriesChart*



1	A	B	C	D	E	F	G
1	Xfr Number			1	2	3	
2	Time (Seconds)	E_EV (V/km)	E_NS (V/km)	2 (Bus 2) [HIGH] ; 1 (Bus 1) [MED] CKT 1	4 (Bus 4) [HIGH] ; 3 (Bus 3) [MED] CKT 1	5 (Bus 5) [HIGH] ; 6 (Bus 6) [MED] CKT 1	Selected GIC(t)
3	0	0	0	0	0	0	0.000
4	10	0.019	0.038	0.048	0.003	0.036	0.036
5	20	0.015	0.05	0.05	0.02	0.014	0.014
6	30	0.028	0.014	0.046	0.053	0.085	0.085
7	40	0.022	-0.032	0.01	0.089	0.096	0.096
8	50	0.014	0.015	0.027	0.017	0.036	0.036
9	60	0.01	0.018	0.025	0.004	0.021	0.021
10	70	0.027	-0.008	0.032	0.076	0.098	0.098
11	80	0.003	0.012	0.011	0.007	0	0.000
12	90	0.019	0.013	0.033	0.032	0.054	0.054
13	100	0.018	0.008	0.028	0.033	0.053	0.053
14	110	0.031	0.006	0.046	0.069	0.101	0.101
15	120	0.006	0.024	0.022	0.014	0.001	0.001
16	130	0.002	0.001	0.003	0.004	0.006	0.006
17	140	0.004	0.017	0.016	0.009	0.002	0.002
18	150	0.005	-0.003	0.005	0.015	0.018	0.018
19	160	0.005	0.034	0.027	0.027	0.009	0.009
20	170	0.005	0.011	0.012	0.001	0.008	0.008





Sensitivity Analysis

Sensitivity Analysis

- “Transformer $I_{\text{effective}}$ GIC Sensitivity” can identify transmission lines with greatest effect on transformer GIC current
- Re-calculate GIC with “Single Snapshot” mode, 8 V/km, 93 degrees, and latitude and Earth Resistivity scaling; no Hotspot Modeling or Capacitive Neutral Blocking
- 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
- Non-Uniform Electric Field Sc
 - Geomagnetic Latitude Sc
 - Earth Resistivity Scaling
 - Earth Resistivity Scaling
 - Time Varying Electric Field Ir

Transformer $I_{\text{effective}}$ 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	NO	29.389
2	1802	Throckmorton 345	447	Throckmorton 115	0		1	YES	25.653
3	2006	Dallas 18 345	115	Dallas 18 115	0		1	NO	23.290
4	1882	Lytle 345	921	Lytle 115	0		1	NO	22.110
5	1788	Cooper 345	1676	Cooper G0	0		1	NO	20.816
6	2007	De Leon 345	421	De Leon 115	0		1	NO	20.778
7	1993	Terrell 2 345	87	Terrell 2 115	0		1	NO	19.109
8	1959	Garland 3 345	23	Garland 3 115	0		1	NO	17.927
9	2003	Lopeno 345	1095	Lopeno 115	0		1	NO	17.614
10	1924	Plano 1 345	13	Plano 115	0		1	NO	17.366

Lines

	From Number	From Name	To Number	To Name	Circuit	$dI_{\text{effective}}/dV$	$dI_{\text{effective}}/dV$	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

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

	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 G0	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 G0	1464	Mcadoo 2 115	1	0.035	0.012	0.00002	
9	1473	Olney 2 115	1872	Olney 2 345	1	-0.028	0.010	0.00004	

Substation Resistance Sensitivity

- 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's 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

Buses Lines Substations Transformers												
	Sub Num	Sub Name	Sub ID	GIC DC Neutral Voltage	GIC Ampt to Neut	Grounding Resistance (Ohms)	GIC Used Grounding Resistance (Ohms)	Thevenin Resistance (Ohms)	Thevenin Voltage (Volts)	GIC Thevenin Ratio	Latitude	Longitude
1	446	Throckmorton	446	-21.43	-108.05	0.000	0.198	0.161	-38.831	0.552	33.188	-99.265
2	135	Cooper	135	22.56	101.73	0.000	0.222	0.347	57.858	0.390	33.396	-95.676
3	427	Gordon	427	-14.18	-63.97	0.000	0.222	0.088	-19.808	0.716	32.588	-98.334
4	1285	Floydada 1	1285	-13.12	-59.18	0.000	0.222	0.404	-37.057	0.354	33.711	-100.384
5	1301	Odonnell	1301	-13.09	-59.02	0.000	0.222	0.210	-25.472	0.514	32.927	-101.764
6	420	De Leon	420	12.79	57.67	0.000	0.222	0.239	26.572	0.481	32.124	-98.574
7	131	Blue Ridge	131	12.12	54.66	0.000	0.222	0.244	25.471	0.476	33.322	-96.378
8	1424	Baytown 4	1424	8.24	52.56	0.000	0.157	0.071	11.958	0.689	29.758	-94.918
9	1324	Knox City	1324	-10.30	-51.93	0.000	0.198	0.148	-17.973	0.573	33.432	-99.854
10	1441	Jacksboro 2	1441	-10.25	-51.68	0.000	0.198	0.130	-16.994	0.603	33.145	-98.353
11	106	Dallas 10	106	9.27	51.20	0.000	0.181	0.077	13.209	0.702	32.710	-96.670

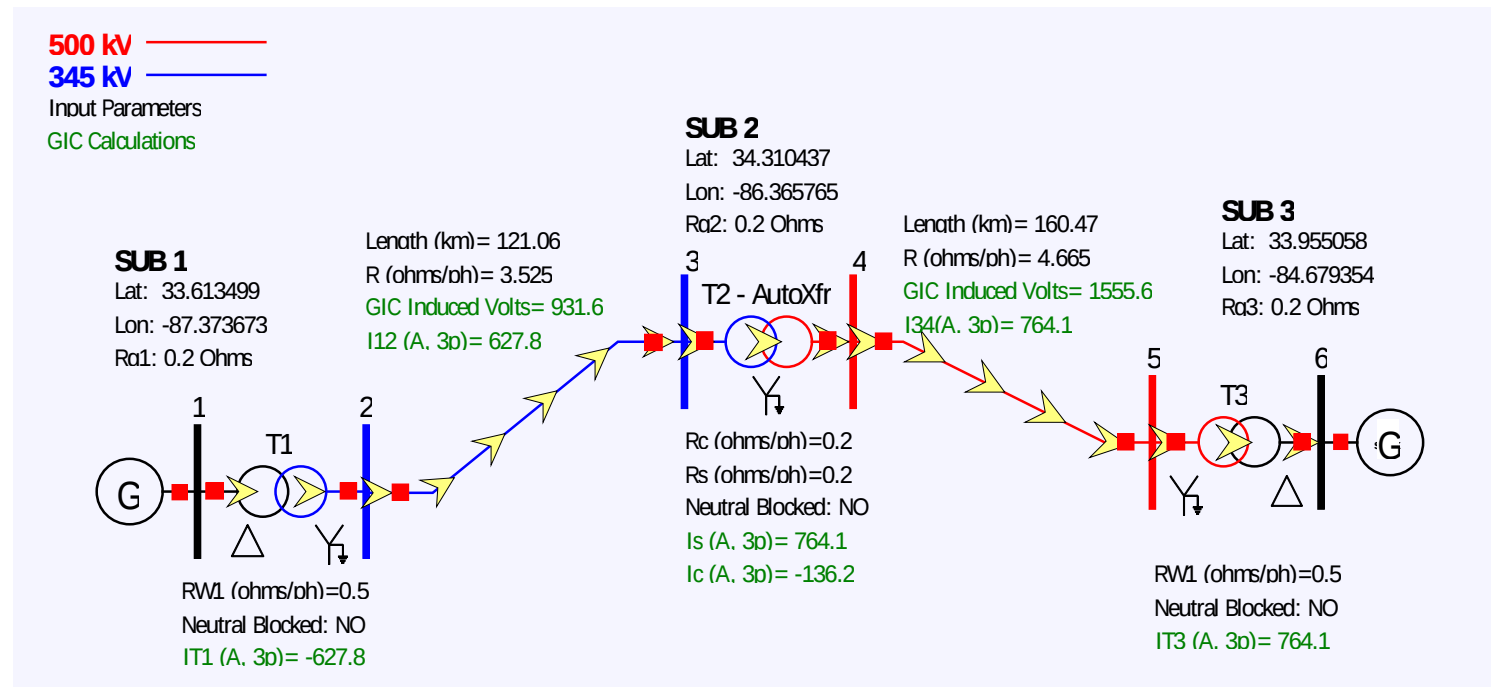


GIC Modeling in Transient Stability

NERC 6-Bus Example



- Described in the NERC Application Guide, Appendix II*
- 2 gwyne-delta GSUs, 1 gwyne-gwyne 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
- Check the box “Include GIC in Power Flow and Transient Stability”
- Set “Current Time” to 0
- Open *Transient Stability Analysis Form*

GIC in Transient Stability

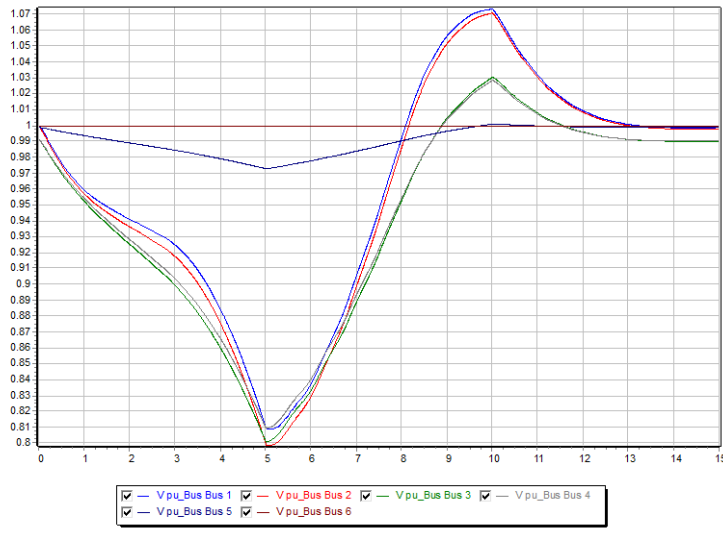


- Run Transient Stability Simulation for 15 seconds
- Time-series plots are generated for generator rotor angle, bus frequency, bus voltage, transformer I_{eff} , transformer GIC MVar losses (by substation), generator MVar output, and generator field current
- More details on using Simulator's Transient Stability Tool are provided in a separate course

