

Theory of Geomagnetic Disturbance Modeling



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Overview



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

Geomagnetic Disturbances (GMDs)



- GMDs are caused by solar corona mass ejections (CMEs); a GMD caused the 1989 Quebec blackout
- GMDs have the potential to severely disrupt the electric grid by causing quasi-dc geomagnetically induced currents (GICs) in the high voltage grid
- Until recently power engineers had few tools to help them assess the impact of GMDs
- PowerWorld has led the way in the development of these tools, with integration into its power flow and transient stability applications

GMD Overview



- Solar corona mass ejections (CMEs) can cause changes in the earth's magnetic field (i.e., dB/dt). These changes in turn produce a non-uniform electric field at the surface
 - Changes in the magnetic flux are usually expressed in nT/minute
 - The magnitude of the induced electric field depends upon the conductivity of the earth's crust going down 100's of km; this conductivity can vary widely!
 - From a 60 Hz perspective the induced electric fields seen by the high voltage transmission lines are essentially dc

GMD Overview



- For large GMDs, the storm “footprint” can be continental in scale
- 1989 North America storm produced a change of 500 nT/minute, while a stronger storm, such as the ones in 1859 or 1921, could produce a 2500 nT/minute variation
 - Determining the precise size of historical storms can be difficult!
 - Earth’s magnetic field is normally between 25,000 and 65,000 nT, with higher values near the poles

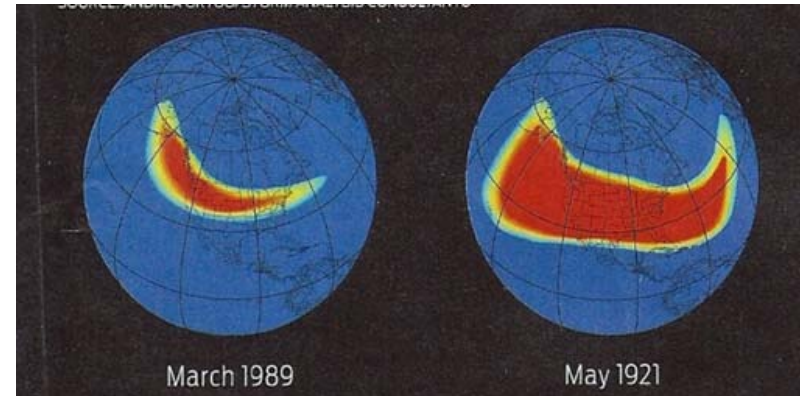


Image source: J. Kappenman, “A Perfect Storm of Planetary Proportions,” *IEEE Spectrum*, Feb 2012, page 29

Electric Fields and Geomagnetically Induced Currents (GICs)



- The induced electric fields are vectors (magnitude and angle); values expressed in units of volts/mile (or volts/km);
 - A 2400 nT/minute storm could produce 5 to 10 v/mile
- The electric fields cause GICs to flow in the high voltage transmission grid
- The induced voltages that drive the GICs can be modeled as dc voltages in the transmission lines.
 - The magnitude of the dc voltage is determined by integrating the electric field variation over the line length
 - Both magnitude and direction of the electric field are important

July 2012 GMD Near Miss



- In July 2014 NASA said in July of 2012 there was a solar CME that barely missed the earth
 - It would likely have caused the largest GMD that we have seen in the last 15 years
- There is still lots of uncertainty about how large a storm is reasonable to consider in electric utility planning

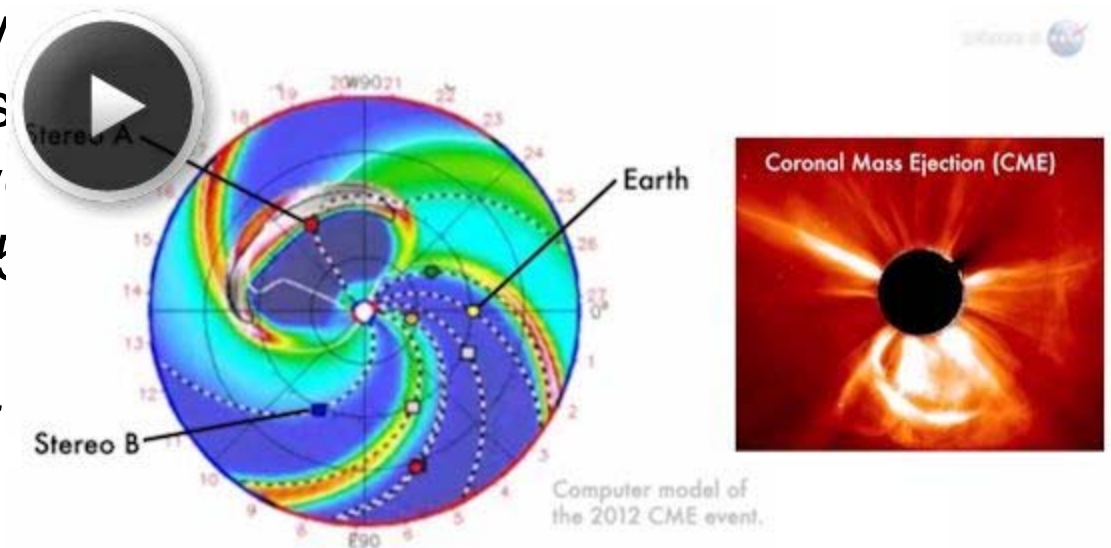
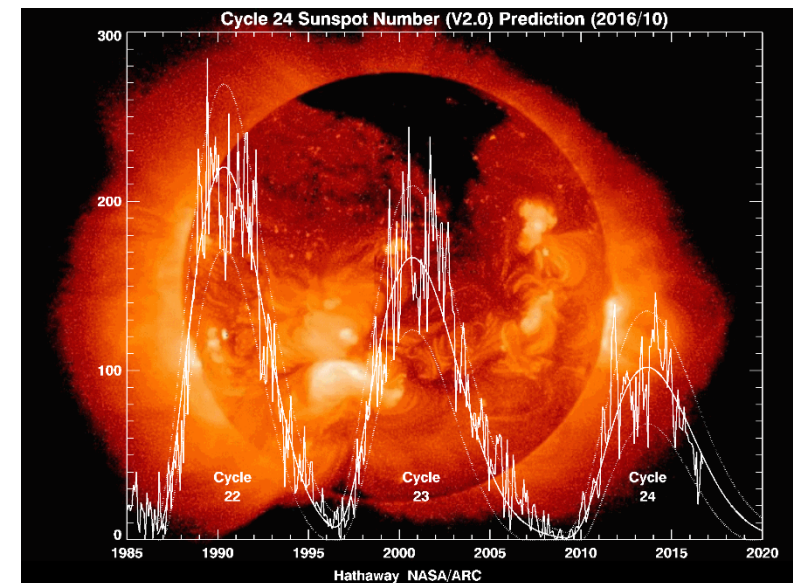
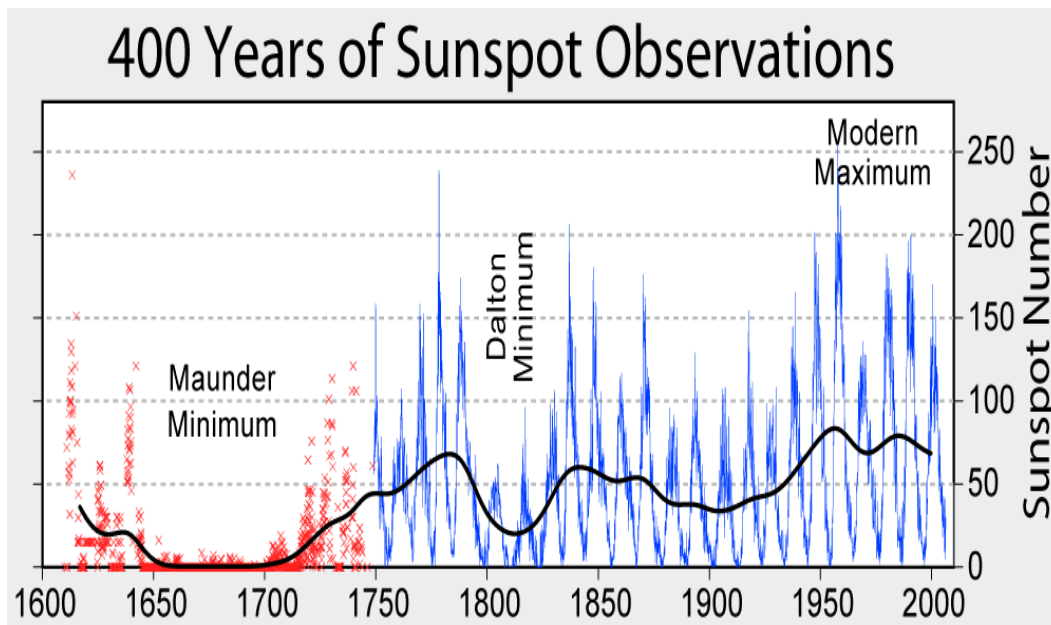


