Steady-State Power System Security Analysis with PowerWorld Simulator

S12: Modeling GMD in PowerWorld Simulator

PowerWorld Corporation

2001 South First Street
Champaign, Illinois 61820
+1 (217) 384.6330

support@powerworld.com
http://www.powerworld.com

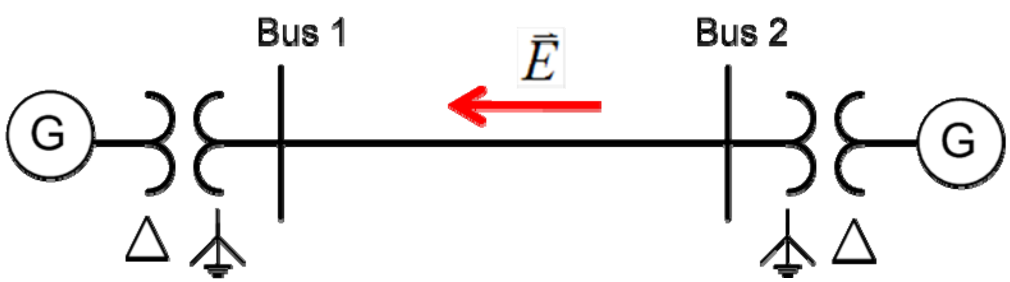
GMD Concepts and Regulatory Environment

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 HEMPs (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.

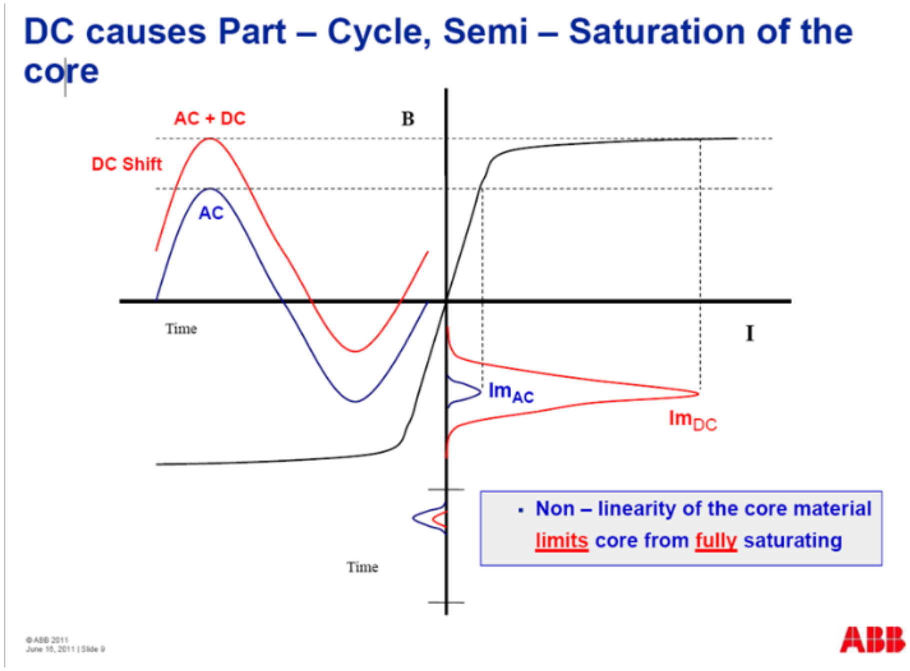


Image Source: Craig Stiegemeier, JASON Presentation, June 2011

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

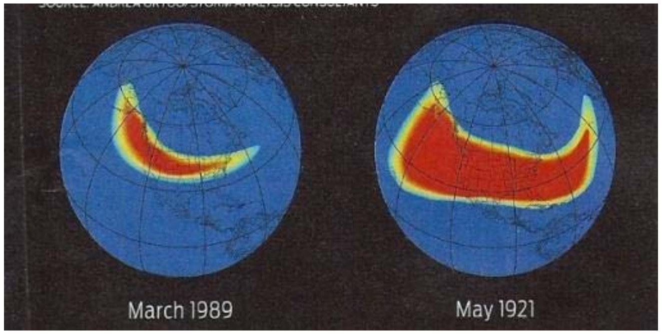
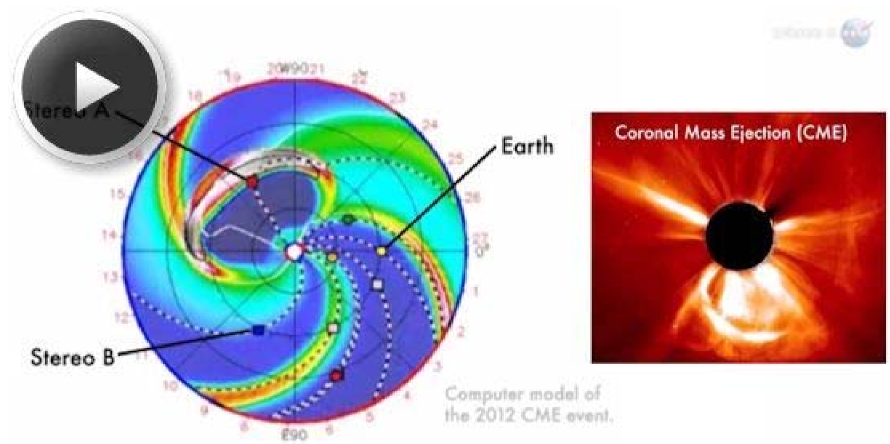


Image source: J. Kappenman, "A Perfect Storm of Planetary Proportions," *IEEE Spectrum*, Feb 2012, page 29

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 uncertainly about how large a storm is reasonable to consider in electric utility planning

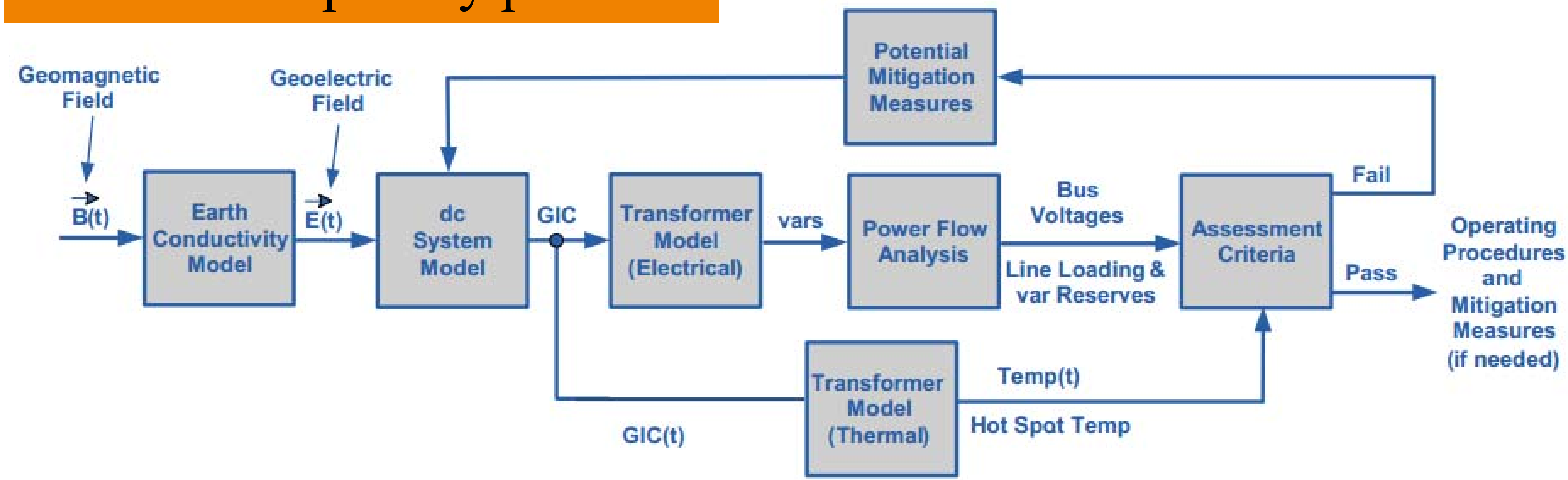
Image Source: science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/

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

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

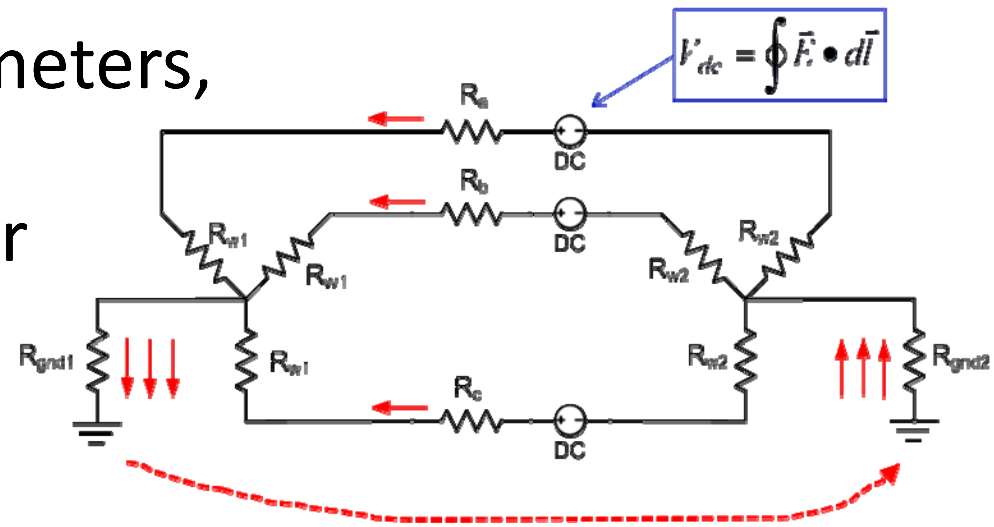
TPL-007-4 Timetable

- 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

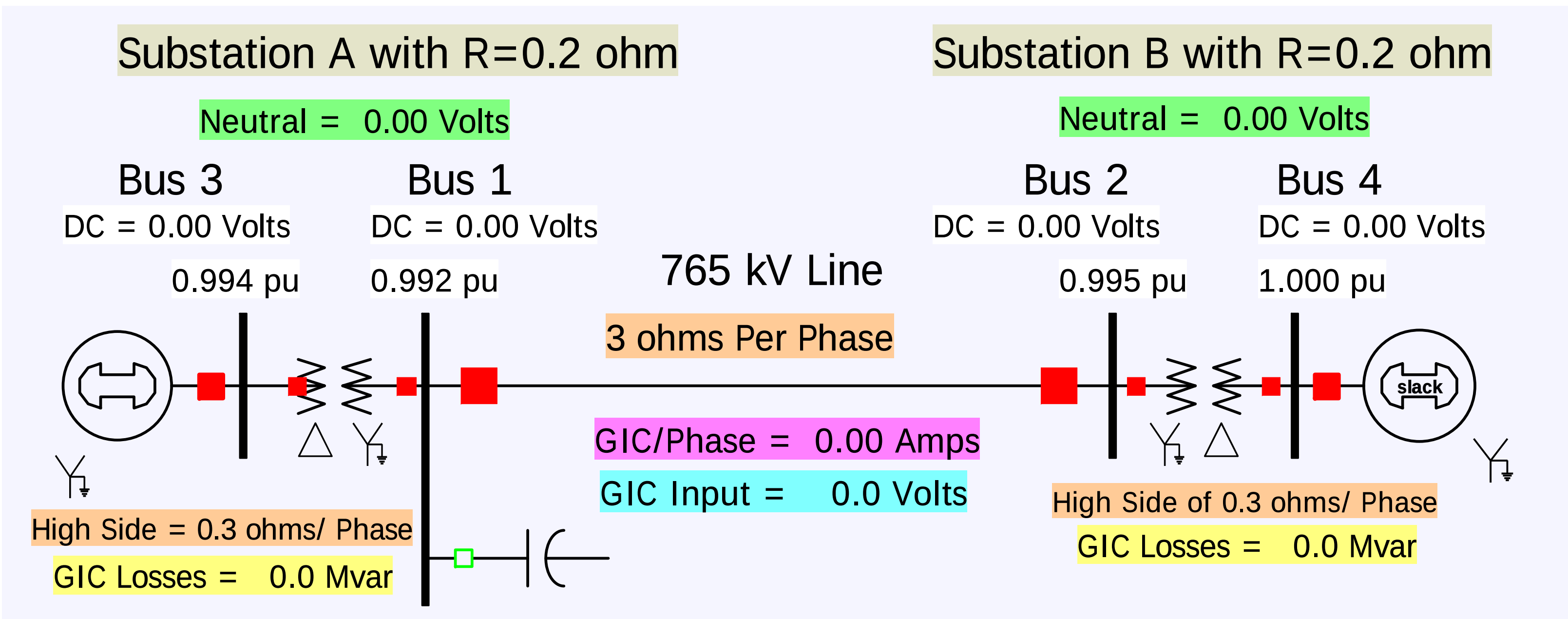
- The starting point for GIC analysis in PowerWorld Simulator is an assumed storm scenario; this is used to determine the transmission line dc voltages
- Characterizing an actual storm can be complicated, and requires detailed knowledge of the associated geology
- February 2012 NERC report recommended 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

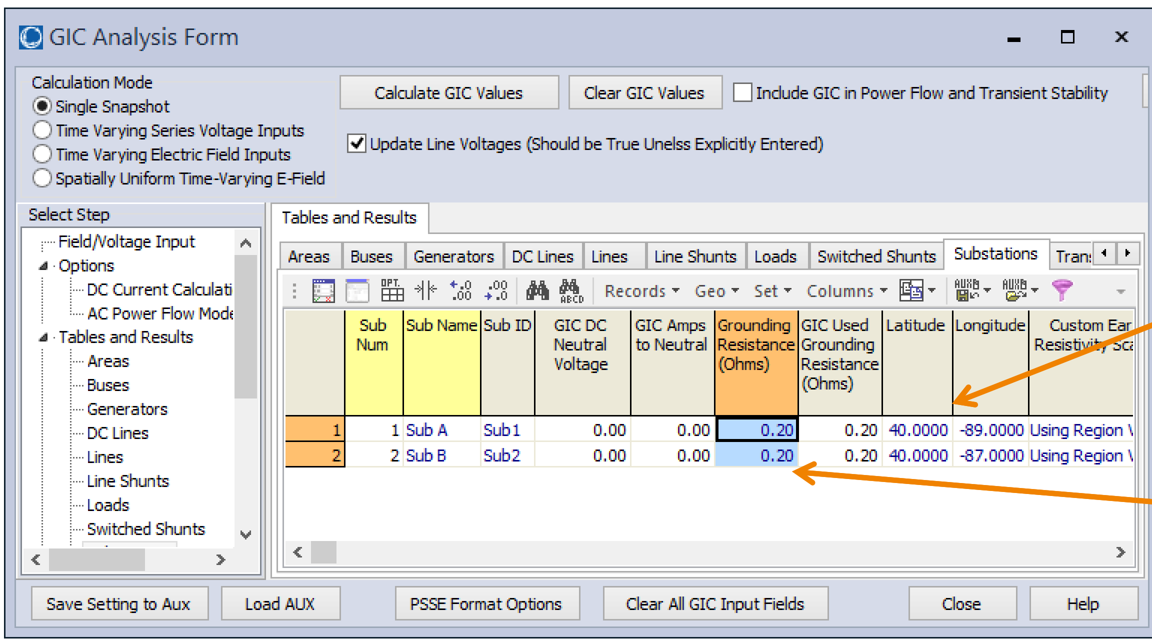
Four-Bus Example

- 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)



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

Grounding resistance = 0.2 Ω

Grounding Resistance

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

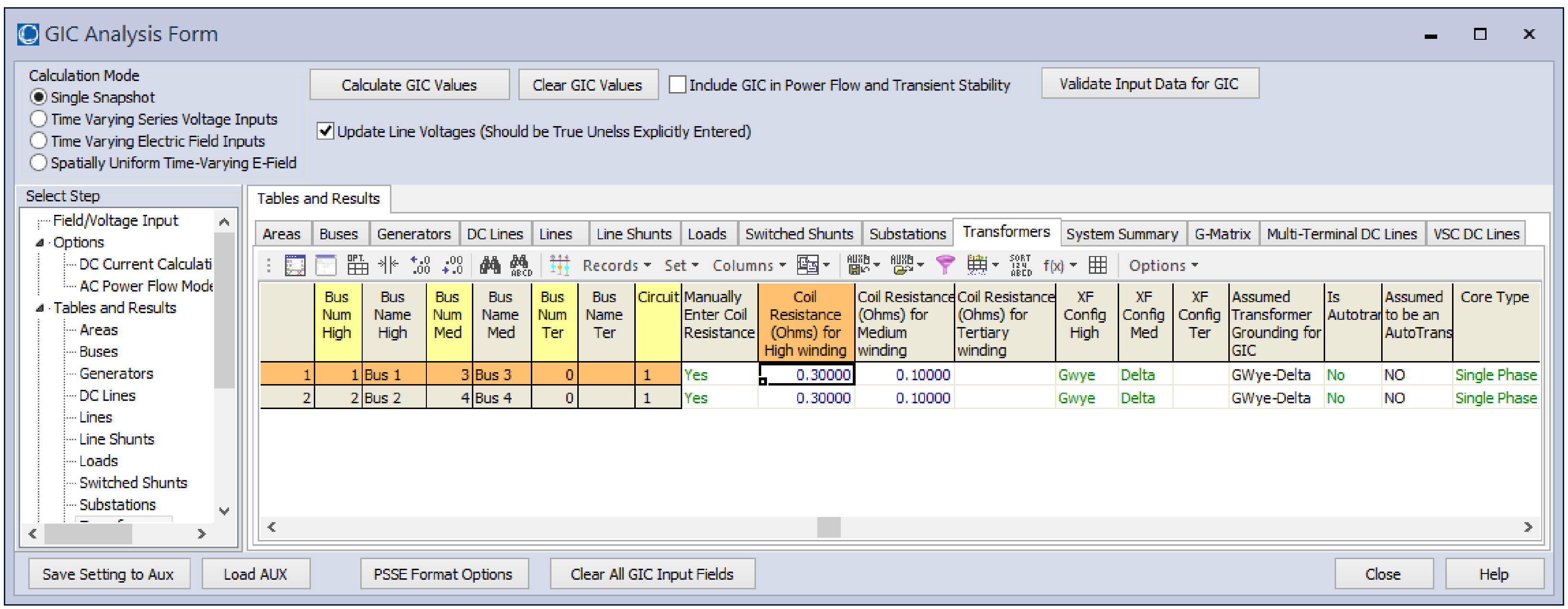
Substation Coordinates

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



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

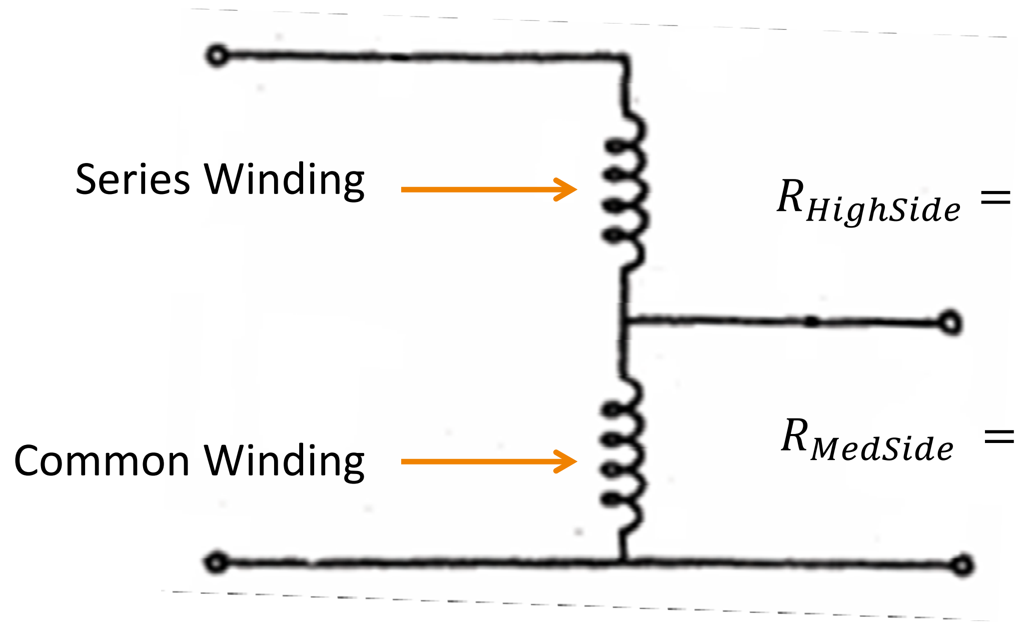
Simulator Assumptions

- 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



<u>Simulator Fields</u>

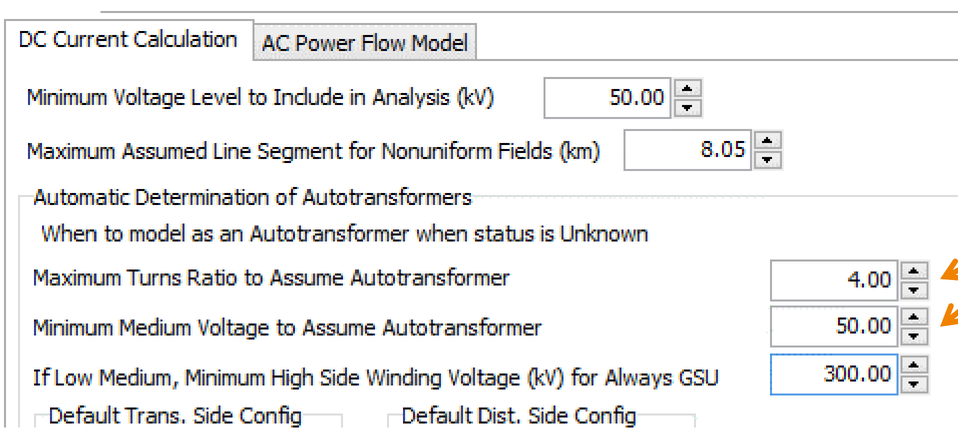
$R_{HighSide} =$ Coil Resistance (Ohms) for High Winding

$R_{MedSide} =$ Coil Resistance (Ohms) for Medium Winding

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

Simulator Assumptions: Autotransformers

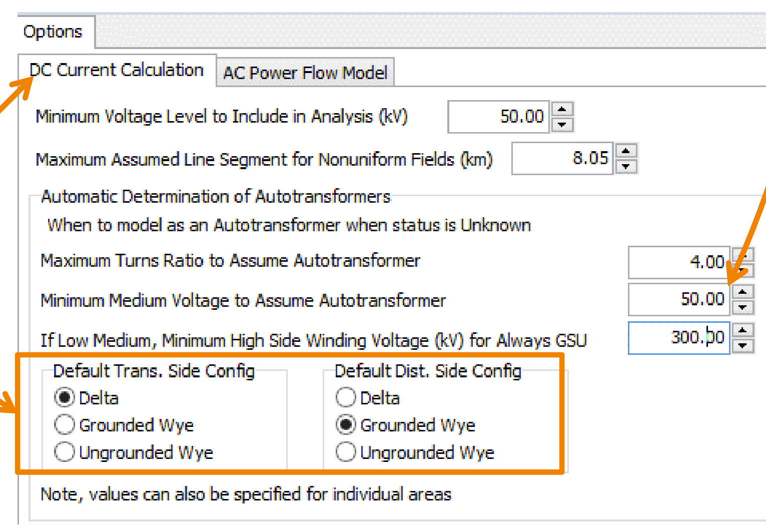
- Some parameters for assumptions applied to unknown transformers are at **Options → DC Current Calculation**
- Units are assumed to be autotransformers if all of the following criteria are met
  - unit is not a phase-shifting transformer
  - high side and low side are at different nominal voltages
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



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)



Simulator Assumptions

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

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

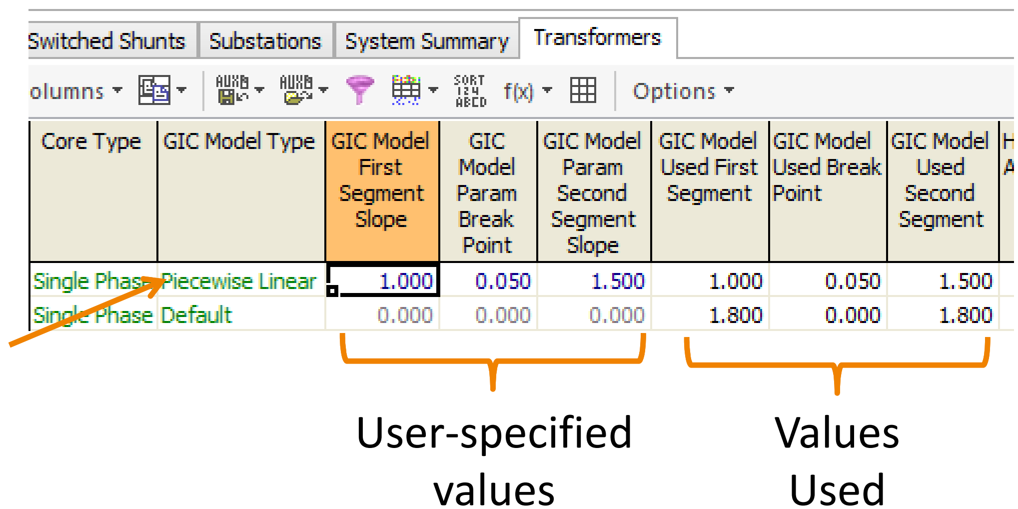
- *K-Factor* relates transformer's effective GIC (I_{GIC}) to 3-phase reactive power loss at nominal voltage