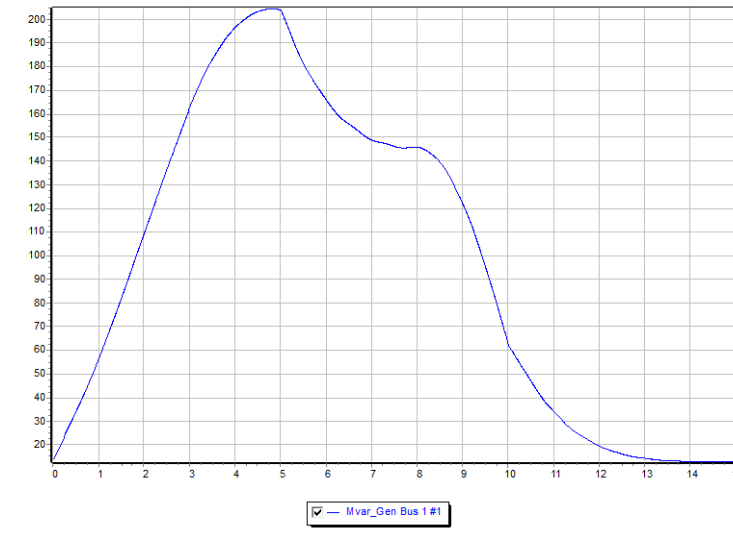
Transient Stability Plots



- 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



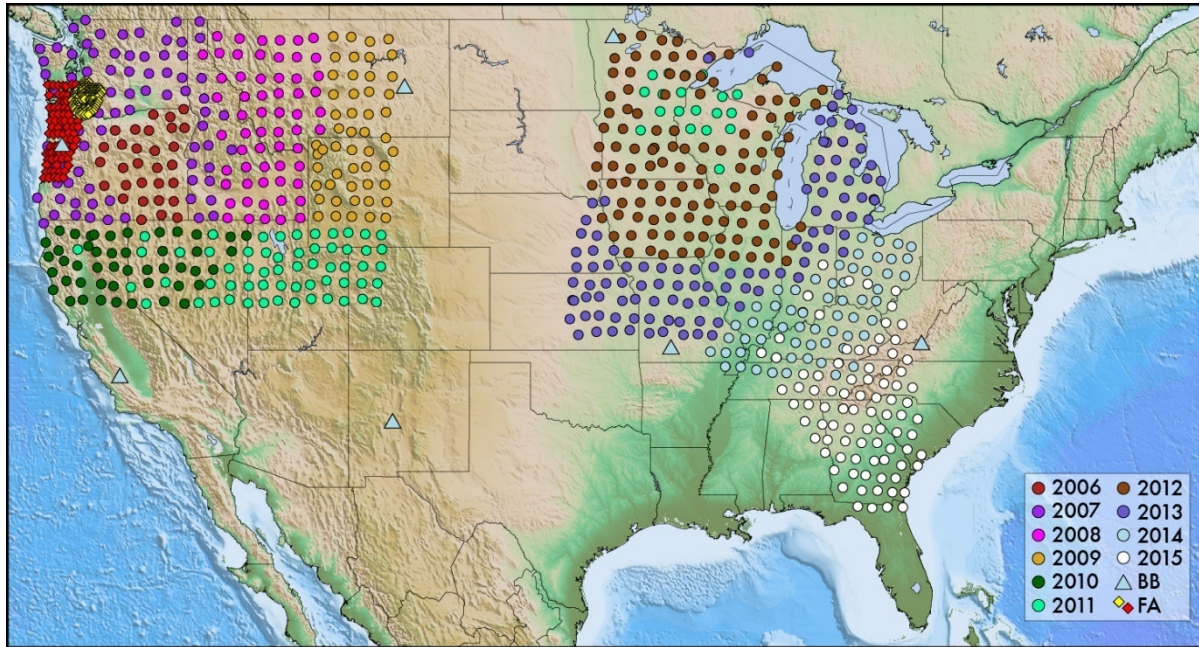
3D Earth Models and Non-Uniform Field Modeling

3-D Earth Models



- 3-D Earth Models produce more complex and realistic non-uniform surface E-field behavior
 - Earthscope (NSF funded 2003-2018)
 - US Magnetotelluric (MT) Array
- Research ongoing at EarthScope, Oregon State University, Incorporated Research Institutions for Seismology (IRIS), and NOAA
- Data gaps still exist, most notably in Canada and parts of Texas
- PowerWorld Simulator's time-varying E-field Calculation Mode can make use of these inputs as researchers and industry develop them

3-D Models and EarthScope



The magnetotelluric (MT) component of USArray, an NSF Earthscope project, consists of 7 permanent MT stations and a mobile array of 20 MT stations that will each be deployed for a period of about one month in regions of identified interest with a spacing of approximately 70 km. These MT measurements consist of magnetic and electric field data that can be used to calculate 3D conductivity deep in the Earth. The MT stations are maintained by Oregon State University's National Geoelectromagnetic Facility, PI Adam Schultz. (www.earthscope.org)

3-D Models and EarthScope



- Earthscope data is processed into magnetotelluric transfer functions that:
 - Define the frequency dependent linear relationship between EM components at a single site.

$$\frac{E_x(\omega)}{B_y(\omega)} = \xi_{xy} \quad (\text{simplified for the 1D case})$$

- Can be used to relate a magnetic field input to and electric field output at a single site

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \xi_{xx} & \xi_{xy} \\ \xi_{yx} & \xi_{yy} \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \end{bmatrix}$$

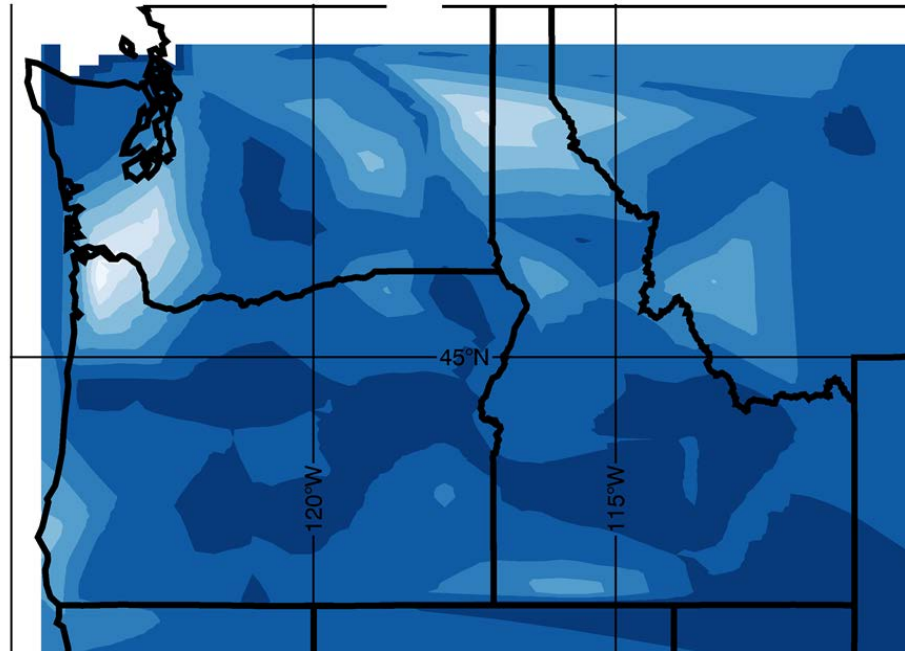
- Are provided in 2x2 impedance tensors by USArray

Reference: Kelbert et al., IRIS DMC Data Services Products, 2011.

Example 3-D Earthscope E-Field



- Image provides a snapshot visualization of the time-varying surface electric fields using Earthscope data

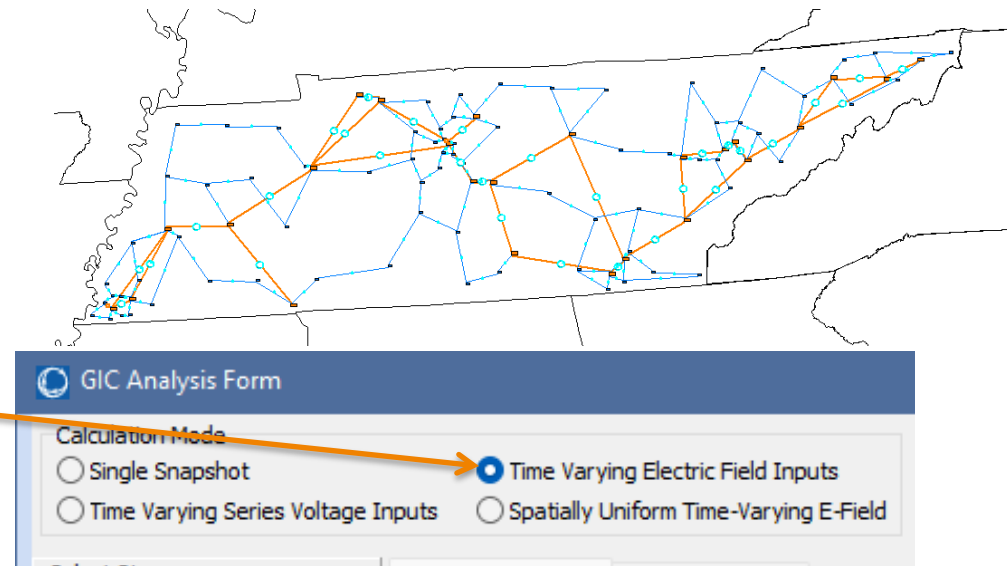


White ~ 10 V/km
Image Provided by
Computational Physics,
Inc, Jenn Gannon

Time Varying Electric Field Inputs



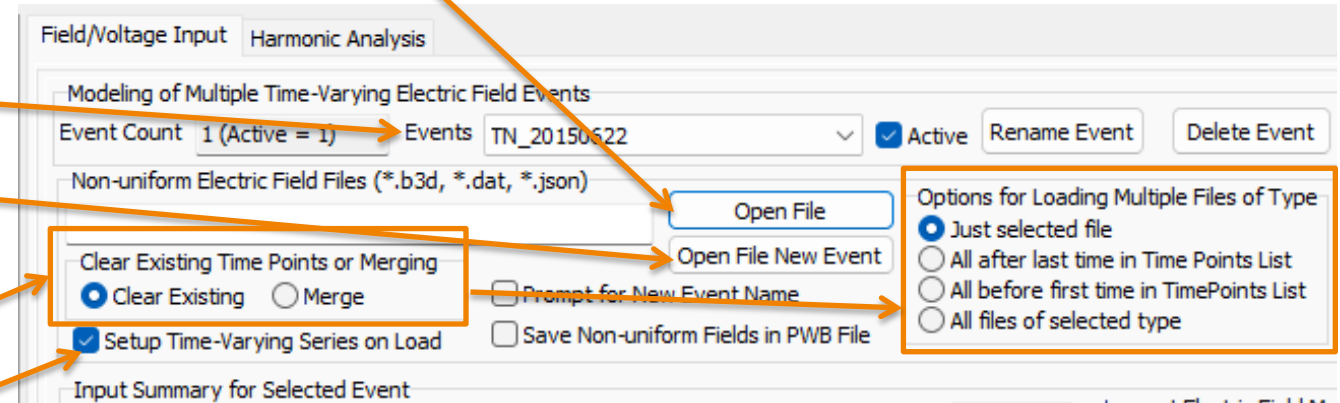
- Binary (B3D) or text (GeoJSON or dat) file formats
- Include time points and geo-spatial (longitude, latitude) points with Eastward and Northward E-field at each point
- Open case **TN150.pwb**
- On the *GIC Analysis Form*, set **Calculation Mode** to “Time Varying Electric Field Inputs”



Time Varying Electric Field Inputs



- By *Non-uniform Electric Field Files* click the *Open File* button and load **TN_20150622.b3d**
- File is loaded as a new “Event”
 - *Open File New Event* will superimpose on Event(s) already loaded
 - Can also overwrite existing files or load multiple
- *Setup Time Varying Series on Load* will create corresponding inputs in “Time Varying Series Voltage Inputs” **Calculation Mode** (needed for Power Flow and Transient Stability Calculations)
 - De-check prior to opening files if you need to manipulate data or load multiple events first
 - Use the *Setup Time Varying Series* button after all other operations are finished in this case



TN_20150622 Event



- Bottom panes show time point data for the currently selected Event
- With sorting, we can quickly identify the time and coordinates of the peak E-Field of the Event

Selected Time Point

	Time Offset, Seconds	Maximum Electric Field, V	Maximum Electric Field Longitude	Maximum Electric Field Latitude	Save in File	Date/Time String	+34.000-0 V/km	+ V/
1	66840.000	1.120	-82.0000	35.5000	YES	6/22/2015 6:34:00 PM (UTC)	0.32359	
2	66830.000	0.988	-82.0000	35.5000	YES	6/22/2015 6:33:50 PM (UTC)	0.22213	
3	66880.000	0.939	-82.0000	35.5000	YES	6/22/2015 6:34:40 PM (UTC)	0.30128	
4	72050.000	0.915	-83.0000	34.5000	YES	6/22/2015 8:00:50 PM (UTC)	0.20362	
5	66850.000	0.914	-82.0000	35.5000	YES	6/22/2015 6:34:10 PM (UTC)	0.30729	
6	72100.000	0.906	-83.0000	34.5000	YES	6/22/2015 8:01:40 PM (UTC)	0.18268	
7	72060.000	0.894	-83.0000	34.5000	YES	6/22/2015 8:01:00 PM (UTC)	0.20681	
8	72020.000	0.847	-83.0000	34.5000	YES	6/22/2015 8:00:20 PM (UTC)	0.17532	