Image Source: science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/

Solar Cycles



- Sunspots follow a 10.7 year cycle (with some variation, and have been observed for hundreds of years)
- We're in solar cycle 24 (first numbered cycle was in 1755); minimum was in 2009, maximum in 2014/2015



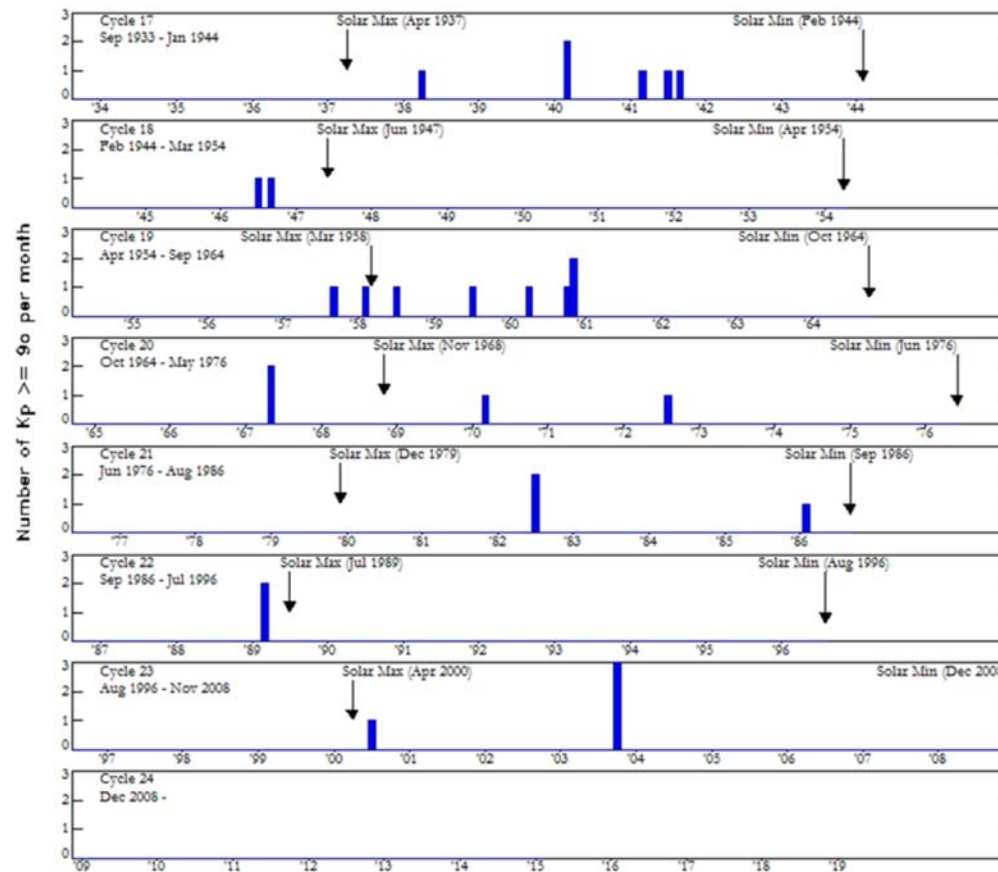
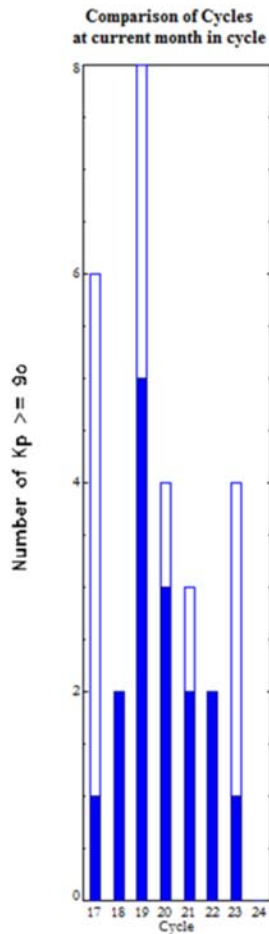
Images from NASA

But Large CMEs Are Not Well Correlated with Sunspot Maximums



Periods with $K_p \geq 9.0$

February 2015
(Month 75)

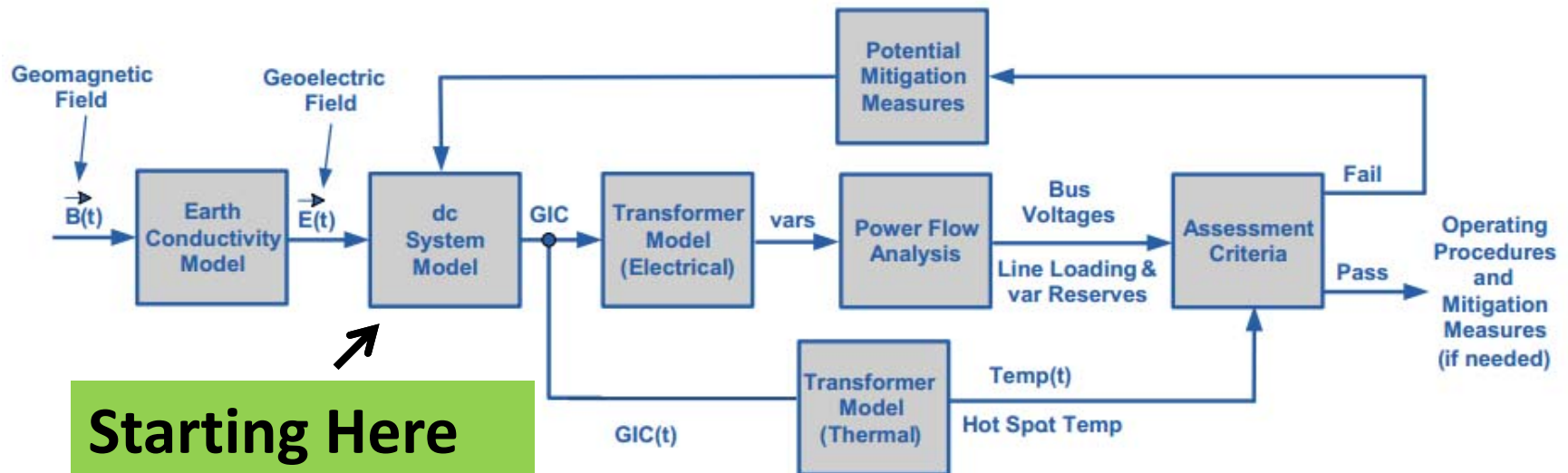


The large 1921 storm occurred four years after the 1917 maximum

Overview of GMD Assessments



In is a quite interdisciplinary problem



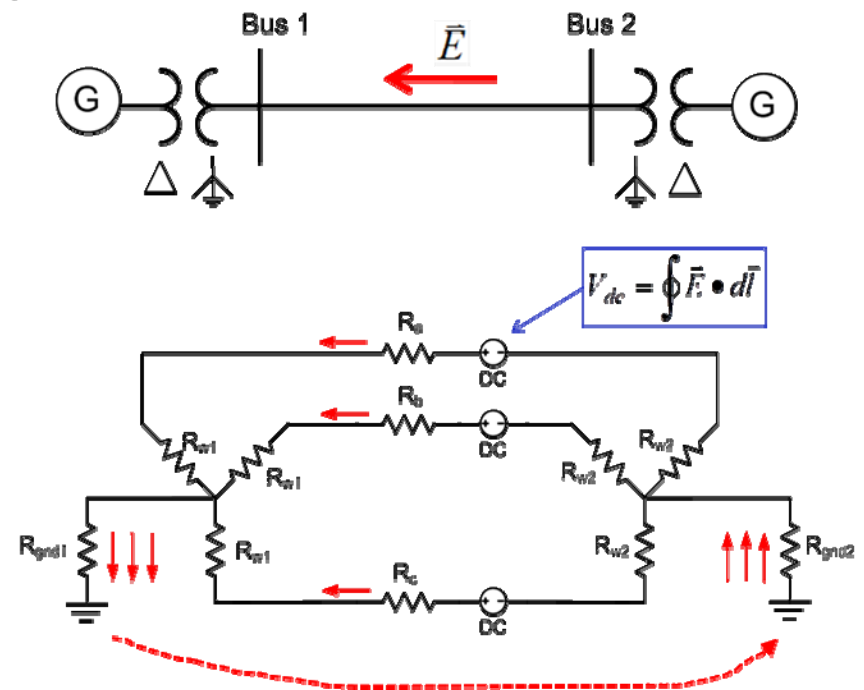
The two key concerns from a big storm are 1) large-scale blackout due to voltage collapse, 2) permanent transformer damage due to overheating

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

Geomagnetically Induced Currents (GICs)



- Along length of a high voltage transmission line, electric fields can be modeled as a dc voltage source superimposed on the lines
- The dc voltage is calculated by integrating the electric field along the line's right-of-way
 - If electric field is uniform the integration is path independent
- The GICs are superimposed on the ac (60 Hz) flows