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

- This looks like a constant current MVar load at the transformer

K-Factor

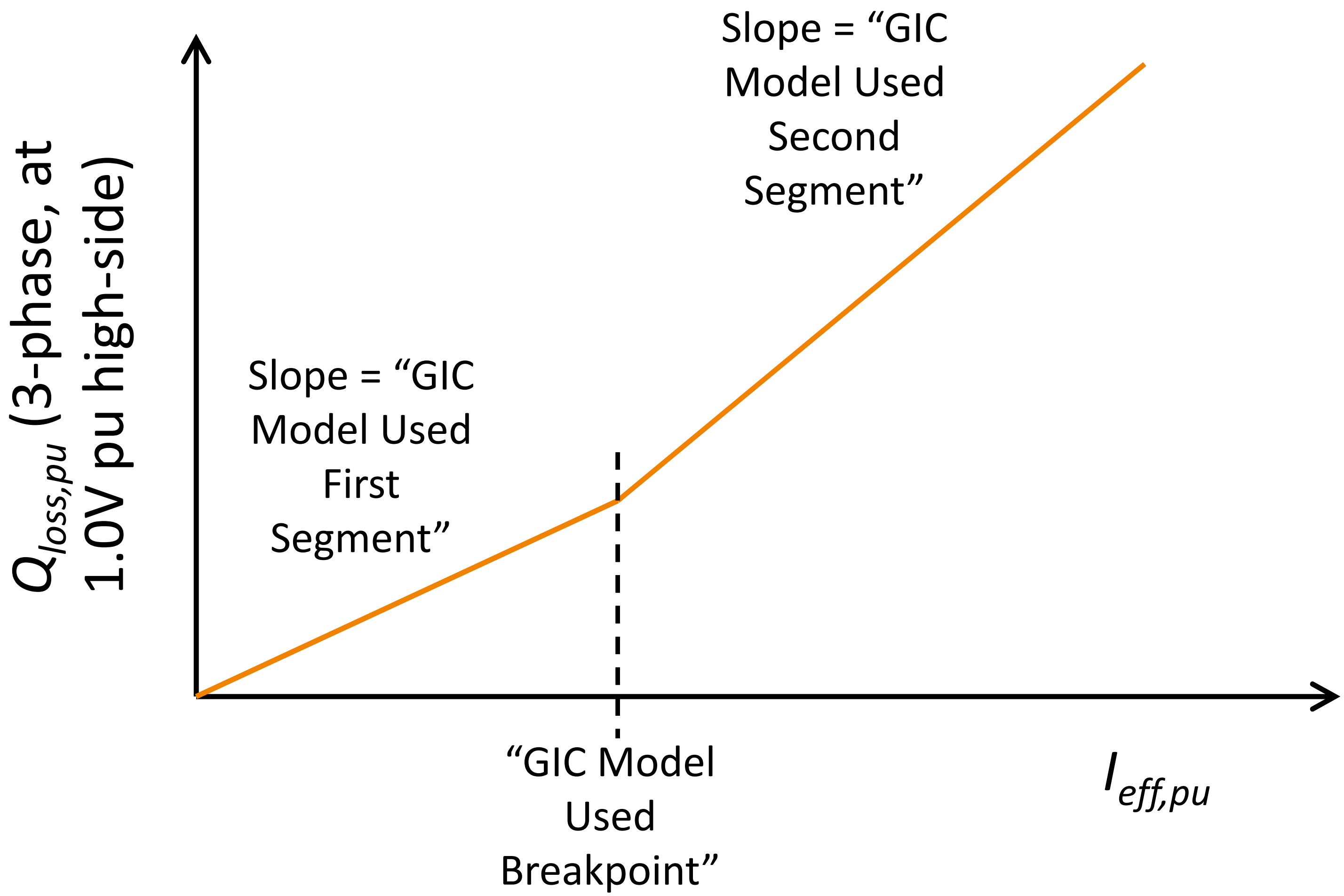
- *K-Factor* may be entered directly as a 2-step piecewise linear value with "GIC Model Type" set to **Piecewise Linear**



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

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

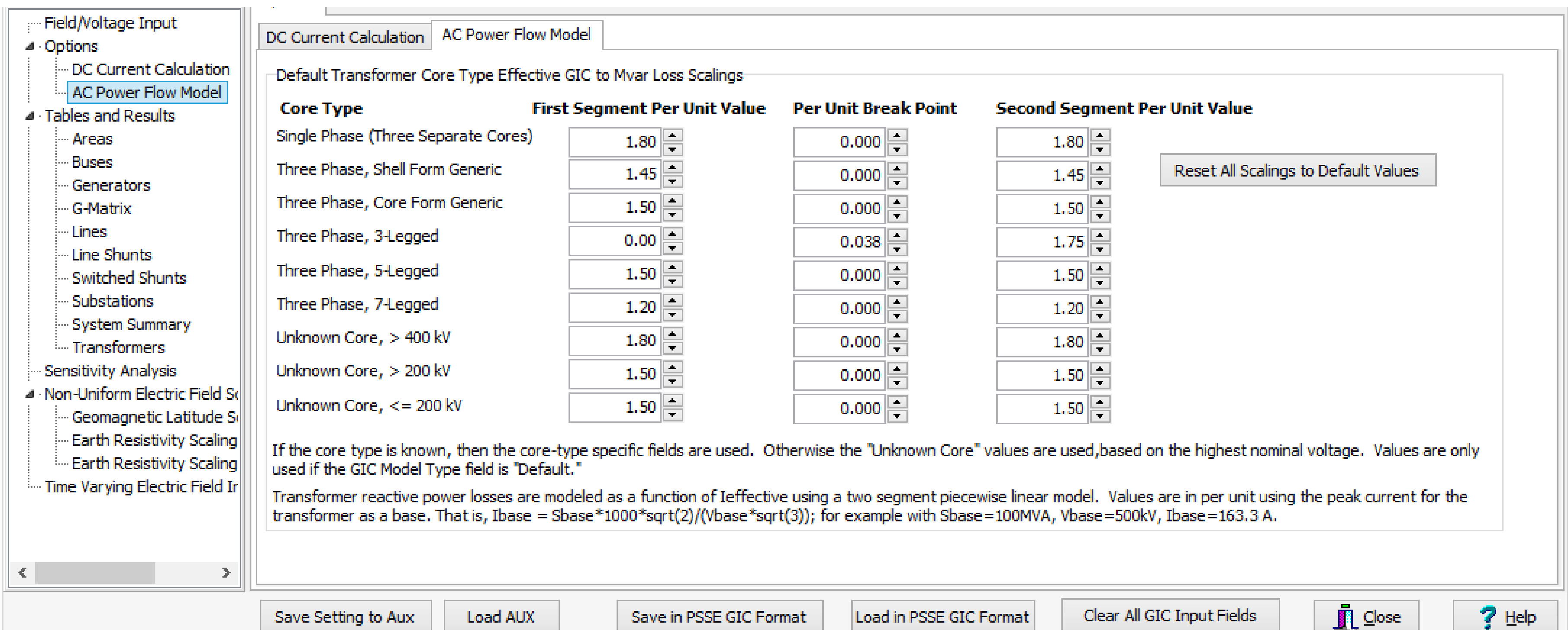
K-Factor



Slope = "GIC Model Used Second Segment"
Slope = "GIC Model Used First Segment"
$Q_{loss,pu}$ (3-phase, at 1.0V pu high-side)
"GIC Model Used Breakpoint"
$I_{eff,pu}$

K-Factor Defaults

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

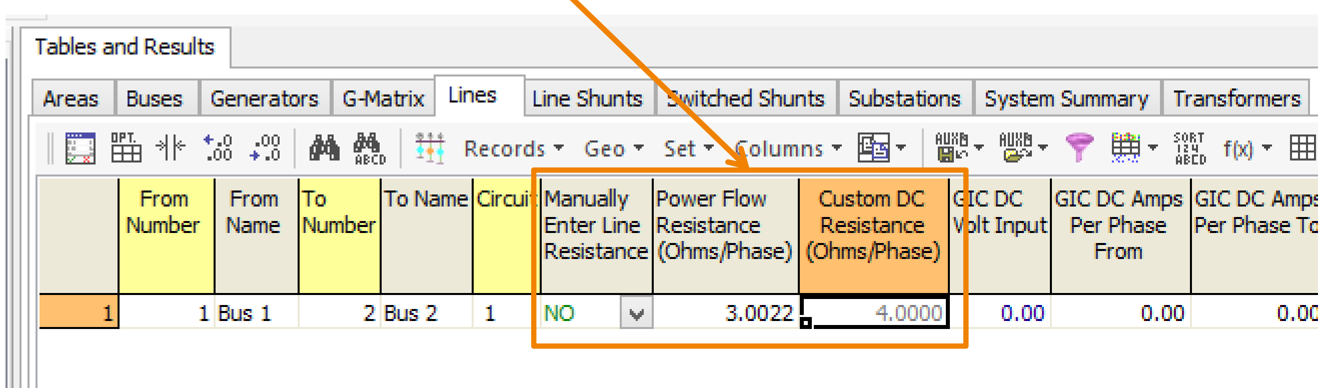


Other Modeling Assumptions

- **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

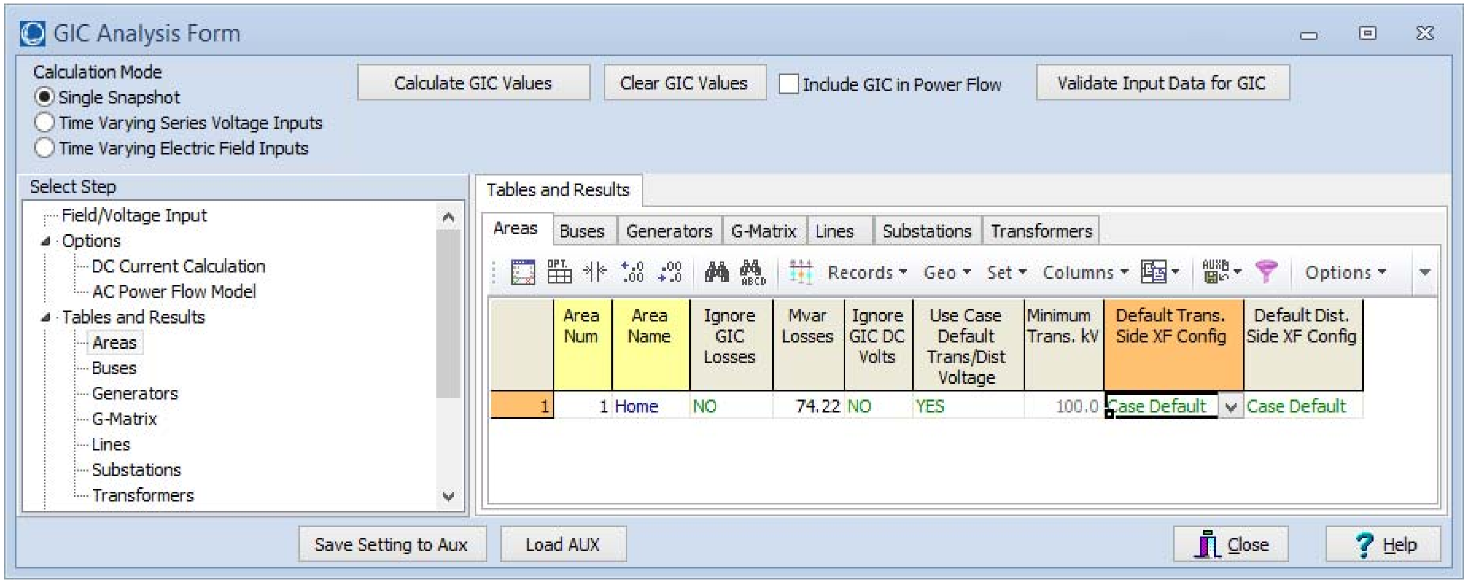
Four Bus Inputs: Transmission Lines

- 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)**



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



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

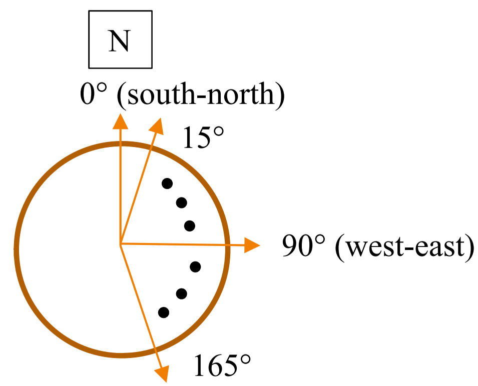
	Number (Name)	Name (Number)	Sub Sub A (1)	Sub Sub B (2)	Bus 1 (Bus 1)	Bus 2 (Bus 2)	Bus 3 (Bus 3)	Bus 4 (Bus 4)
1	Sub 1 (Sub A)	Sub Sub A (1)	15.0000		-10.0000		-0.0000	
2	Sub 2 (Sub B)	Sub Sub B (2)		15.0000		-10.0000		-0.0000
3	Bus 1 (Bus 1)	Bus Bus 1 (1)	-10.0000		10.9993	-0.9993	0.0000	
4	Bus 2 (Bus 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

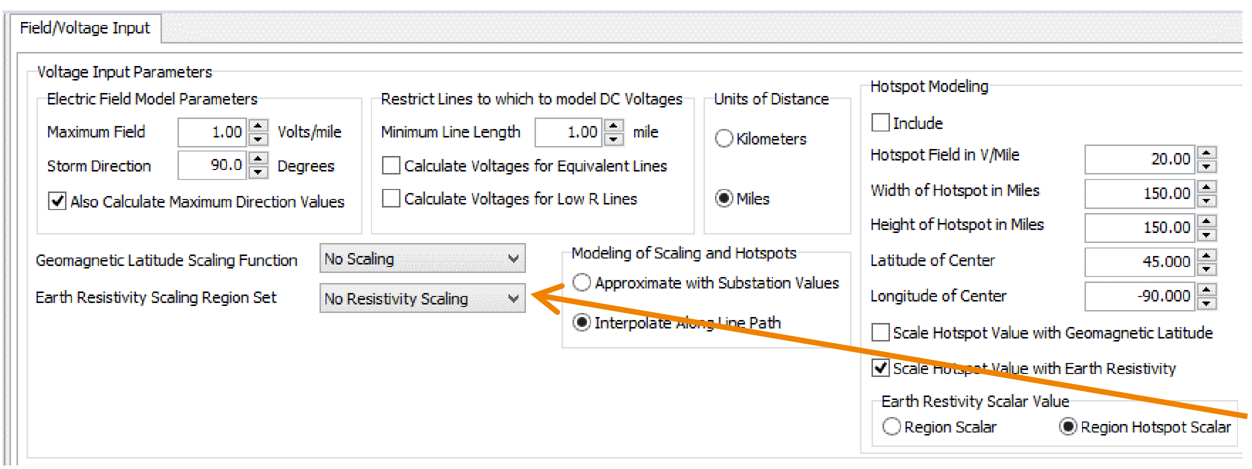
G-Matrix

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

Uniform Electric Field Modeling

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

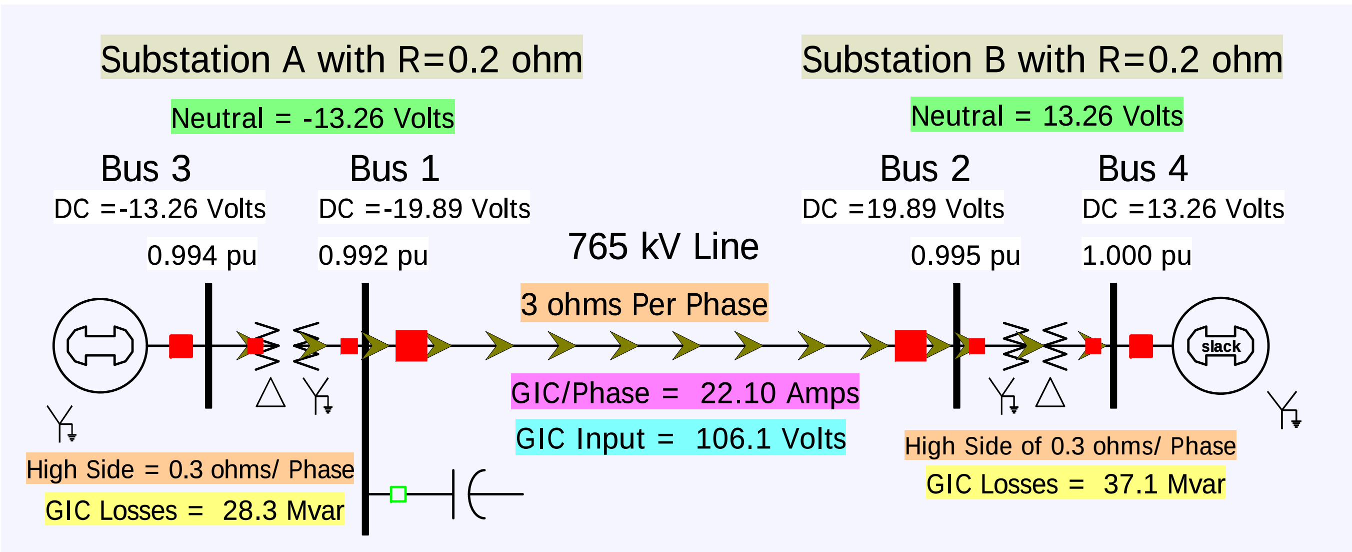




α and β scaling factors for Benchmark Event

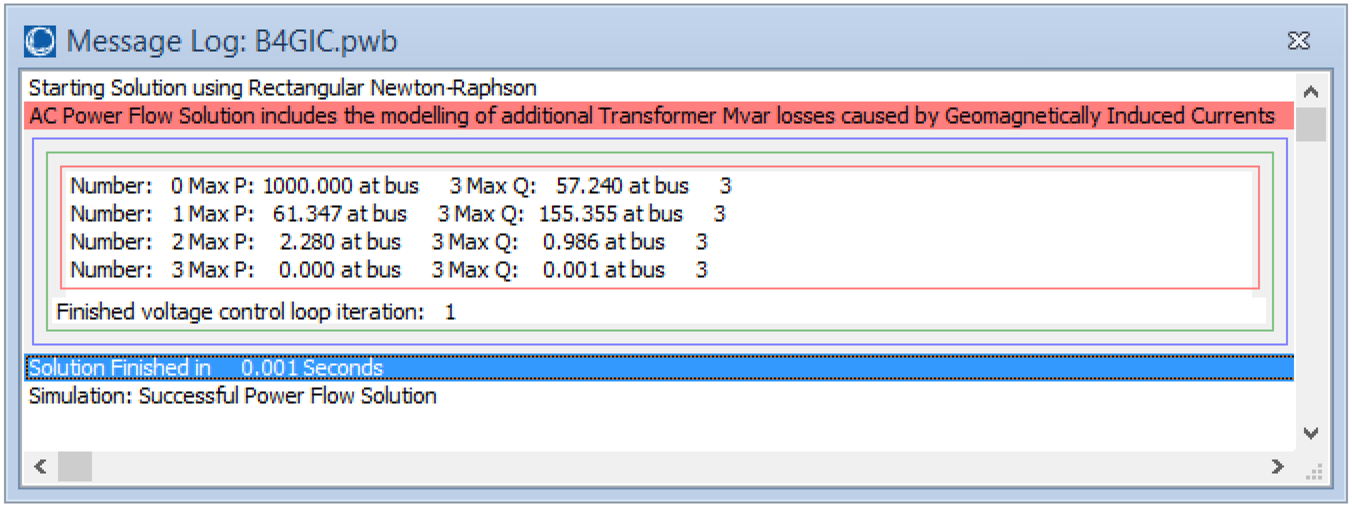
Uniform Electric Field Modeling

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

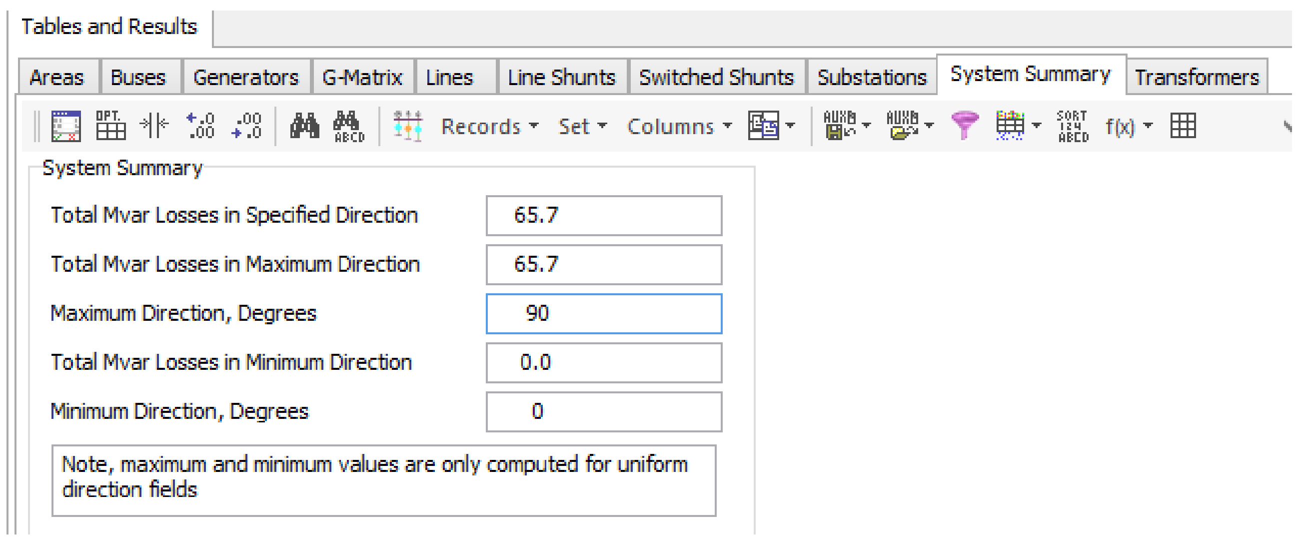


Maximum Direction Values

- 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

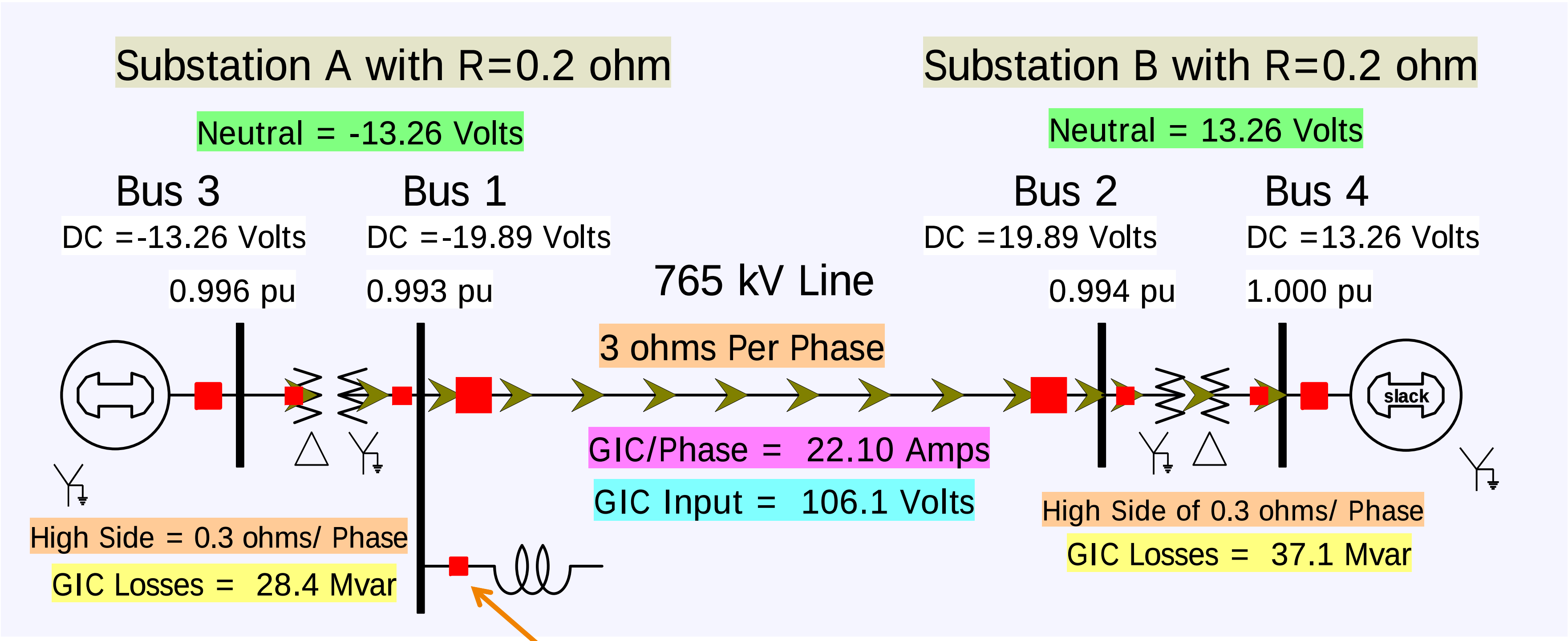
- In this case, maximum direction aligns with the only transmission line (90 degrees)
- Minimum direction is orthogonal to the line (0 degrees)



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

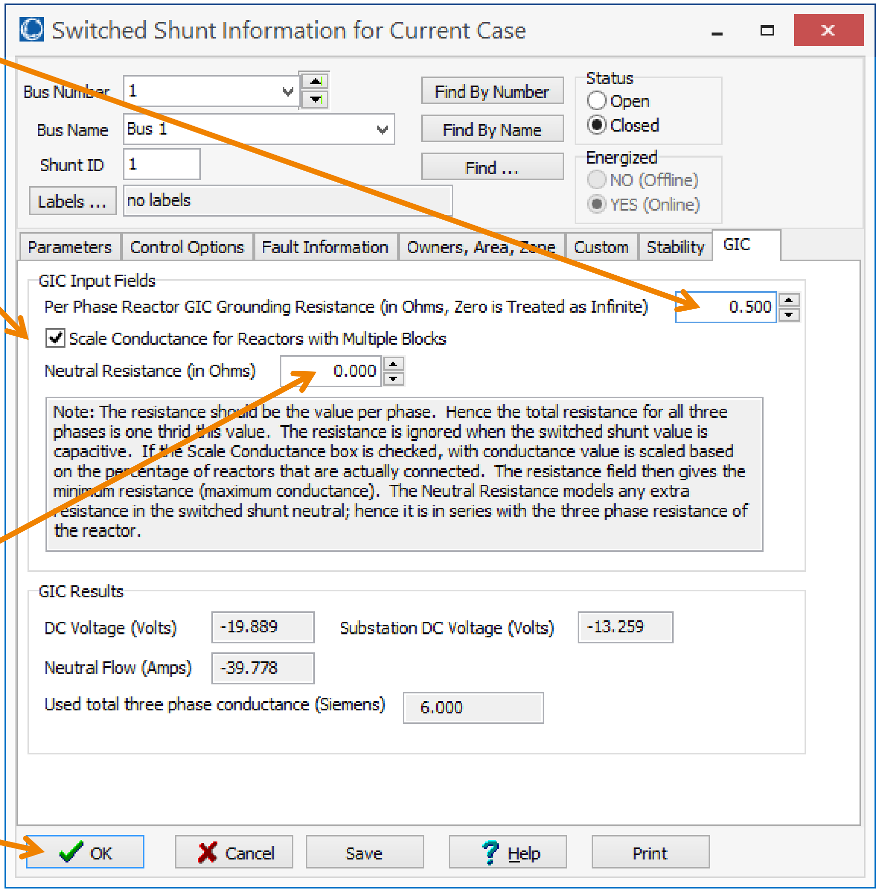
Switched Shunt Example



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 Example

- Recalculate the GIC Values
- Note changes in GIC flows and the G-Matrix

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

Records ▾ Set ▾ Columns ▾ f(x) ▾ Options ▾

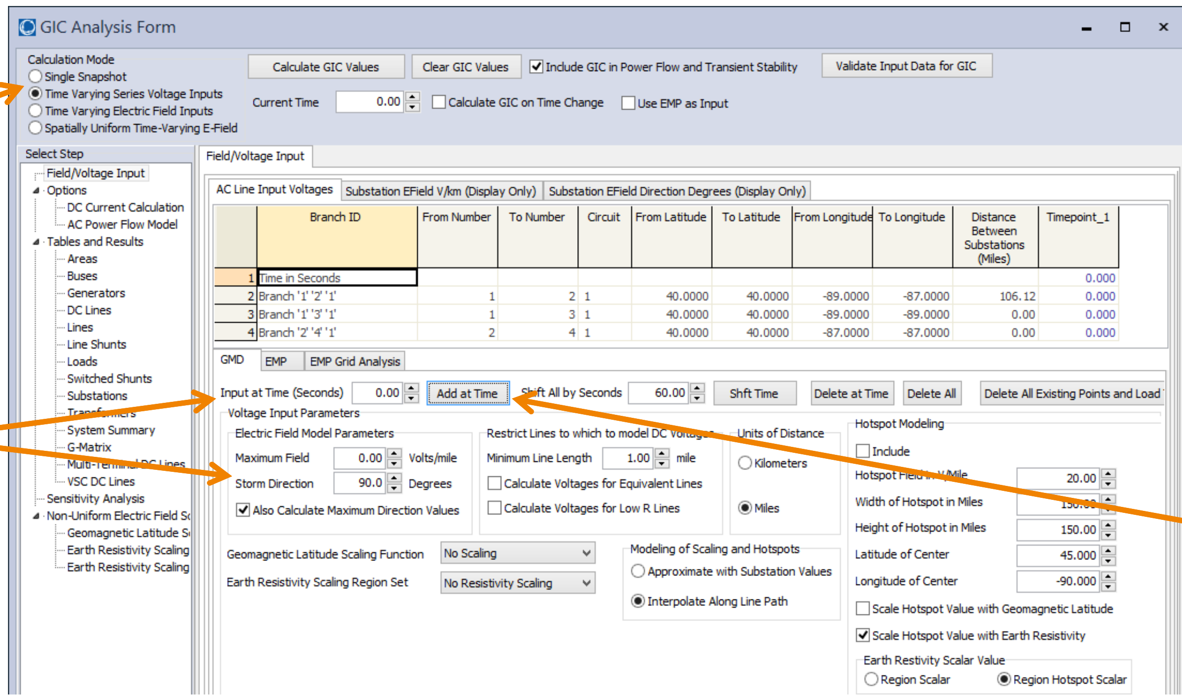
	Number (Name)	Name (Number)	Sub Sub A (1)	Sub Sub B (2)	Bus 1 (Bus 1)	Bus 2 (Bus 2)	Bus 3 (Bus 3)	Bus 4 (Bus 4)
1	Sub 1 (Sub A)	Sub Sub A (1)	21.0000		-16.0000		-0.0000	
2	Sub 2 (Sub B)	Sub Sub B (2)		15.0000		-10.0000		-0.0000
3	Bus 1 (Bus 1)	Bus Bus 1 (1)	-16.0000		16.9993	-0.9993	0.0000	
4	Bus 2 (Bus 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