Corresponding E-field at each geolocation

Latitude	34.00	Longitude	-89.75	Get Interpolated value	Eastward	0.000	Northward	0.000
Time Point Grid Preview (First Entry is the Eastward Value, the Second the Northward)								
	Longitude	Latitude	Distance to Station (km)	Electric Field East, V/km	Electric Field North, V/km	Electric Field Magnitude V/km	Electric Field Angle, Compass Degrees	Data Quality
1	-82.0000	35.5000	-1.0000	1.1144	0.1067	1.120	84.5289	0
2	-83.0000	34.5000	-1.0000	0.1519	-0.9392	0.951	170.8146	0
3	-82.0000	36.0000	-1.0000	0.8909	0.2275	0.920	75.6759	0
4	-82.0000	35.0000	-1.0000	0.8689	0.0822	0.873	84.5955	0
5	-82.5000	35.5000	-1.0000	0.8166	0.0508	0.818	86.4386	0
6	-82.5000	35.0000	-1.0000	0.6663	-0.4391	0.798	123.3853	0

GIC Calculation and Power Flow



- Set the “Current Time” to match desired time point (e.g. 66840, at the peak E-field)
- Check “Include GIC in Power Flow and Transient Stability”
- Optionally “Set Present as Base” in **Difference Flows**
- Click “Calculate GIC Values” and then solve the power flow
- Optionally browse GIC and AC power flow quantities

The screenshot shows the 'GIC Analysis Form' window. It features several controls: 'Calculation Mode' with radio buttons for 'Single Snapshot', 'Time Varying Electric Field Inputs' (selected), 'Time Varying Series Voltage Inputs', and 'Spatially Uniform Time-Varying E-Field'. There are buttons for 'Calculate GIC Values' and 'Clear GIC Values'. A checkbox 'Include GIC in Power Flow and Transient Stability' is checked. A text field 'Current Time Offset from Reference (Seconds)' contains '66840.00'. Other options include 'Calculate GIC on Time Change' (unchecked), 'Validate Input Data for GIC', and 'Clear All GIC Input and Values'. At the bottom, there are tabs for 'Field/Voltage Input' and 'Harmonic Analysis', and a 'Select Step' dropdown.

Calculating Results for the Entire Time Series



- The prior technique works well for closely examining GICs and power flow solutions for a few key timepoints
- The Transient Stability and Time Step Simulation tools are better suited for bulk calculations over many points or the entire time series
- Return to **Field/Voltage Input** page
- Switch the **Calculation Mode** to “Time Varying Series Voltage Inputs”
- Verify that DC input voltages are populated for branches across timepoints (0 to 172790)

Field/Voltage Input		Harmonic Analysis													
AC Line Input Voltages		Substation EField V/km (Display Only)							Substation EField Direction Degrees (Display Only)						
	Branch ID	From Number	To Number	Circuit	From Latitude	To Latitude	From Longitude	To Longitude	Distance Between Substations (km)	Timepoint_1	Timepoint_2	Timepoint_3	Timepoint_4	Timepoint_5	Timepoint_6
1	Time in Seconds									0.000	10.000	20.000	30.000	40.000	50.000
2	Branch '144' '1' '1'	144	1 1		36.0282	36.0282	-87.9858	-87.9858	0.00	0.000	0.000	0.000	0.000	0.000	0.000
3	Branch '2' '14' '1'	2	14 1		36.4362	36.4751	-86.8408	-87.2991	41.31	-0.152	-0.126	-0.093	-0.078	-0.053	-0.051
4	Branch '2' '21' '1'	2	21 1		36.4362	36.2387	-86.8408	-86.7329	23.96	0.030	0.014	0.014	0.003	0.004	-0.006
5	Branch '19' '3' '1'	19	3 1		35.9840	36.2233	-86.5424	-86.1935	41.14	0.078	0.087	0.059	0.071	0.045	0.065
6	Branch '141' '3' '1'	141	3 1		36.3156	36.2233	-86.4004	-86.1935	21.22	0.033	0.025	0.018	0.014	0.008	0.007
7	Branch '4' '18' '1'	4	18 1		36.0522	36.1306	-86.6325	-86.6131	8.87	0.010	0.014	0.010	0.013	0.009	0.014

GIC in Transient Stability



- Open **Transient Stability** dialog and go to **Options → Power System Model → Common** page
- Check “Just Calculate GIC with No Network Solution” (allows fast computation of time-varying GIC quantities without transient stability numeric integration)

—Geomagnetic Induced Current Options—

Include GIC Effects (Option Set on GIC Form)

☒ Just Calculate GIC with No Network Solution

GIC XF Time Constant (Sec)  

GIC in Transient Stability



- Go to **Simulation** → **Control** page
- Set the Start Time, End Time, and Time Step to correspond to the GIC input data (or any desired subset)

Simulation Add... C

Control Definitions Violations

Simulation Time Values

Start Time (seconds)

End Time (seconds)

Time Step (seconds)

Specify Time Step in

☒ Seconds

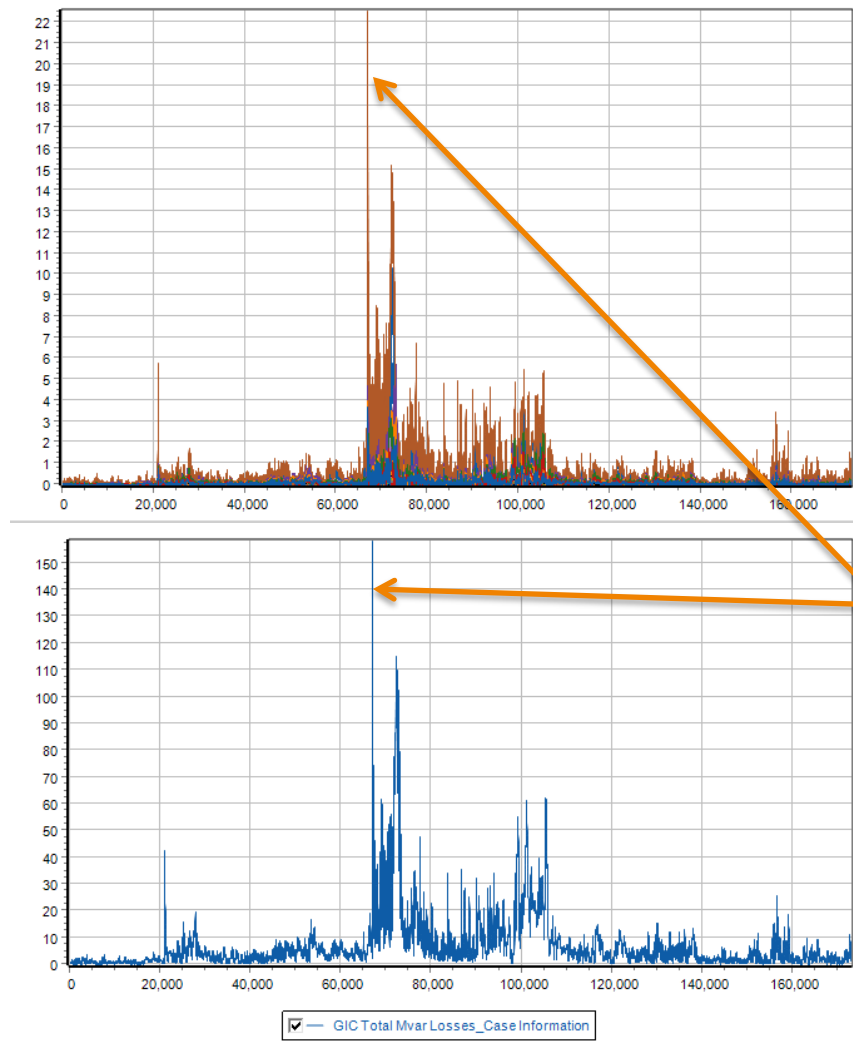
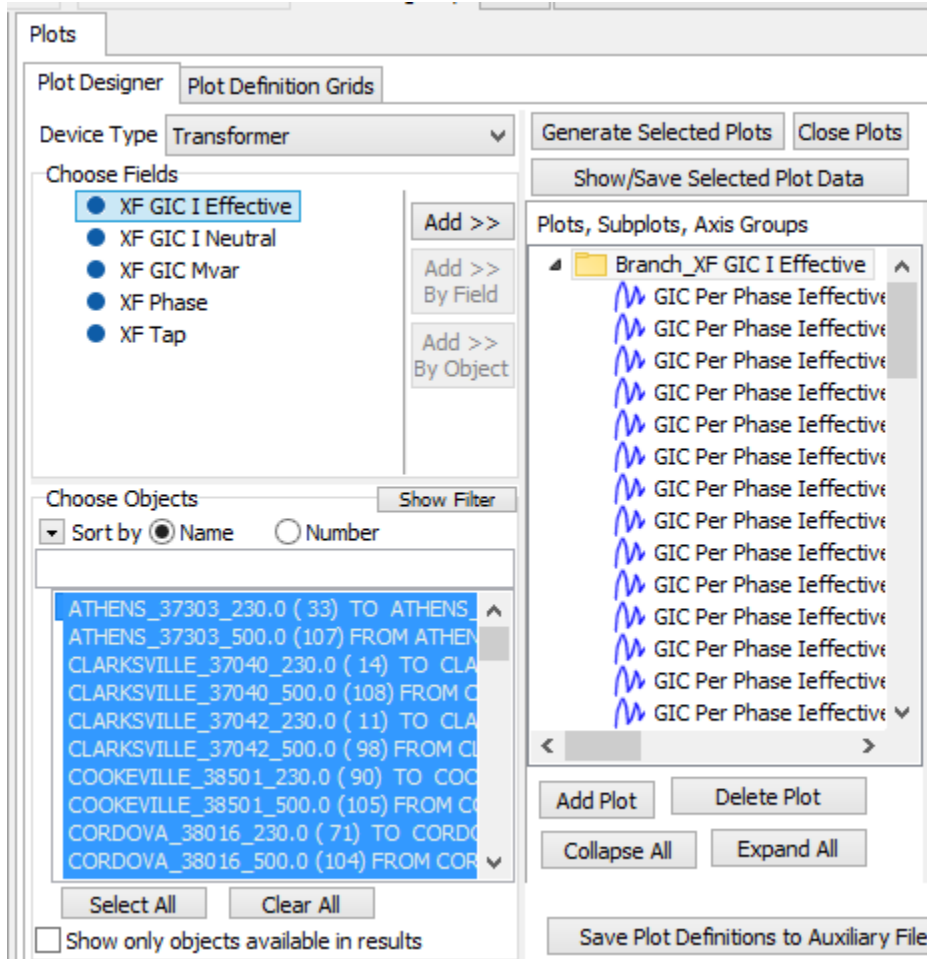
☐ Cycles

Create Plot Definitions



- Go to **Plots → Plot Designer** page and create plots
 - *Device Type* “Transformer” and *Field* “XF GIC I Effective”
 - *Device Type* “Case Information” and *Field* “GIC Total Mvar Losses”
- Details on plotting tool are covered in the Transient Stability Training
- Click “Run Transient Stability”

GIC Time Series Plots



Mouse Over plot traces for details; verify that peak losses and transformer GIC occur at t=66,840

GIC Time Series Tables



- Go to **Results from RAM → Time Values** page and **Transformer** and **System → Case Information** subpages
- View tabular results for objects of interest
- Sort to identify time periods with highest transformer GICs or system losses