GIC Calculations for Large Systems



- With knowledge of the pertinent transmission system parameters and the GMD-induced line voltages, the dc bus voltages and flows are found by solving a linear equation $\mathbf{I} = \mathbf{G} \mathbf{V}$ (or $\mathbf{J} = \mathbf{G} \mathbf{U}$)
 - $\mathbf{J}$ and $\mathbf{U}$ may be used to emphasize these are dc values, not the power flow ac values
 - The $\mathbf{G}$ matrix is similar to the $\mathbf{Y}_{bus}$ except 1) it is augmented to include substation neutrals, and 2) it is just resistive values (conductances)
 - Being a linear equation, superposition holds
 - The current vector contains the Norton injections associated with the GMD-induced line voltages

GIC Calculations for Large Systems



- In determining the **G** matrix for the dc GICs, knowing the transformer configurations is crucial
 - Delta windings have no path to ground, and hence look like an open circuit
 - Transmission to distribution transformers look like an open circuit (if delta on the high side)
 - Autotransformers are modeled differently than regular transformer
 - For three-winding transformers, the tertiary winding has no impact (if delta)
- Series capacitors look like an open circuit

GIC Calculations for Large Systems

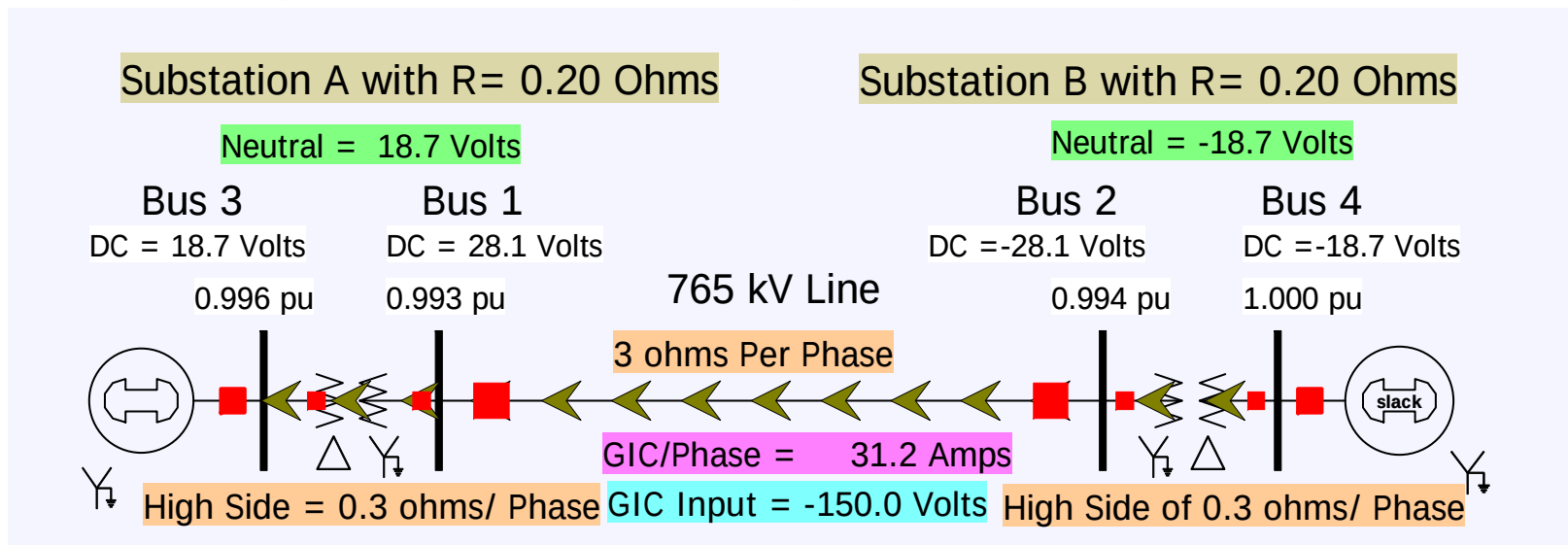


- Factoring the sparse $\mathbf{G}$ matrix and doing the forward/backward substitution takes about 1 second for the 60,000 bus Eastern Interconnect Model
- The current vector ($\mathbf{I}$) depends upon the assumed electric field along each transmission line
 - This requires that substations have correct geo-coordinates
- With nonuniform fields an exact calculation would be path dependent, but just assuming a straight line path is probably sufficient (given all the other uncertainties!)

Four Bus Example (East-West Field)

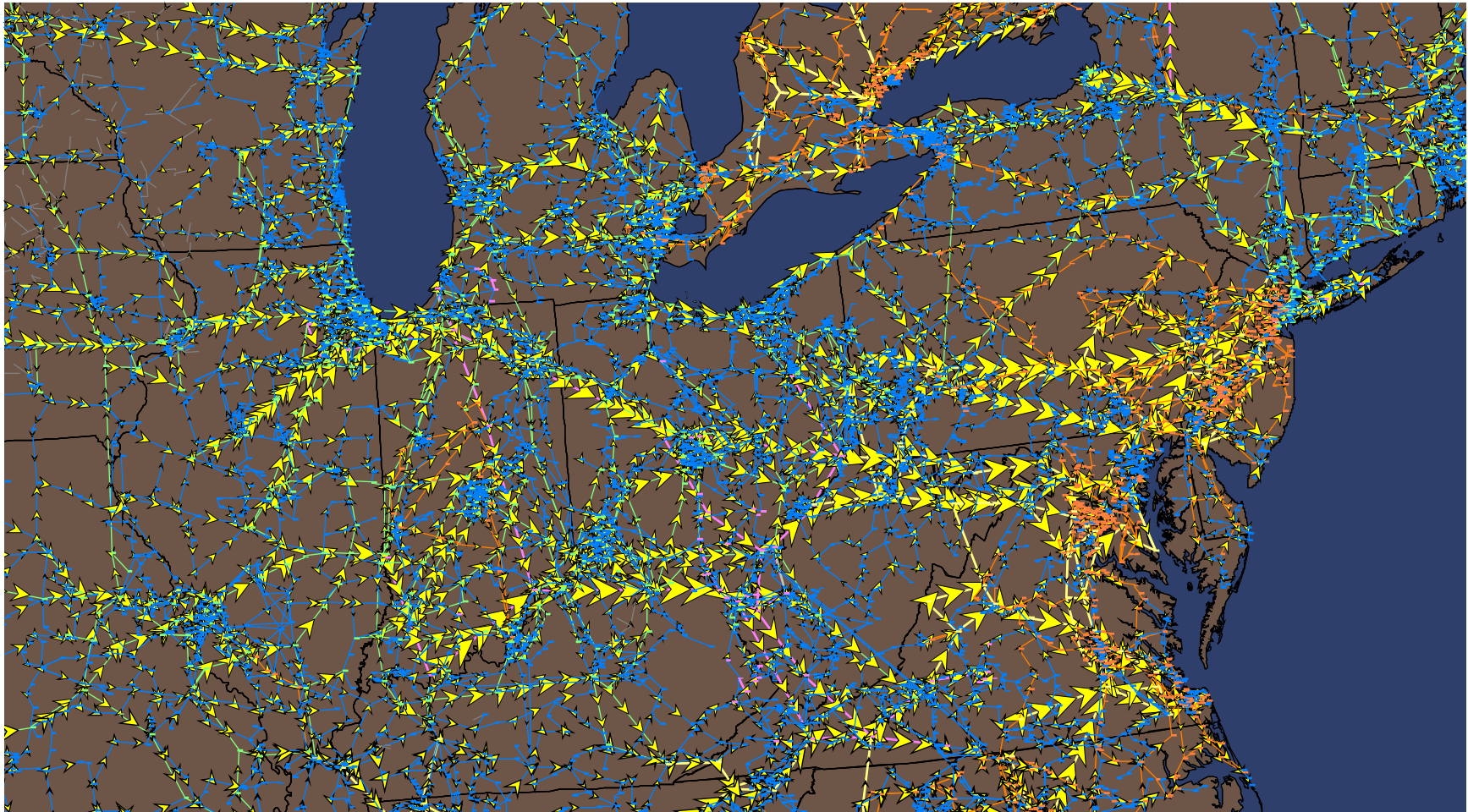


$$I_{GIC,3Phase} = \frac{150 \text{ volts}}{(1 + 0.1 + 0.1 + 0.2 + 0.2) \Omega} = 93.75 \text{ amps or } 31.25 \text{ amps/phase}$$