Time-Varying Series Voltage Inputs

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

Calculation mode

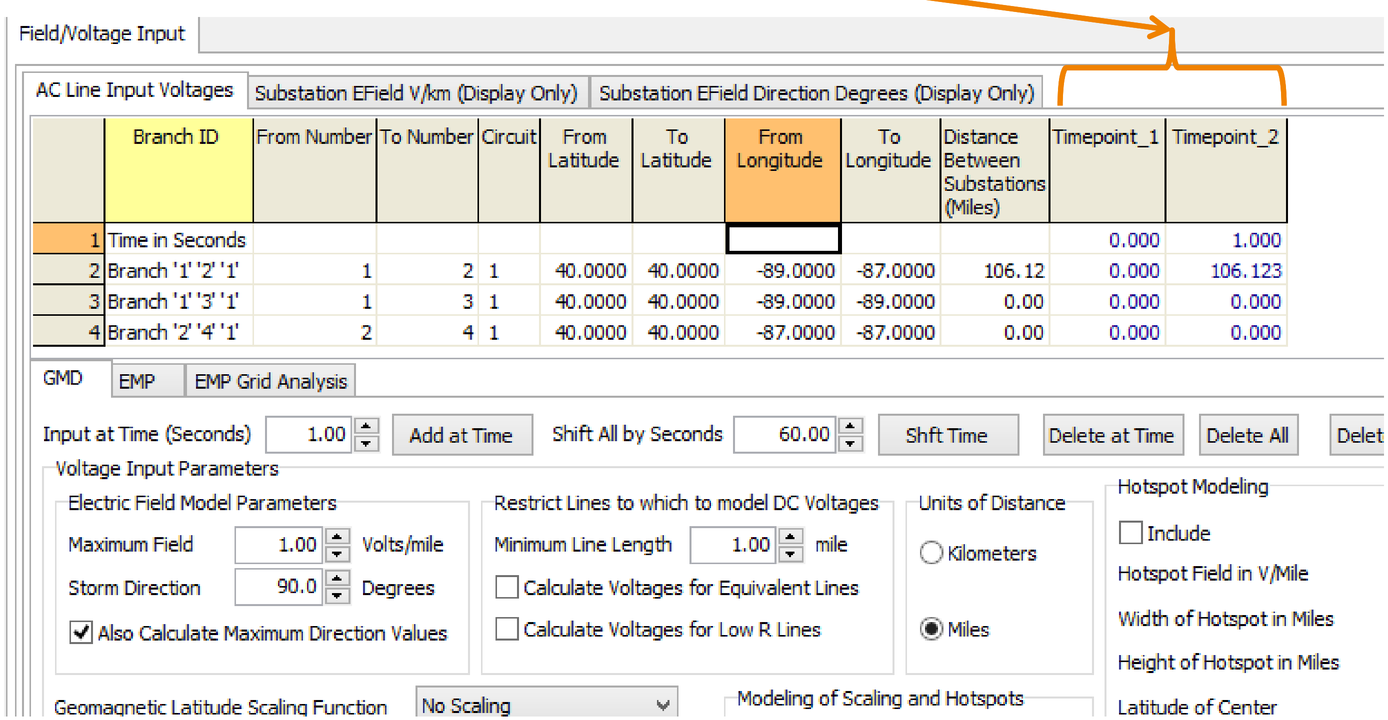
Time and Field input



Click **Add at Time**

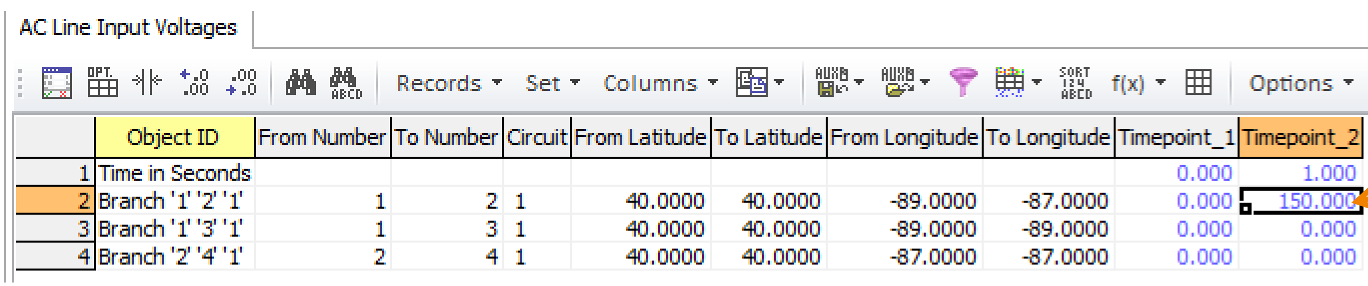
Time-Varying Inputs

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



Time-Varying Inputs

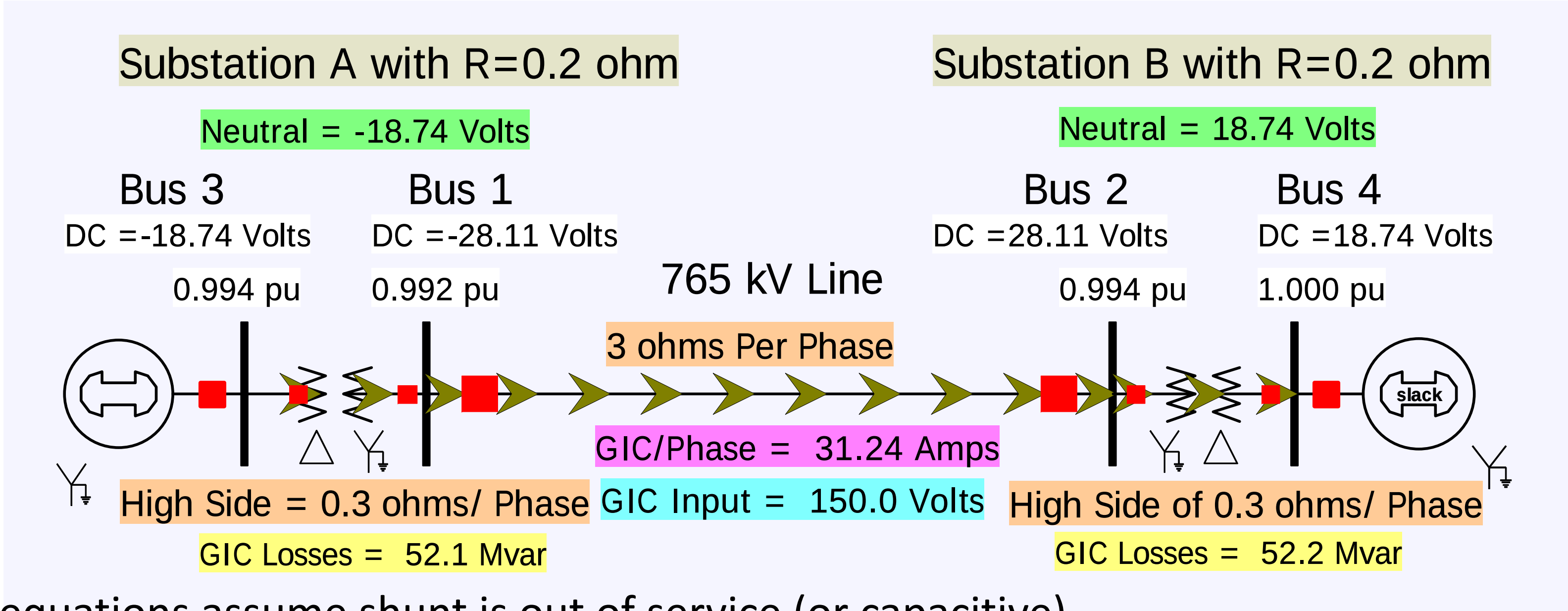
- Change "Current Time" and click **Calculate GIC Values** or check "Calculate GIC on Time Change" box
- Values are linearly interpolated between Timepoints for which inputs are provided
- You may also manually edit input voltages or timepoint values



	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 5852.25Ω = 3Ω/phase or 1Ω, 3-phase

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

Substation grounding resistance 0.2Ω each, 3-phase

Data Interchange

PSS/E GIC Format

- Simulator can read and write data in the PSS/E *.gic text file format
- 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 **PSSE Format Options** button, choose “Save in PSSE GIC Format”, and save the file

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 **PSSE Format Options** button, choose "Load in PSSE GIC Format", and load the just-created file

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

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

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

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 conductity in S/m

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

Frequency Domain Analysis With Uniform Conductance

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

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

- The magnitude relationship is then

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

$$|E(\omega)| = |Z(w)\,\mathrm{H}(\omega)|$$

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

For example, assume σ of 0.001 S/m and a 500nT/minute maximum variation at 0.002 Hz.

Then $\mathrm{B}(\omega) = 660\times10^{-9}$ T and

$$E(\omega) = \sqrt{\frac{2\pi\times0.002\times\mu_0}{0.001}}\,\frac{660\times10^{-9}\ \mathrm{T}}{\mu_0}$$

$$E(\omega) = 0.00397\times0.525 = 2.1\ \mathrm{V/km}$$

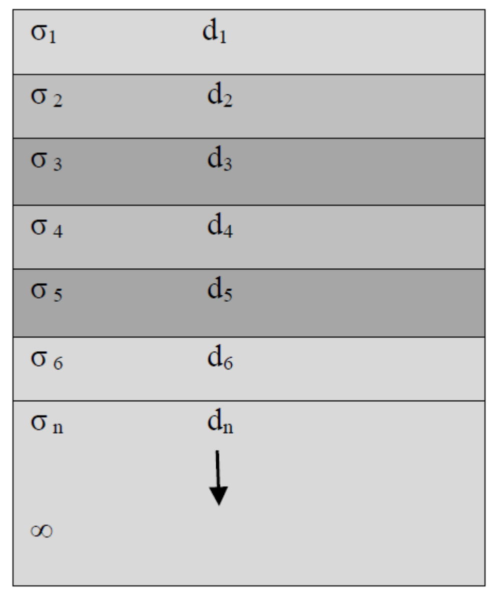
1-D Earth Models

- 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

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

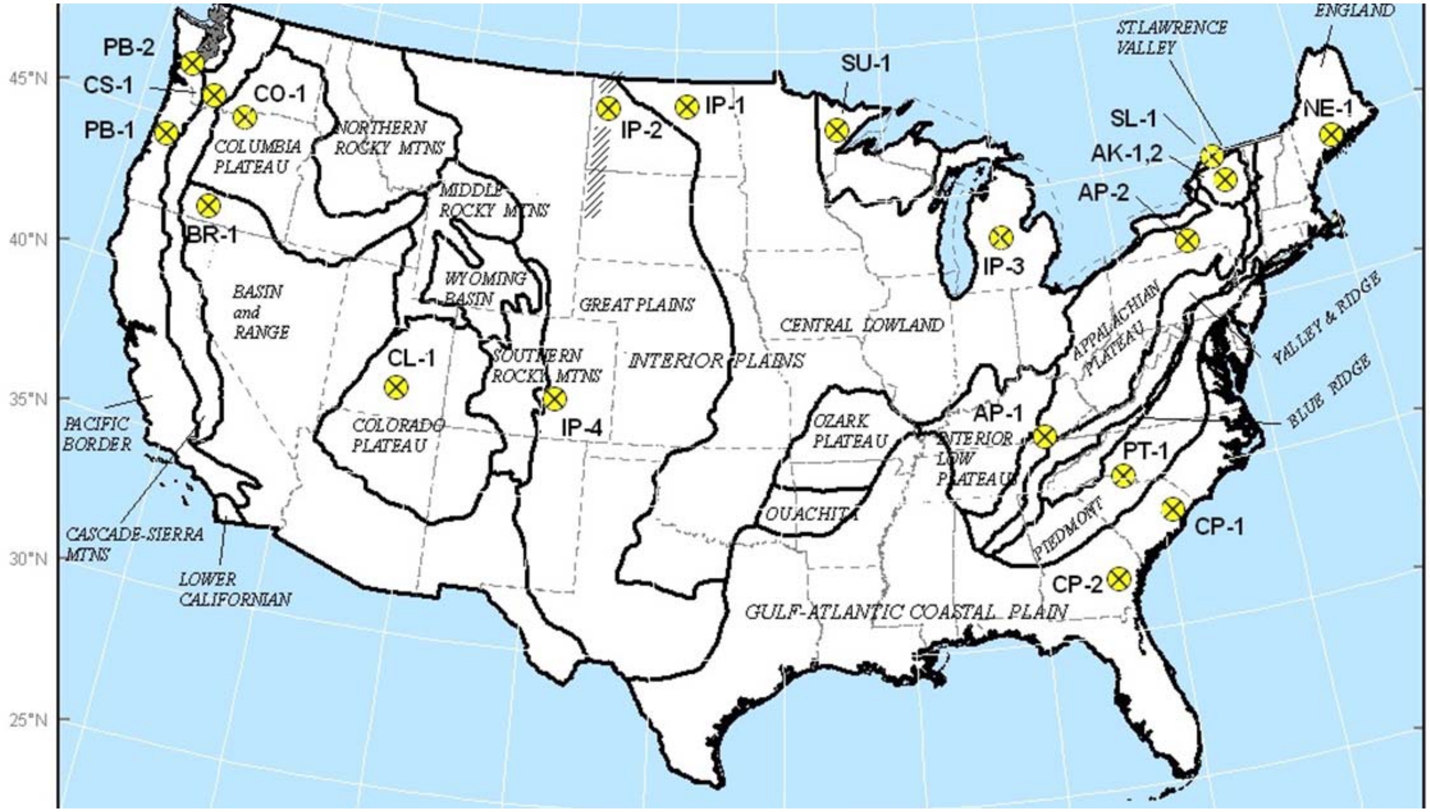
- With the impedance at the top of layer m given as

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

- Recursion is applied up to the surface layer

USGS 1-D Conductivity Regions

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



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

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

1-D Earth Models

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

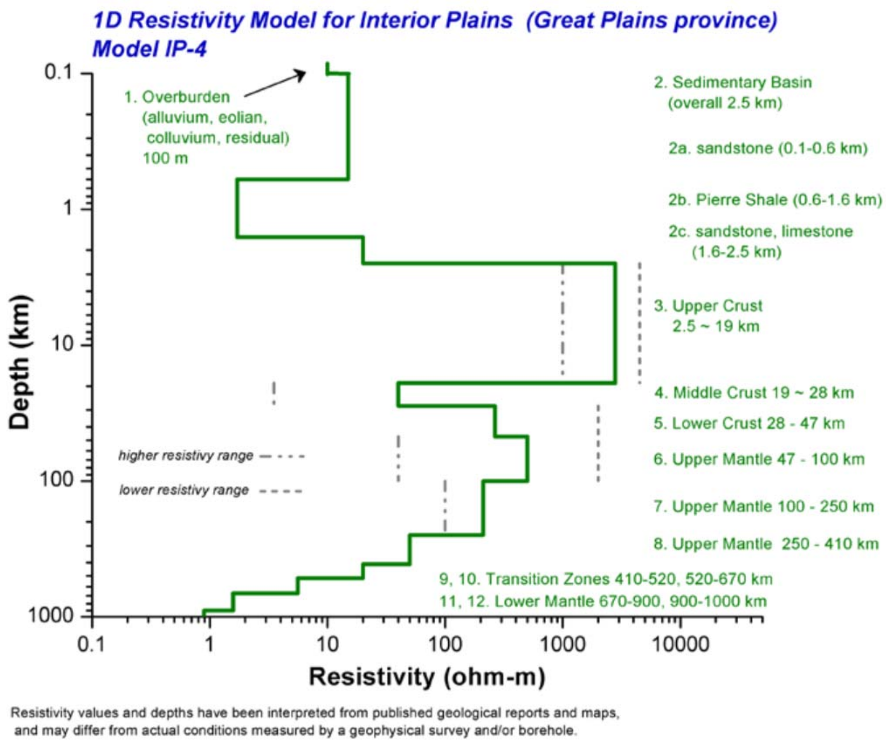
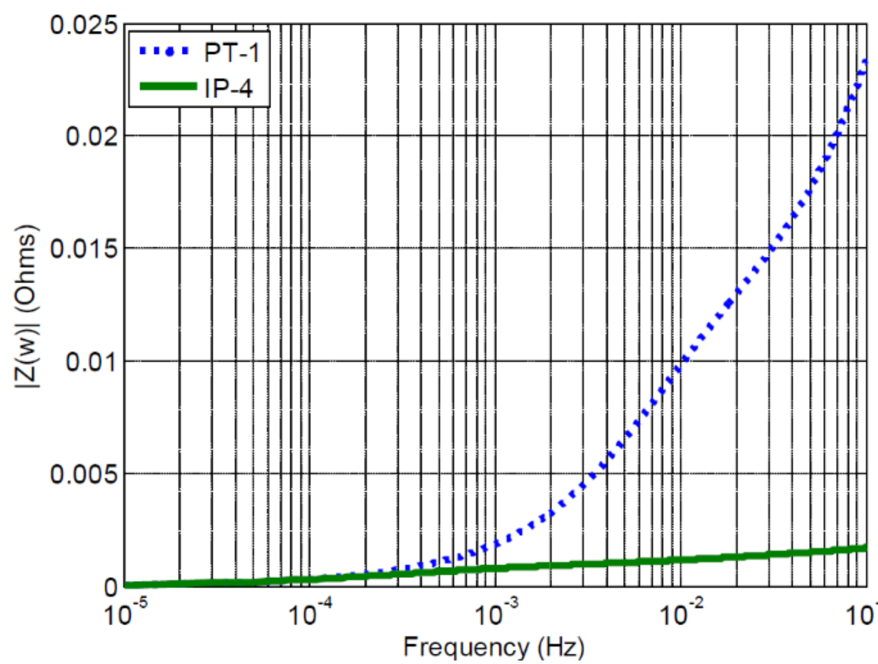


Figure 9: Frequency response of two layered Earth conductivity models.



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

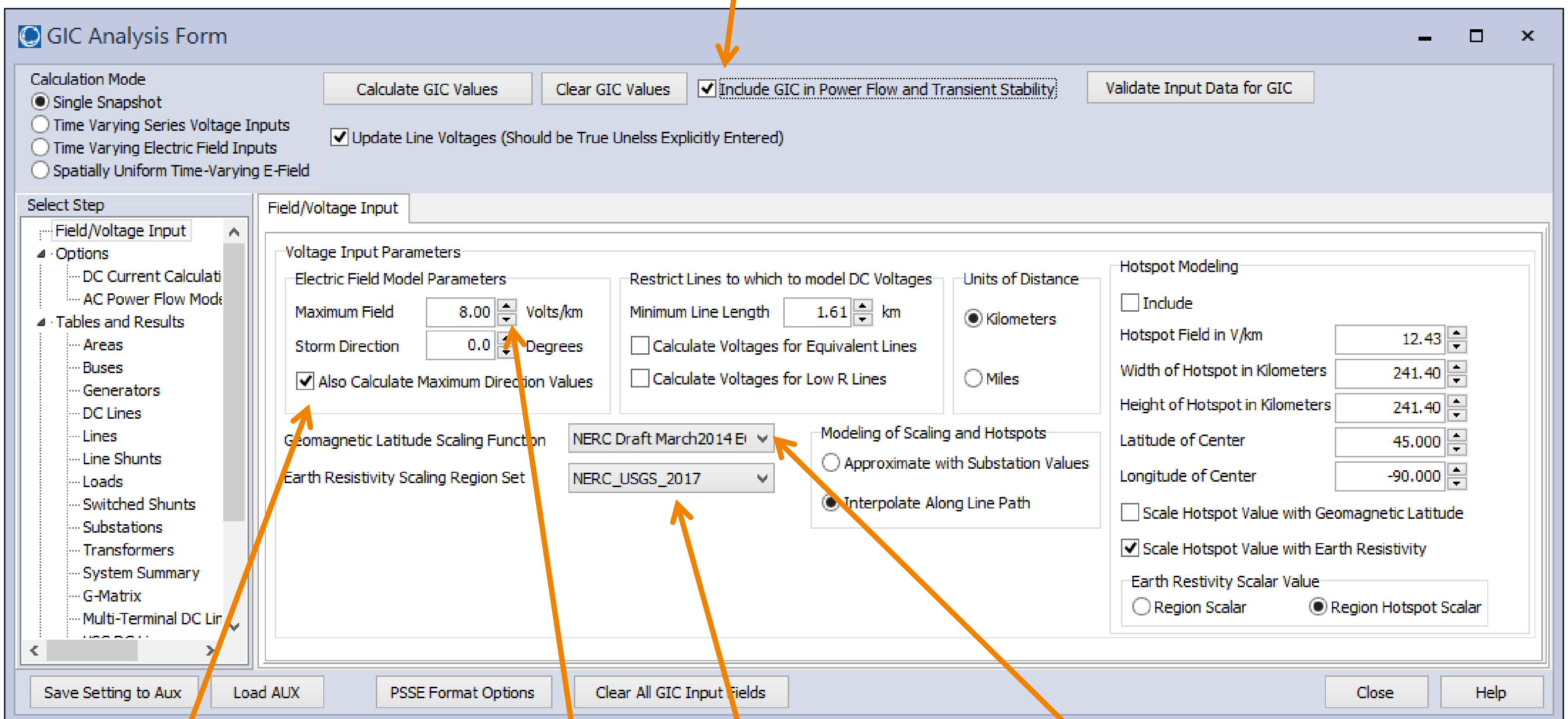
$E_{peak} = 8 \times \alpha \times \beta$ V/km
$\alpha = 0.001e^{0.115L}$
Where β is a scaling factor for earth resistivity and L is geomagnetic latitude in degrees

