ECEN 615
Methods of Electric Power Systems Analysis

Lecture 24: Geomagnetic Disturbances

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Announcements

- Read Chapter 8 and Appendices 3B and 3E of Chapter 3
- Homework 6 is due today and Homework 7 by Nov 24
- The second exam will be in class on Nov 17
  - Distance learners will be able to take the exam from Nov 16 to Nov 18
- Associated with Homework 7 there can be optional student presentations on Nov 24
  - See the homework document for details
- Regular lecture on November 19

High-Impact, Low-Frequency Events

- Growing concern to consider what the NERC calls calls High-Impact, Low-Frequency Events (HILFs); others call them black sky days
  - Large-scale, potentially long
  - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) HEMPs
- The next several slides will consider GMDs and HEMPs

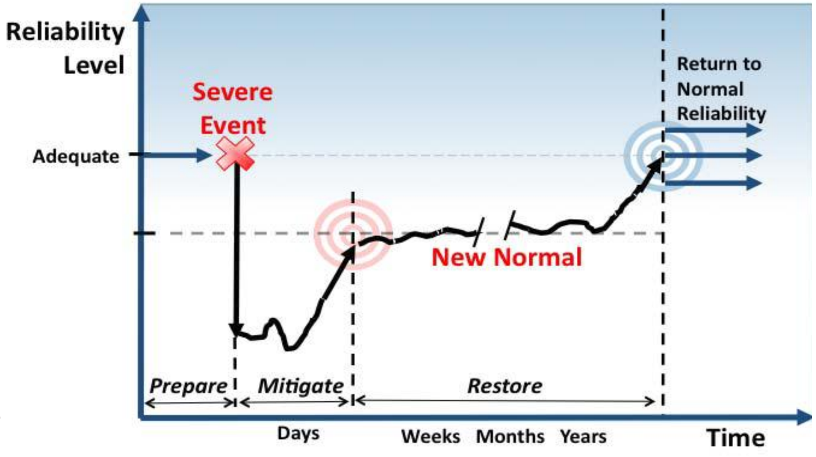


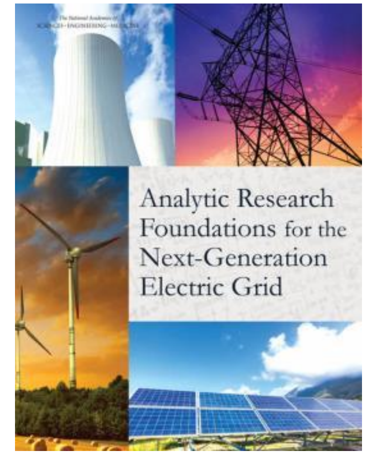
Image Source: NERC, 2012

Reliability and Resiliency

- Keeping the lights on involves designing and operating the electric grid with a goal of simultaneously increasing two related but ultimately different concepts: reliability and resiliency
- Reliability: suitable or fit to be relied on: dependable
  - One of the key benefits of interconnected electric grids
- Resiliency: an ability to recover from or adjust easily to misfortune or change
  - A key focus of electric grid protection systems almost from day one, but there is a more recent focus on acknowledging that large-scale blackouts cannot be totally prevented, so we must be able to bounce back

Two New US National Academies Reports

- Analytic Research Foundations for the Next-Generation Electric Grid, 2016
- Enhancing the Resilience of the Nation's Electricity System, 2017
  - "While minimizing the likelihood of large-area, long-duration outages is important, a resilient system is one that acknowledges that such outages can occur, prepares to deal with them, minimizes their impact when they occur, is able to restore service quickly, and draws lessons from the experience to improve performance in the future"



Some Electric Grid Risks

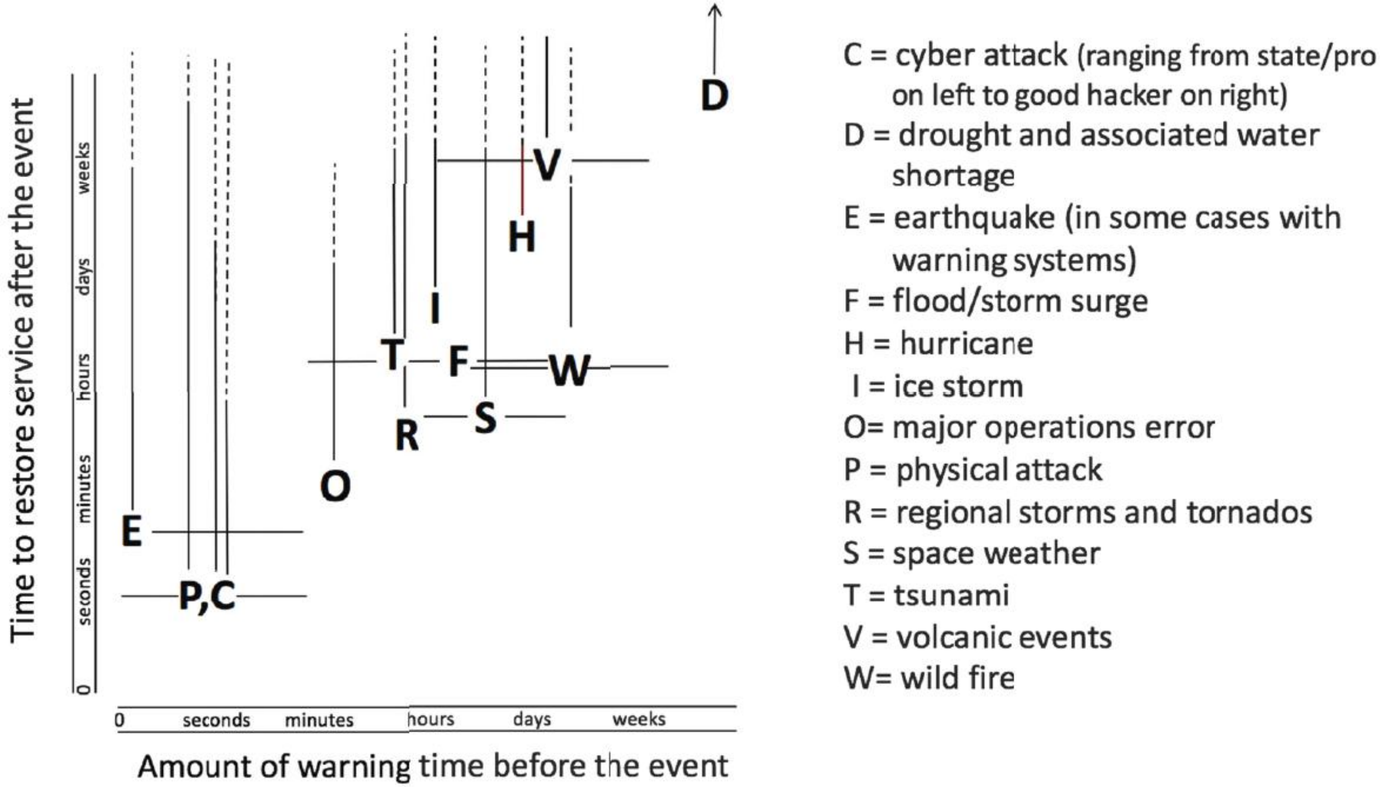
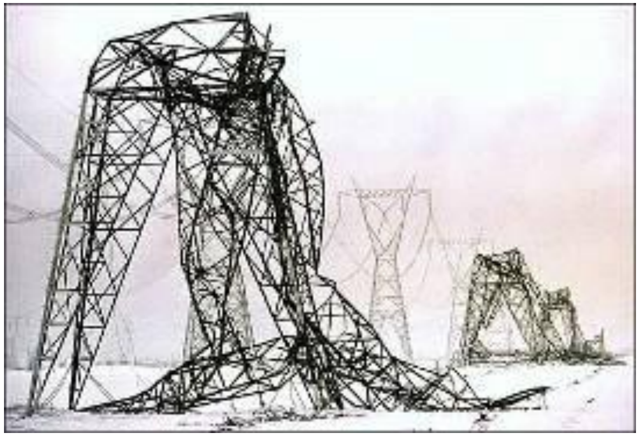


FIGURE 3.1 Mapping of events that can cause disruption of power systems. The horizontal placement provides some indication of how much warning time there may be before the event. The vertical axis provides some indication of how long it may take to recover after the event. Lines provide a representation