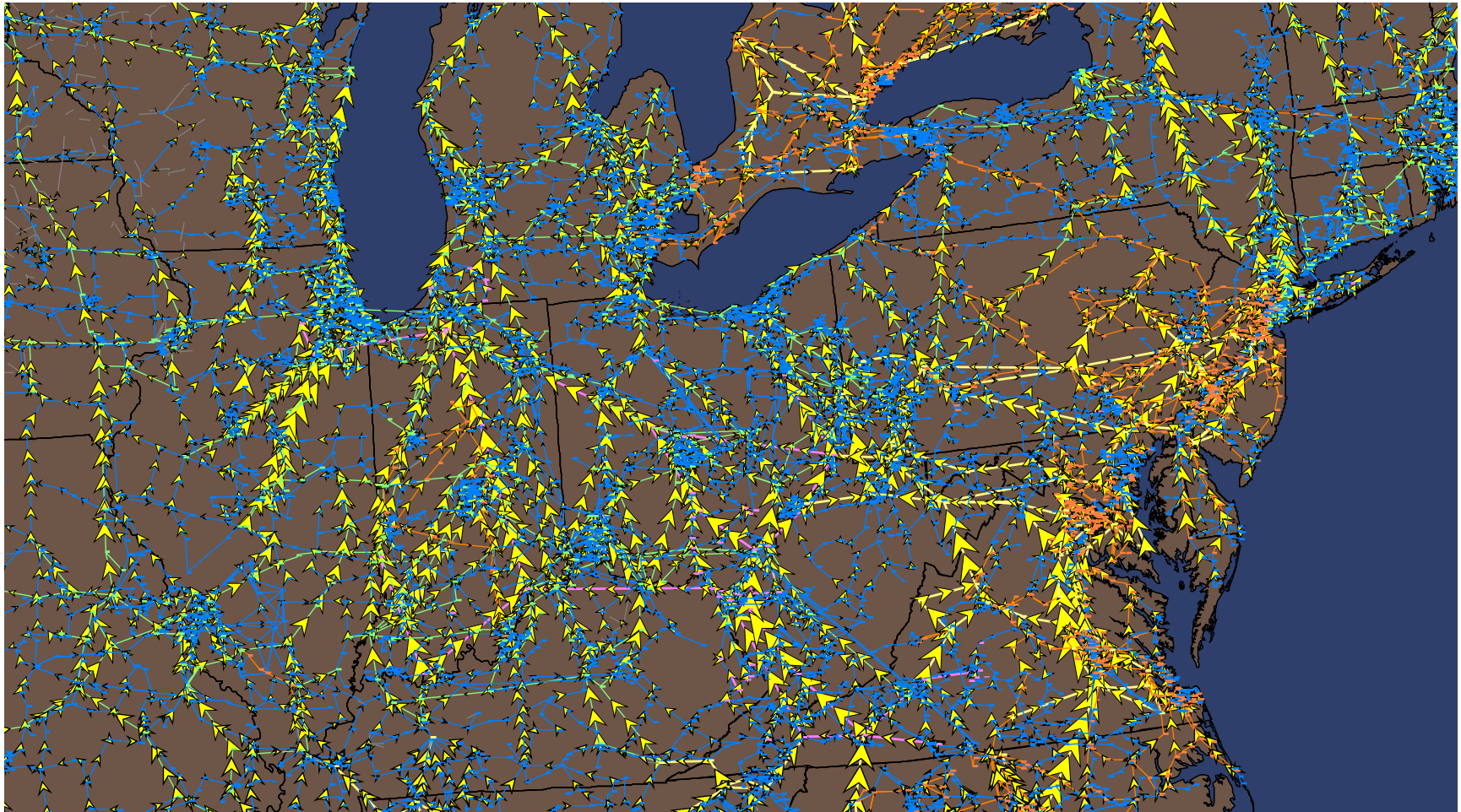


The line and transformer resistance and current values are per phase so the total current is three times this value. Substation grounding values are total resistance. Brown arrows show GIC flow.

GICs, Generic EI, 5 V/km East-West



GICs, Generic EI, 5 V/km North-South



Determining GMD Storm Scenarios



- The starting point for the GIC analysis is an assumed storm scenario; determines the line dc voltages
- Matching an actual storm can be complicated, and requires detailed knowledge of the associated geology
- GICs vary linearly with the assumed electric field magnitudes and reactive power impacts on the transformers is also mostly linear
- Working with space weather community to determine highest possible storms
- NERC proposed a non-uniform field magnitude model that FERC has partially accepted (FERC had a workshop on this model on March 1, 2016)

Electric Field Linearity

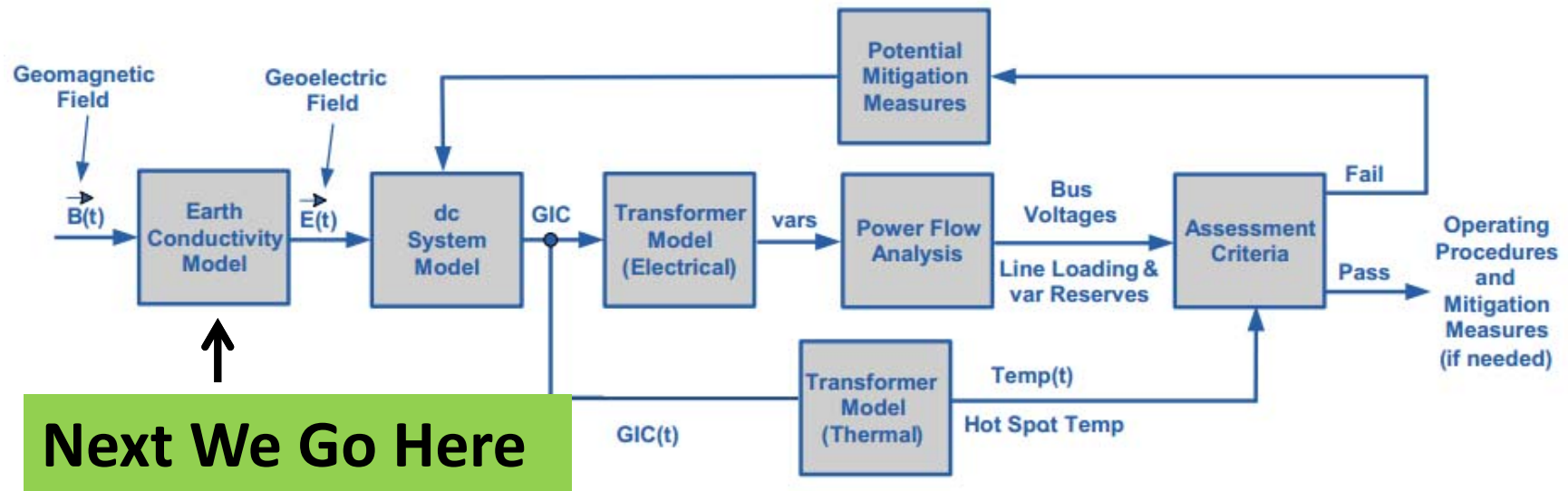


- If an electric field is assumed to have a uniform direction every where (like with the current NERC model), then the calculation of the GICs is linear
 - The magnitude can be spatially varying
- This allows for very fast computation of the impact of time-varying functions (like with the NERC event)
- PowerWorld now provides support for loading a specified time-varying sequence, and quickly calculating all of the GIC values

Overview of GMD Assessments



In is a quite interdisciplinary problem



Next We Go Here

The two key concerns from a big storm are 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

Impact of Earth Models: Relationship Between dB/dT and E



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

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

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

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 in way to oppose the change that produced it
- The induced fields tend to cancel the magnetic field variation, leading to decreased fields. This gives rise to a frequency dependent skin depth

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

where f is the B field variation in Hz

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

σ is the conductivity in S/m

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

Frequency Domain Analysis With Uniform Conductance



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

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

- The magnitude relationship is then

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

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

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

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

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

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

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

A more resistive earth gives higher electric fields

Typical Conductance and Resistivity Values



- Soil conductance is often expressed in its inverse of resistivity in $\Omega\text{-m}$; values can vary widely
 - Topsoil varies widely with moisture content, from 2500 $\Omega\text{-m}$ when dry to about 20 $\Omega\text{-m}$ when very wet
 - Clay is between 100-200 $\Omega\text{-m}$