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



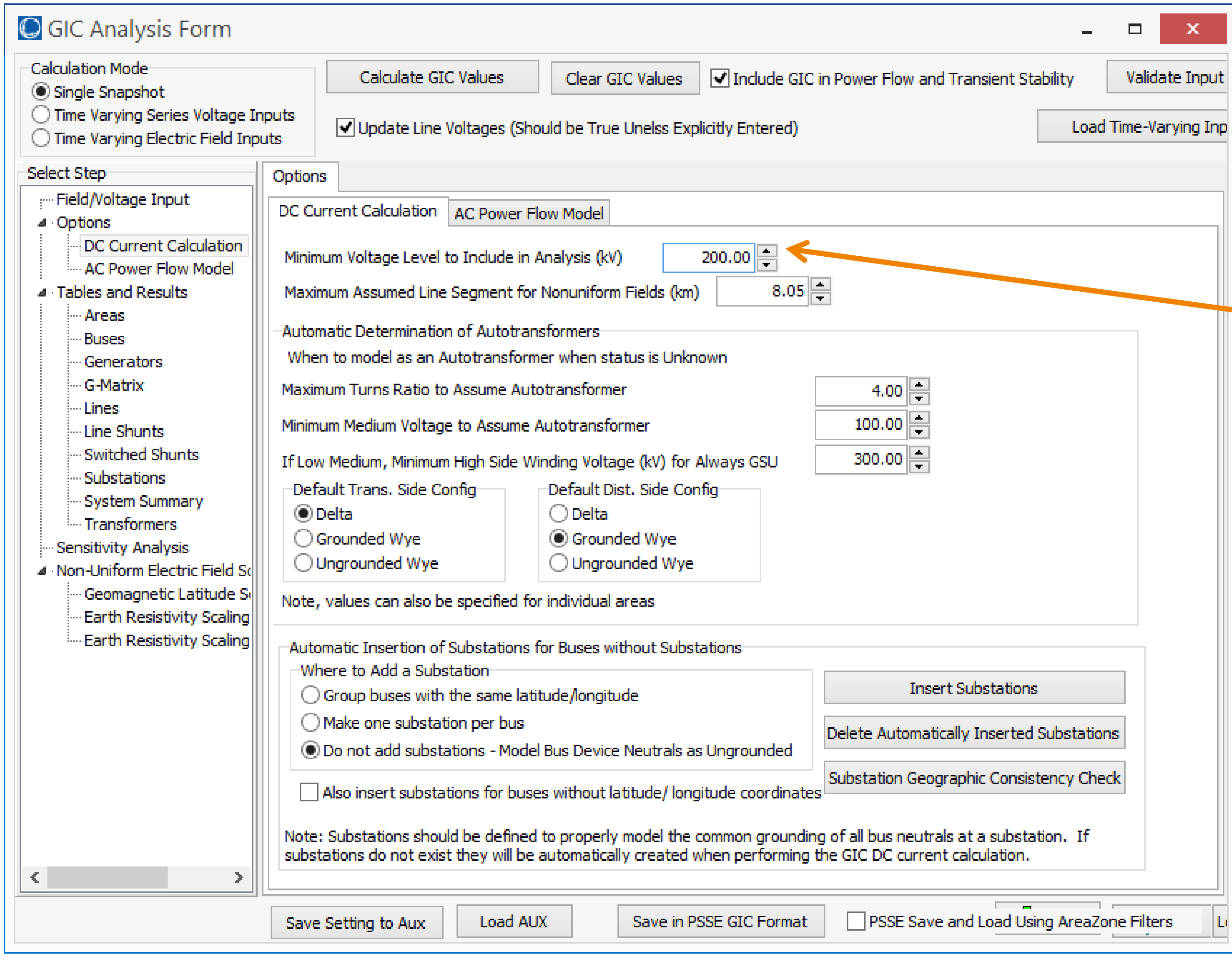
Calculate Max Direction

E_{peak} = 8 V/km

β based on USGS earth resistivity models loaded from aux

α calculated from Equation II-1 in NERC Guide

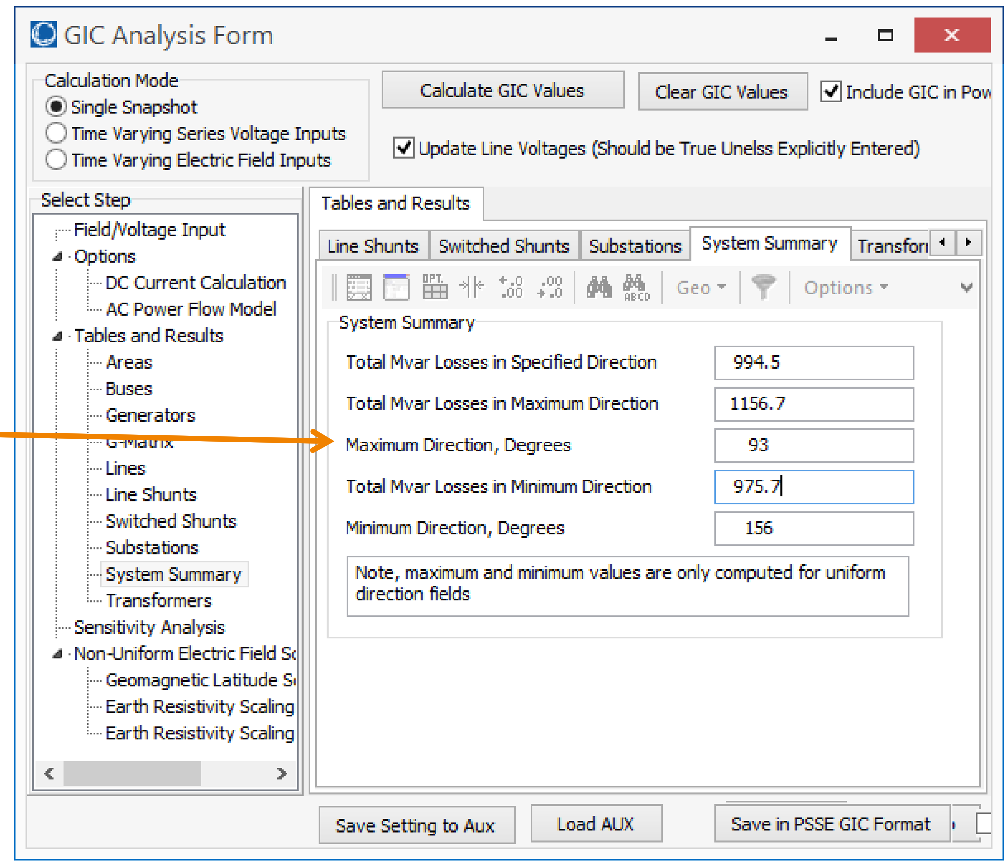
Benchmark GMD Event Example



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

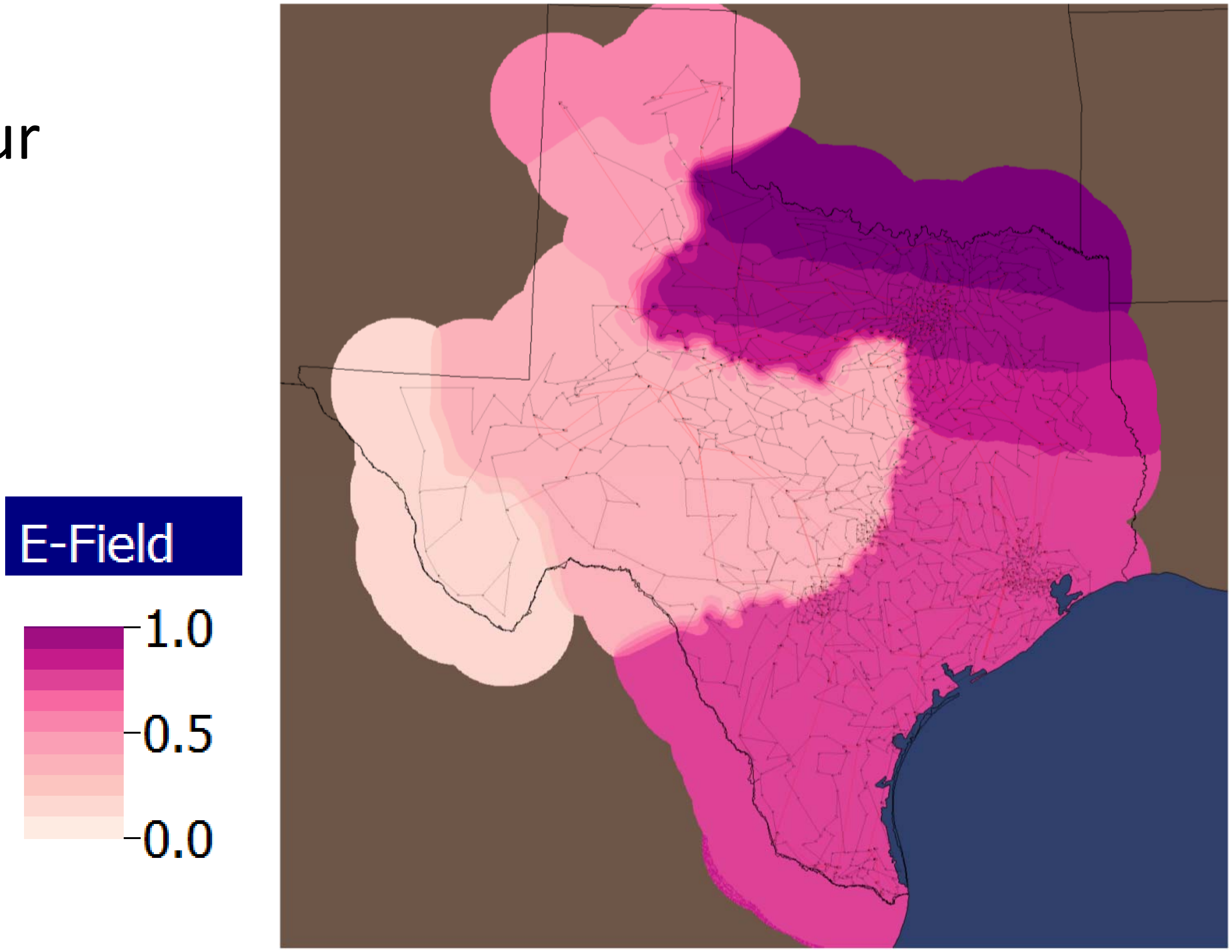
Benchmark GMD Event Example

- 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



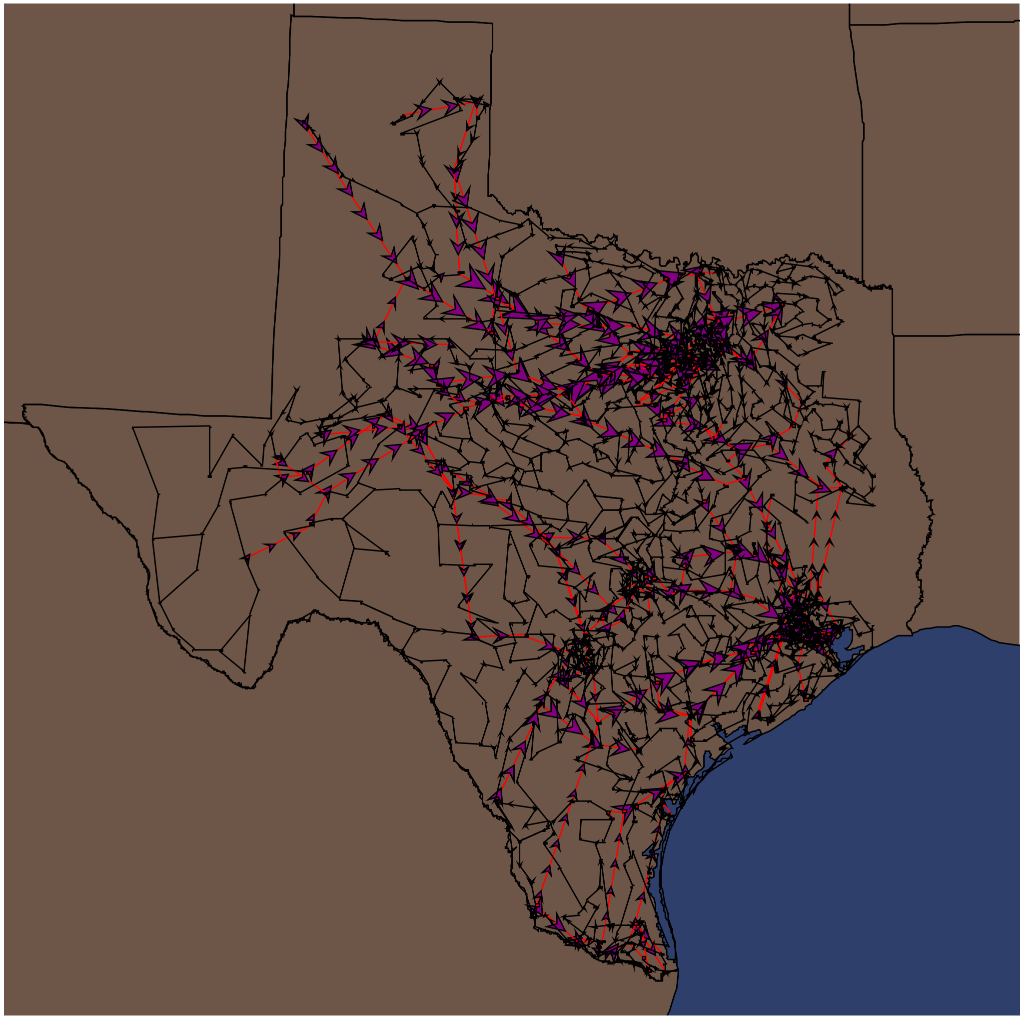
Benchmark GMD Event

- E-field Contour (V/km)

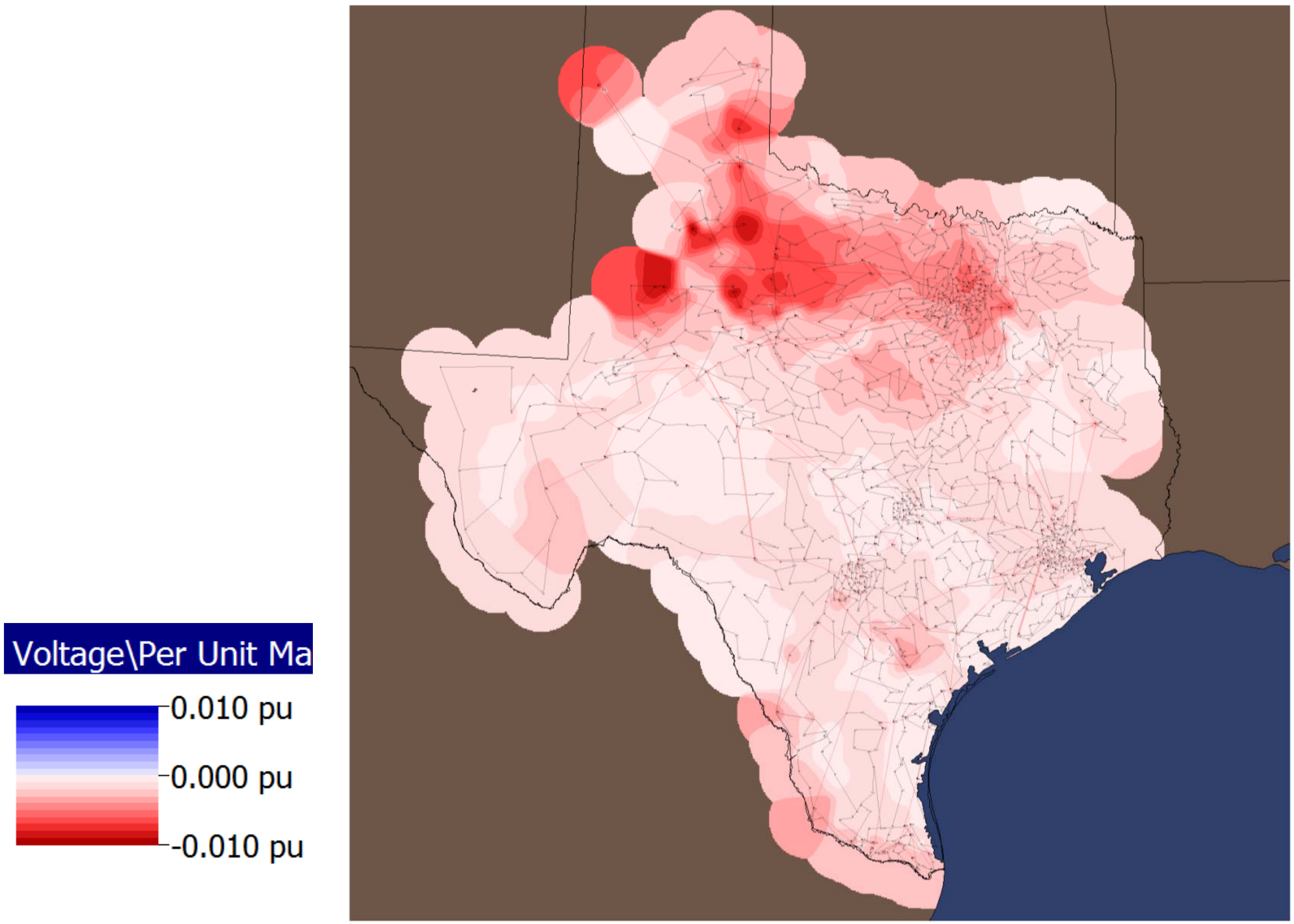


Benchmark GMD Event Example

- Show Custom Float 1 in Animated Flows



Difference Flows: Voltage Contour



Benchmark Event Time Series

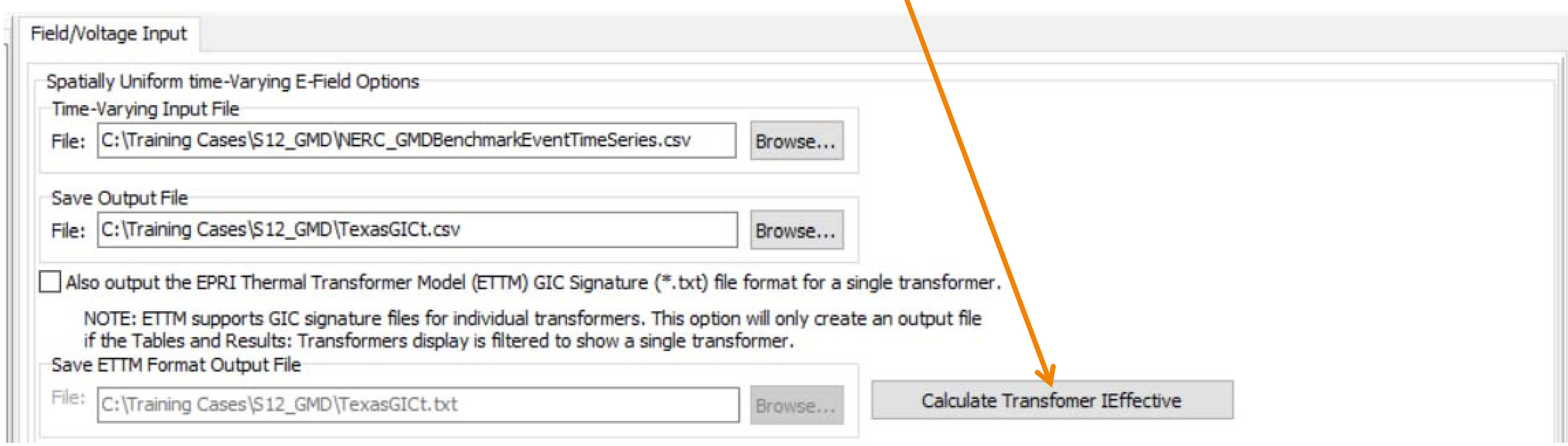
- Simulator can automatically generate a csv file of GIC(t) time series for a uniform time-varying E(t) field
- Sample input file *NERC_GMDBenchmarkEventTimeSeries.csv*
  - 10-second samples matching **Figures 2 and 3** in the NERC *Benchmark Geomagnetic Disturbance Event Description*
  - fields are 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 >= 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”

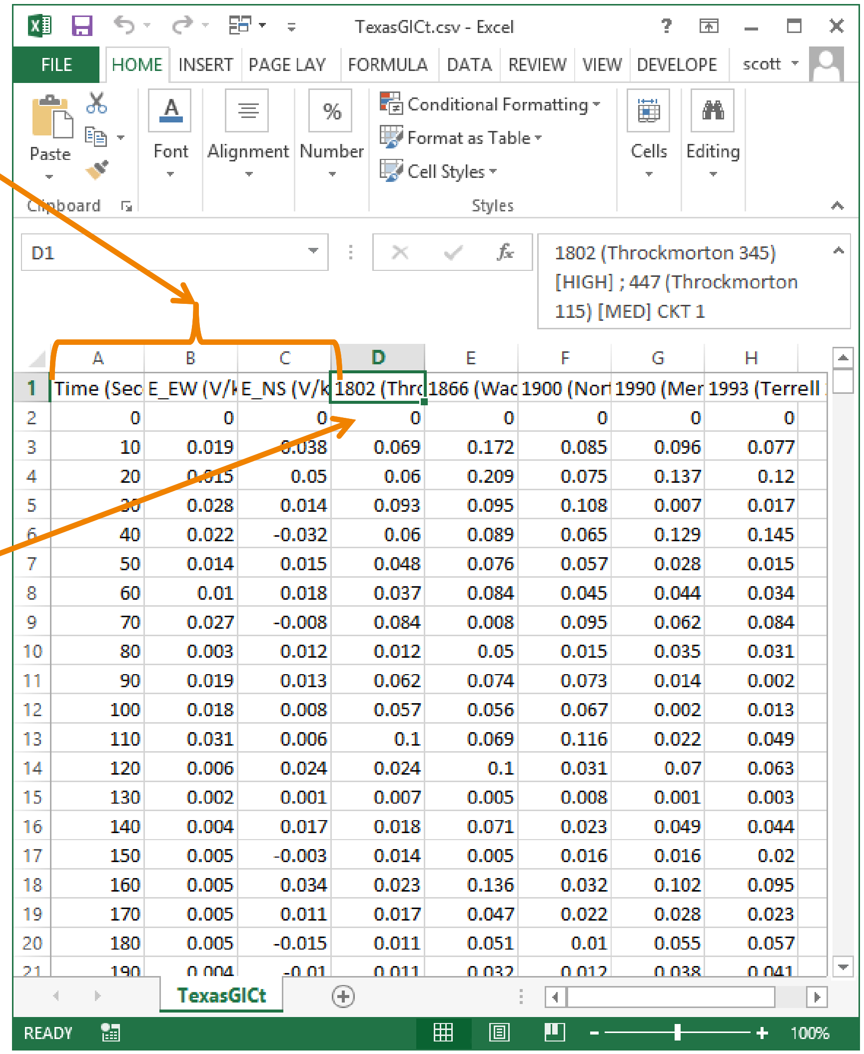


Benchmark Event Time Series

- 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/k	E_NS (V/k	1802 (Thro	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

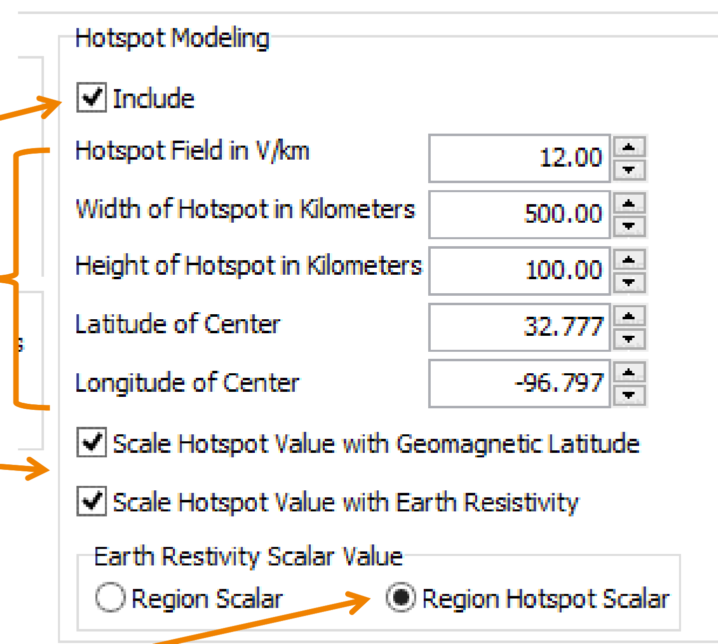
- The NERC-TPL-007-2 Supplemental GMD Event may be included in Simulator with Hotspot Modeling

Include Hotspot

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

Apply scale factors

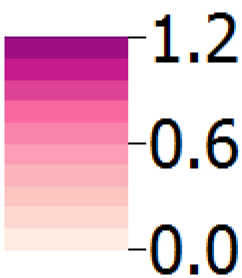
Apply supplemental Earth resistivity factor inside the Hotspot

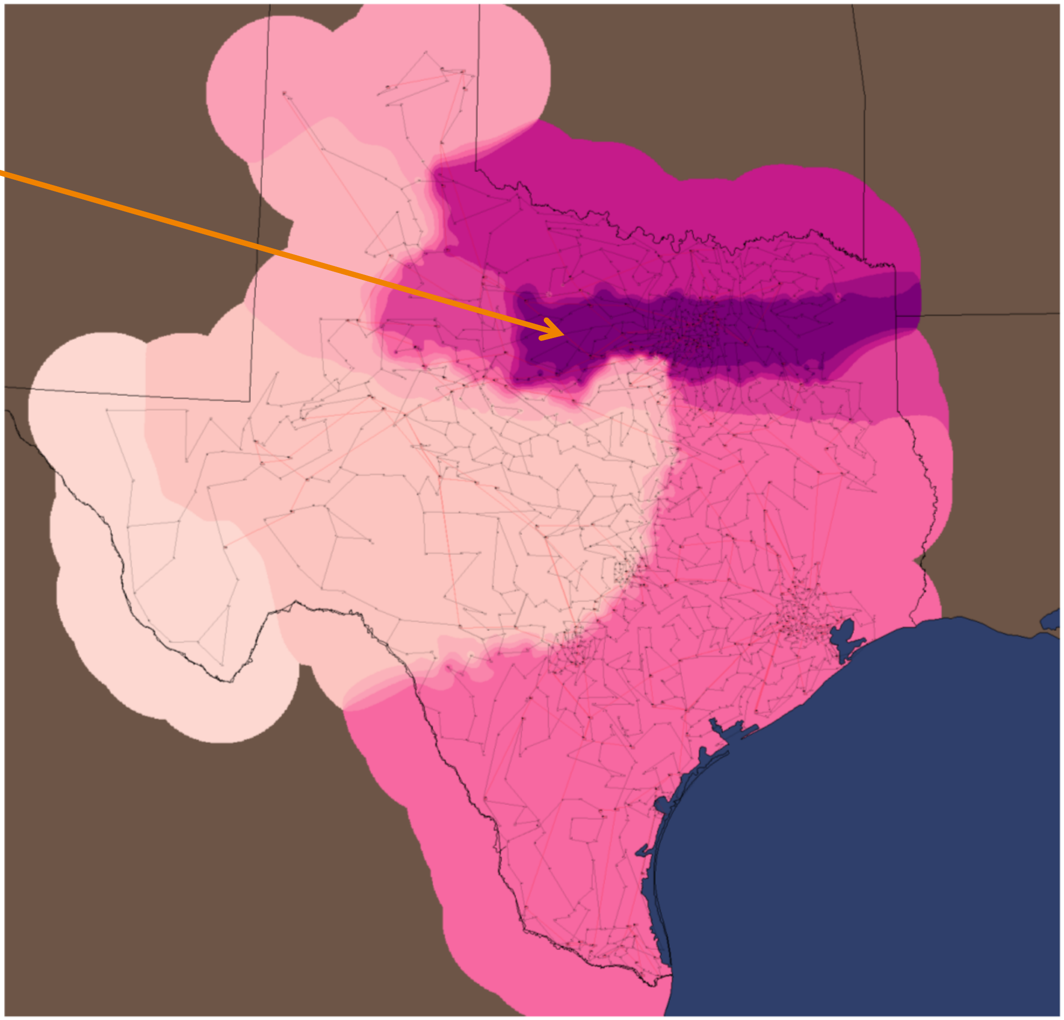


Supplemental GMD Event

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 >= 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)

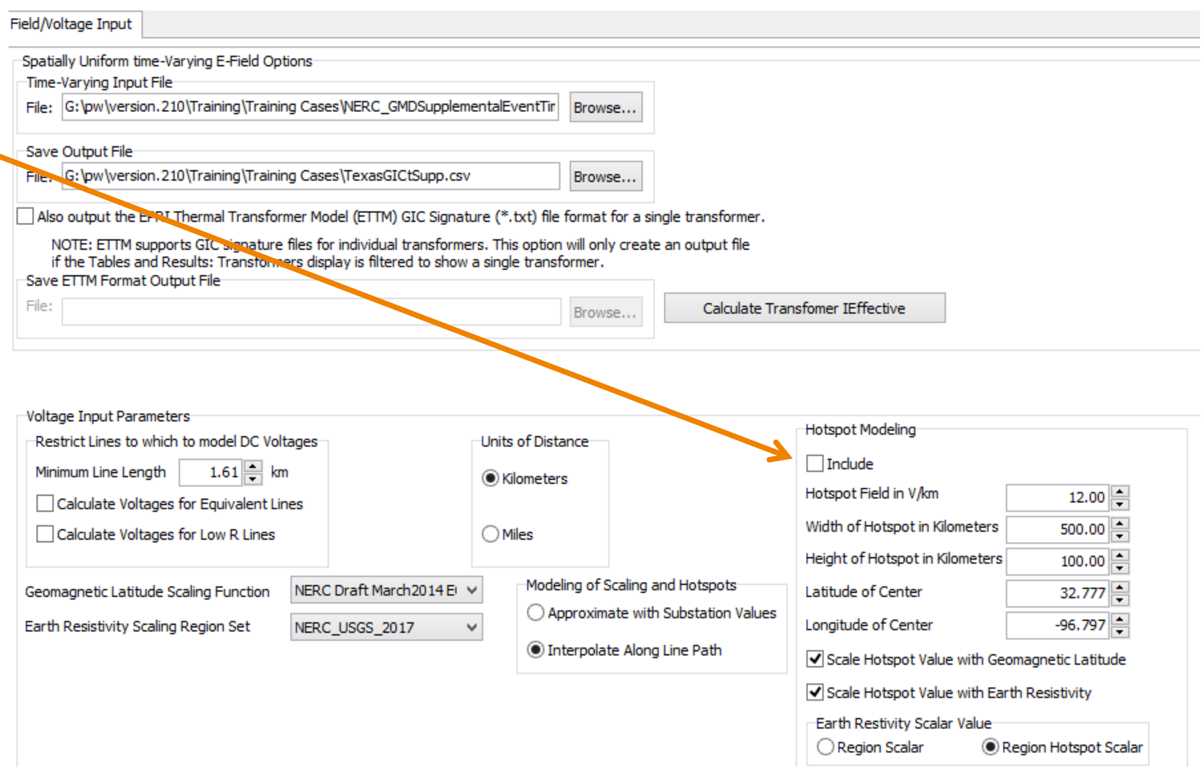
Non-Uniform Electric Field Scaling Functions