Grid Needs to Be Resilient to Disturbances on Different Time Frames

- Events short and long-term
  - Lightning strikes can usually be cleared within seconds
  - But ice, tornados and hurricanes can bring large-scale damage over long timer periods
- Need to consider all conditions



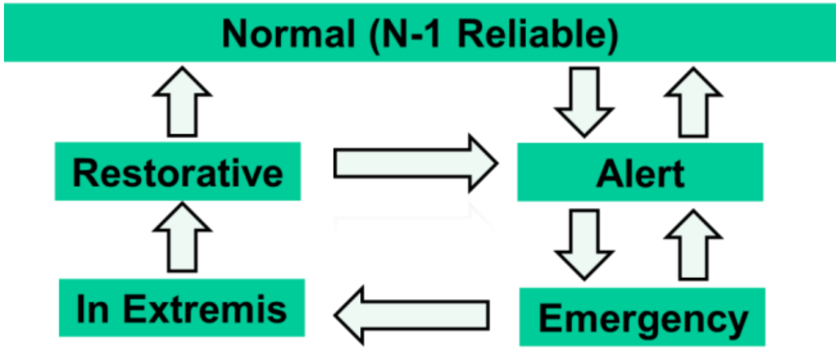
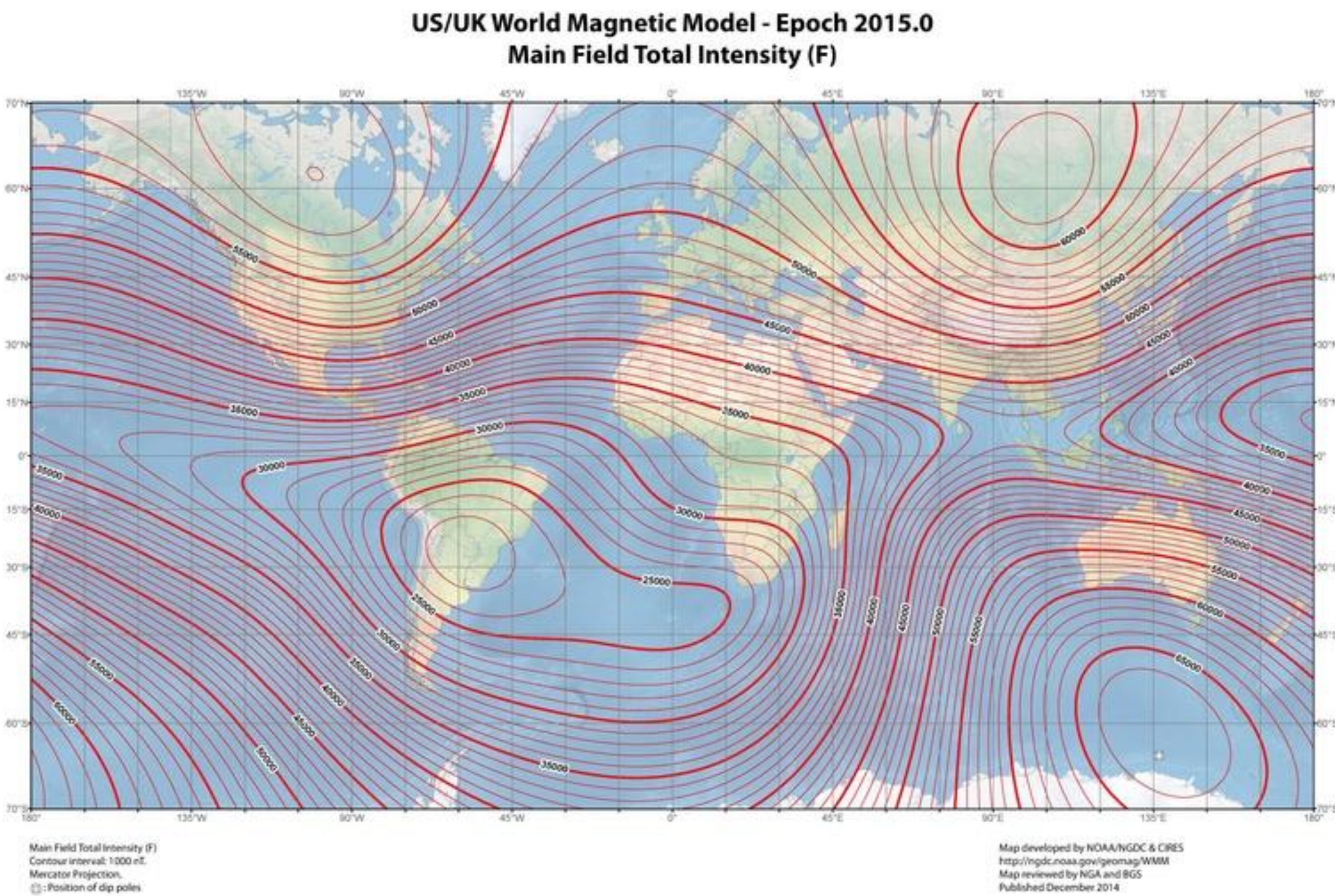


Image Derived From L.H. Fink and K. Carlsen, Operating under stress and strain, *IEEE Spectrum*, March 1978, pp. 48-53

Geomagnetic Disturbances (GMDs)

- GMDs are caused by solar corona mass ejections (CMEs) impacting the earth's magnetic field
- A GMD caused a blackout in 1989 of Quebec
- They 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
- GMD assessment tools are now moving into the realm of power system planning and operations engineers; required by NERC Standards (TPL 007-1, 007-2)

Earth's Magnetic Field



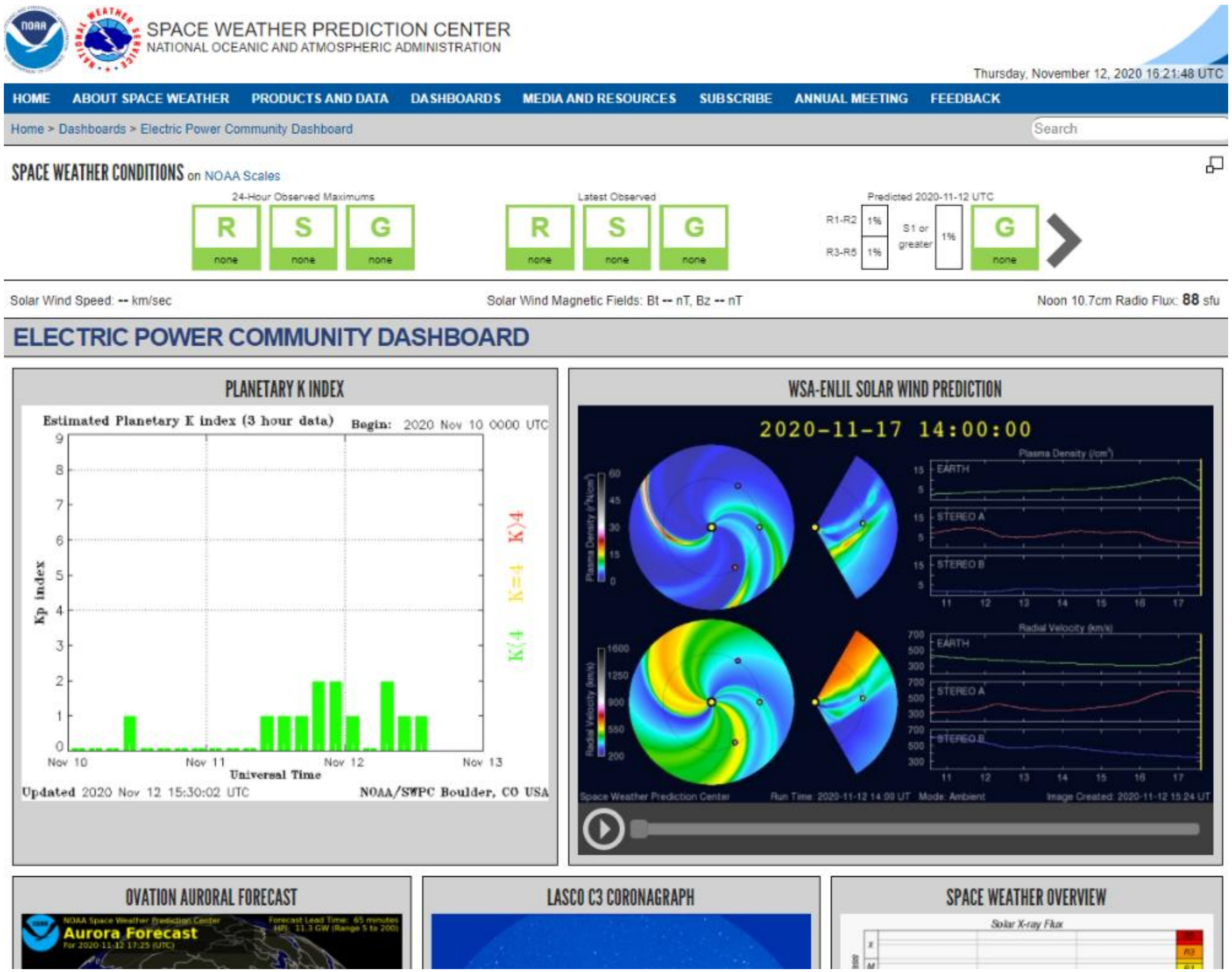
The earth's magnetic field is usually between 25,000 and 65,000 nT