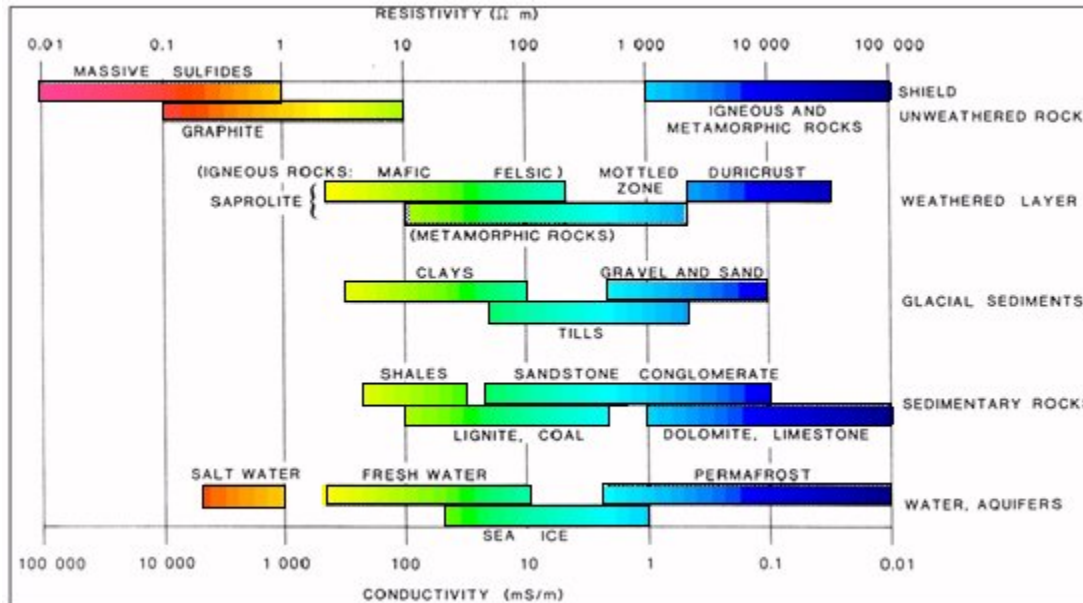


Image source:
<https://www.eoas.ubc.ca/courses/eosc350/content/foundations/properties/resistivity.htm>

1-D Earth Models

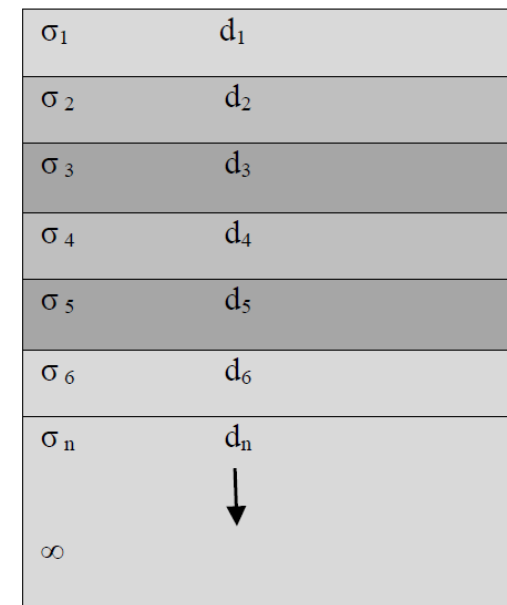


- With a 1-D model the earth is model as a series of conductivity layers of varying thickness
- The impedance at a particular frequency is calculated using a recursive approach, starting at the bottom, with each layer m having a propagation constant

- At the bottom level n

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

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



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

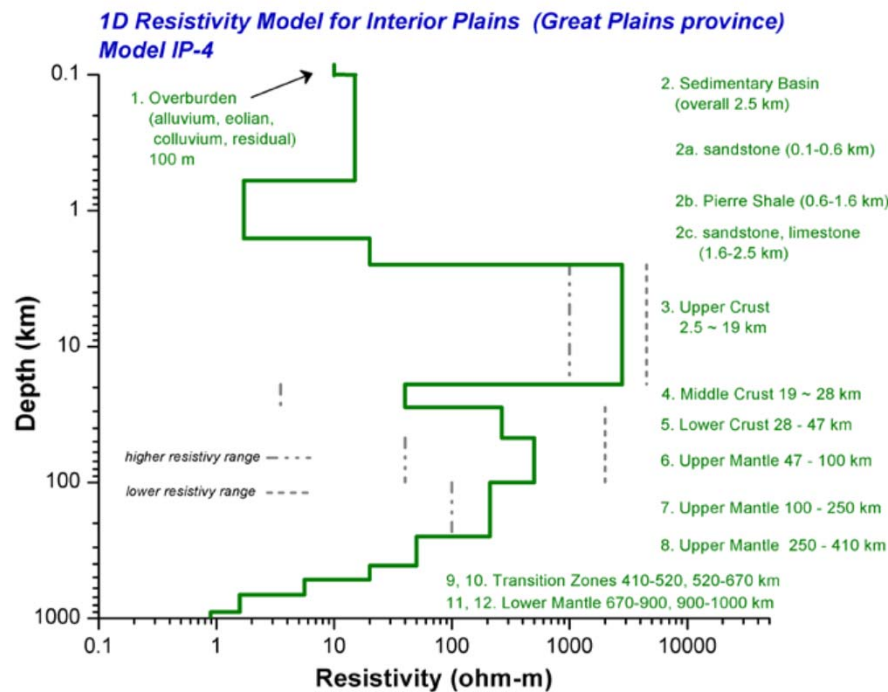


These region scalings are now being used for power flow GMD analysis

1-D Earth Models

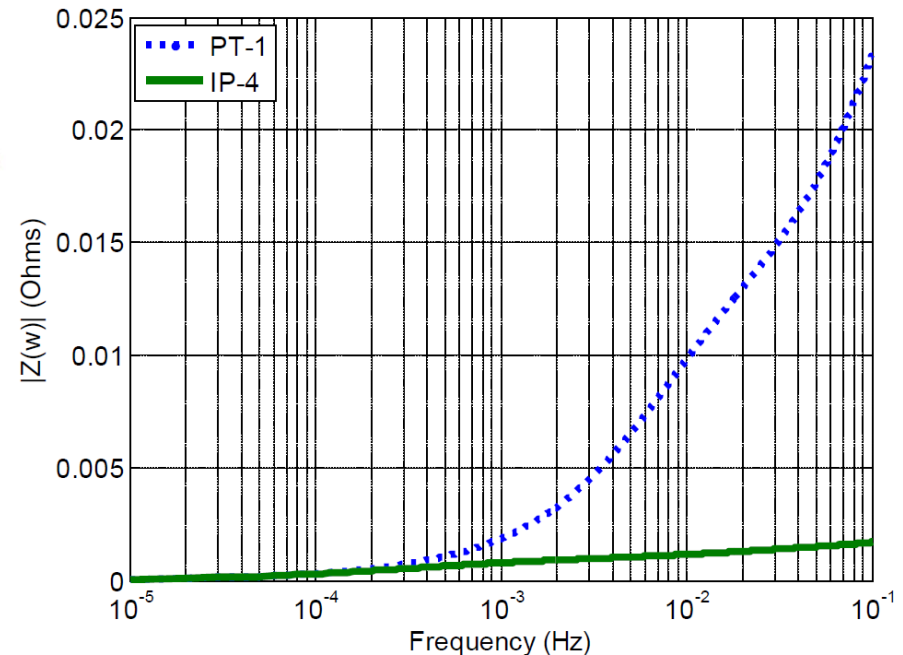


- Image on left shows an example 1-D model, whereas image on right shows the $Z(\omega)$ variation for two models



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.

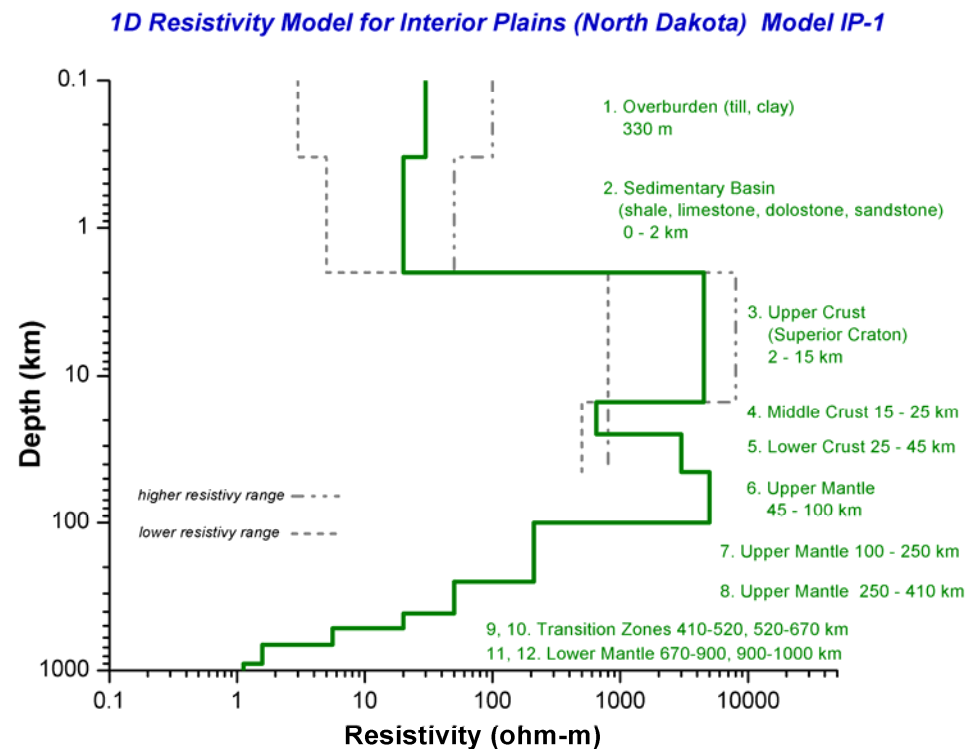
Figure 9: Frequency response of two layered Earth conductivity models.