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



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

Records ▾ Set ▾ Columns ▾ f(x) ▾ Options ▾

	Bus Num High	Bus Name High	Bus Num Med	Bus Name Med	Bus Num Ter	Bus Name Ter	Circuit	Transformer Per Phase Effective GIC, Amps	Maxim IEffec	Transformer Per Unit Effective GIC	GIC Mvar Losses	Maximum Mvar Losses	Maximum IEffective 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	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	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	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	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	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	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	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	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	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

Records ▾ Set ▾ Columns ▾ f(x) ▾ Options ▾

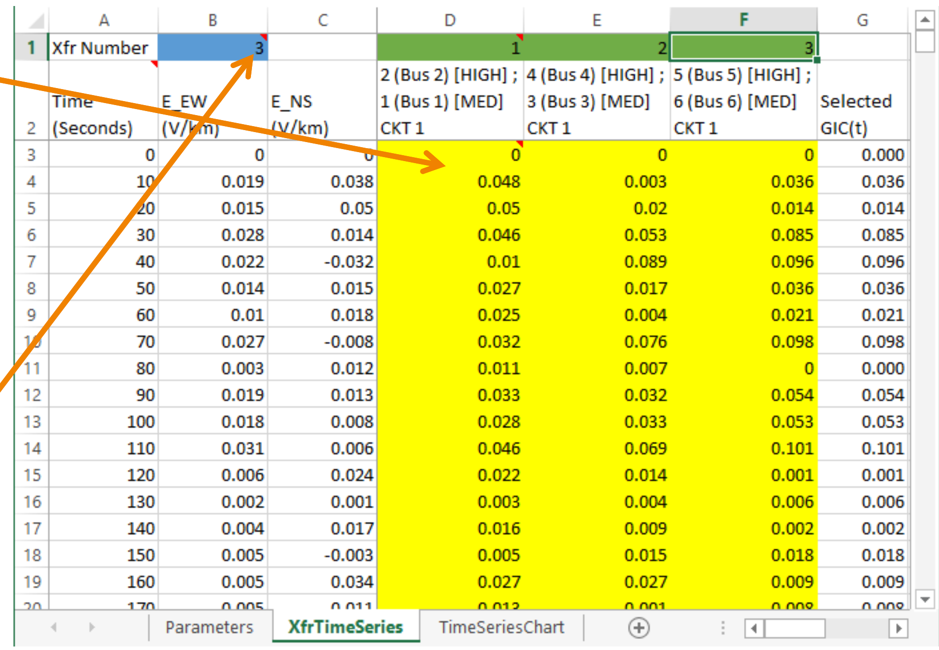
	Bus Num High	Bus Name High	Bus Num Med	Bus Name Med	Bus Num Ter	Bus Name Ter	Circuit	Transformer Per Phase Effective GIC, Amps	Maximum Effective	Transformer Per Unit Effective GIC	GIC Mvar Losses	Maximum Mvar Losses	Maximum IEffective Direction (Degrees)	Neutral Current (Amps)	Maximum Neutral Amps	Maximum Neutral Current Degrees	Ignore GIC Losses	GIC Blocked for Transformer Neutral
126	1788	Cooper 345	136	Cooper 115	0		1	5.305	6.1726	0.022	3.45	4.01	60.2	0.000	0.00	91.0	NO	YES
127	1788	Cooper 345	1676	Cooper G0	0		1	0.000	0.0000	0.000	0.00	0.00	91.0	0.000	0.00	91.0	NO	YES
128	1788	Cooper 345	136	Cooper 115	0		2	5.305	6.1726	0.022	3.45	4.01	60.2	0.000	0.00	91.0	NO	YES
129	1933	Coppell 345	9	Coppell 115	0		1	7.221	7.2277	0.031	4.52	4.52	88.6	38.814	38.87	87.9	NO	NO
130	463	Copperas Cove 2 115	1698	Copperas Cove 2 G0	0		1	0.709	0.9202	0.001	0.15	0.20	130.6	-2.128	2.76	130.6	NO	NO
131	1908	Corpus Christi 10 345	1068	Corpus Christi 10 115	0		1	5.248	8.2985	0.022	3.40	5.38	141.7	9.887	14.43	137.7	NO	NO

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*

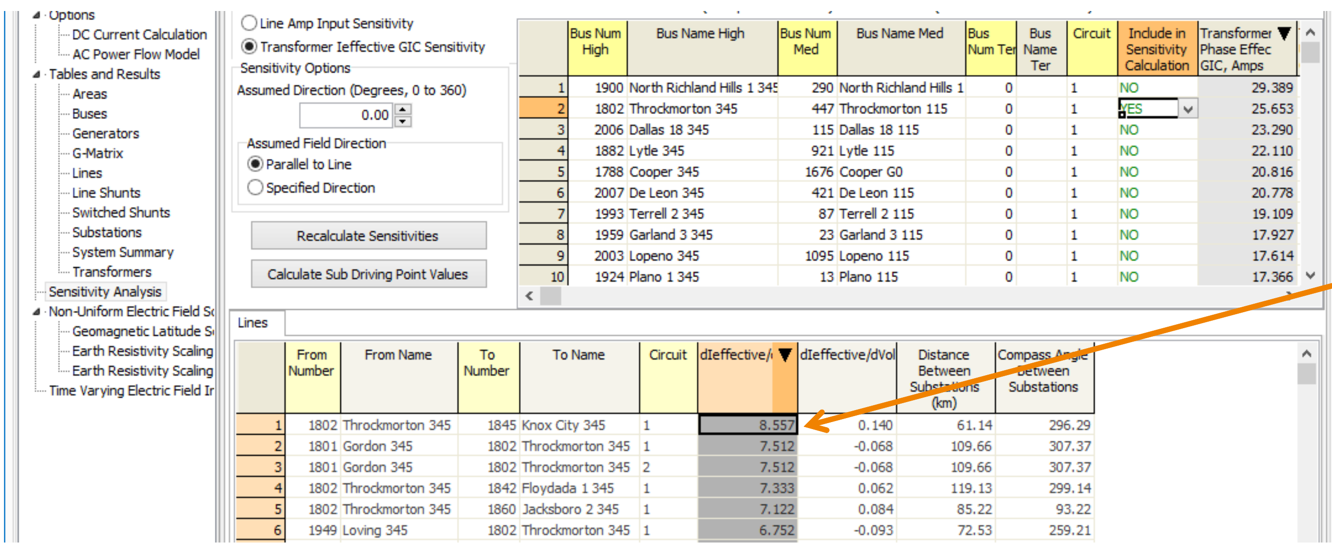


	A	B	C	D	E	F	G
1	Xfr Number	3		1	2	3	
2	Time (Seconds)	E_EW (V/km)	E_NS (V/km)	2 (Bus 2) [HIGH] ; 1 (Bus 1) [MED] CKT 1	4 (Bus 4) [HIGH] ; 3 (Bus 3) [MED] CKT 1	5 (Bus 5) [HIGH] ; 6 (Bus 6) [MED] CKT 1	Selected GIC(t)
3	0	0	0	0	0	0	0.000
4	10	0.019	0.038	0.048	0.003	0.036	0.036
5	20	0.015	0.05	0.05	0.02	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

Sensitivity Analysis

Sensitivity Analysis

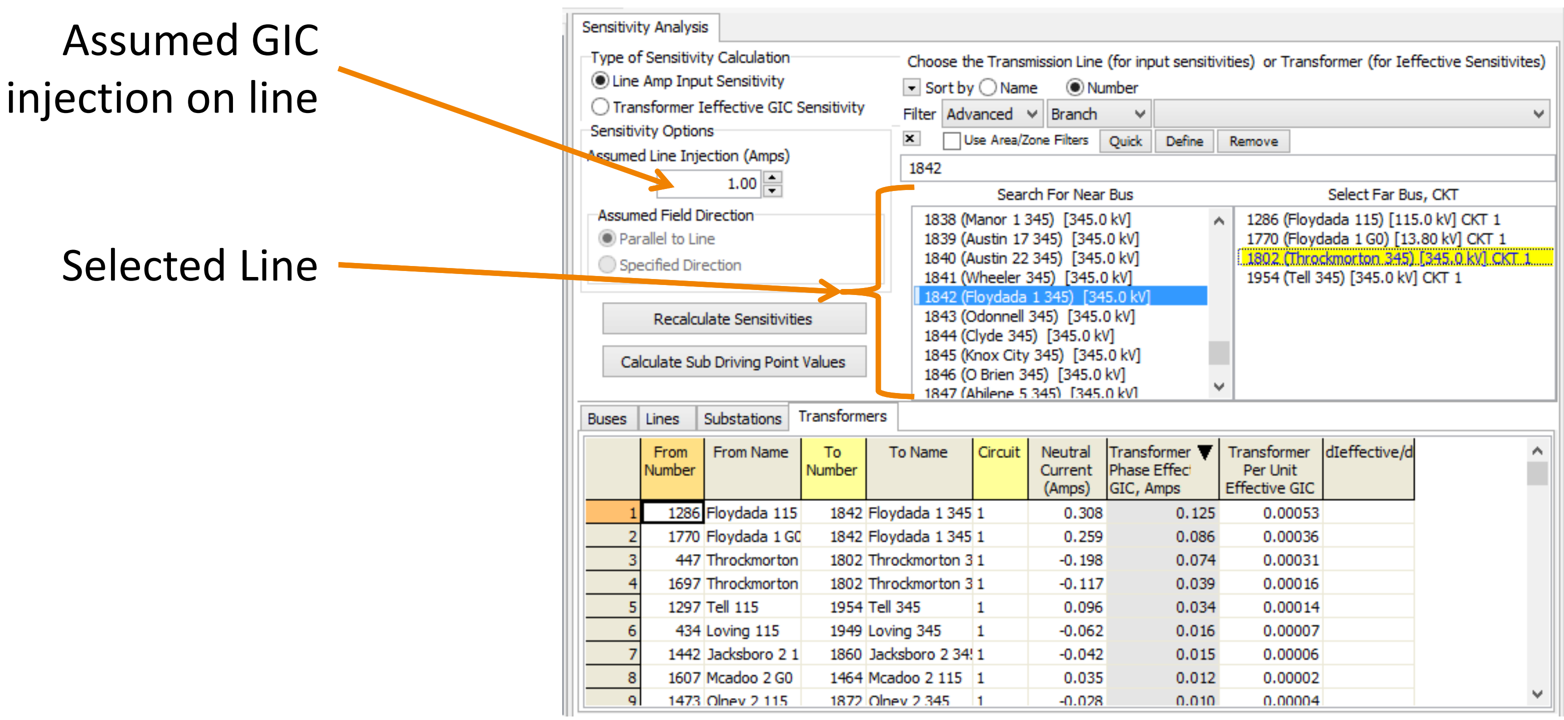
- "Transformer $I_{effective}$ GIC Sensitivity" can identify transmission lines with greatest effect on transformer GIC current
- Re-calculate GIC with "Single Snapshot" mode, 8 V/km, 93 degrees, and latitude scaling
- Sort transformers by $I_{effective}$
- Include Throckmorton 345/115 kV in Sensitivity Calculation
- Click **Recalculate Sensitivities**
- $dI_{effective}$ /d E_{field} indicates change in $I_{effective}$ for a 1 V/km variation in E-field on the line in question



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



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

$$\Re_i := \frac{R_i}{R_i + R_{TH,i}}$$

Substation Resistance Sensitivity Example

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

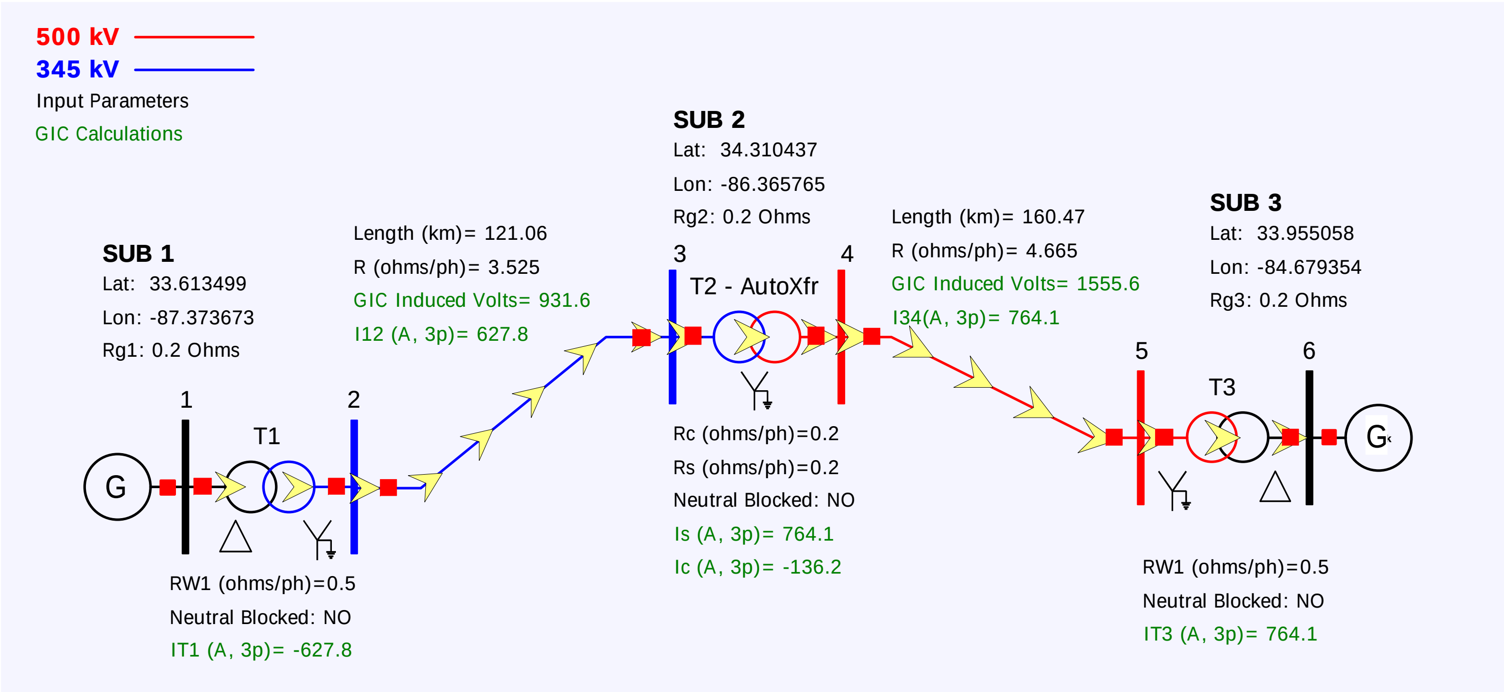
Buses | Lines | Substations | Transformers

	Sub Num	Sub Name	Sub ID	GIC DC Neutral Voltage	GIC Am 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	-96.679

GIC Modeling in Transient Stability

NERC 6-Bus Example

- Described in the NERC Application Guide, Appendix II*
- 2 gwye-delta GSUs, 1 gwye-gwye 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

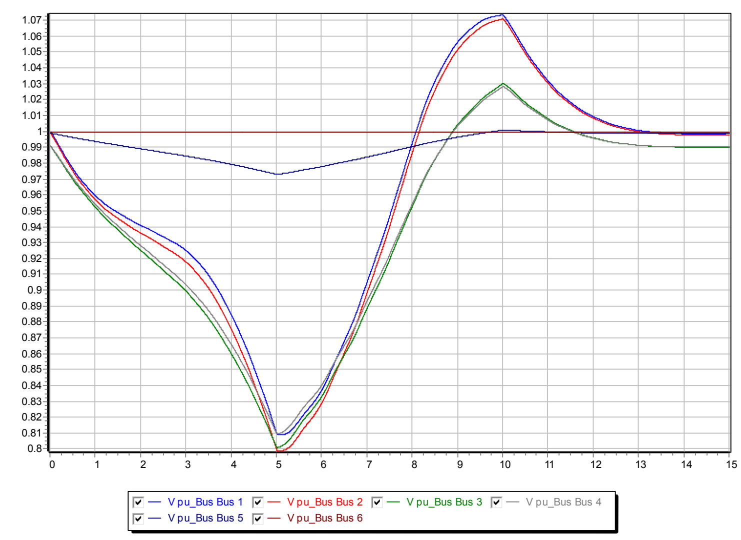
- Open *GIC Analysis Form* and select the **Calculation Mode** "Time Varying Series Voltage Inputs"
- Insert 3 time points to create a 5 second rise from 0 V/km to 15V/km at 90 degrees and a 5 second decline to 0 V/km
- Check the box "Include GIC in Power Flow and Transient Stability"
- Set "Current Time" to 0
- Open *Transient Stability Analysis* Form

GIC in Transient Stability

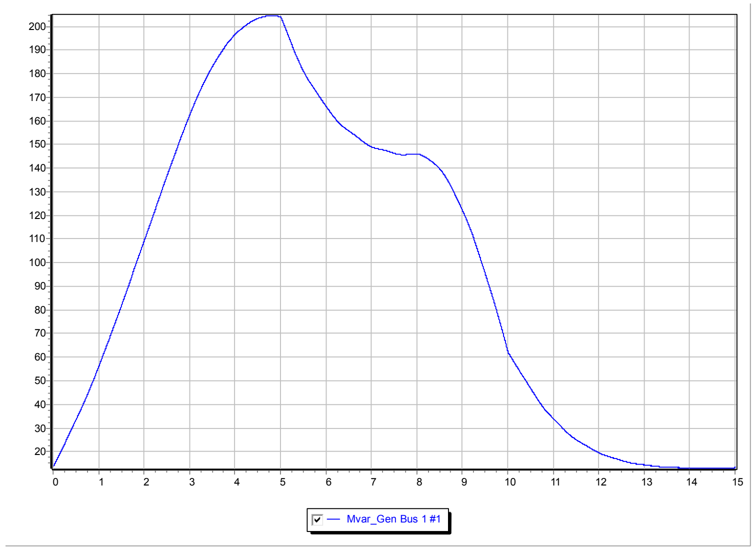
- Run Transient Stability Simulation for 15 seconds
- Time-series plots are generated for generator rotor angle, bus frequency, bus voltage, transformer I_{eff} , transformer GIC MVar losses (by substation), generator MVar output, and generator field current
- More details on using Simulator's Transient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

Transient Stability Plots

- Bus Voltages



- Generator MVar



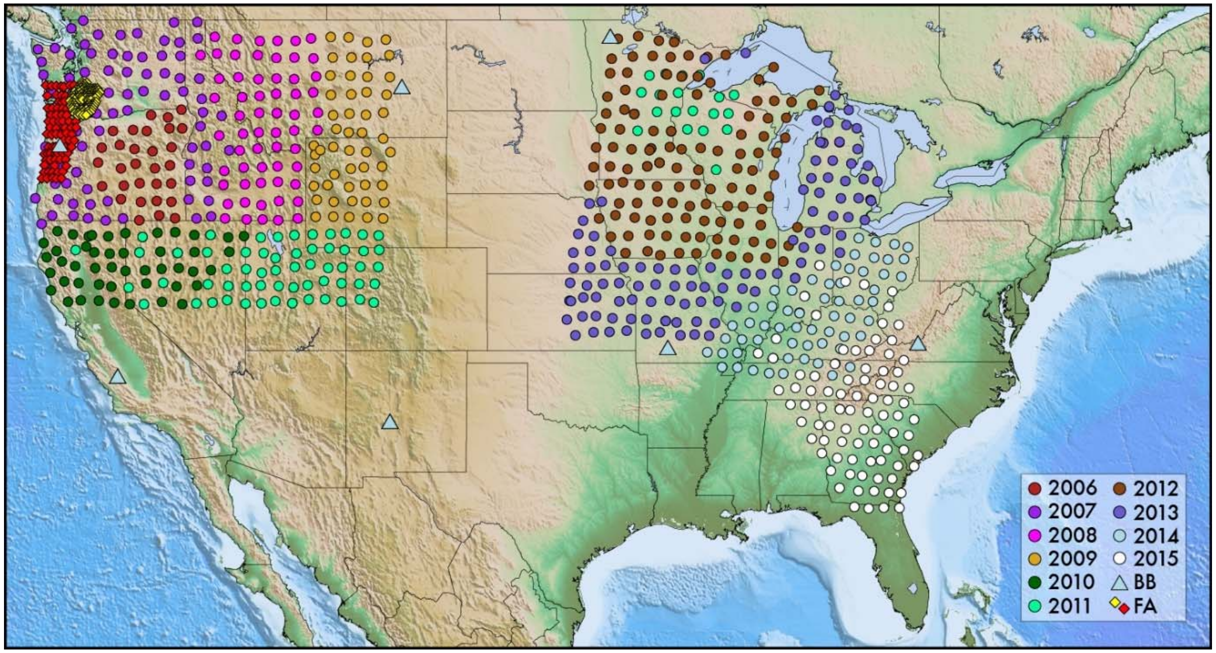
- Note generator at bus 1 exceeds its power flow limit of 50 MVar for several seconds
- Simulation in power flow leads to collapse at t=4.2
- Increasing peak field strength beyond 20 V/km leads to collapse in transient stability simulation

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 Southwest
- 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.

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

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

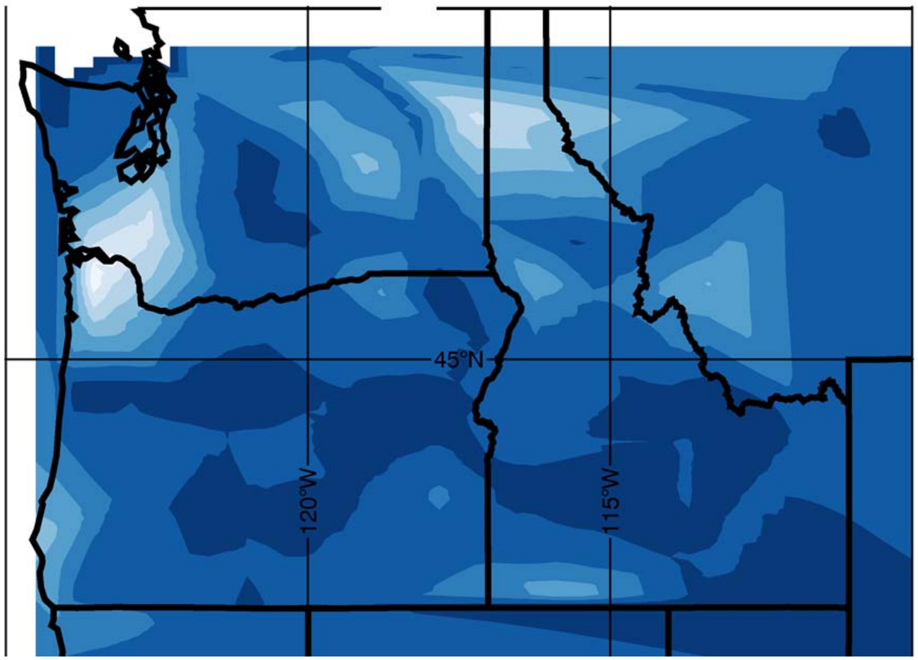
$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} \xi_{xx} & \xi_{xy} \\ \xi_{yx} & \xi_{yy} \end{bmatrix} \cdot \begin{bmatrix} Bx \\ By \end{bmatrix}$$

- Are provided in 2x2 impedance tensors by USArray

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

Example 3-D Earthscope E-Field

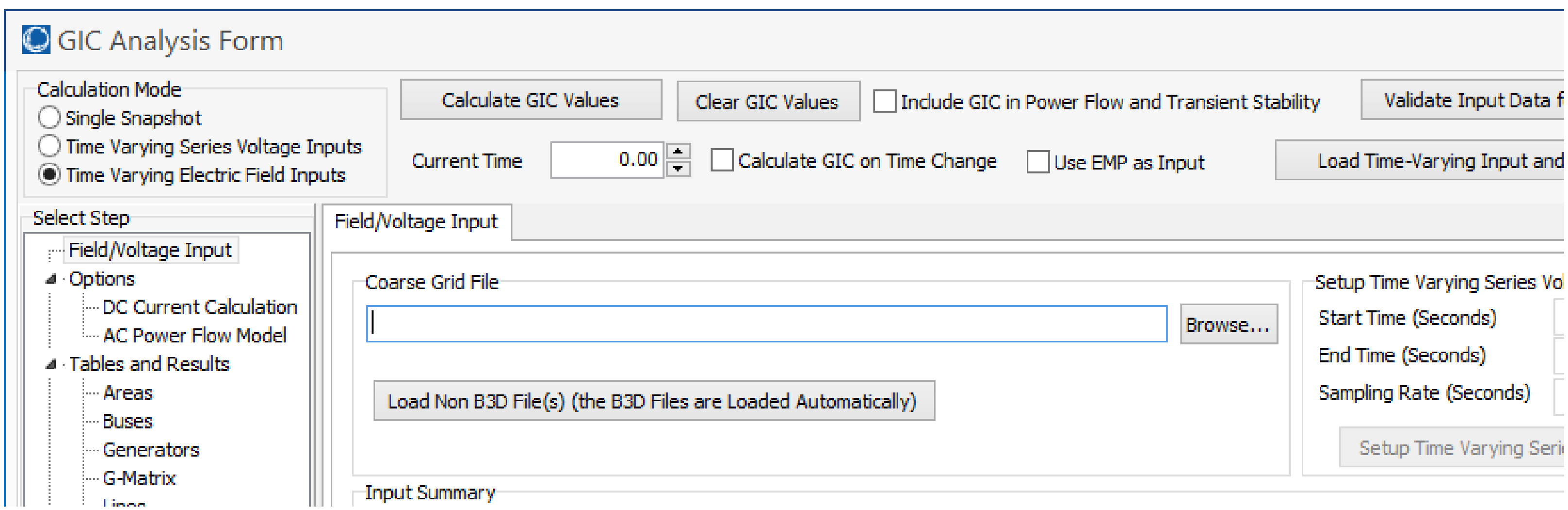
- Image provides a snapshot visualization of the time-varying surface electric fields using Earthscope data



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

Time Varying Electric Field Inputs

- Binary (B3D) or text (csv) file formats
- GeoJSON format in development
- Include times points and geo-spatial (longitude, latitude) grid with Eastward and Northward E-field at each point



Time Varying Electric Field Inputs

- Coarse Grid File (required)
  - specifies time points and resolution (in degrees latitude and longitude) of geo-spatial grid
  - contains Eastward and Northward E-field magnitude for each grid point and time
- Fine Grid Files (optional)
  - detailed data at a higher spatial resolution than the Coarse Grid
  - may be used for regions with high E-field gradients (e.g. coastal effects)

Example: B3D File

- Open case **TN150.pwb** and the *GIC Analysis Form*
- Choose **Calculation Mode** “Time Varying Electric Field Inputs”
- Load *Coarse Grid File* **TN_20150622.b3d** (from *Browse…* button)

Example: B3D File

Change Time Point to view its grid points

Summary

Input Summary

Starting Time (Seconds)	0.00	Starting Latitude	34.00	Starting Longitude	-90.00
Ending Time (Seconds)	172790.00	Ending Latitude	37.00	Ending Longitude	-82.00
Number of Time Points	17280	Latitude Increment	0.500	Longitude Increment	0.500
Non-Uniform Time Point	0.0000	Preview Offset (Seconds)	0.00	Preview Time	