Time	Transformer 33 (ATHENS_3 TO 107 (ATHENS_3 CKT 1 XF GIC I Effective	Transformer 40 (HIXSON_3 TO 94 (HIXSON_3 CKT 1 XF GIC I Effective	Transformer 43 (JONESBOR TO 97 (JONESBOR CKT 1 XF GIC I Effective	Transformer 45 (ELIZABETH TO 103 (ELIZABETH CKT 1 XF GIC I Effective
66840	3.7176	0.4353	15.4434	22.5654
66880	3.0885	0.5446	12.6078	19.3476
66850	3.3867	0.0072	12.4381	19.0452
66830	2.1809	1.6391	13.3064	18.515
66890	2.5186	1.0956	11.076	17.1193
72050	1.5193	2.2183	10.7232	15.1958
72060	1.5811	2.1045	10.5911	15.0946
72170	1.6704	1.8952	10.3548	14.8751
72260	1.583	1.8674	10.0983	14.5039
72160	1.5808	1.8621	10.0115	14.358
72040	1.4909	1.8766	9.8965	14.0511
72330	1.251	2.2272	9.8403	13.9701

Time	Case Information GIC Total Mvar Loss
66840	157.8304
66850	141.2637
66880	139.8141
66890	126.2713
66830	119.7296
72060	114.6927
72050	114.6621
72170	113.1524
66860	111.9942
72260	109.9402
72160	109.1893
66870	108.3116
72330	107.6892
72100	107.4555
72130	106.7667
72180	105.7058
72040	105.2566
72120	104.3553

ch

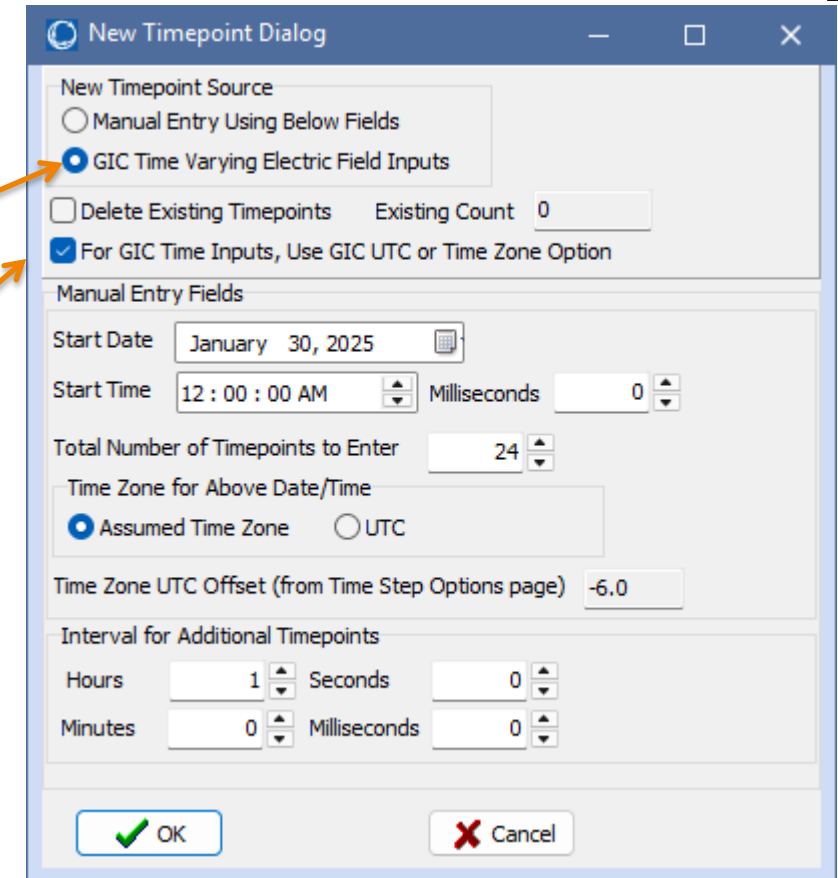
GIC with Time Step Simulation



- For events with higher frequency variation, such as high-altitude electromagnetic pulse E3 (HEMP E3), it may be appropriate to also perform a transient stability dynamic simulation
- For most solar GMD, the steady state power flow is more salient
- Transient Stability can be used for quick calculation of time-varying GIC – then you can perform a power flow on those time periods with the highest GIC or reactive power losses
- The Time Step Simulation (TSS) can also be used to perform multi-period power flows

GIC with Time Step Simulation

- Open Tools – Time Step Simulation
- Click “Insert Time Points”
- For **New Timepoint Source**, choose “GIC Time Varying Electric Field Inputs” and check “For GIC Time Inputs, Use GIC UTC or Time Zone Option”
- Click “OK”



The screenshot shows the 'New Timepoint Dialog' window. The 'New Timepoint Source' section has two radio buttons: 'Manual Entry Using Below Fields' (unselected) and 'GIC Time Varying Electric Field Inputs' (selected). Below these are two checkboxes: 'Delete Existing Timepoints' (unselected) and 'For GIC Time Inputs, Use GIC UTC or Time Zone Option' (checked). The 'Manual Entry Fields' section includes a 'Start Date' field set to 'January 30, 2025', a 'Start Time' field set to '12 : 00 : 00 AM' with a 'Milliseconds' field set to '0', a 'Total Number of Timepoints to Enter' field set to '24', a 'Time Zone for Above Date/Time' section with 'Assumed Time Zone' (selected) and 'UTC' (unselected), and a 'Time Zone UTC Offset (from Time Step Options page)' field set to '-6.0'. The 'Interval for Additional Timepoints' section has four spinners: 'Hours' (1), 'Minutes' (0), 'Seconds' (0), and 'Milliseconds' (0). At the bottom are 'OK' and 'Cancel' buttons.



GIC with Time Step Simulation



- The Solution Type “GIC Only (No Power Flow)” allows quick calculation of GIC quantities, similar to the “Just Calculate GIC with No Network Solution” in Transient Stability

	Date	Time	Skip	Processed	Solution Type	Run Contingency	Solved
1	06/22/2015	12:00:00 AM	NO	NO	Single Solution	NO	Not Started
2	06/22/2015	12:00:10 AM	NO	NO			
3	06/22/2015	12:00:20 AM	NO	NO			
4	06/22/2015	12:00:30 AM	NO	NO			
5	06/22/2015	12:00:40 AM	NO	NO			
6	06/22/2015	12:00:50 AM	NO	NO			
7	06/22/2015	12:01:00 AM	NO	NO			
8	06/22/2015	12:01:10 AM	NO	NO			
9	06/22/2015	12:01:20 AM	NO	NO			
10	06/22/2015	12:01:30 AM	NO	NO			

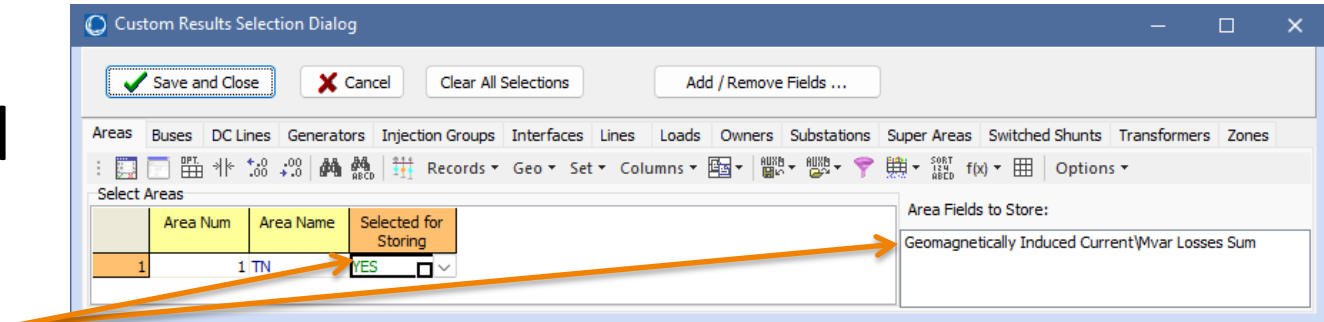
- Single Solution
- Unconstrained OPF
- OPF
- SCOPF
- GIC Only (No Power Flow)
- Apply Only [With Weather]
- Toggle All

- If we want to compute AC power flow quantities, however, leave all Solution Types as “Single Solution”

GIC with Time Step Simulation



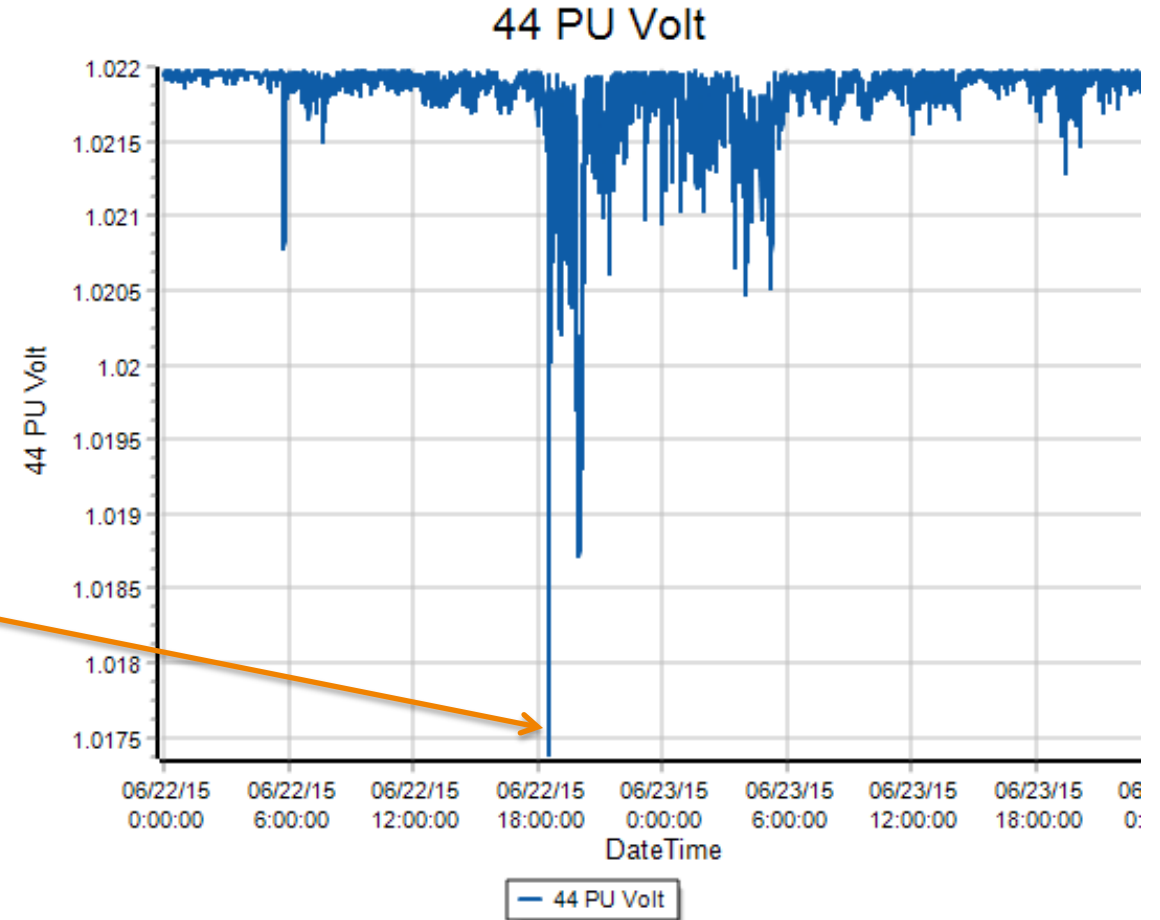
- Go to the **Results** page and choose the “View/Modify” button under the Results Definition group
- Click “Add/Remove Fields” and choose
 - “Geomagnetically Induced Current\Mvar Losses Sum” for Area 1 (TN)
 - Geomagnetically Induced Current\Transformer Per Phase Effective GIC” for all transformers
 - “Voltage\Per Unit Magnitude” for all buses
 - Any other desired quantities
- Click “Save and Close”