Image Source: Wikepedia

Earth's Magnetic Field Variations

- The earth's magnetic field is constantly changing, though usually the variations are not significant
  - Larger changes tend to occur closer to the earth's magnetic poles
- The magnitude of the variation at any particular location is quantified with a value known as the K-index
  - Ranges from 1 to 9, with the value dependent on nT variation in horizontal direction over a three hour period
  - This is station specific; higher variations are required to get a k=9 closer to the poles
- The Kp-index is a weighted average of the individual station K-indices; G scale approximately is Kp - 4

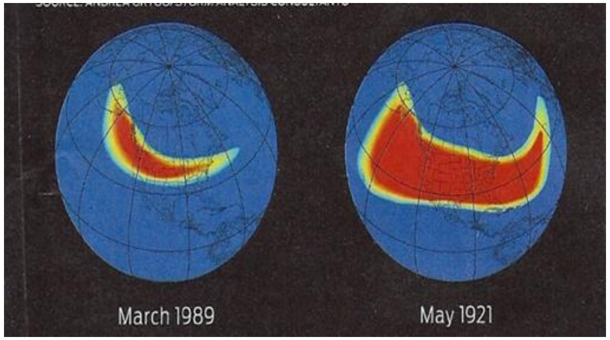
Space Weather Prediction Center has an Electric Power Dashboard



www.swpc.noaa.gov/communities/electric-power-community-dashboard

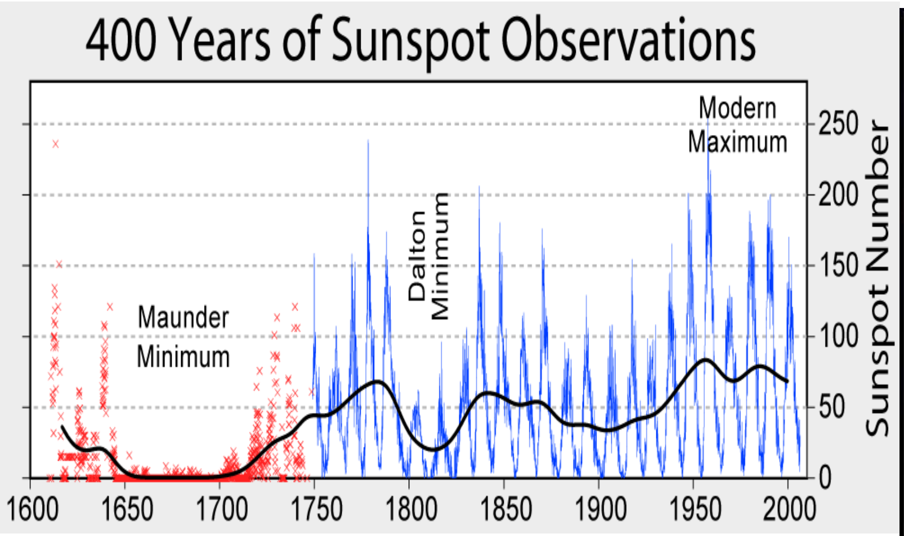
GMD and the Grid

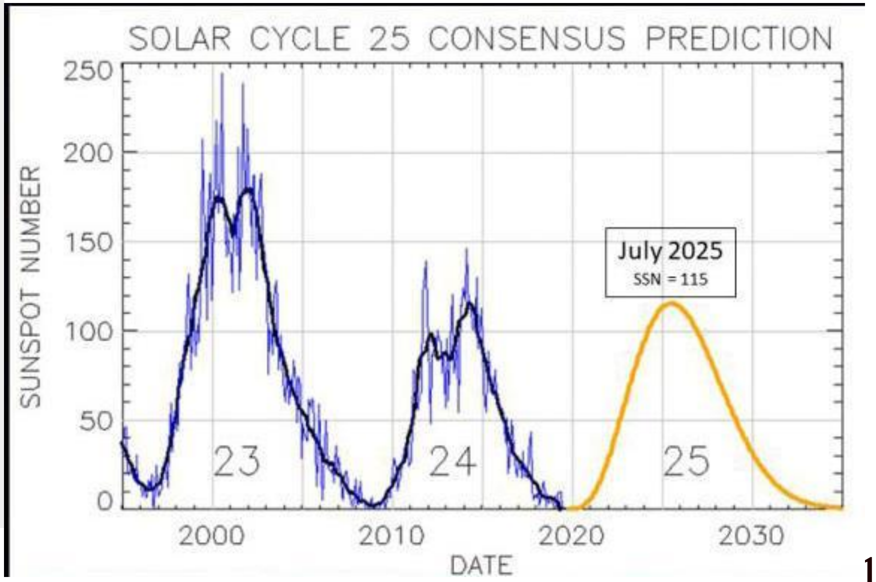
- Large solar corona mass ejections (CMEs) can cause large changes in the earth's magnetic field (i.e., dB/dt). These changes in turn produce a non-uniform electric field at the surface
  - Changes in the magnetic flux are usually expressed in nT/minute; from a 60 Hz perspective they are almost dc
  - 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 2500 nT/minute variation
  - Storm "footprint" can be continental in scale