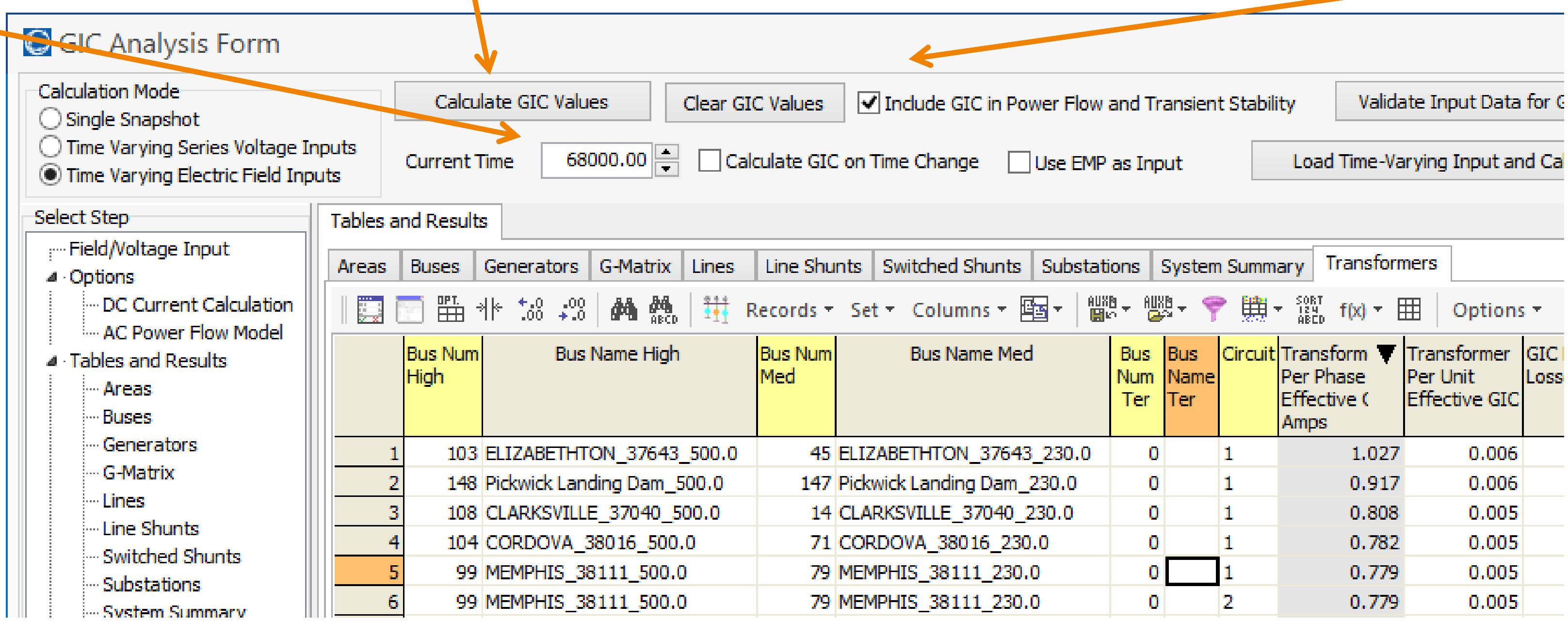
Time Point Grid Data

Time Point Grid Preview (First Entry is the Eastward Value, the Second the Northward)

Lat	Lon: -90.000	Lon: -89.500	Lon: -89.000	Lon: -88.500	Lon: -88.000	Lon: -87.500	Lon: -87.000
37.000	0.007,-0.004	0.003,-0.003	0.003,-0.001	0.002, 0.000	0.001, 0.000	0.002, 0.001	0.003, 0.000
36.500	0.004,-0.003	0.001,-0.002	0.002,-0.001	0.002, 0.000	0.002, 0.001	0.001, 0.001	0.004,-0.000
36.000	0.002,-0.001	0.000,-0.001	0.001,-0.001	0.001, 0.000	0.002, 0.000	0.002, 0.000	0.001, 0.000
35.500	0.002,-0.001	0.002,-0.000	0.003, 0.000	-0.000, 0.000	0.000, 0.000	0.001, 0.002	0.001, 0.001
35.000	0.002,-0.001	0.002,-0.001	0.002,-0.000	0.002, 0.000	0.001, 0.000	-0.001, 0.001	-0.000, 0.001
34.500	0.002,-0.001	0.002,-0.001	0.002,-0.001	0.002,-0.000	0.002, 0.000	0.007, 0.002	-0.001, 0.001
34.000	0.002,-0.000	0.002,-0.000	0.002,-0.000	0.002,-0.000	0.002,-0.001	0.002, 0.000	0.005, 0.001

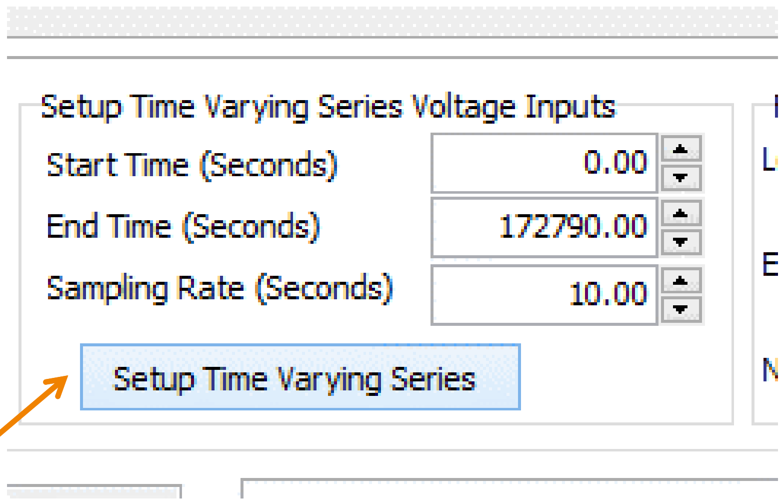
GIC Calculation and Power Flow

- Set the “Current Time” to match desired time point
- Optionally check “Include GIC in Power Flow and Transient Stability”
- Click “Calculate GIC Values” and/or solve the power flow



Calculate Entire Time Series in Transient Stability

- Return to **Field/Voltage Input** page
- Optionally adjust "Start Time", "End Time", or "Sampling Rate"



- Click "Setup Time Varying Series" button
- Equivalent Transmission Line inputs are created for the **Calculation Mode** "Time Varying Electric Field Inputs"

Time Varying Series Voltage Inputs

- Change **Calculation Mode** to "Time Varying Series Voltage Inputs"
- Time Points created at sampling interval between Start Time and End Time

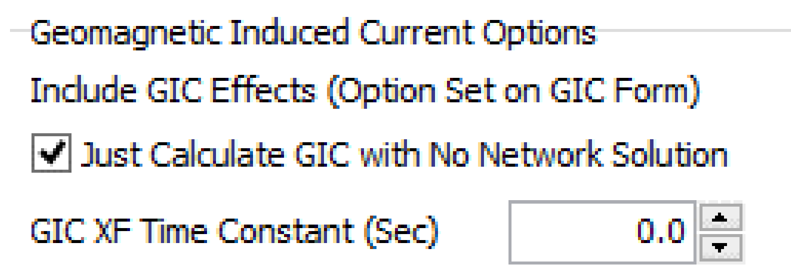
Field/Voltage Input

AC Line Input Voltages

	Branch ID	From Number	To Number	Circuit	From Latitude	To Latitude	From Longitude	To Longitude	Distance Between Substations (km)	Timepoi	Timepoi	Timepoi	Timepoi	Timepoi	Timepoi	Timepoi	Timepoi
1	Time in Seconds									0.000	10.000	20.000	30.000	40.000	50.000	60.000	70.000
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	0.000	0.000
3	Branch '2' '14' '1'	2	14	1	36.4362	36.4751	-86.8408	-87.2991	41.31	0.012	-0.001	0.006	-0.004	0.003	-0.009	-0.015	-0.003
4	Branch '2' '21' '1'	2	21	1	36.4362	36.2387	-86.8408	-86.7329	23.96	-0.061	-0.049	-0.038	-0.030	-0.023	-0.019	-0.021	-0.029
5	Branch '19' '3' '1'	19	3	1	35.9840	36.2233	-86.5424	-86.1935	41.14	0.045	0.054	0.036	0.046	0.030	0.045	0.055	0.044
6	Branch '141' '3' '1'	141	3	1	36.3156	36.2233	-86.4004	-86.1935	21.22	-0.013	-0.006	-0.006	-0.002	-0.002	0.002	0.003	-0.004
7	Branch '4' '18' '1'	4	18	1	36.0522	36.1306	-86.6325	-86.6131	8.87	0.011	0.011	0.008	0.008	0.005	0.007	0.009	0.009

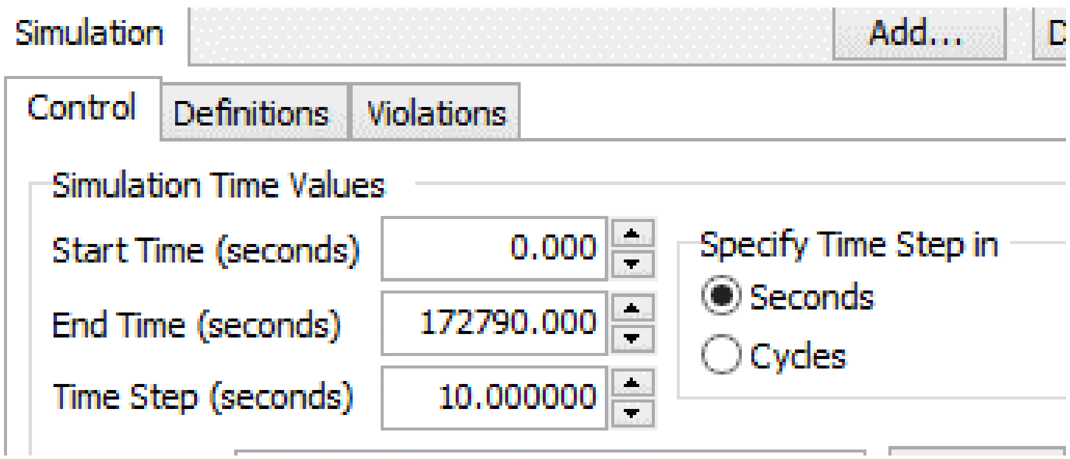
GIC in Transient Stability

- 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)



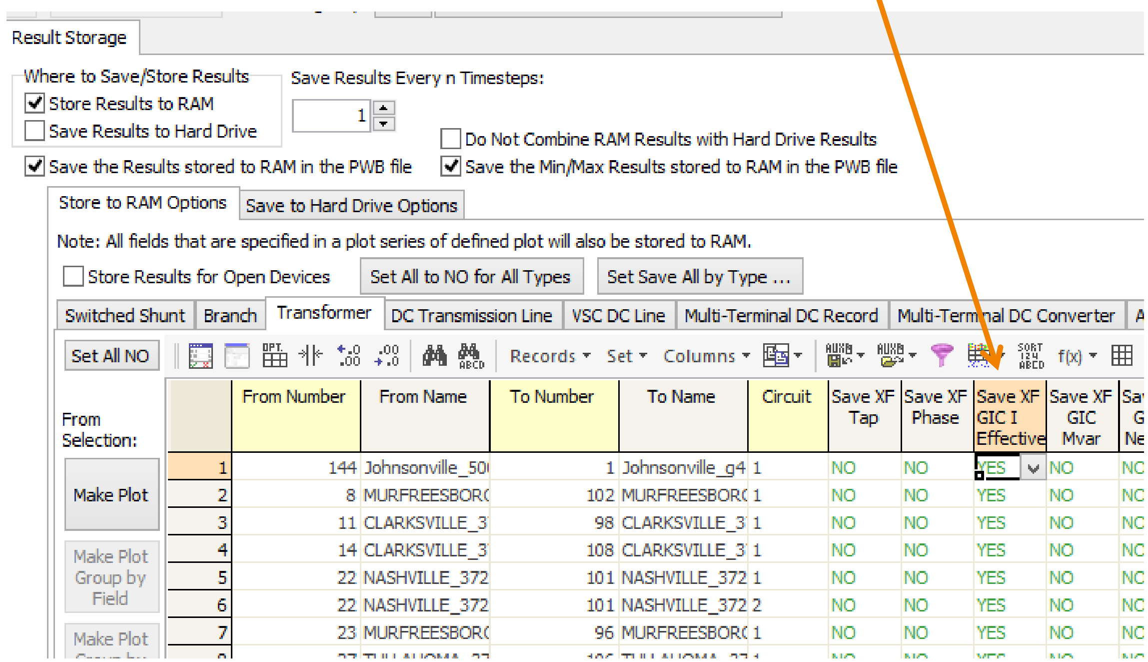
GIC in Transient Stability

- 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)



Results Storage

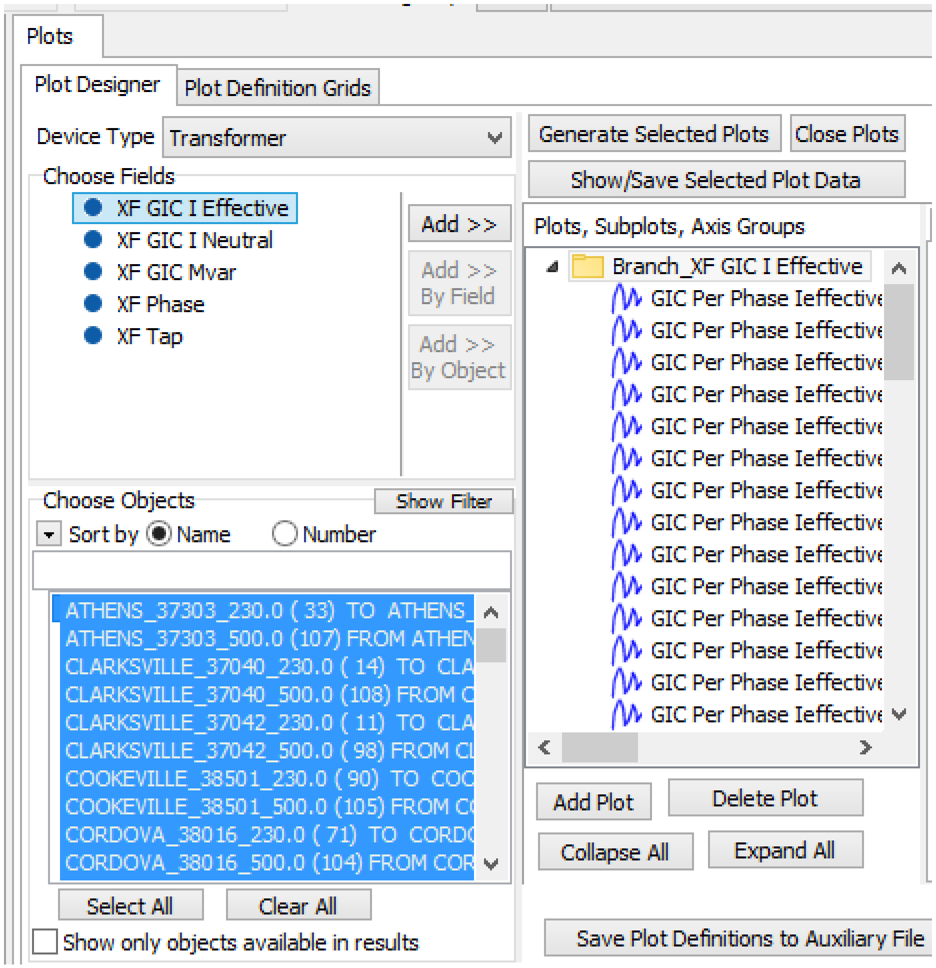
- Go to **Results Storage** page and subpages
- *Save XF GIC I Effective* for all **Transformers** and *Save GIC Total Mvar Losses* for **Case Information**

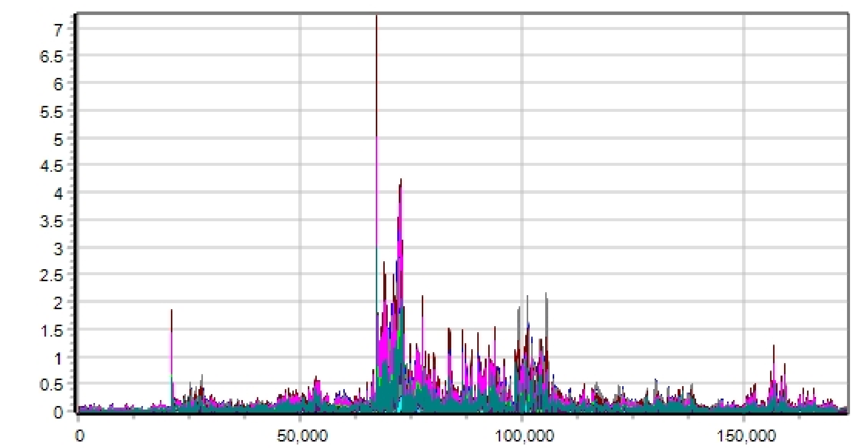


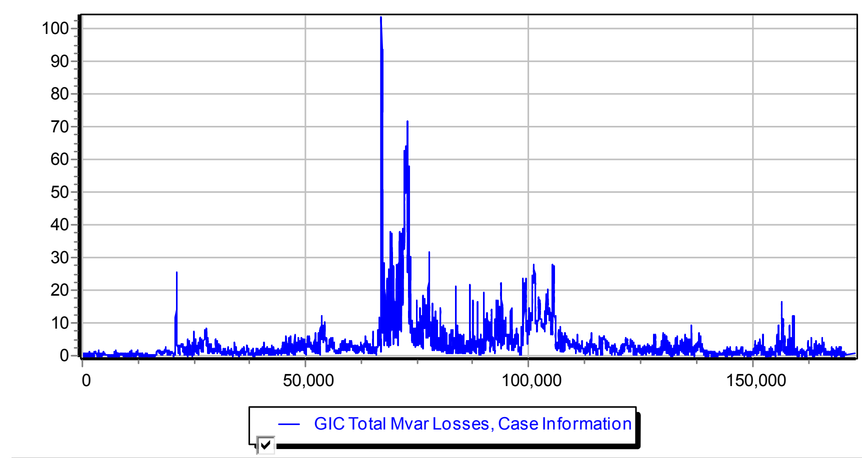
Plot Results

- Click "Run Transient Stability"
- Go to Plots 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

GIC Time Series Plots







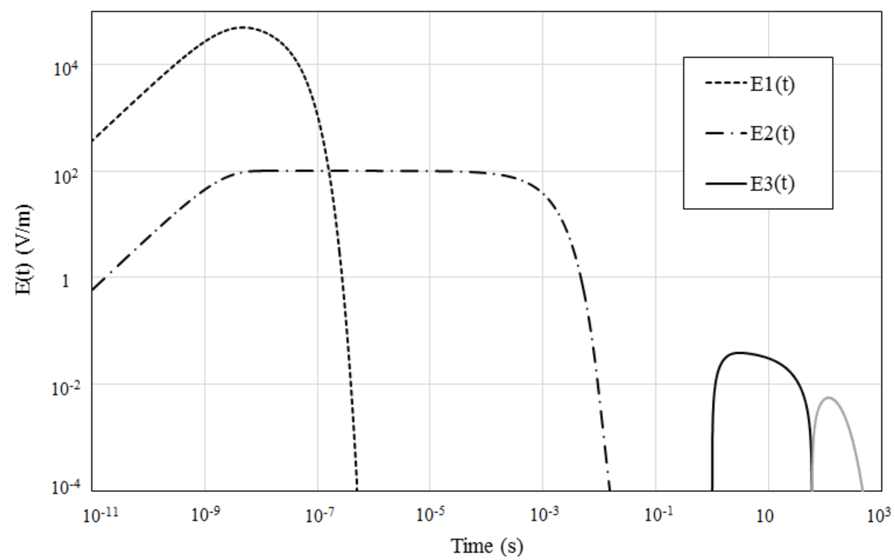
High-Altitude Electromagnetic Pulse (HEMP)

Eletromagnetic Pulse (EMP)

- Broadly defined, an electromagnetic pulse is any transient burst of electromagnet 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) cause 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

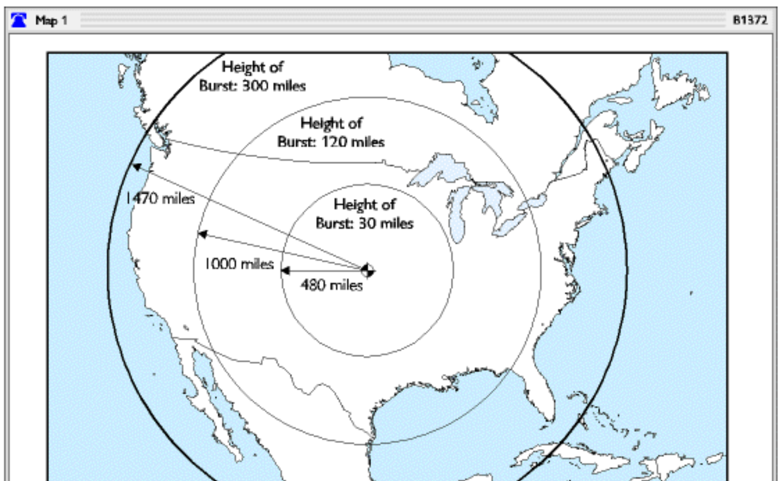


- E2, with electric fields of up to 100 volts per meter, is similar to lightning
- Much of talk is on E3, which is similar to GMDs

Image Source: IEC 1000-2-9 Figure

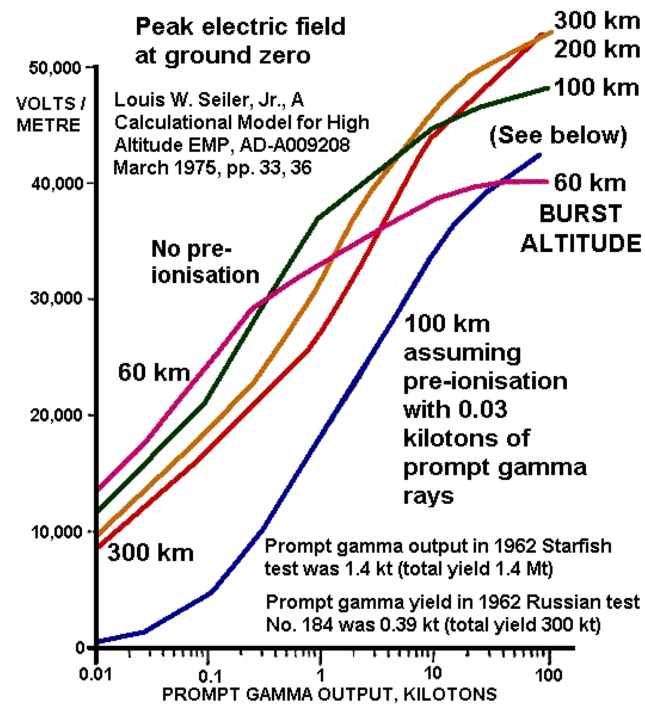
HEMP Impact vs. Size and Altitude

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



Area Effected by an Electromagnetic Pulse, by Height of Burst

Source: Gary Smith, "Electromagnetic Pulse Threats," testimony before the House National Security Committee, July 16, 1997.

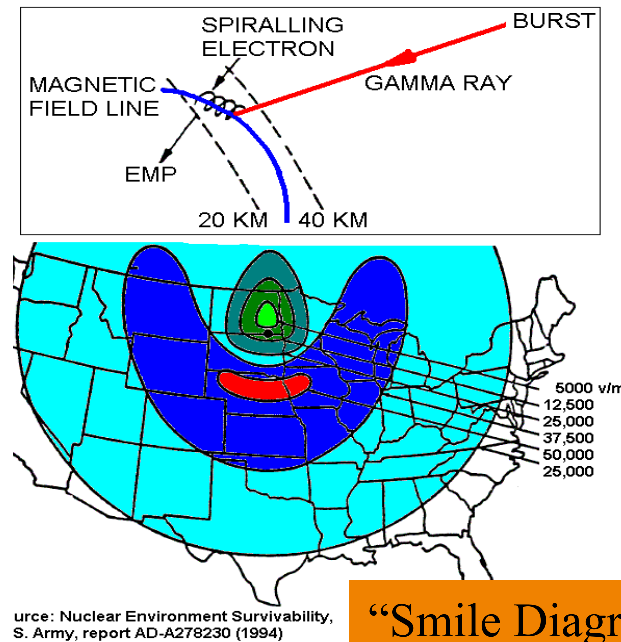


Low altitude EMPs can still have large footprints

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



"Smile Diagram"

- The E2 pulse is created by scattered gamma rays and neutron gamma rays

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

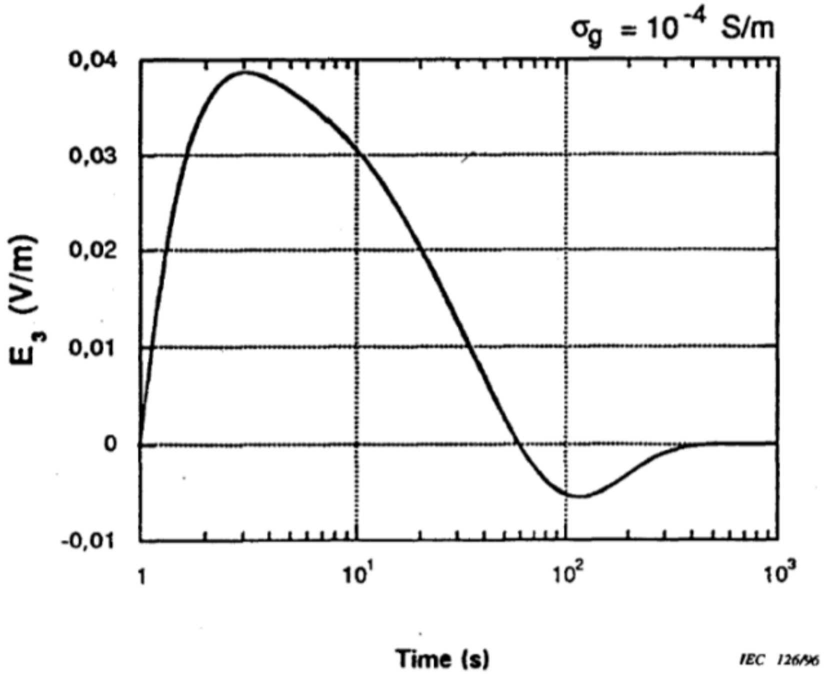
- Because of large footprint, small energy density in the E1, so devices can be protected by Faraday cages
  - The allowable size of apertures depends on the wavelength and hence the frequency (l=c/f); a ballpark figure is no larger than 1/10 the wavelength; for 1 GHz this is about 3 cm
  - Incoming 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"