GIC with Time Step Simulation



- Click the “Do Run” button
- Examine Results in Tables and/or Plot Columns (**Columns** → **Plot Column(s)** from the Case Information Toolbar)
- Bus 44 per-unit voltage: minimum coincides with time of maximum reactive power losses



Real-Time and Historic GMD E-Fields



- Surface Electric Fields are calculated in near real-time by the NOAA Space Weather Prediction Center (SWPC) using both 1D and 3D EMTF Earth Models
 - These can be downloaded in GeoJSON format and read into PowerWorld Simulator
 - <https://www.swpc.noaa.gov/products/geoelectric-field-models-1-minute>
- SWPC data is also compiled for several significant historic GMD events and downloadable from the PowerWorld Knowledge Base
 - <https://www.powerworld.com/knowledge-base/historic-gmd>



High-Altitude Electromagnetic Pulse (HEMP)

Electromagnetic Pulse (EMP)



- Broadly defined, an electromagnetic pulse is any transient burst of electromagnetic energy
- Characterized by their magnitude, frequencies, footprint, and type of energy
- There are many different types, such as static electricity sparks, interference from gasoline engine sparks, lightning, electric switching, geomagnetic disturbances (GMDs) caused by solar corona mass ejections (CMEs), nuclear electromagnetic pulses, and non-nuclear EMP weapons

HEMP Time Frames



- The impacts of a high-altitude EMP (HEMP) are typically divided into three time frames: E1, E2 and E3
- The quickest, E1 with maximum electric fields of 10's of kV per meter, can impact unshielded electronics
- E2, with electric fields of up to 100 volts per meter, is similar to lightning
- Much of talk is on E3, which is similar to GMDs

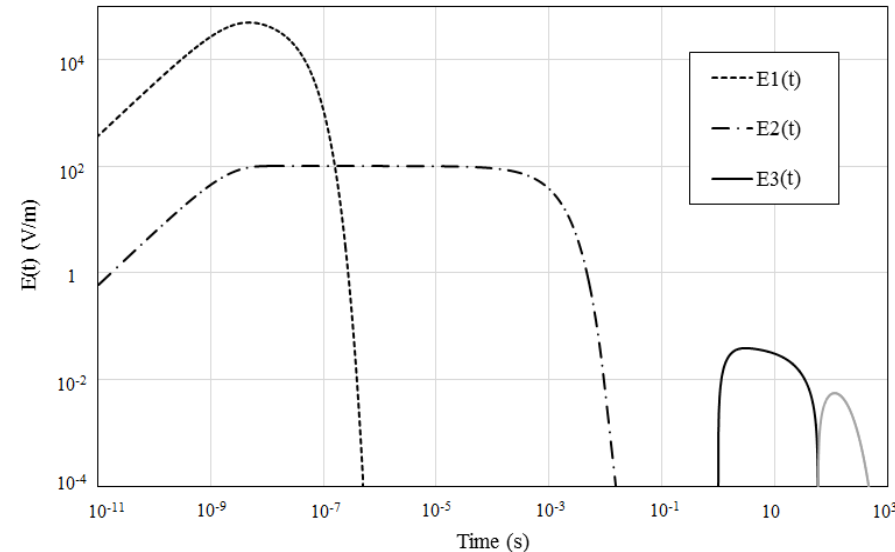
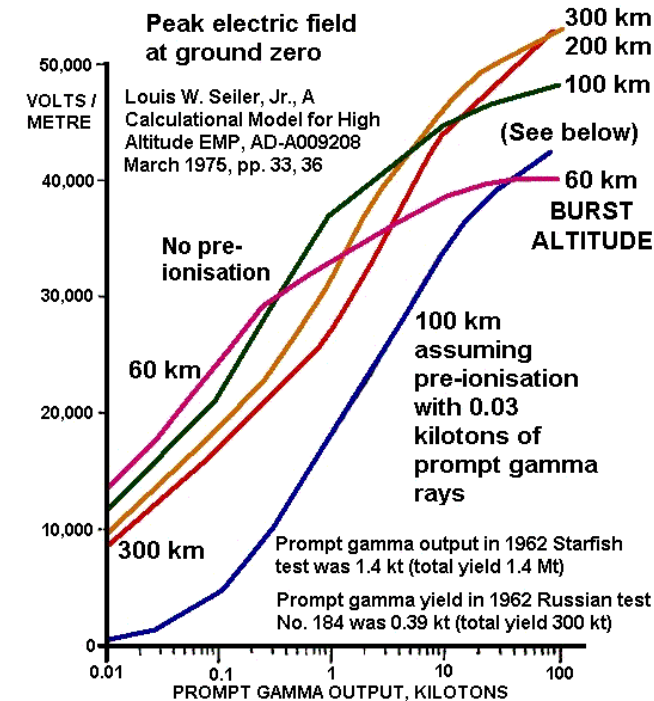
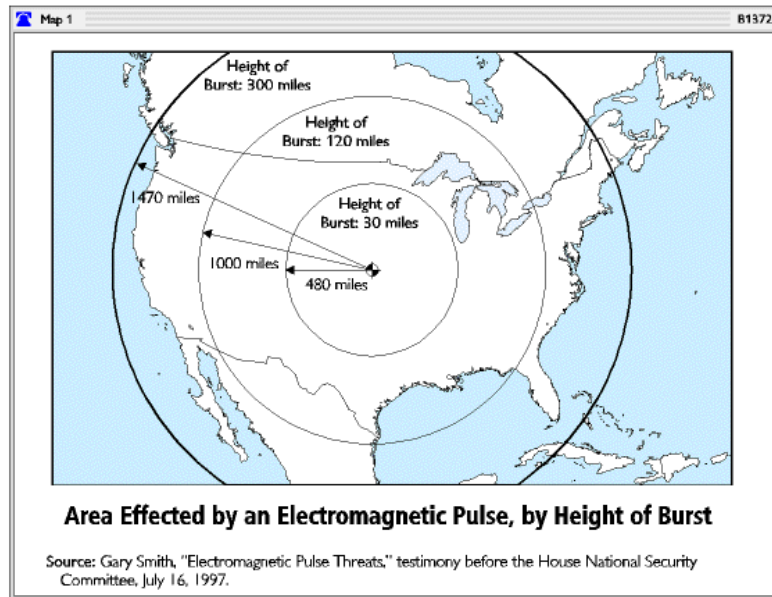


Image Source: IEC 1000-2-9 Figure

HEMP Impact vs. Size and Altitude

- EMP impacts do not scale linearly with weapon size
 - Even quite small weapons (such as 10 kilotons) can produce large EMPs

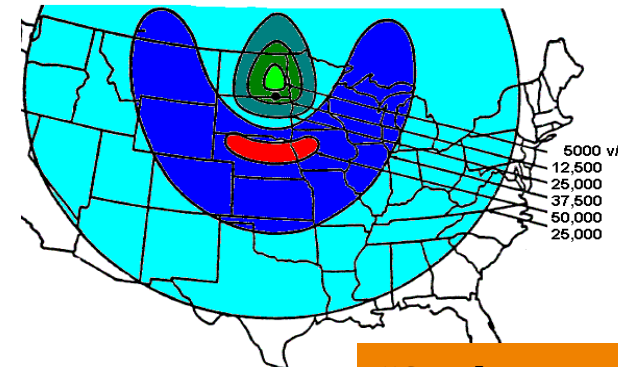
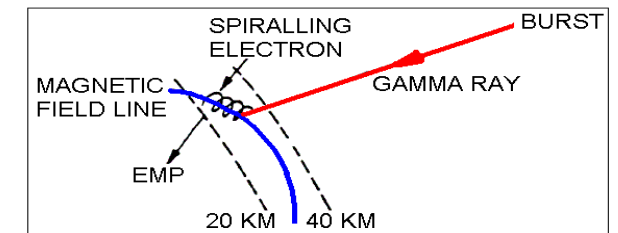


Low altitude EMPs can still have large footprints

Image Sources: en.wikipedia.org/wiki/Nuclear_electromagnetic_pulse

EMP E1 and E2 Mechanisms

- In a nuclear explosion, the E1 pulse is produced by the gamma radiation stripping electrons from atoms
 - Known as the Compton effect; explained by Conrad Longmire at Los Alamos in 1963
 - Electron flow is diverted by earth's magnetic field
 - Mostly line of sight impacts; highest impacts south of detonation in Northern Hemisphere
- The E2 pulse is created by scattered gamma rays and neutron gamma rays



Source: Nuclear Environment Survivability, S. Army, report AD-A278230 (1994)

“Smile Diagram”

Source: “The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, MetaTech-R-320, January 2010



EMP E1 Protection



- Because of large footprint, small energy density in the E1, so devices can be protected by Faraday cages
 - The allowable size of apertures depends on the wavelength and hence the frequency ($\lambda = c/f$); a ballpark figure is no larger than 1/10 the wavelength; for 1 GHz this is about 3 cm
 - Incoming wires are also an issue
 - Military Standard 188-125-1 (“HIGH-ALTITUDE ELECTROMAGNETIC PULSE (HEMP) PROTECTION FOR GROUND-BASED C41 FACILITIES PERFORMING CRITICAL, TIME-URGENT MISSIONS PART 1 FIXED FACILITIES”) provides useful guidance
 - Another useful reference is MetaTech Report R-320, “The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid”

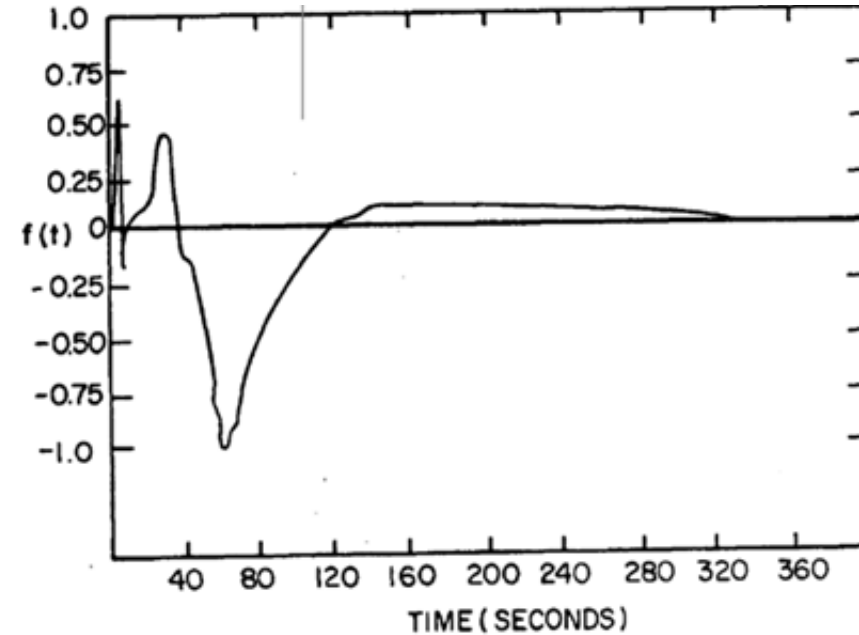
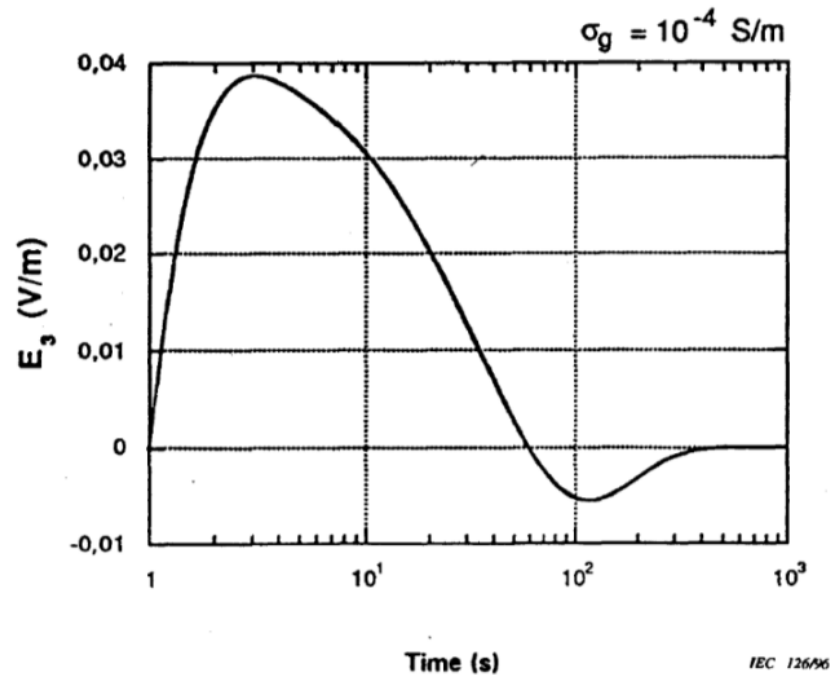
Source: “The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid,”
MetaTech-R-320, January 2010