1-D Earth Models: Interior Plains (IP-1) Example



- All details can be seen at <https://geomag.usgs.gov/conductivity/>

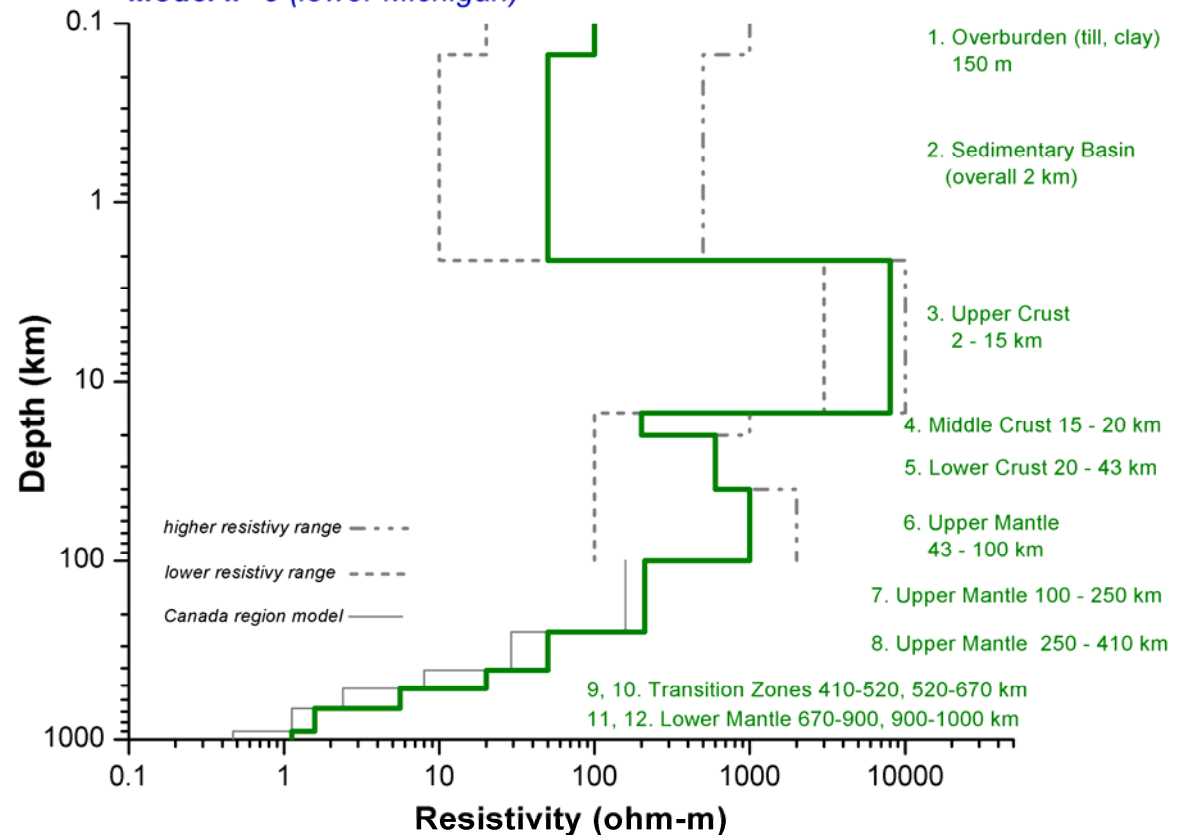


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1-D Earth Models: Interior Plains Michigan (IP-3) Example

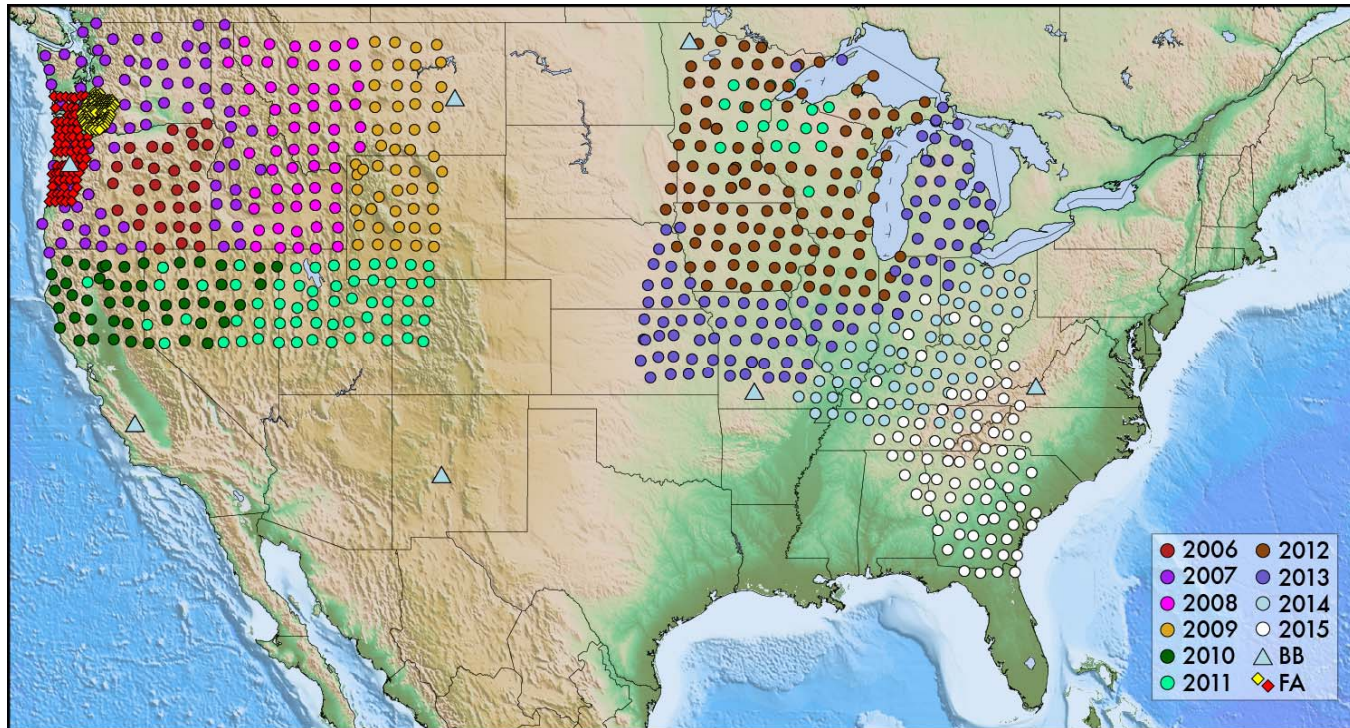


**1D Resistivity Model for Central Lowland-East Lake Section
Model IP-3 (lower Michigan)**



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.

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

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

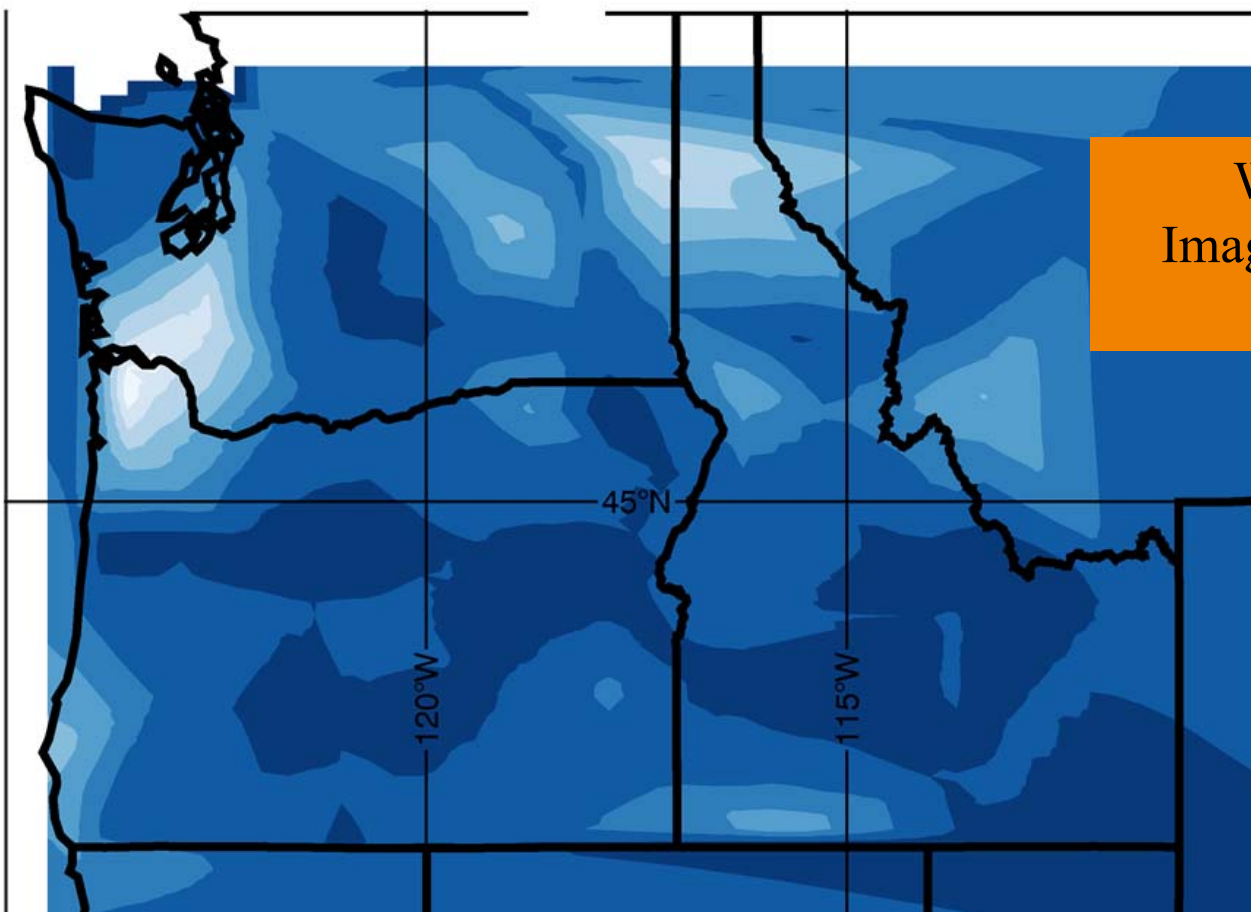
- Are provided in 2x2 impedance tensors by USArray