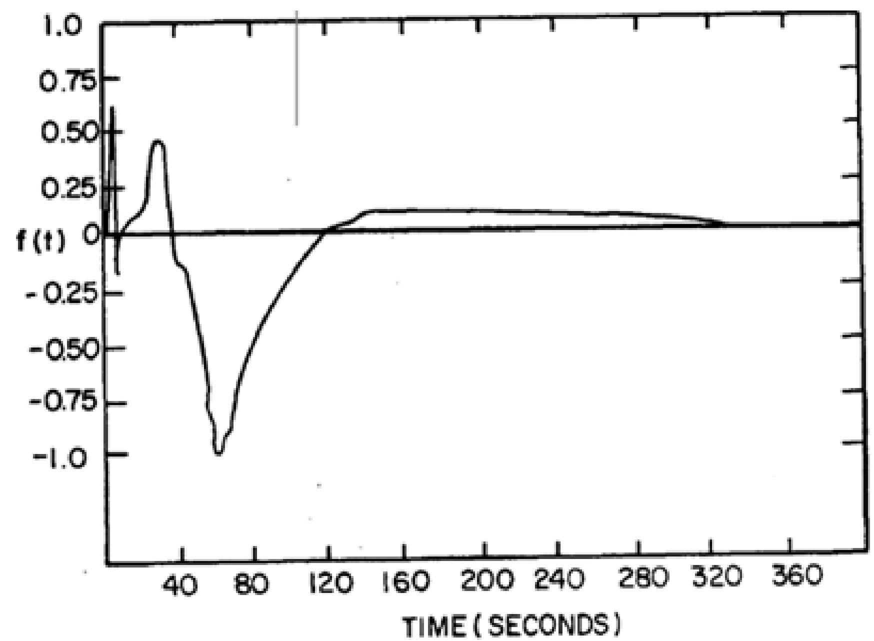
Source: "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, MetaTech-R-320, January 2010

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

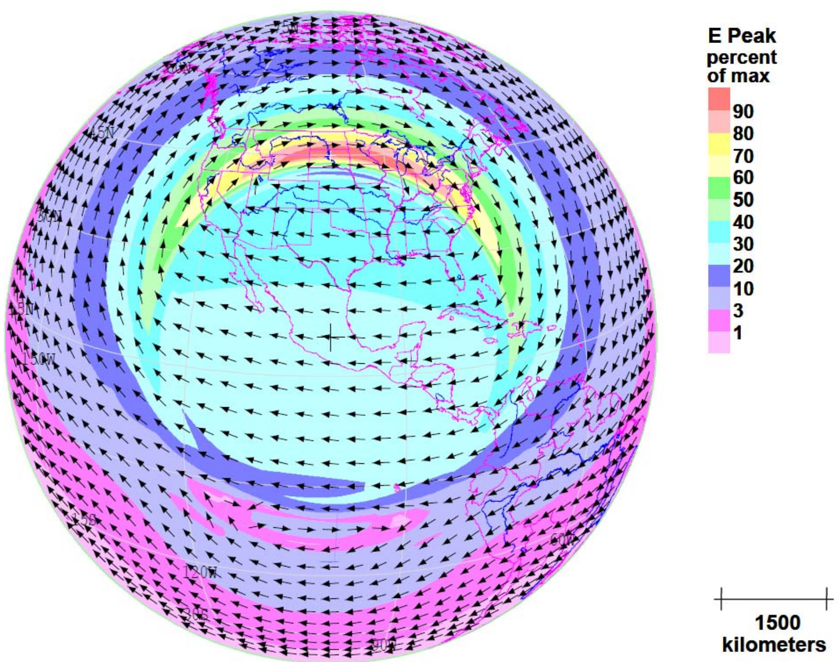




Left Image: IEC 1000-2-9, Figure 9, Right Image: ORNL "Study to Assess the Effects of Magnetohydrodynamic Electromagnetic Pulse on Electric Power Systems Phase I Final Report," May 1985, Figure 8

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

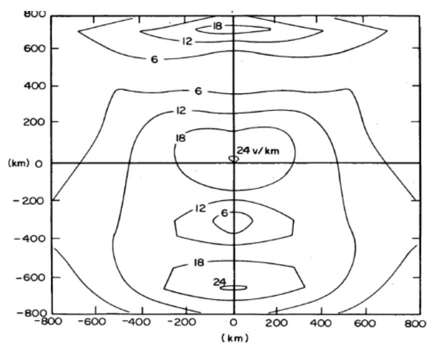
Image Source: Metatech R-321, Figure 2-4

HEMP E3B

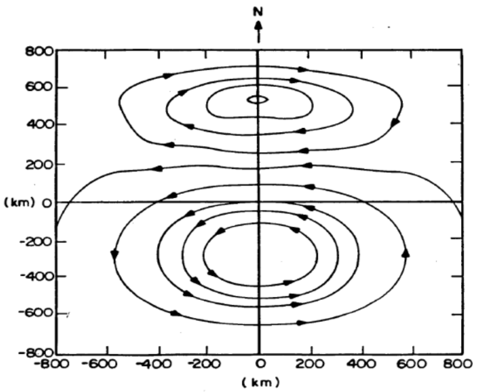
- ORNL 1985 models the E3B electric field as the product of a spatially independent time function (fig 8), and time independent spatial magnitude and directions (fig 9 and 10)

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

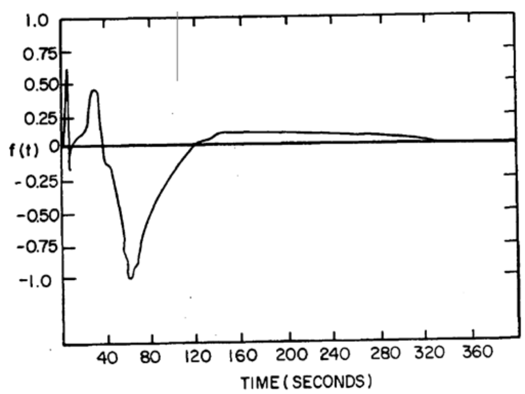
=



X



X



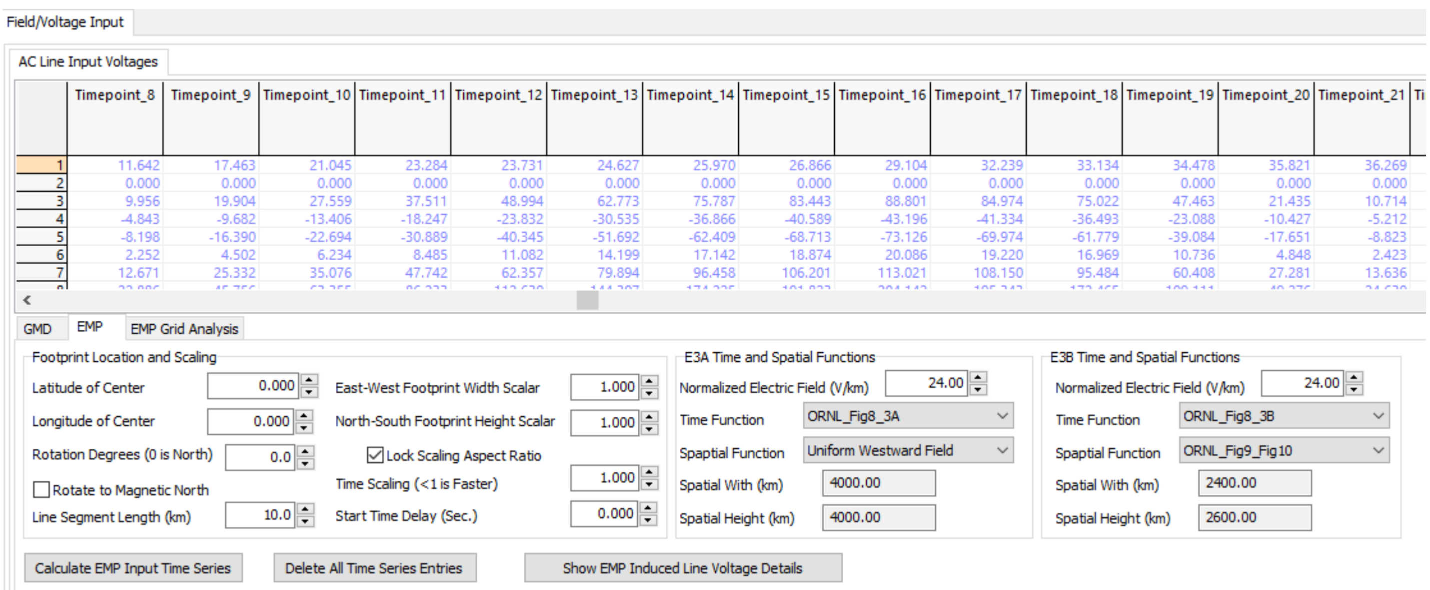
Values were calculated assuming a uniform conductivity of 0.001 S/m

HEMP E3 Waveforms

- Sources of initial time and spatial waveforms implemented in PowerWorld Simulator
  - "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.

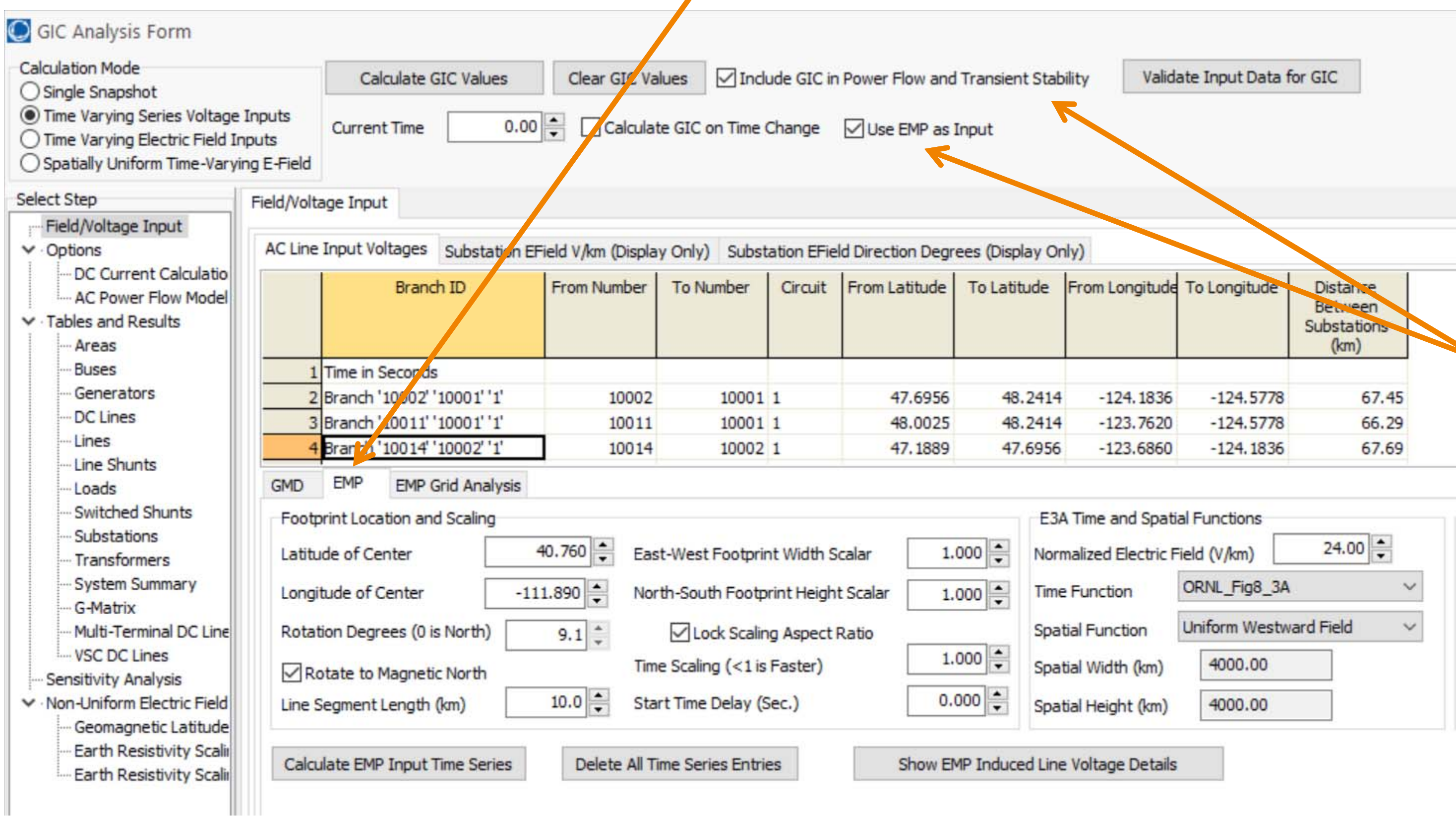
Auto-Creating HEMP Electric Fields

- Simulator can auto-create time and spatially-varying electric fields associated with de-classified EMP waveforms based on location, time functions, and spatial functions



Auto-Creating HEMP Electric Fields

- Choose “Time Varying Series Voltage Inputs” **Calculation Mode** and **Field/Voltage Input → EMP** subtab



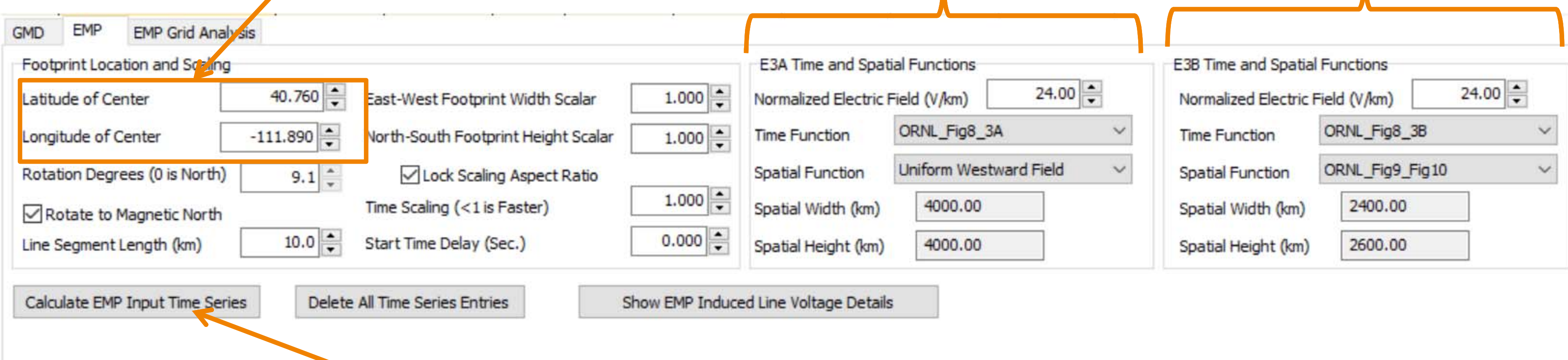
Include GIC in Power Flow and Transient Stability and Use EMP as Input

Example HEMP Parameters

Location of Center: 40.76, -111.89 for Salt Lake City

E3A: ORNL_Fig8_3A, Uniform Westward Field, 24 V/km

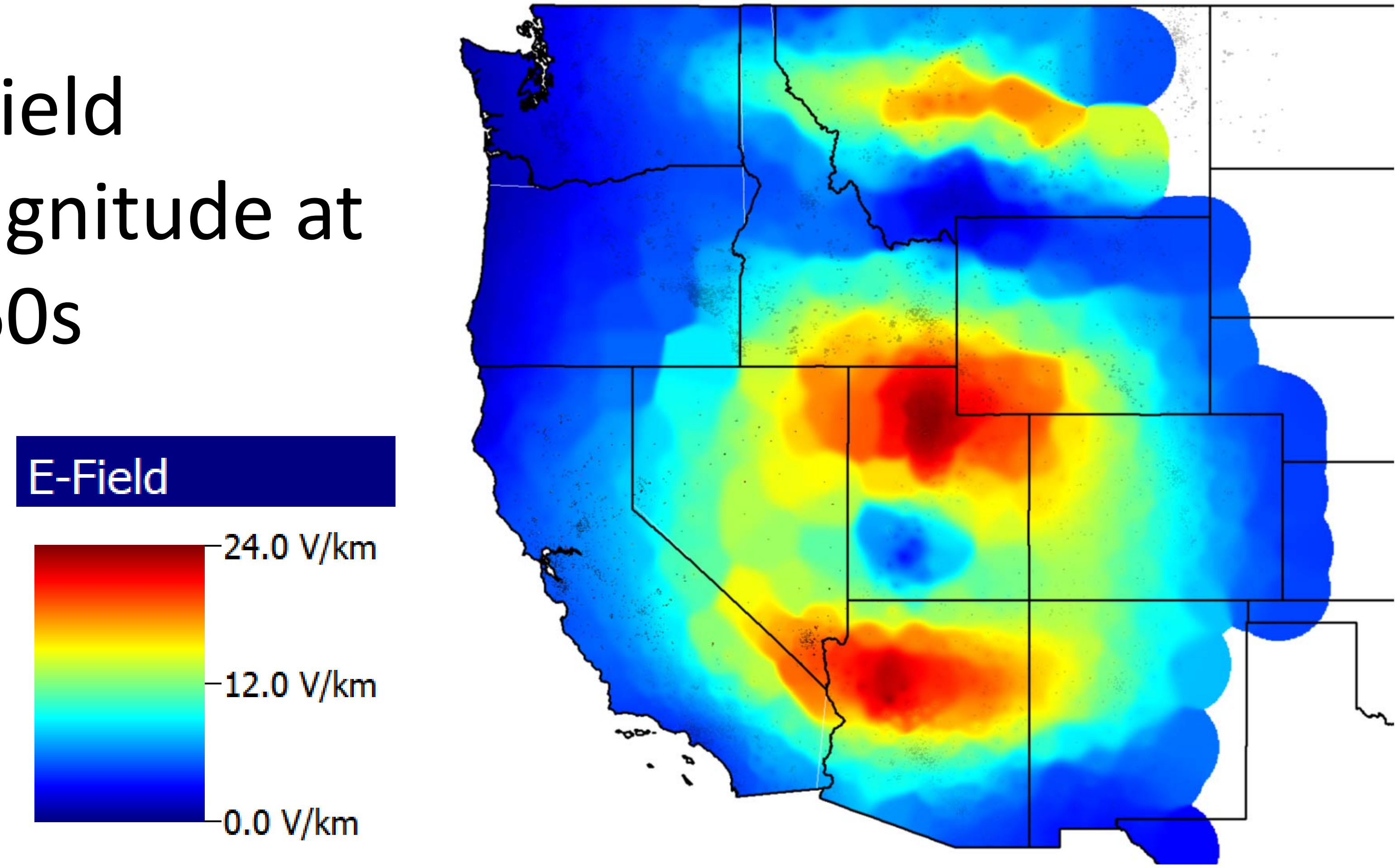
E3B: ORNL_Fig8_3B, ORNL_Fig9_Fig10, 24 V/km



Click Calculate EMP Input Time Series

ORNL E3B Peak Contour

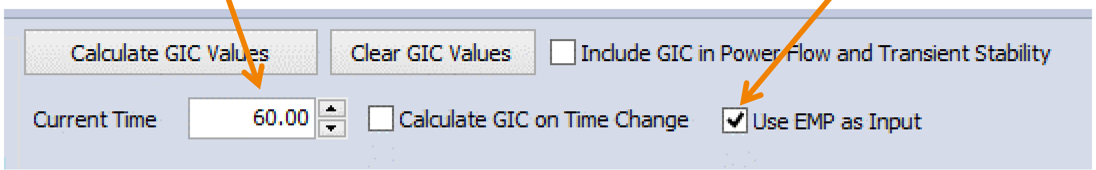
E-Field Magnitude at t=60s



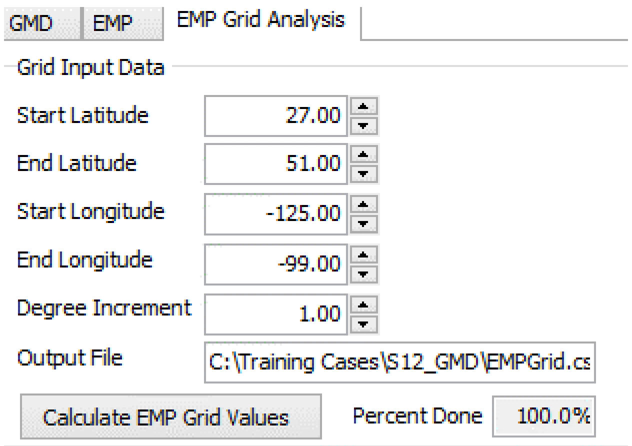
EMP Grid Analysis

Set Current Time to 60s

Use EMP as Input



Sample Western Grid Parameters

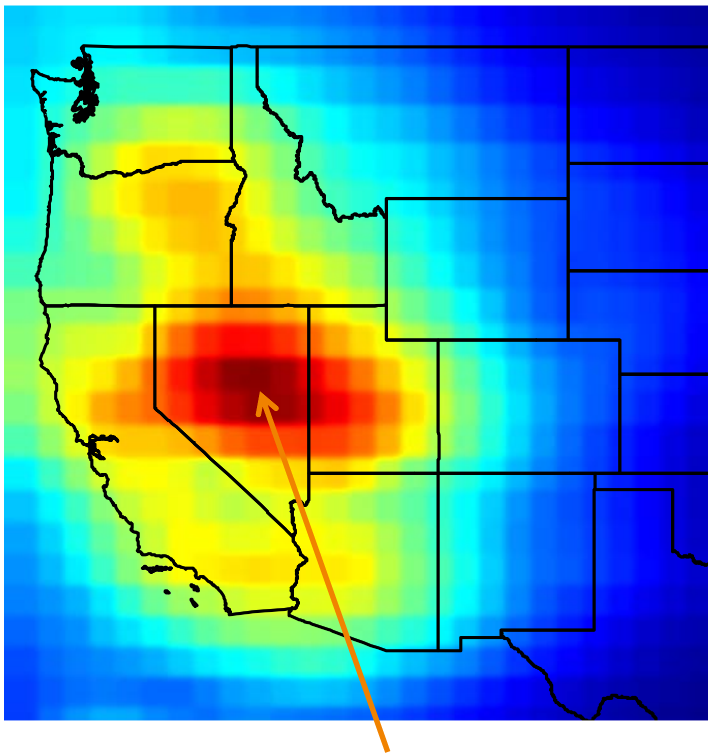


EMP Grid Analysis

- Sorting results reveals worst-case locations for losses or single-transformer Effective GIC
- With a little effort, could contour on “dummy substations” aligned to grid locations

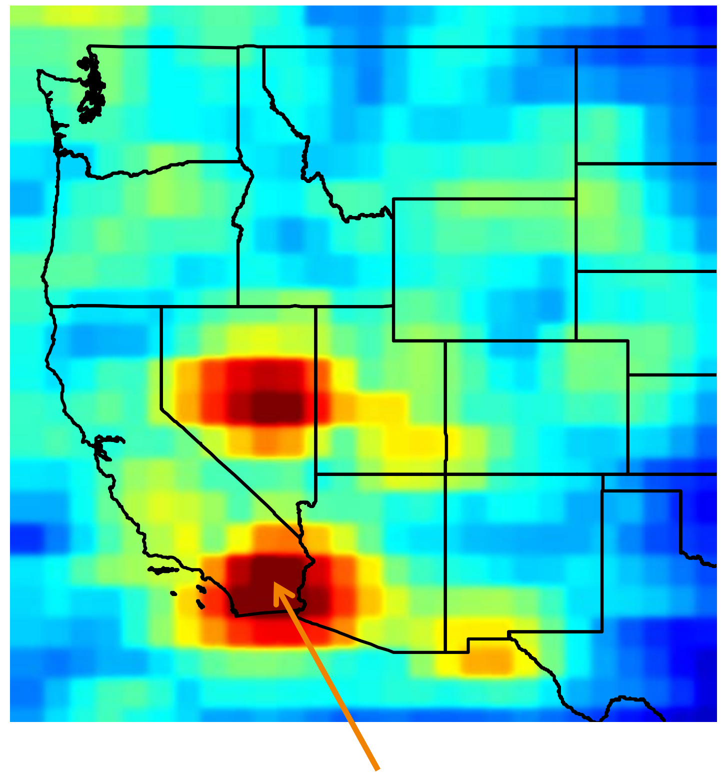
EMP Grid Analysis

Mvar Losses at E3B Peak



40N, 116W
94,217 MVar

Maximum Single-Transformer Ieffective at E3B Peak



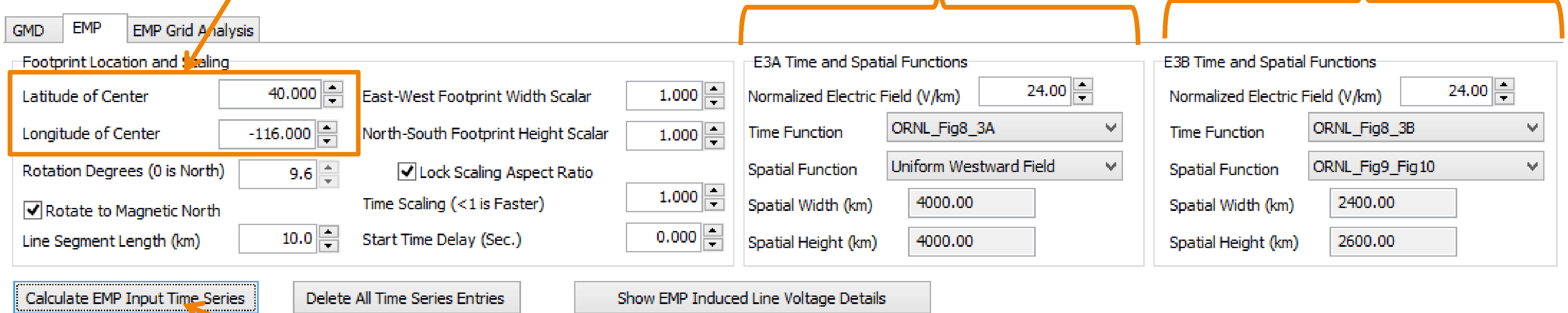
33N, 116W
1095 A, 765 kV Phase-Shifting Xfr