High-Altitude Electromagnetic Pulse (HEMP)



- The late-time (E3) effects of a nuclear detonation tens-hundreds of km over the surface of the Earth gives rise to geomagnetic disturbances (GMD) similar to a coronal mass ejection from the sun
- The E3 is usually broken into two components
 - E3A “Blast Wave” caused by the expansion of the nuclear fireball, expelling the Earth’s magnetic field
 - E3B “Heave” as bomb debris and air ions follow geomagnetic lines at about 130 km, making the air rise, which gives rise to a current and an induced electric field

HEMP E3A and E3B

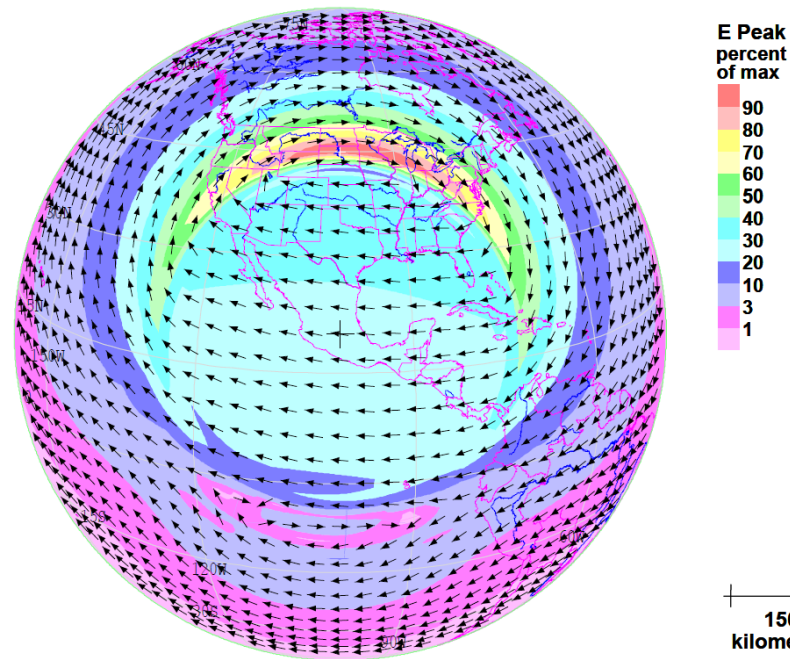


Left Image: IEC 1000-2-9, Figure 9, Right Image: ORNL “Study to Assess the Effects of Magnetohydrodynamic Electromagnetic Pulse on Electric Power Systems Phase I Final Report,” May 1985, Figure 8

HEMP E3A



- For a uniform earth conductivity model, the E3A Blast wave can be modeled as a fairly uniform east-west electric field
- Similar to a uniform GMD over a very wide area



Because of the relatively large, uniform electric field area, the effect is somewhat insensitive to location within CONUS

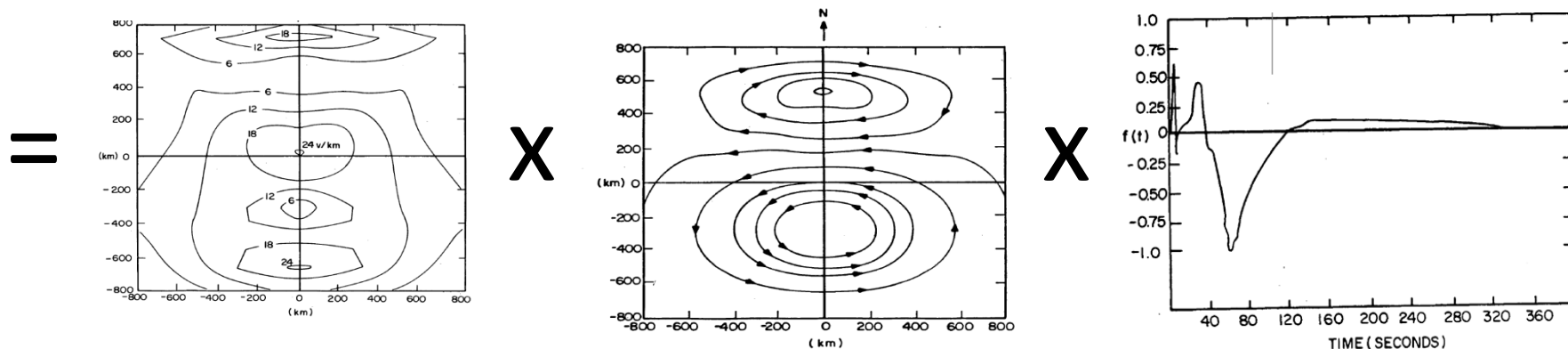
Image Source: Metatech R-321, Figure 2-4

HEMP E3B



- ORNL 1985 models the E3B electric field as the product of a spatially independent time function (fig 8), and time independent spatial magnitude and directions (fig 9 and 10)

$$\bar{E}(x, y, t) = \varepsilon(x, y) \bar{e}(x, y) f(t)$$



Values were calculated assuming a uniform conductivity of 0.001 S/m

HEMP E3 Waveforms

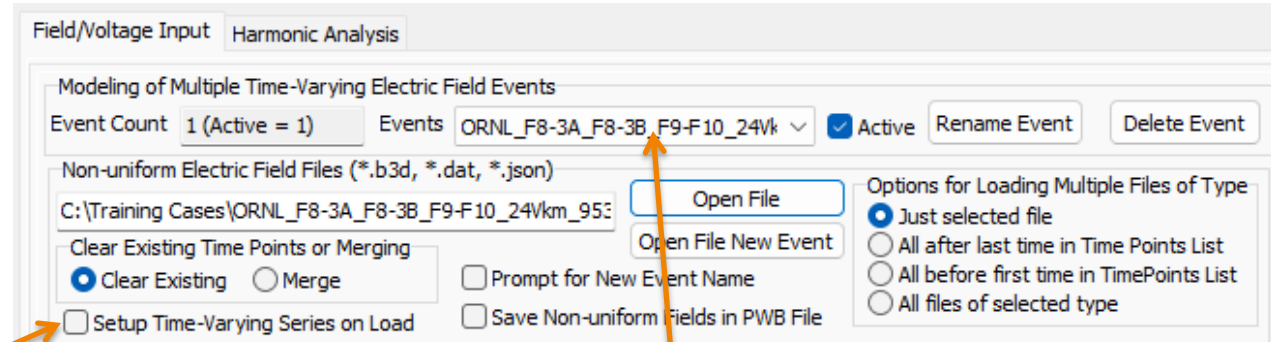


- Select sources of published and publicly available waveforms
 - “Study to Assess the effects of Magnetohydrodynamic Electromagnetic Pulse on Electric Power System, Phase 1, Final Report,” Martin Marietta Energy Systems Inc. Oak Ridge National Labs. 1985.
 - “IEC 61000-2-9 – Electromagnetic Compatibility (EMC) – Part 2: Environment – Section 9: Description of HEMP Environment – Radiated Disturbance. Basic EMC Publication,” International Electrotechnical Commission. Feb. 19, 1996.
- Download these (b3d format) from the PowerWorld Knowledge Base
<https://www.powerworld.com/knowledge-base/emp-waveforms-based-on-published-research>

Example: Oak Ridge National Labs Waveform



- Open Case *ACTIVSg10k.pwb*
- Open the *GIC Analysis Form* and set **Calculation Mode** to “Time Varying Electric Field Inputs” and de-check the box “Setup Time-Varying Series on Load”
- Load the file from the Knowledge Base:
ORNL_F8-3A_F8-3B_F9-F10_24Vkm_953W419N.b3d



Shift the Event Center



- Note that the event is centered at 95.3 degrees west longitude, 41.9 degrees north latitude
- Suppose we want to shift it to 112 west, 41 north (near Salt Lake City)
- Set “Latitude Shift (Deg.)” to -0.9, “Longitude Shift (Deg.)” to -16.7, and click “Shift, Scale and or Stretch all Time Point Grid Values”

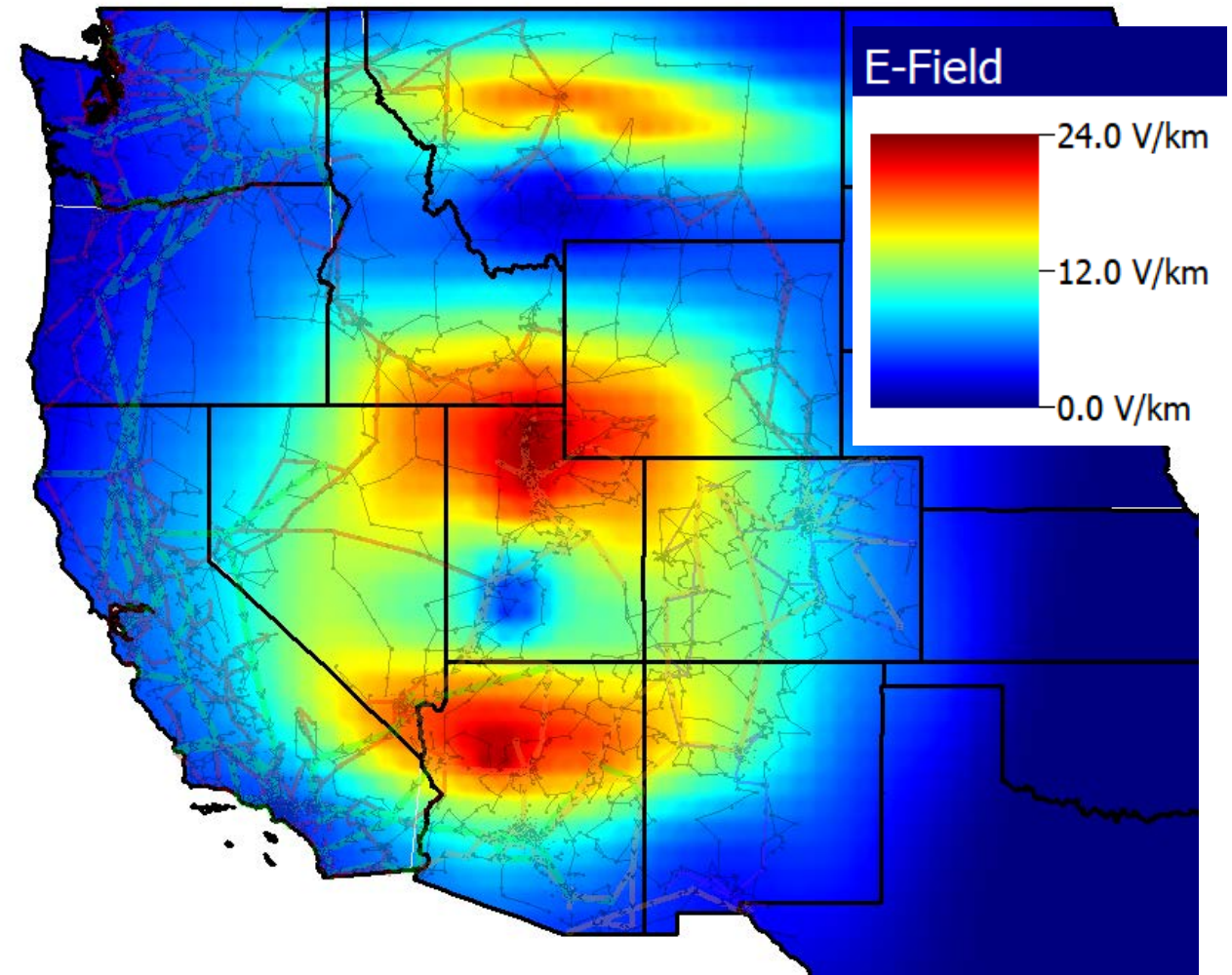
Scale or Shift All Input Points

Latitude Shift (Deg.)	-0.900	Magnitude Scalar	1.000	Stretch Scalar	1.000
Longitude Shift (Deg.)	-16.700	Shift, Scale and or Stretch all Time Point Grid Values			