Solar Cycles

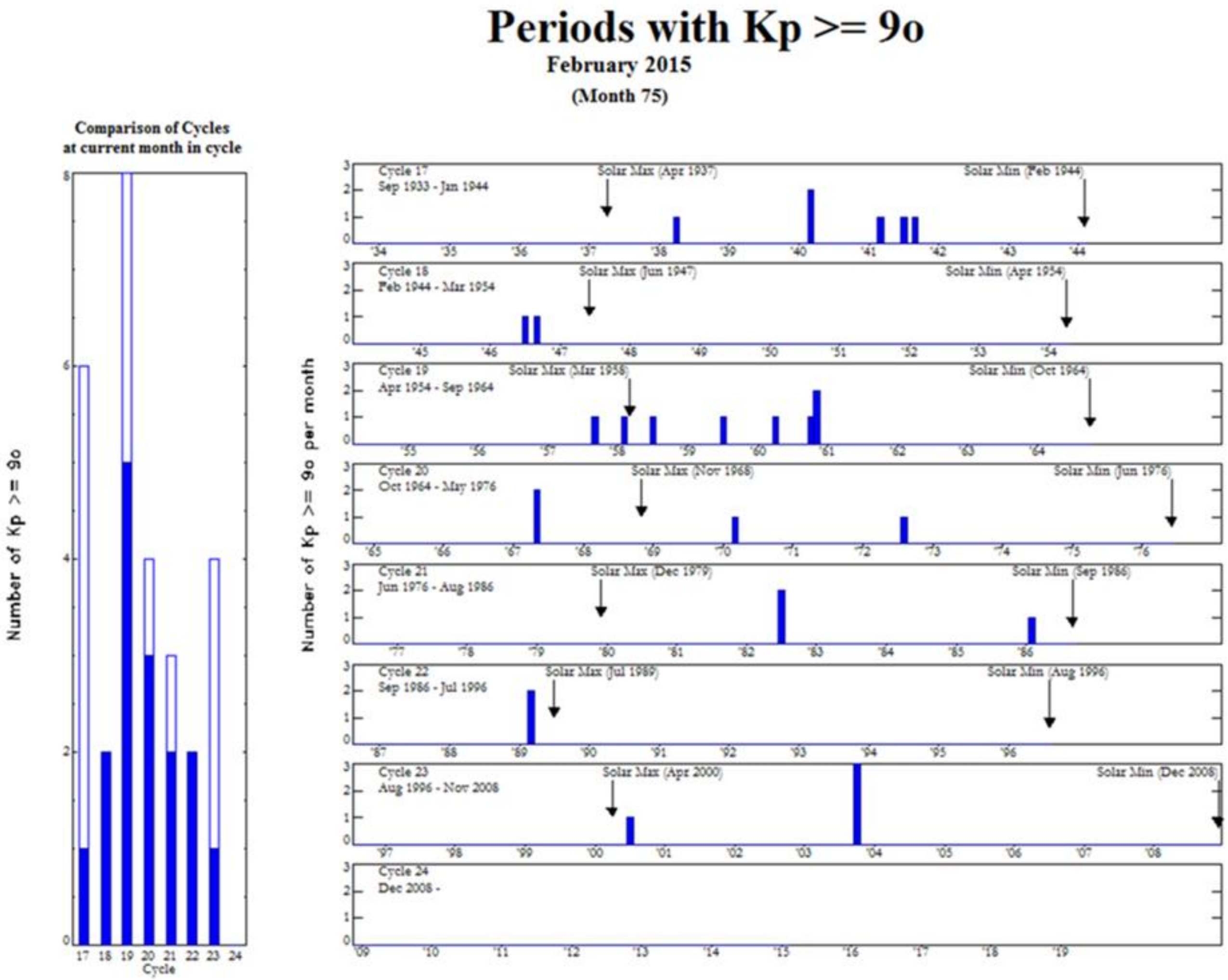
- Sunspots follow an 11 year cycle, and have been observed for hundreds of years
- We're finishing solar cycle 24 (first numbered cycle was in 1755); last minimum was in 2009, maximum in 2014/2015; now close to a minimum





Images from NASA, NOAA

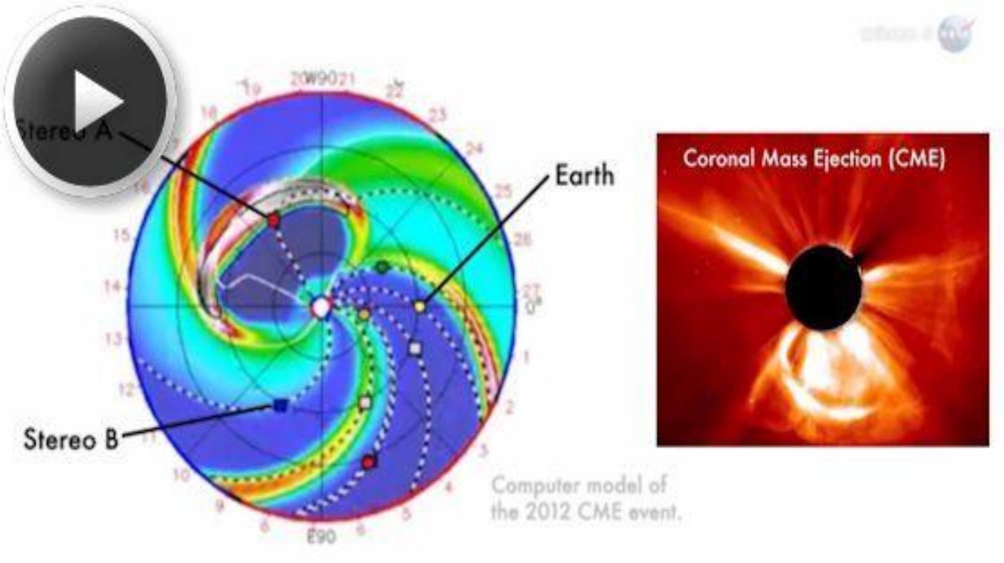
But Large CMEs Are Not Well Correlated with Sunspot Maximums



The large 1921 storm occurred four years after the 1917 maximum

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 150 years

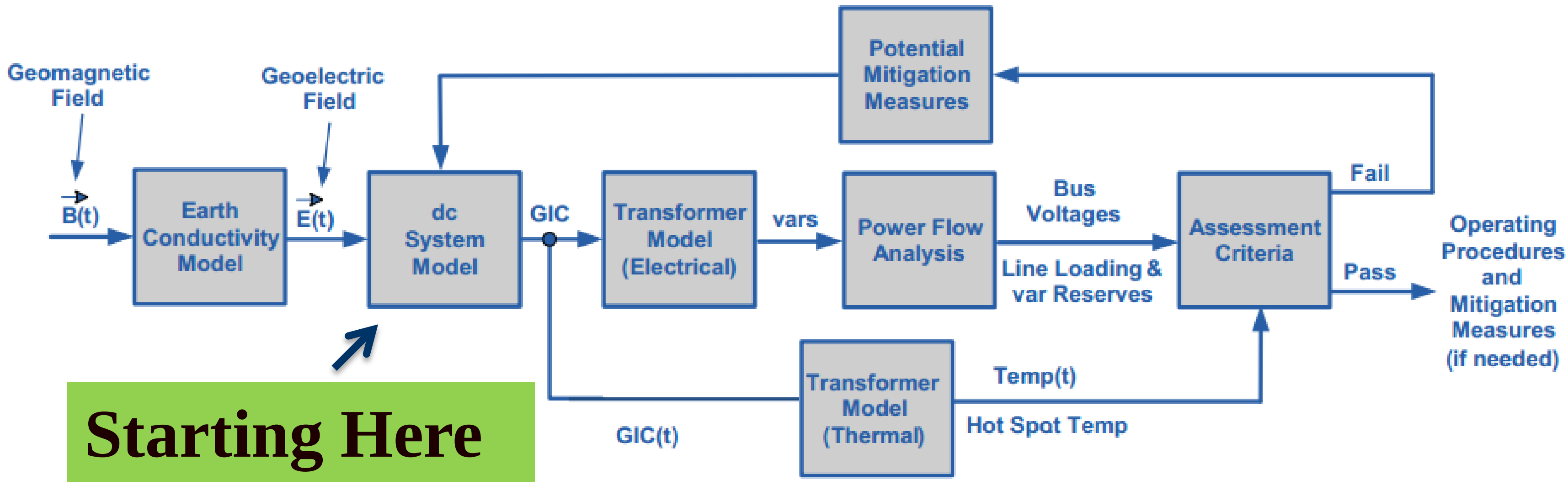


- There is still lots of uncertainly about how large a storm is reasonable to consider in electric utility planning

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

Overview of GMD Assessments

In is a quite interdisciplinary problem



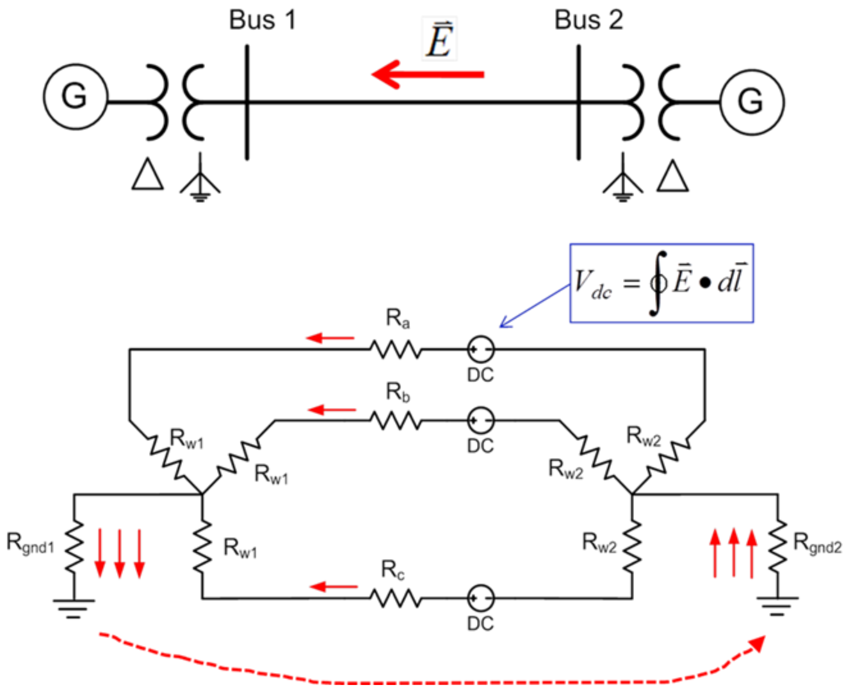
Starting Here

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

Geomagnetically Induced Currents (GICs

- GMDs cause slowly varying electric fields
- Along length of a high voltage transmission line, electric fields can be modeled as a dc voltage source superimposed on the lines
- These voltage sources produce quasi-dc geomagnetically induced currents (GICs) that are superimposed on the ac (60 Hz) flows