Maximum Mvar Location

E3A: ORNL_Fig8_3A, Uniform Westward Field, 24 V/km

E3B: ORNL_Fig8_3B, ORNL_Fig9_Fig10, 24 V/km

Location of Center: 40, -116



Click Calculate EMP Input Time Series

Resulting DC Input Voltages

Field/Voltage Input

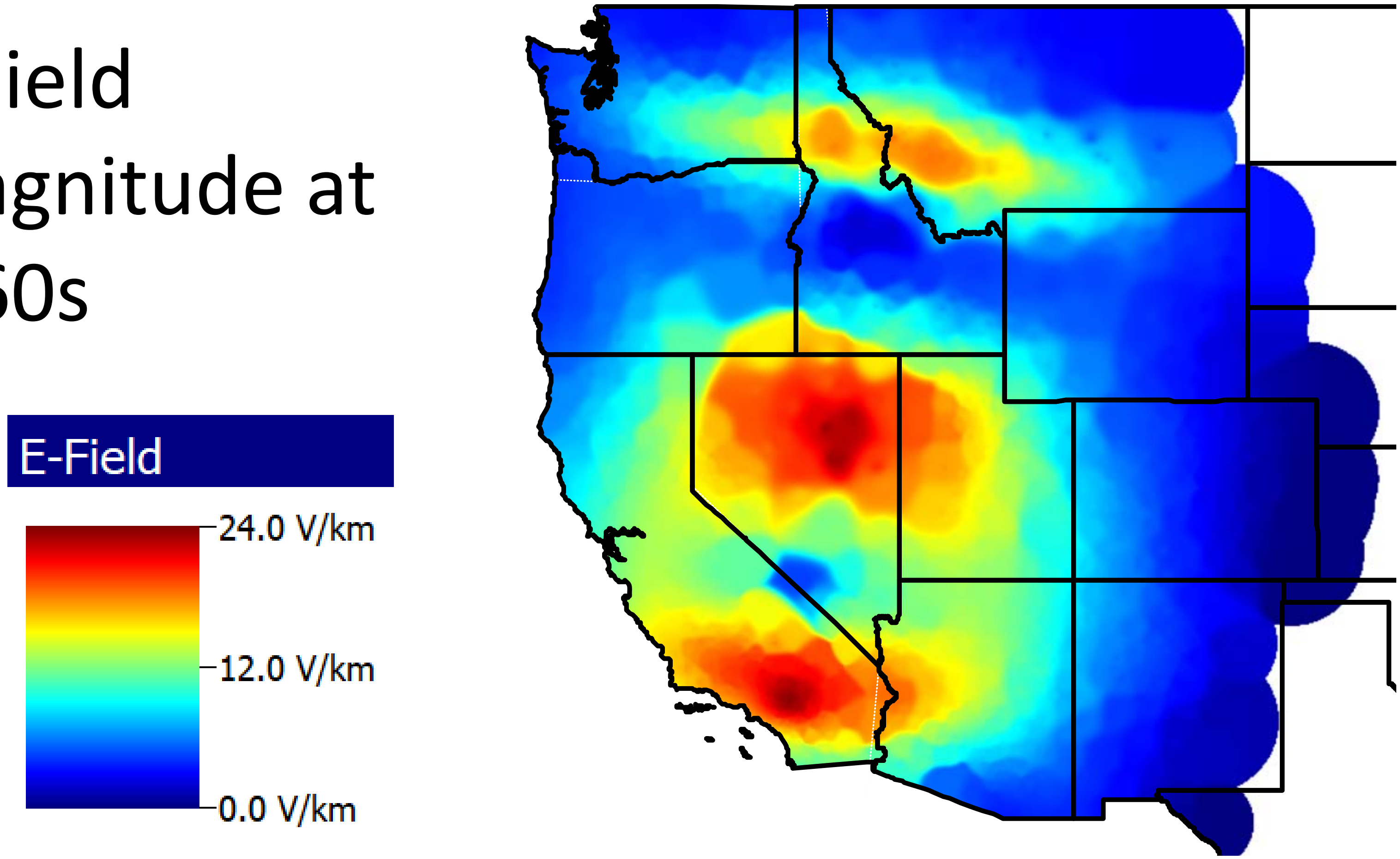
AC Line Input Voltages | Substation EField V/km (Display Only) | Substation EField Direction Degrees (Display Only)

	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	Timepoint_7	Timepoint_8	Timepoint_9	Timepoint_10	Timepoint_1
1	Time in Seconds									0.000	3.134	3.582	5.373	6.716	7.164	8.507	10.000	10.000	11.642	17.463
2	Branch '10002' '10001' '1'	10002	10001	1	47.6956	48.2414	-124.1836	-124.5778	67.45	0.000	155.444	292.382	573.662	351.599	-144.341	-3.704	0.000	0.000	4.282	8.560
3	Branch '10011' '10001' '1'	10011	10001	1	48.0025	48.2414	-123.7620	-124.5778	66.29	0.000	255.261	480.133	942.036	577.377	-237.028	-6.082	0.000	0.000	-5.821	-11.638
4	Branch '10014' '10002' '1'	10014	10002	1	47.1889	47.6956	-123.6860	-124.1836	67.69	0.000	184.256	346.576	679.993	416.770	-171.095	-4.390	0.000	0.000	4.167	8.331
5	Branch '10004' '10003' '1'	10004	10003	1	46.9275	47.0400	-124.1719	-124.0570	15.26	0.000	-25.921	-48.756	-95.662	-58.631	24.070	0.618	0.000	0.000	3.423	6.843
6	Branch '10003' '10010' '1'	10003	10010	1	47.0400	47.1743	-124.0570	-123.8474	21.82	0.000	-52.325	-98.421	-193.106	-118.355	48.588	1.247	0.000	0.000	5.048	10.092
7	Branch '10937' '10003' '1'	10937	10003	1	46.9728	47.0400	-123.7739	-124.0570	22.79	0.000	89.188	167.757	329.145	201.734	-82.817	-2.125	0.000	0.000	-1.469	-2.936
8	Branch '10004' '10005' '1'	10004	10005	1	46.9275	46.9275	-124.1719	-124.1719	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	Branch '10004' '10937' '1'	10004	10937	1	46.9275	46.9728	-124.1719	-123.7739	30.72	0.000	-115.219	-216.721	-425.212	-260.614	106.989	2.745	0.000	0.000	4.874	9.744
10	Branch '10006' '10007' '1'	10006	10007	1	46.3165	46.3165	-124.0612	-124.0612	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

- Set Current Time to 60 (corresponds to E3B peak)
- Check "Include GIC in Power Flow and Transient Stability" and "Use EMP as Input"
- Click **Calculate GIC Values**

ORNL E3B E-Field Contour

E-Field Magnitude at t=60s



Saved View: West EMP E-field

Power Flow Mismatches

Mismatches | Substations | Buses

Records ▾ Geo ▾ Set ▾ Columns ▾ Options ▾

Filter Advanced ▾ Bus ▾ Find... Remove Quick Filter ▾

	Number	Name	Area Name	Type	Mismatch MW	Mismatch Mvar	Mismatch MV.
1	28737	DESERT CENTER	Southeast California	PQ	0.00	-2659.02	2659.02
2	26126	BURBANK 10 2	Southwest California	PQ	-0.00	-2309.72	2309.72
3	26048	FELLOWS 1 1	Southwest California	PQ (Remotely Re	0.00	-1788.10	1788.10
4	13554	KLAMATH FALLS	Oregon	PQ (Remotely Re	0.00	-1684.47	1684.47
5	28717	HINKLEY 1 1	Southeast California	PQ	0.00	-1357.73	1357.73
6	26142	SANTA MARGARI	Southwest California	PQ	0.00	-1119.84	1119.84
7	20387	REDDING 8 1	Northern California	PQ (Remotely Re	0.00	-1096.55	1096.55
8	29024	CARLSBAD 6 1	Southeast California	PQ (Remotely Re	0.00	-1055.25	1055.25
9	30313	VALMY 1	Nevada	PQ (Remotely Re	0.00	-958.32	958.32
10	29039	HUNTINGTON BE.	Southeast California	PQ (Remotely Re	0.00	-851.64	851.64
11	26152	TUPMAN 2 1	Southwest California	PQ	0.00	-851.27	851.27
12	10717	WENATCHEE 4 1	Washington	PQ (Remotely Re	0.00	-825.93	825.93
13	21684	COYOTE 1	Bay Area	PQ (Remotely Re	0.00	-768.21	768.21
14	40967	ARLINGTON 10 1	Arizona	PQ (Remotely Re	0.00	-752.93	752.93
15	40956	GILA BEND 6 1	Arizona	PQ (Remotely Re	0.00	-738.04	738.04
16	40794	PHOENIX 73 1	Arizona	PQ (Remotely Re	0.00	-714.06	714.06
17	13580	LOWELL 4 1	Oregon	PQ (Remotely Re	0.00	-709.73	709.73
18	20436	OROVILLE 5 1	Northern California	PQ (Remotely Re	0.00	-707.58	707.58

Most large losses occur near hotspots in Southern California and Northern Nevada

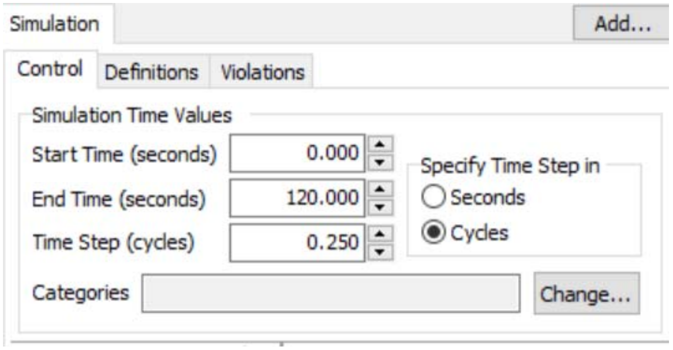
Power Flow Solution fails to converge!

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

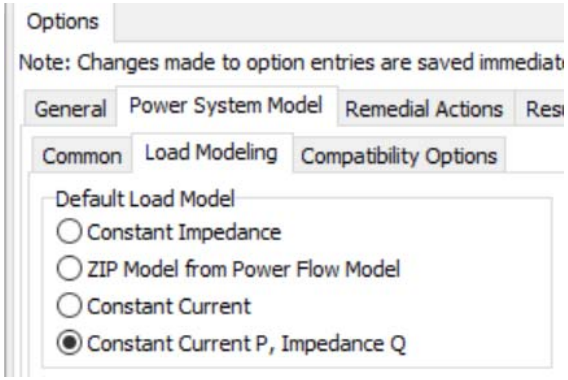
Transient Stability Analysis

- Reset **Current Time** on **GIC Analysis** dialog to 0
- Open **Transient Stability** dialog from **Tools** Ribbon
- **Simulation → Control** Parameters: 0.25 cycle time step works well for EMP waveforms



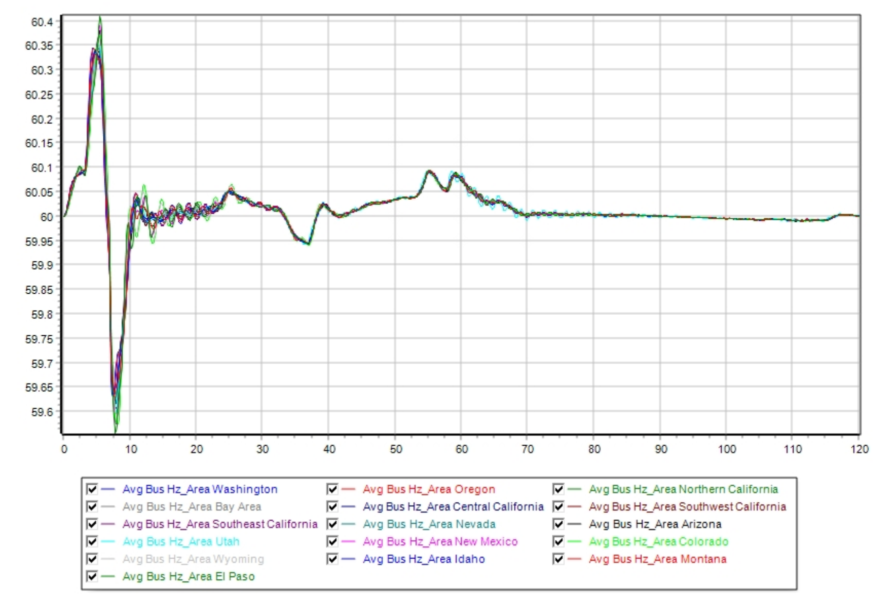
Transient Stability Analysis

- Disable any existing Transient Contingency Elements (set "Enabled" field to Never)
- **Options → Power System Model → Load Modeling**: use "Constant Current P, Impedance Q"

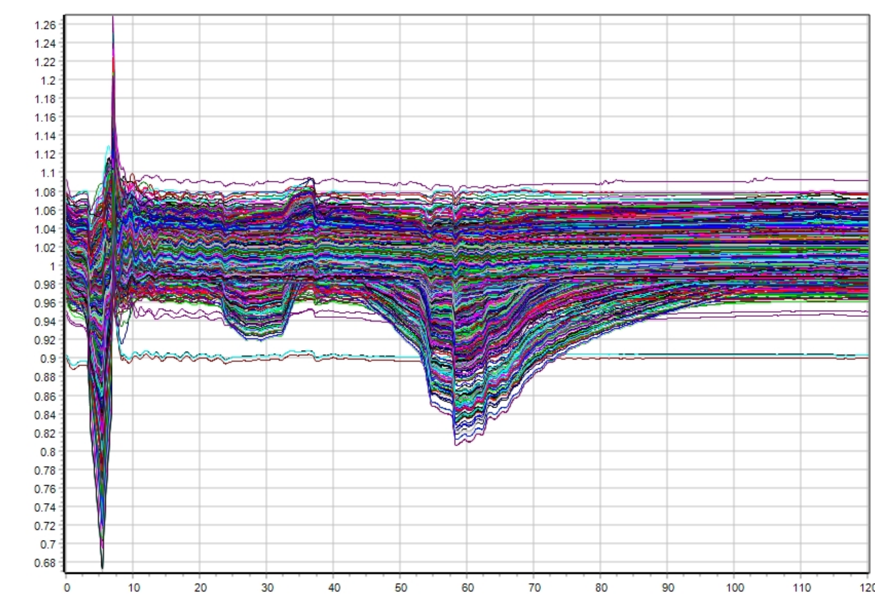


- Click **Run Transient Stability**

Transient Stability Plots



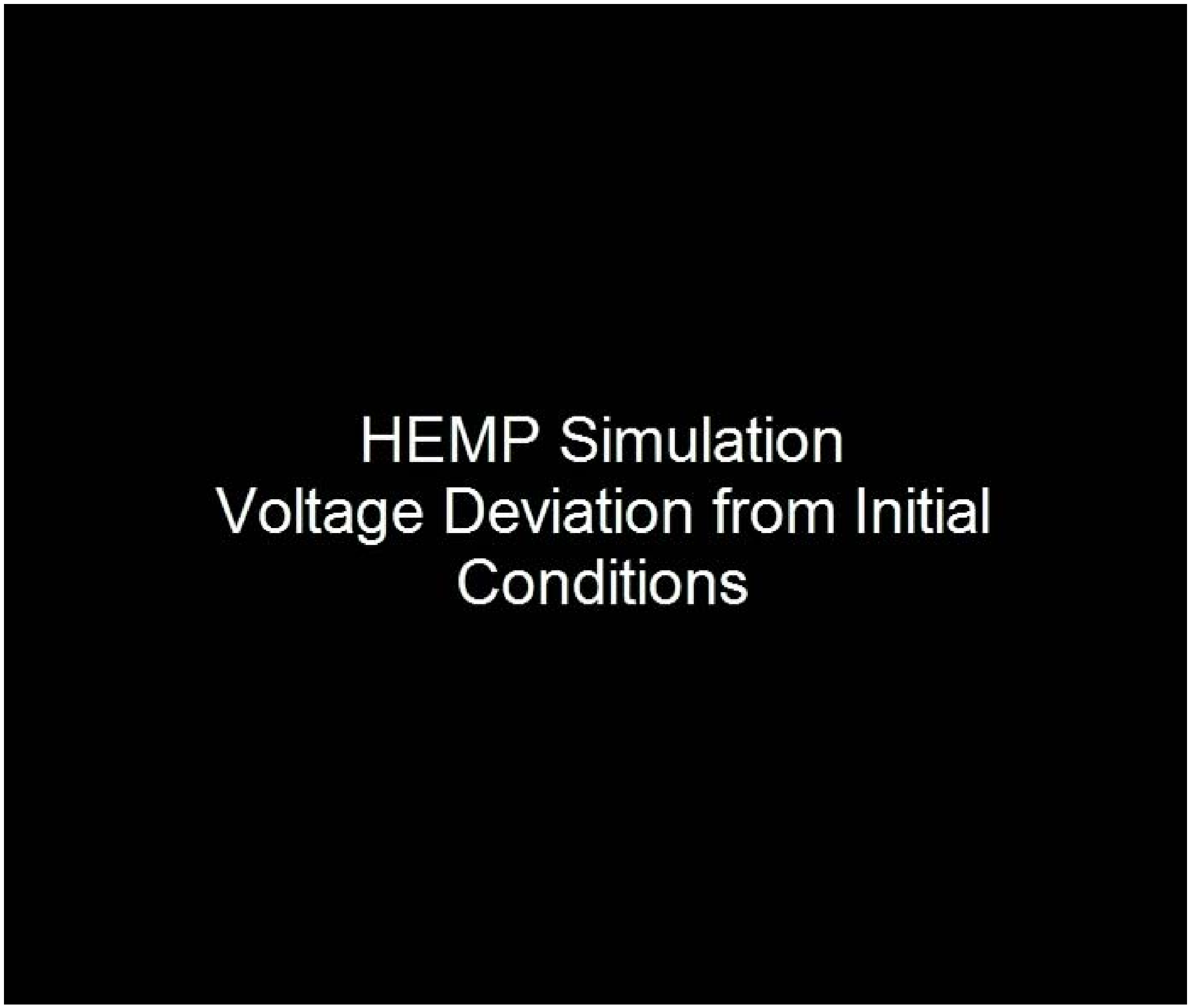
Frequency:
Average by Area



Bus Voltage

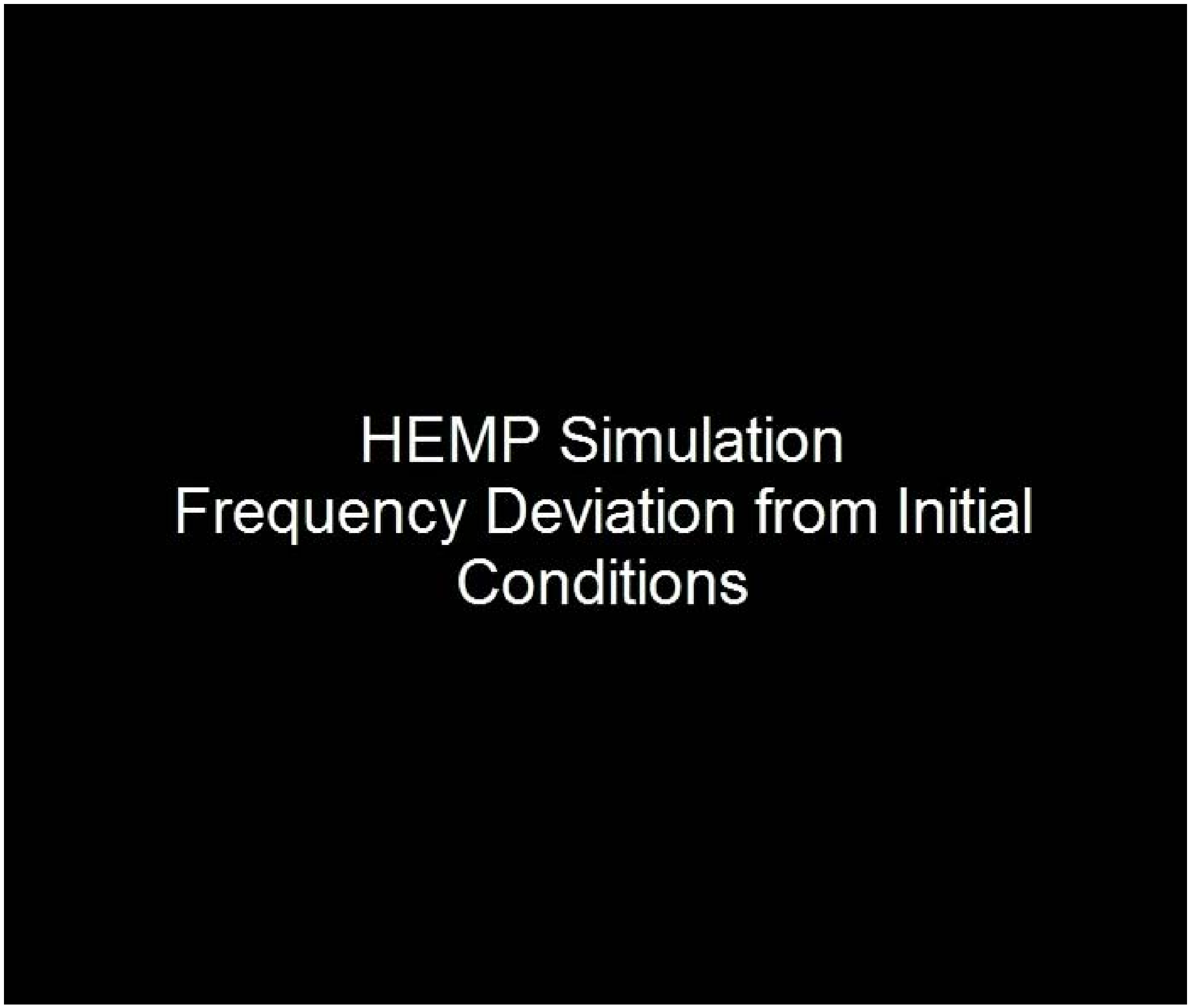
Transient Stability:

Voltage Visualization



Transient Stability:

Frequency Visualization

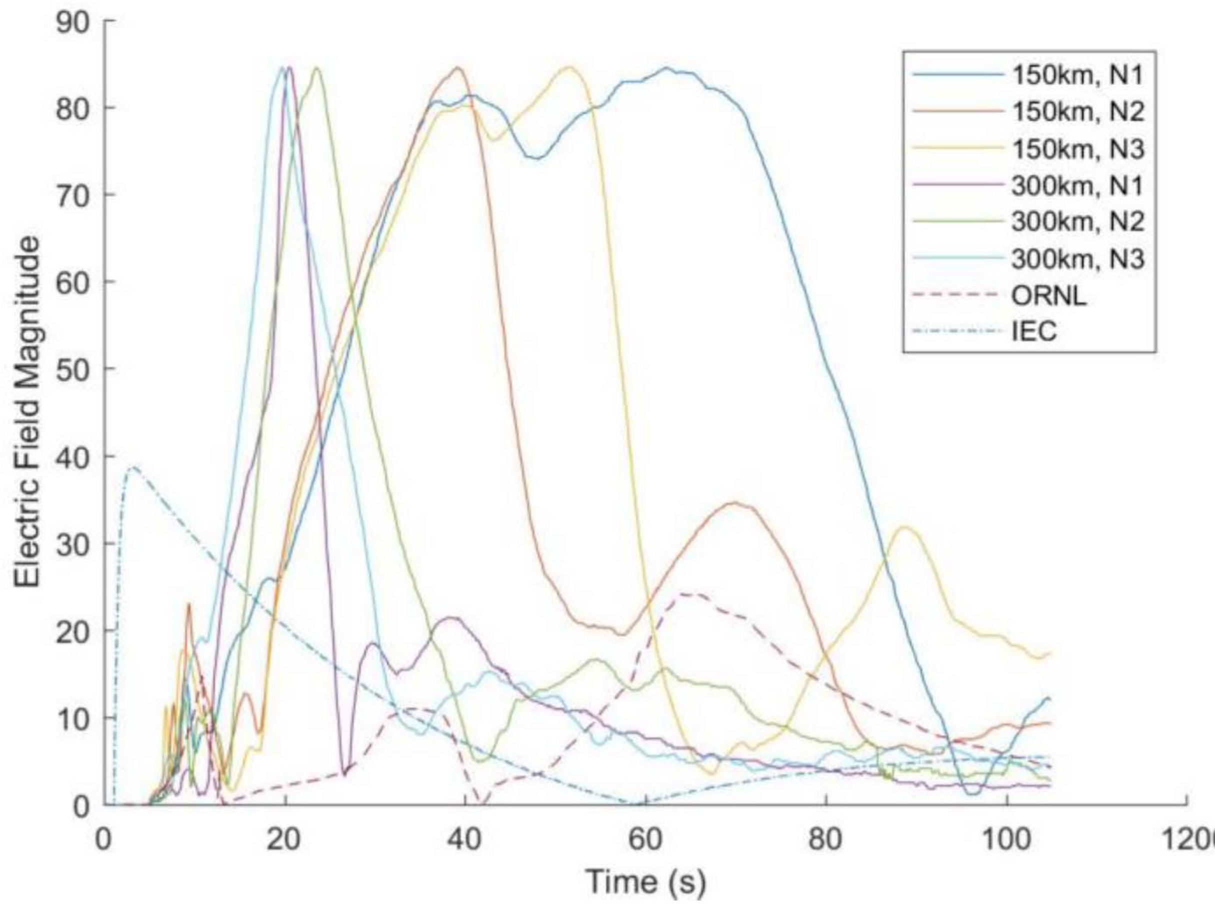


HEMP Future Studies

- 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”

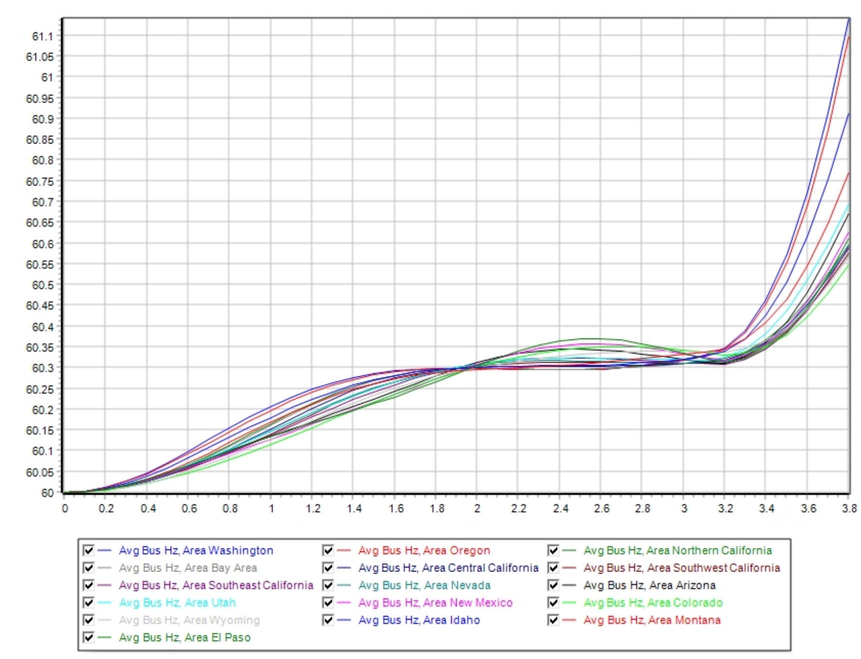
HEMP Waveform Comparison

- 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.

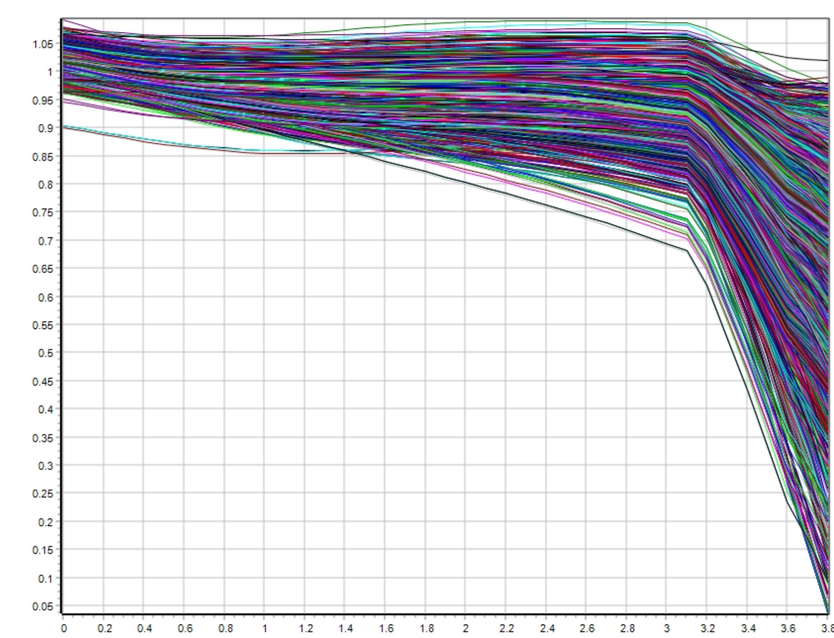


Transient Stability Plots:

85 V/km Peak



Frequency:
Average by Area



Bus Voltage:
Collapse at t=3.9s!