ORNL E3B Peak Contour



- Note the Maximum Electric Field, V/km occurs at $t=60s$; this is during the E3B phase
- Set the “Current Time Offset from Reference (Seconds)” to 60 and Calculate GIC Values
- On the one-line diagram, contour the Spatial Data “GIC\Electric Field Magnitude (V/km)” with values shown
- Shown here with Emphasis Filter on Background Lines



Power Flow Mismatches at t=60



Mismatches									
Records Geo Set Columns Find... Remove Quick Filter									
Number	Sub Num	Sub Name	Name	Area Name	Type	Mismatch MW	Mismatch Mv	Mismatch MVA	
1	60867	60423	CRAIG 2	CRAIG 2 1	Colorado	PQ (Remotely Regul	0.00	-1304.05	1304.05
2	28737	28421	DESERT CENTER	DESERT CENTER	Southeast California	PQ	0.00	-1127.61	1127.61
3	40922	40480	PAGE 3	PAGE 3 1	Arizona	PQ (Remotely Regul	0.00	-851.52	851.52
4	60884	60426	WELLINGTON	WELLINGTON 4 1	Colorado	PQ (Remotely Regul	0.00	-822.01	822.01
5	40783	40452	PAGE 2	PAGE 2 1	Arizona	PQ (Remotely Regul	0.00	-757.57	757.57
6	26126	25577	BURBANK 10	BURBANK 10 2	Southwest California	PQ	-0.00	-752.80	752.80
7	13554	13282	KLAMATH FALLS	KLAMATH FALLS 5 1	Oregon	PQ (Remotely Regul	0.00	-739.27	739.27
8	28717	28416	HINKLEY 1	HINKLEY 1 1	Southeast California	PQ	0.00	-724.07	724.07
9	40967	40489	ARLINGTON	ARLINGTON 10 1	Arizona	PQ (Remotely Regul	0.00	-682.84	682.84
10	40429	40265	FLAGSTAFF	FLAGSTAFF 3 2	Arizona	PQ	0.00	-624.36	624.36
11	11038	10498	METALINE FALLS	METALINE FALLS 1	Washington	PQ (Remotely Regul	0.00	-615.75	615.75
12	50395	50219	CASTLE DALE	CASTLE DALE 2 1	Utah	PQ (Remotely Regul	0.00	-611.83	611.83
13	20387	20208	REDDING 8	REDDING 8 1	Northern California	PQ (Remotely Regul	0.00	-570.98	570.98
14	40794	40455	PHOENIX 73	PHOENIX 73 1	Arizona	PQ (Remotely Regul	0.00	-553.70	553.70
15	13580	13289	LOWELL 4	LOWELL 4 1	Oregon	PQ (Remotely Regul	0.00	-549.59	549.59
16	40909	40476	TONOPAH 4	TONOPAH 4 1	Arizona	PQ (Remotely Regul	0.00	-532.37	532.37
17	40956	40487	GILA BEND 6	GILA BEND 6 1	Arizona	PQ (Remotely Regul	0.00	-526.60	526.60
18	30313	30178	VALMY	VALMY 1	Nevada	PQ (Remotely Regul	0.00	-521.08	521.08
19	30369	30191	LAS VEGAS 72	LAS VEGAS 72 1	Nevada	PQ (Remotely Regul	0.00	-506.31	506.31
20	40991	40493	ARLINGTON	ARLINGTON 11 1	Arizona	PQ (Remotely Regul	0.00	-502.54	502.54
21	40760	40446	SAINT JOHN	SAINT JOHN 2 1	Arizona	PQ (Remotely Regul	0.00	-474.26	474.26
22	50380	50215	VERNAL 3	VERNAL 3 1	Utah	PQ (Remotely Regul	0.00	-461.02	461.02
23	50451	50231	GRANTSVILLE	GRANTSVILLE 2 2	Utah	PQ (Gens at Var Limi	0.00	-452.05	452.05
24	30399	30197	LAS VEGAS 74	LAS VEGAS 74 1	Nevada	PQ (Remotely Regul	0.00	-440.26	440.26
25	40187	40120	PHOENIX 16	PHOENIX 16 2	Arizona	PQ	0.00	-438.59	438.59

Many large losses occur near hotspots, buses with multiple transformers

Power Flow Solution fails to converge!

EMP Modeling

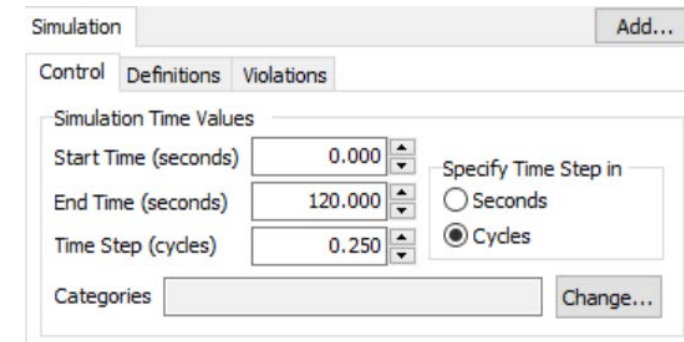


- HEMP disturbances have faster rise times than solar GMD, but may last only several minutes
- It often makes sense to analyze EMP in the transient stability domain
 - Incorporate load shedding, generator exciters, excitation limiters, and other characteristics not modeled in power flow

Transient Stability Analysis



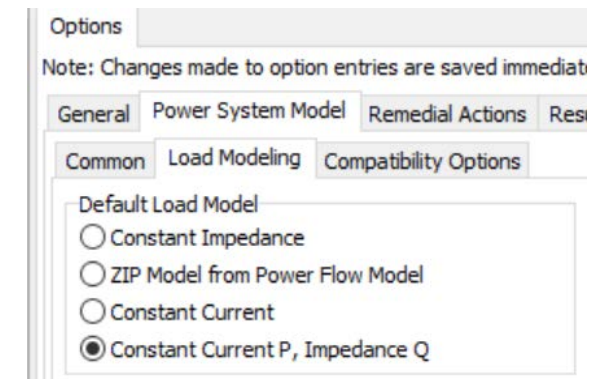
- Reset **Current Time** on **GIC Analysis** dialog to 0
- Click the “Setup Time Varying Series” button, then switch the **Calculation Mode** to “Time Varying Series Voltage Inputs”
- Solve the power flow
- Open **Transient Stability** dialog from **Add Ons** Ribbon
- **Simulation → Control**
Parameters: 0.25 cycle time step works well for EMP waveforms