GIC Calculations for Large Systems

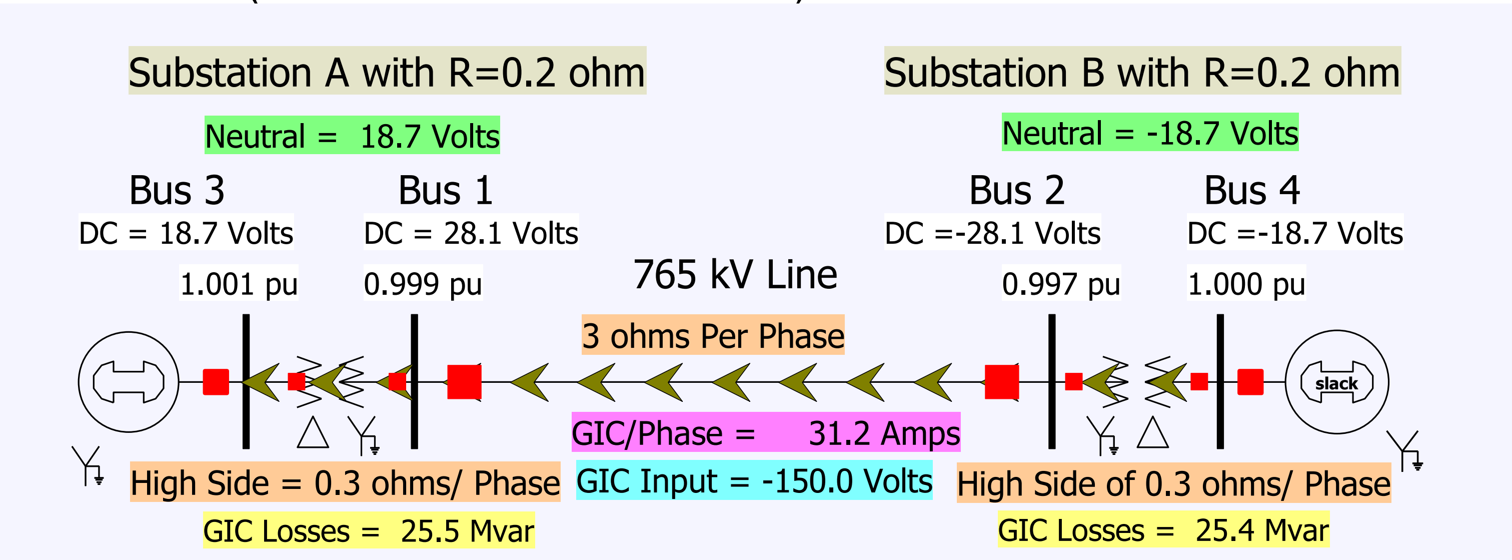
- With knowledge of the pertinent transmission system parameters and the GMD-induced line voltages, the dc bus voltages and flows are found by solving a linear equation **I** = **G V** (or **J = G U**)
  - **J** and **U** may be used to emphasize these are dc values, not the power flow ac values
  - The **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)
    - Only depends on resistance, which varies with temperature
  - 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

- Factoring the sparse **G** matrix and doing the forward/backward substitution takes about 1 second for the 60,000 bus Eastern Interconnect Model
- The current vector (**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 a assuming a straight line path is probably sufficient (given all the other uncertainties!)

Four Bus Example (East-West Field)

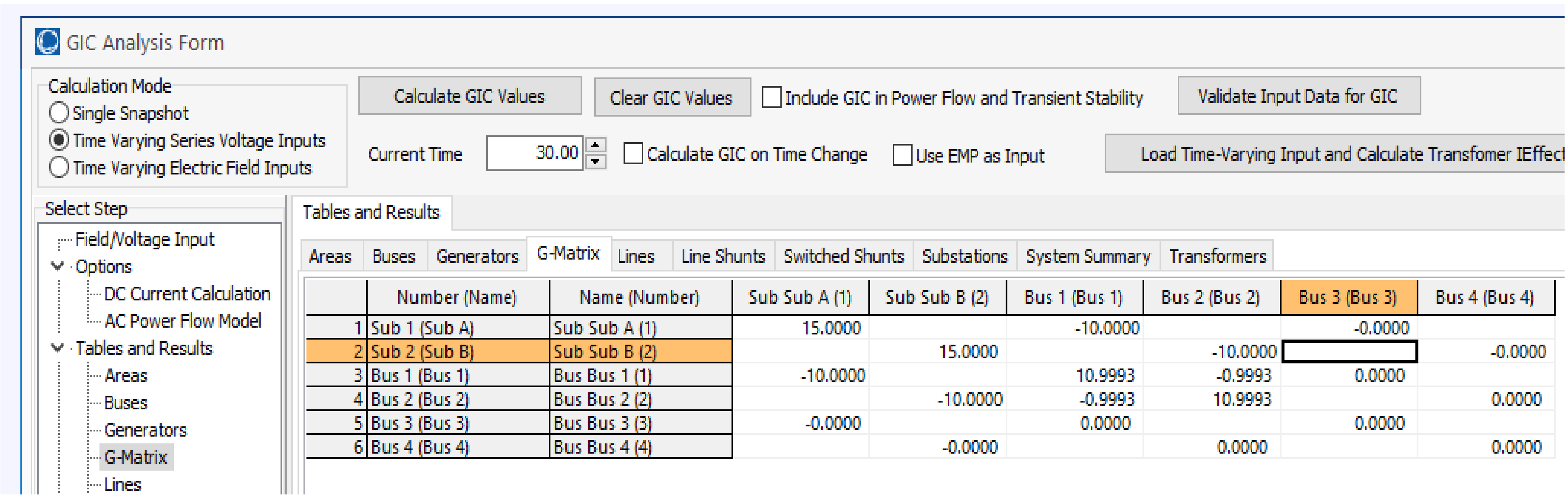
$$I_{GIC,3Phase} = \frac{150\,\text{volts}}{(1+0.1+0.1+0.2+0.2)\Omega} = 93.75\ \text{amps or } 31.25\ \text{amps/phase}$$



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.