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

Example 3-D Earthscope Model Results

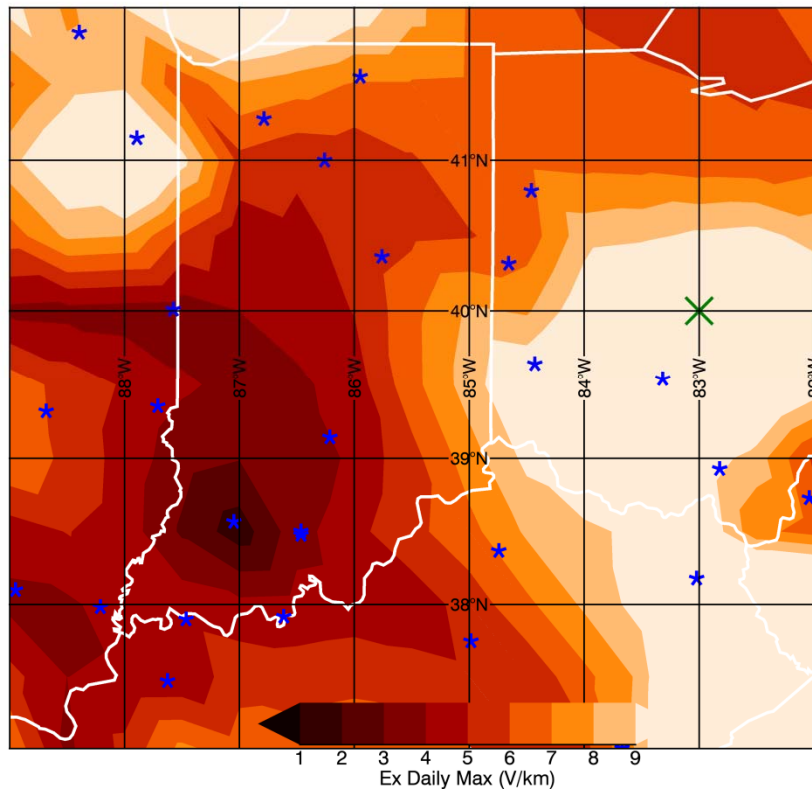


- Image provides a snapshot visualization of the time-varying surface electric fields using Earthscope data

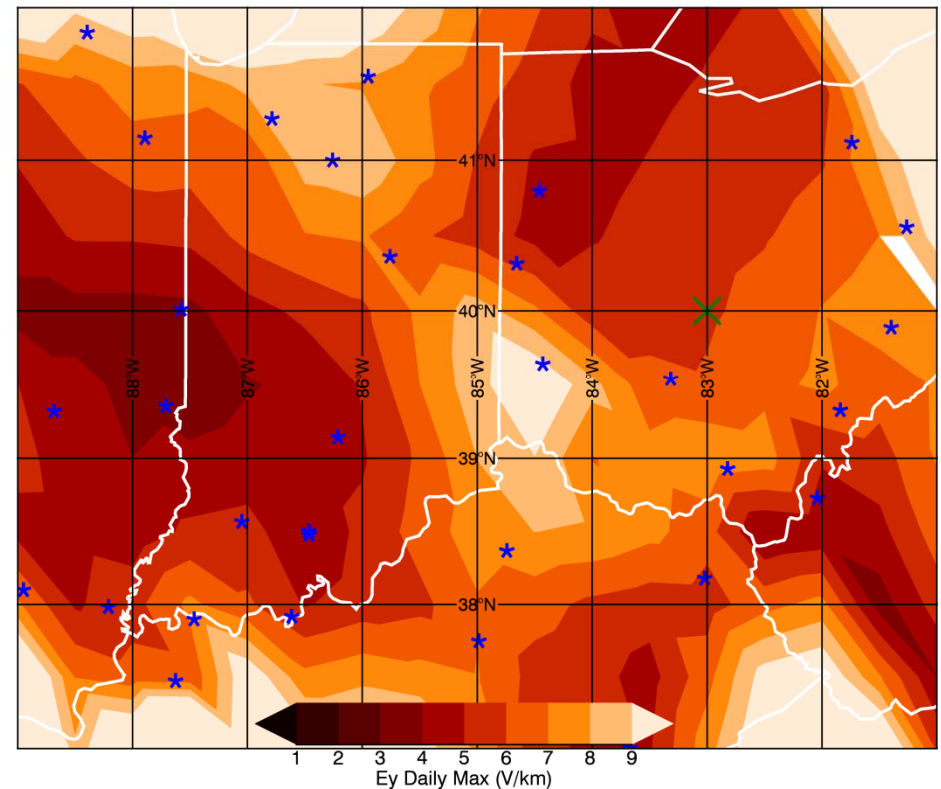


White ~ 10 V/km
Image Provided by Jenn
Gannon

Example 3-D Earthscope Model Results



This is for the NERC event; Jenn said there are some regions where the Earthscope results give radially different results, depending on the year of the data!