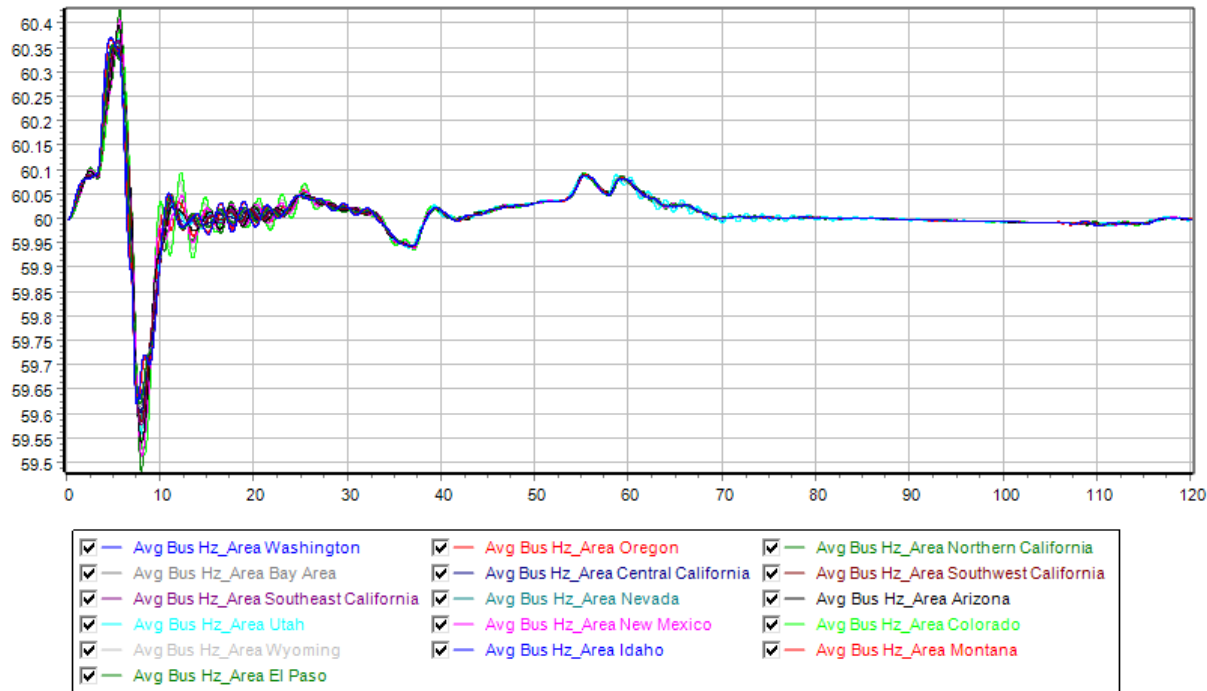
Transient Stability Analysis



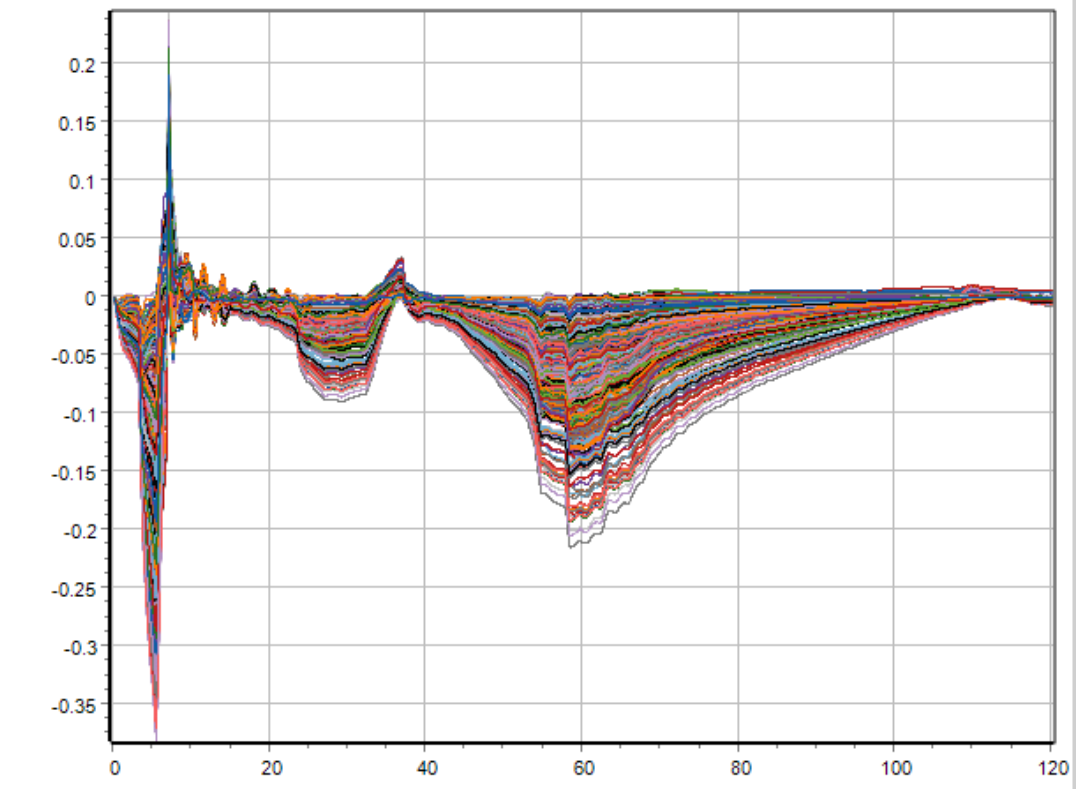
- Disable any existing Transient Contingency Elements (set “Enabled” field to Never)
- **Options → Power System Model → Load Modeling:**
For “Default Load Model”, use
“Constant Current P, Impedance Q”
- Add a plot for all Load Objects, V pu, Actual Deviation
- Click **Run Transient Stability**



Transient Stability Plots



Frequency:
Average by Area



Load Bus Voltage Deviation

HEMP Future Studies

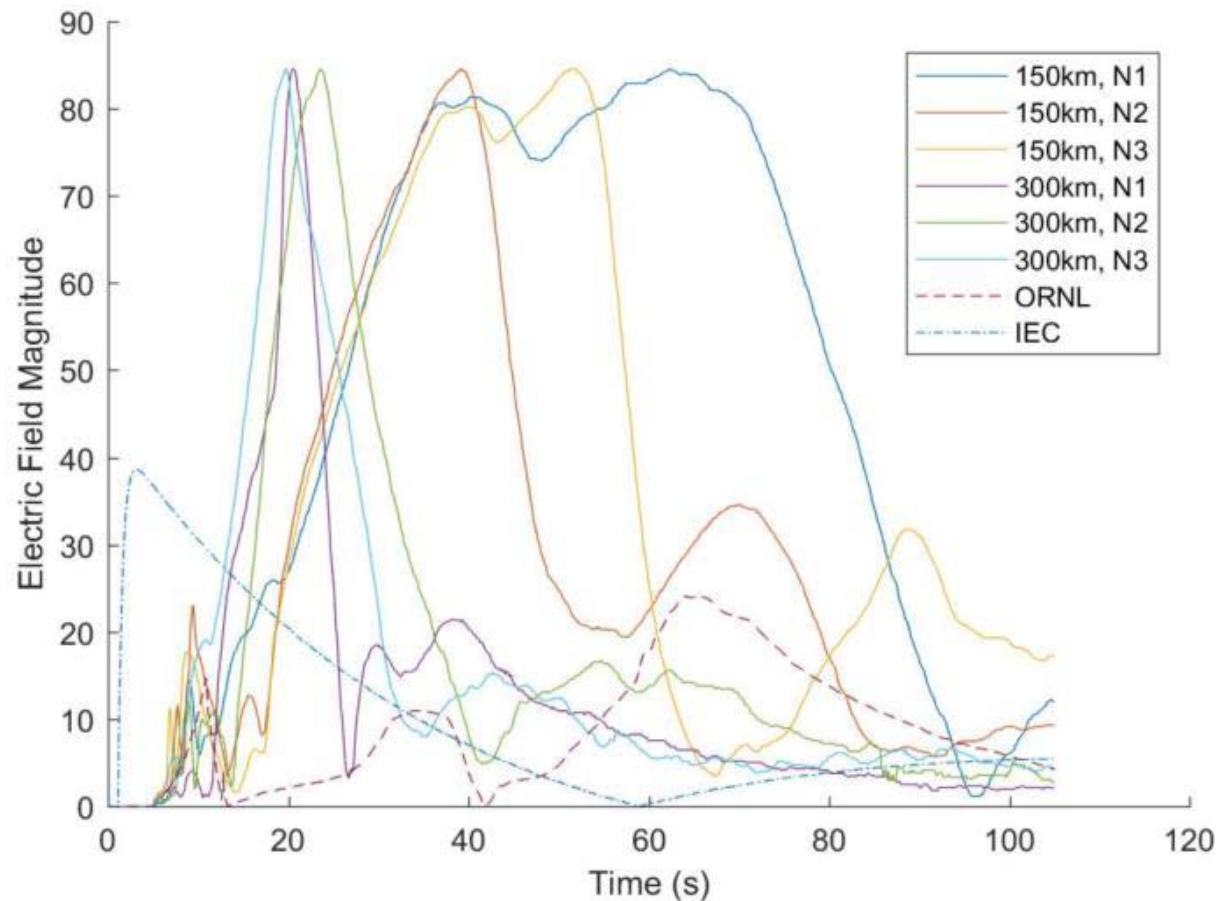


- Report of the “Commission to Assess the Threat to the United States from EMP Attack” (EMP Commission) was released to public
- “A realistic unclassified peak level for E3 HEMP would be 85 V/km for CONUS as described in this report”

HEMP Waveform Comparison

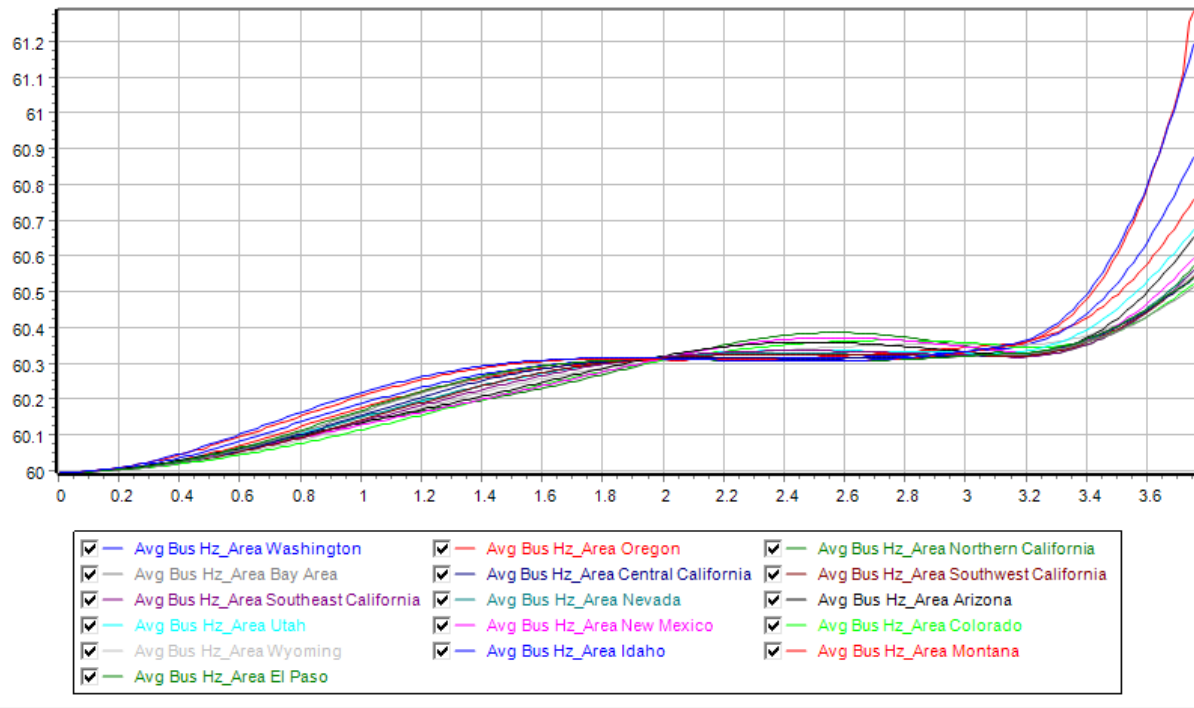


- Plot of newly-released electric field waveforms, the ORNL 1985 waveform, and the IEC 1996 waveform
- Source: Lee, R. and Overbye, T. J.; “Comparing the Impact of HEMP Electric Field Waveforms on a Synthetic Grid”, submitted to *North American Power Symposium*, 2018.

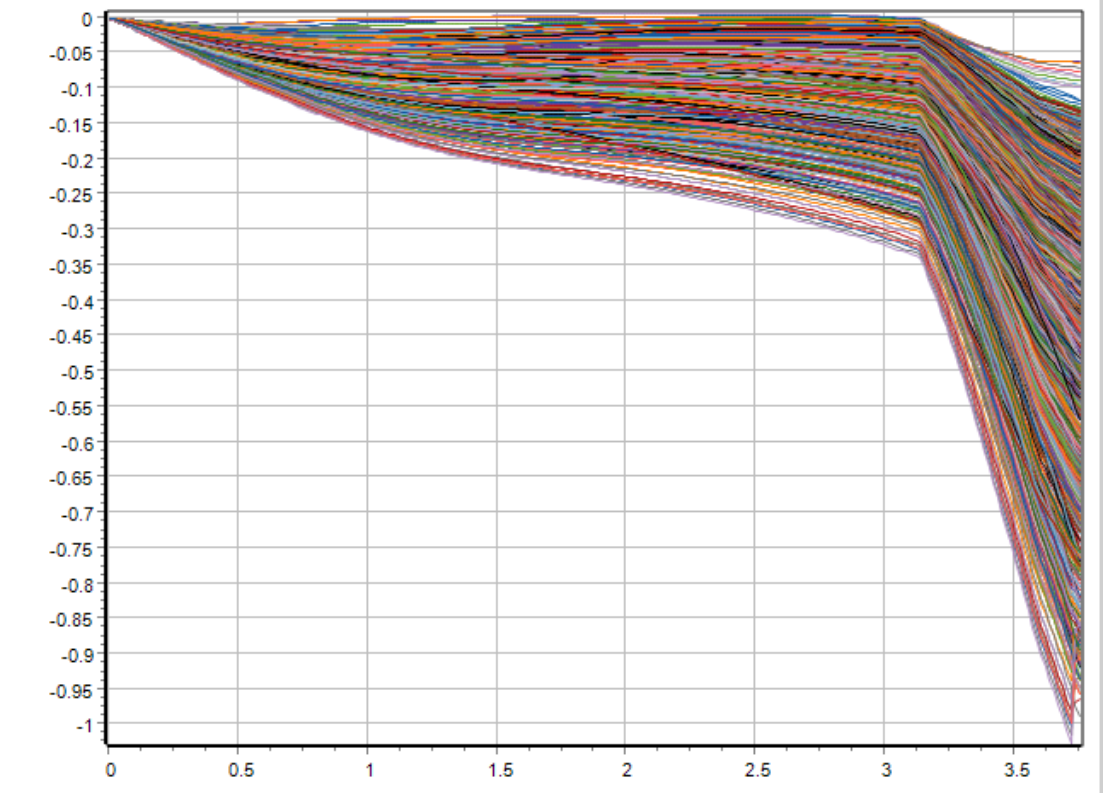


Transient Stability Plots:

Scale Event to 85 V/km Peak (Magnitude Scalar ~ 3.6)



Frequency:
Average by Area



Bus Voltage:
Collapse at $t=3.8s$!

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