Case name is **GIC_FourBus**

Four Bus Example GIC G Matrix

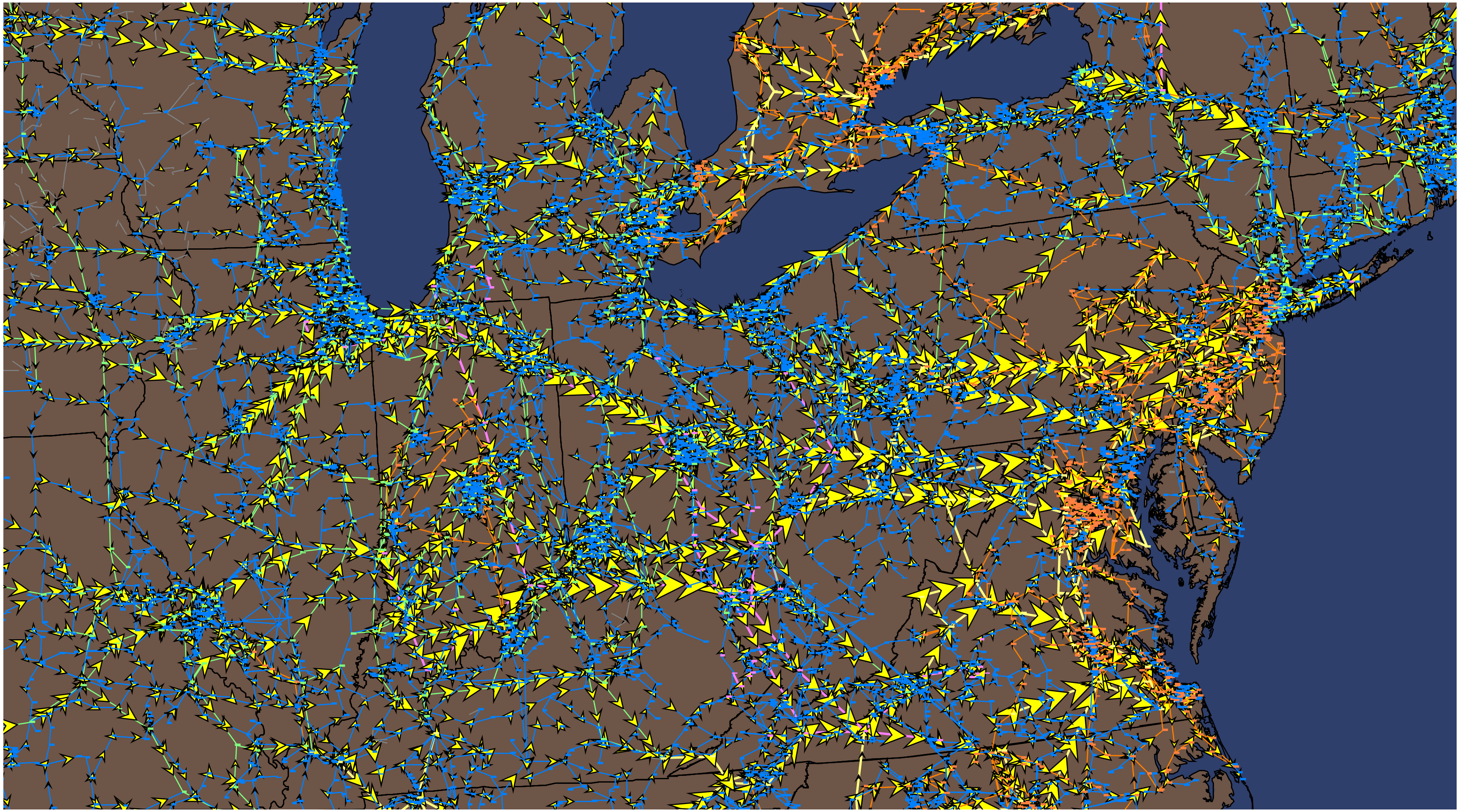


	Number (Name)	Name (Number)	Sub Sub A (1)	Sub Sub B (2)	Bus 1 (Bus 1)	Bus 2 (Bus 2)	Bus 3 (Bus 3)	Bus 4 (Bus 4)
1	Sub 1 (Sub A)	Sub Sub A (1)	15.0000		-10.0000		-0.0000	
2	Sub 2 (Sub B)	Sub Sub B (2)		15.0000		-10.0000		-0.0000
3	Bus 1 (Bus 1)	Bus Bus 1 (1)	-10.0000		10.9993	-0.9993	0.0000	
4	Bus 2 (Bus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

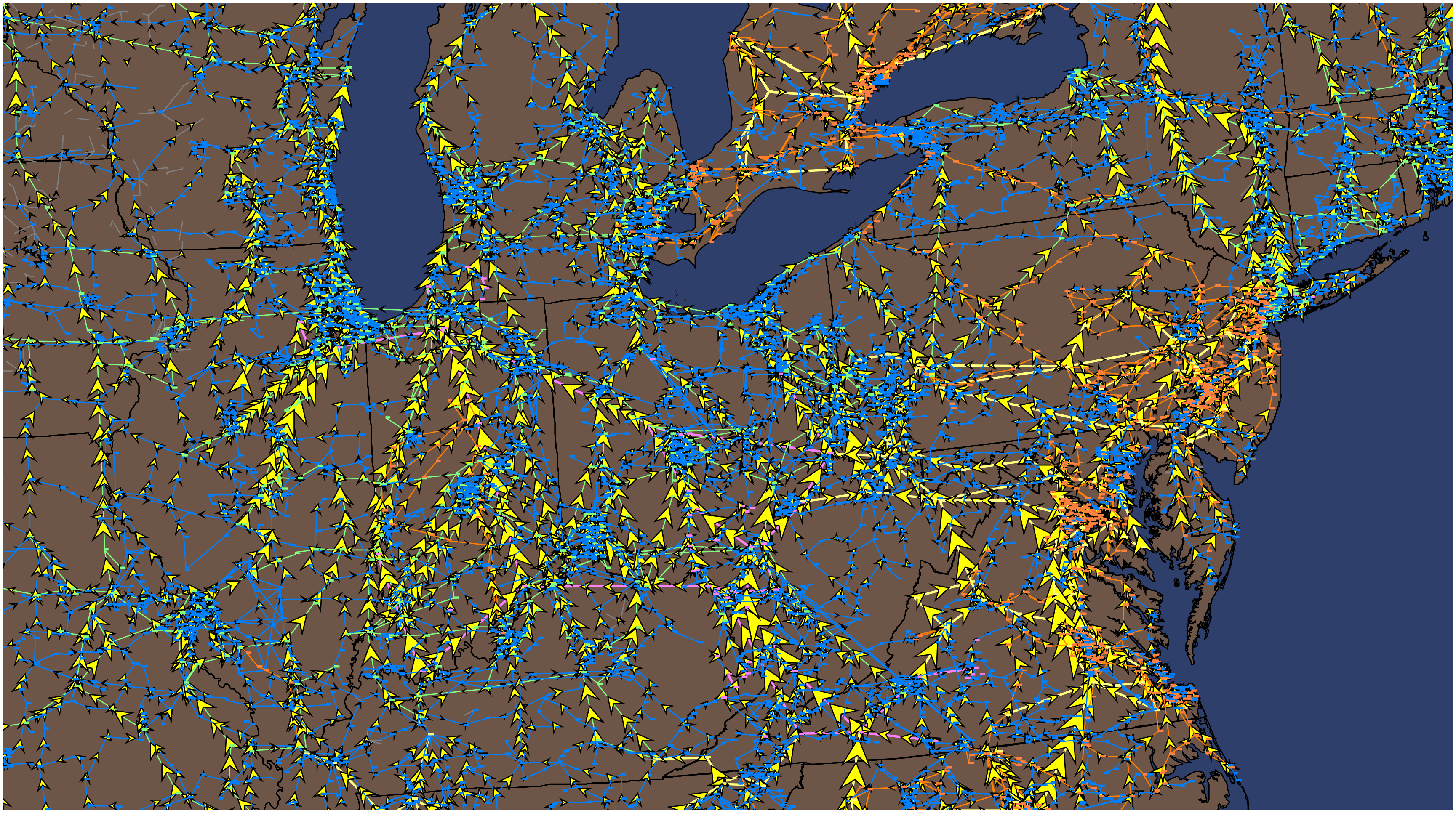
$$\mathbf{U} = [\mathbf{G}]^{-1}\,\mathbf{J}$$

$$\begin{bmatrix} 18.75 \\ -18.75 \\ 28.12 \\ -28.12 \end{bmatrix} = \begin{bmatrix} 15 & 0 & -10 & 0 \\ 0 & 15 & 0 & -10 \\ -10 & 0 & 11 & -1 \\ 0 & -10 & -1 & 11 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 150 \\ -150 \end{bmatrix}$$

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; sets the line dc voltages
- Matching an actual storm can be complicated, and requires detailed knowledge of the 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, but also with hotspots

Electric Field Linearity

- If an electric field is assumed to have a uniform direction everywhere (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