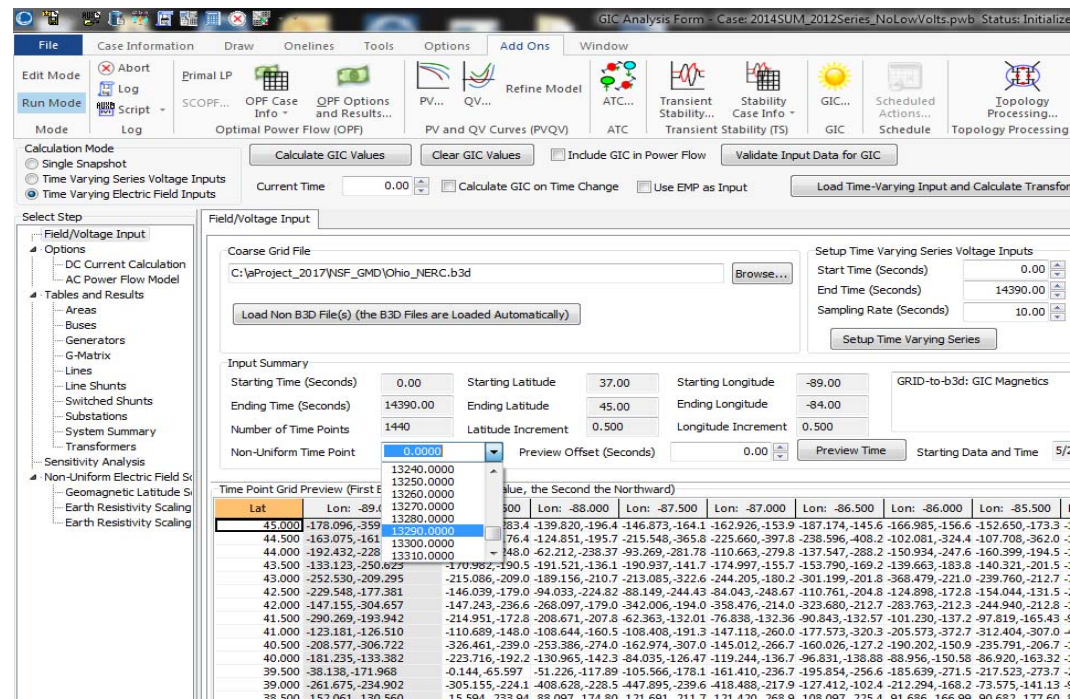


White ~ 10 V/km
Image Provided by Jenn Gannon

PowerWorld Support for Full 3D Models



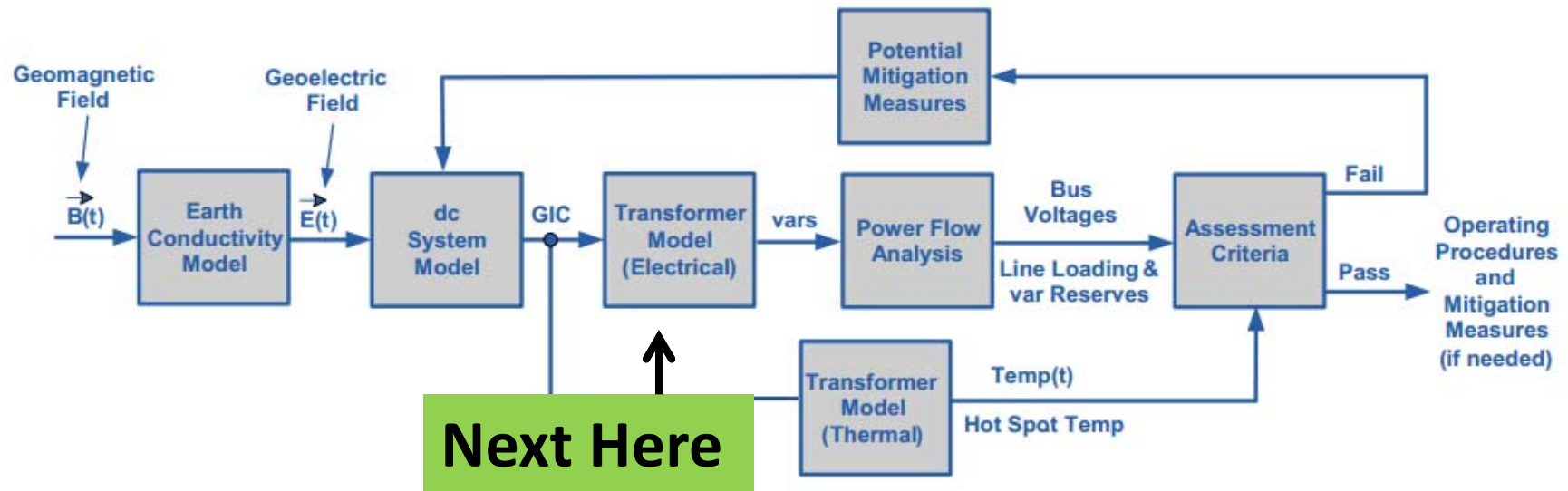
- We've recently enhanced PowerWorld to provide support for 3D earth models
 - Third party (e.g., Jenn Gannon with CPI) provides a time-varying, geographic definition of the electric fields; specified in a *.b3d file
 - This is definitely at the research stage though!!



Overview of GMD Assessments



In is a quite interdisciplinary problem



Next Here

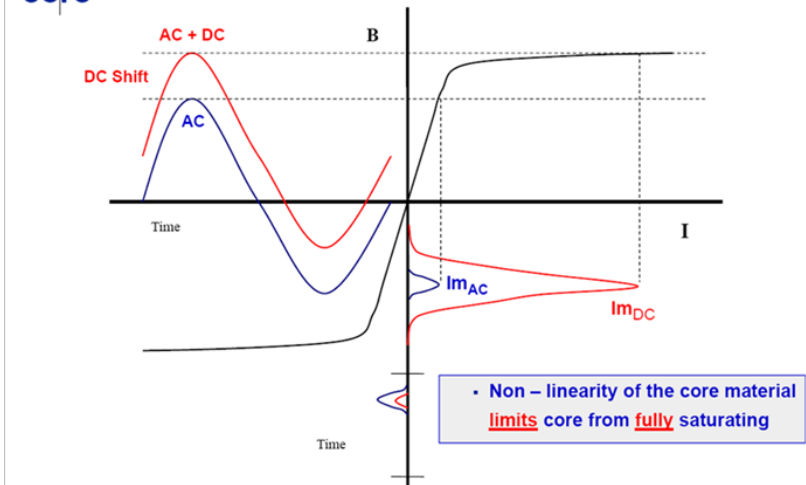
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Transformer Impacts of GICs

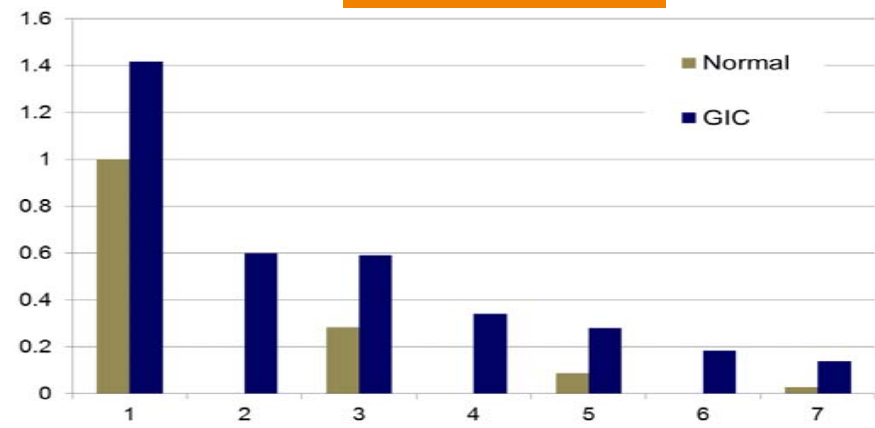
- The GICs superimpose on the ac current, causing transformers saturation for part of the ac cycle
- This cause large harmonics; in the positive sequence these harmonics can be represented by increased reactive power losses in the transformer

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



ABB

Harmonics



Images: Craig Stiegemeier and Ed Schweitzer, JASON Presentations,

June 2011

Relating GICs to Transformer Mvar Losses



- Transformer positive sequence reactive power losses vary as a function of both the GICs in the transformer coils and the ac voltage
- A common modeling approach is to use a linear model

$$Q_{loss} = KV_{pu} I_{GIC, Eff}$$

- The $I_{GIC, Eff}$ is an effective current that is a function of the GICs in both coils; whether auto or regular the equation is

$$I_{GIC, Eff} = \left| \frac{a_t I_{GIC, H} + I_{GIC, L}}{a_t} \right| \quad \text{where } a_t \text{ is the turns ratio}$$

Confusions!



- $I_{GIC, Eff}$ is a dc value, whereas Q_{loss} is the total ac losses
- From a GIC perspective, the three phases are in parallel; hence there can be confusion as to whether the GICs are per phase or total (per phase is common and used in PowerWorld)
- Since Q_{loss} varies linearly with voltage, the nominal high voltage of the transformer (e.g., 500 kV, 345 kV, etc.) needs to be embedded in the K
 - An initial approach was to assume a K for 500 kV; the K then needed to be scaled for other voltages

Specifying Transformer Losses Scalars in Per Unit



- Alternative approach (used here) of representing the K values in per unit
 - Using a base derived from transformer's high side voltage
 - Current base using the peak value

$$I_{base,highkv,peak} = \frac{S_{base,xf} 1000 \sqrt{2}}{V_{base,highkv} \sqrt{3}}$$

Peak (or "crest") value used since this is a dc current base

- Convert to per unit by dividing Q_{loss} by $S_{base,xf}$

$$\frac{Q_{loss}}{S_{base,xf}} = \frac{V_{pu} K_{old} \frac{V_{base,highkv}}{500} 1000 I_{GIC,eff} \sqrt{2}}{V_{base,highkv} I_{base,highkv,peak} \sqrt{3}}$$

$$Q_{loss,pu} = V_{pu} \left(\frac{1000 \sqrt{2} K_{old}}{500 \sqrt{3}} \right) I_{eff,pu} = V_{pu} (1.633 K_{old}) I_{eff,pu} = V_{pu} K_{new} I_{eff,pu}$$

$$K_{new} = 1.633 K_{old}$$

K_{old} based on an assumed 500 kV

GMD Enhanced Power Analysis Software



- By integrating GIC calculations directly within power flow and transient stability engineers can see the impact of GICs on their systems, and consider mitigation options
- GIC calculations use many of the existing model parameters such as line resistance. Some non-standard values are also needed; either provided or estimated
 - Substation grounding resistance
 - transformer grounding configuration and coil resistance
 - whether auto-transformer or three-winding transformer,
 - generator step-up transformer parameters

The Impact of a Large GMD

From an Operations Perspective



- Would be maybe a day warning but without specifics
 - Satellite at Lagrange point one million miles from earth would give more details, but just 30 minutes beforehand
 - Would strike quickly; rise time of minutes, rapidly covering a good chunk of the continent
- Reactive power loadings on hundreds of transformers could sky rocket
- Power system software like state estimation could fail
- Control room personnel would be overwhelmed
- The storm could last for days with varying intensity
- Waiting until it occurs to prepare is not a good idea!



Wrap-up Questions and Comments