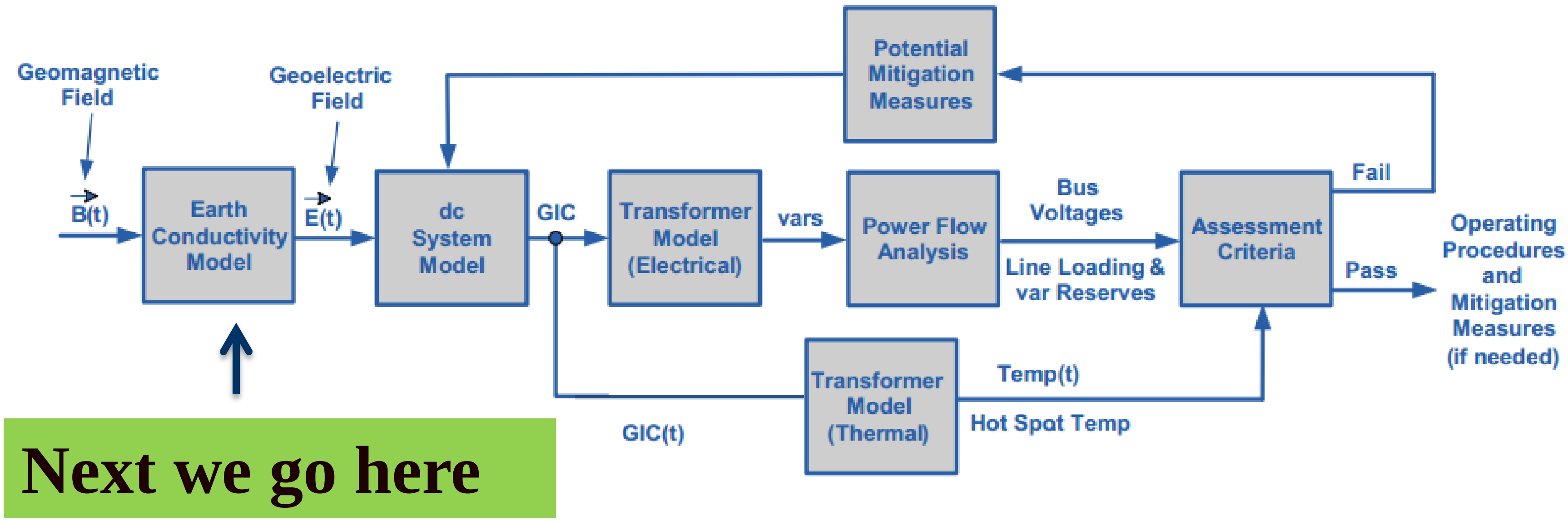


Image Source: http://www.nerc.com/pa/Stand/WebinarLibrary/GMD_standards_update_june26_ec.pdf

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

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

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

Relationship Between dB/dT and E

- 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

B(ω) =660×10^{-9} T and

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

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

A more resistive earth gives higher electric fields

Typical Conductance and Resistivity Values

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

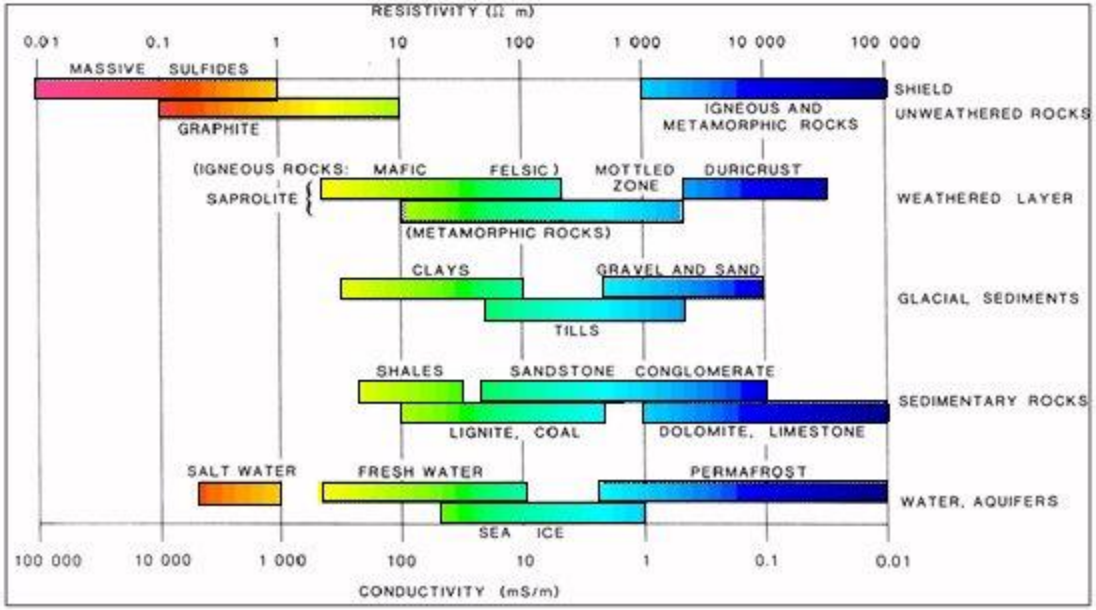


Image source: https://www.eoas.ubc.ca/courses/eosc350/content/foundations/properties/resistivity.htm

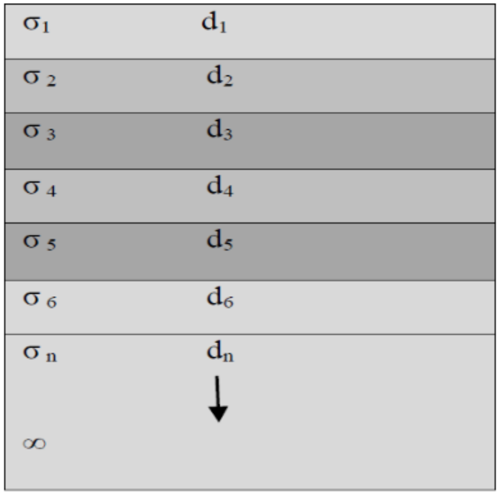
1-D Earth Models

- 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

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

- At the bottom level n

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



1-D Layers

1-D Earth Models

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

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

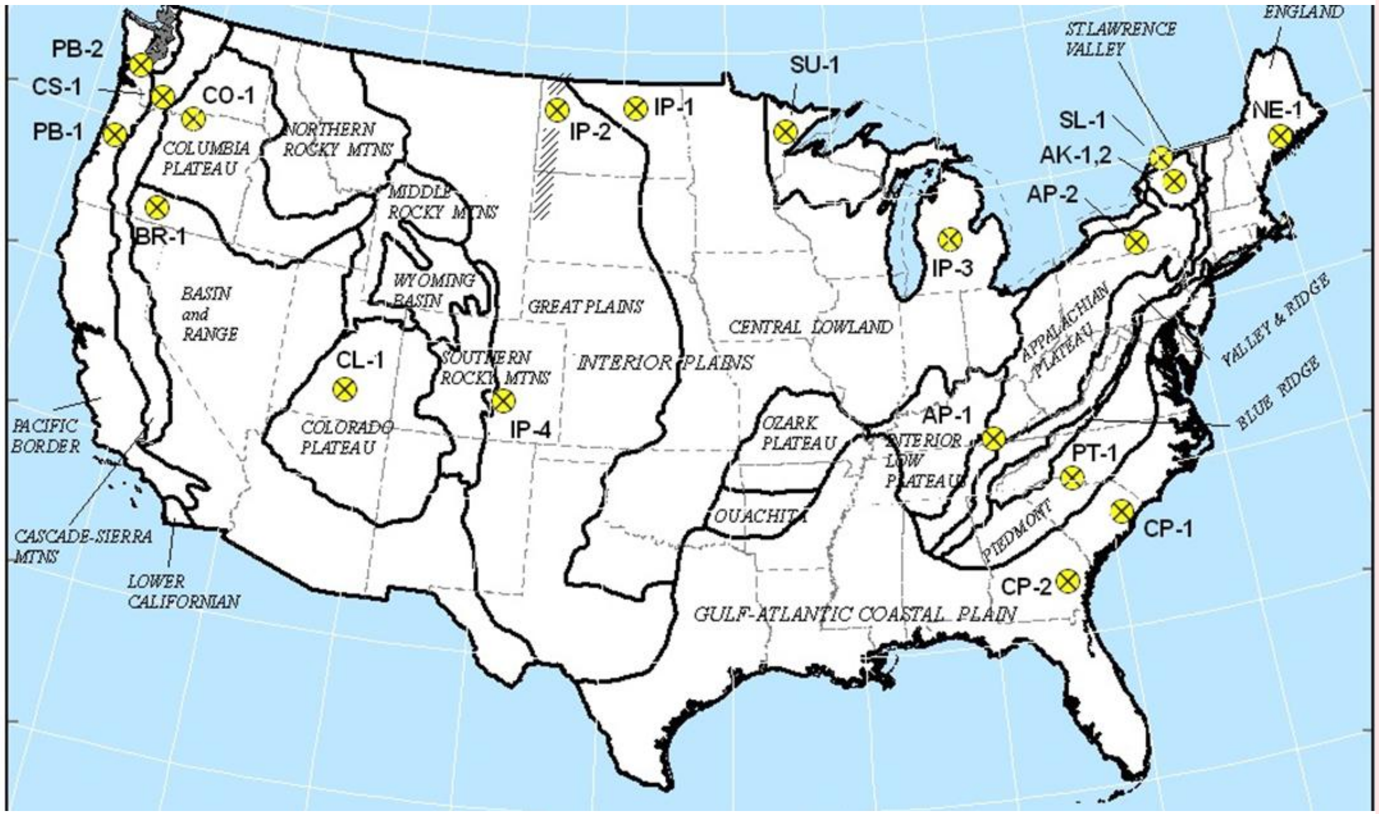
- With the impedance at the top of layer m given as

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

- 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

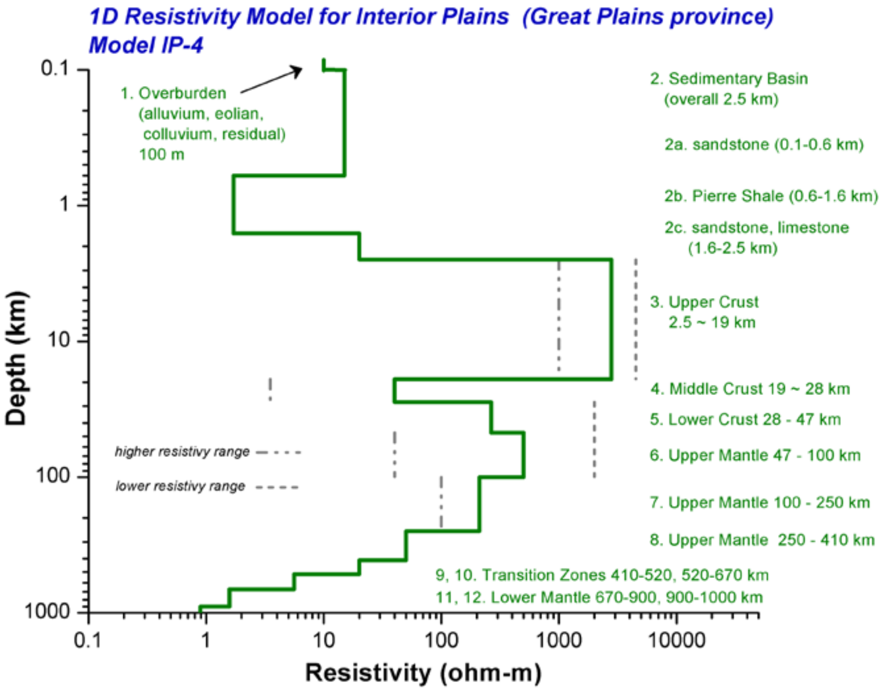


These regional scalings are now being used for power flow GMD analysis, and are being updated

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

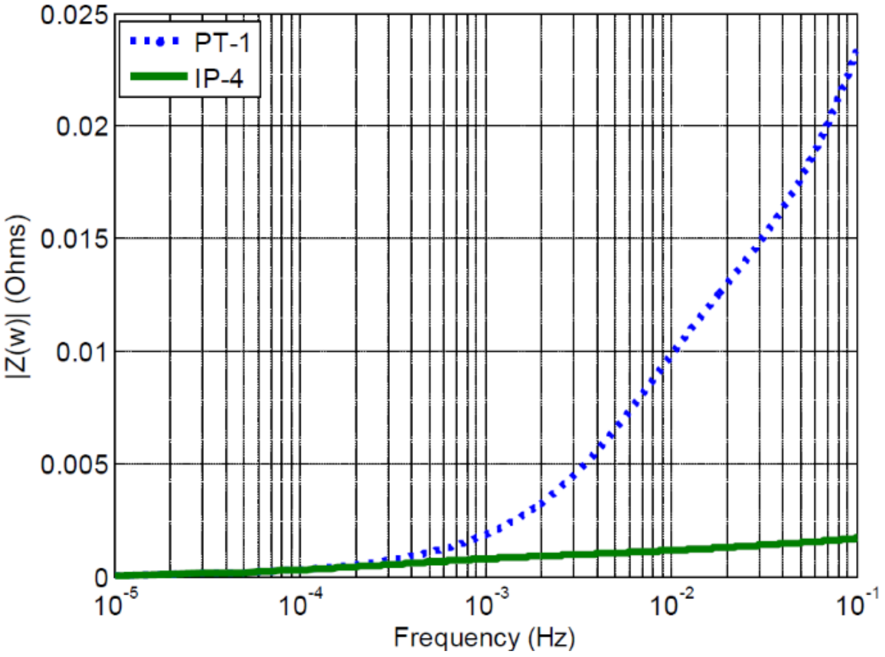
1-D Earth Models

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

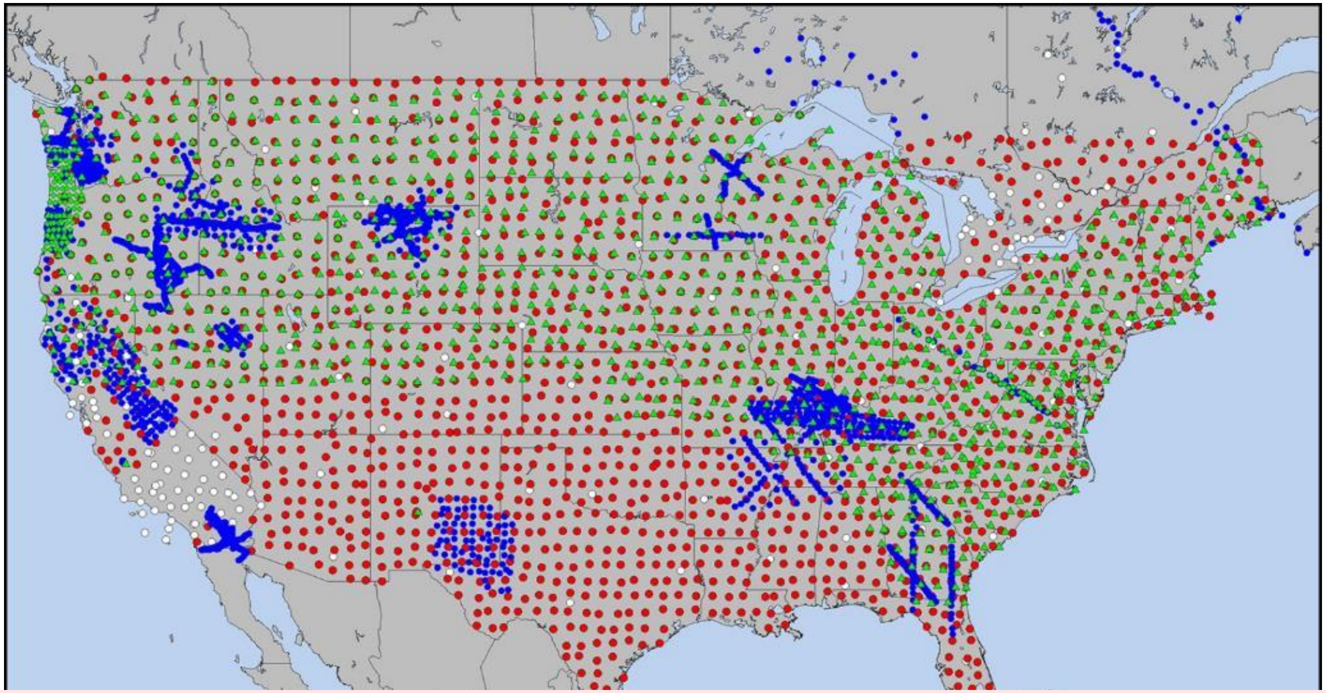


Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

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



3-D Models and EarthScope



USArray in the Lower 48 U.S. and Southeastern Canada. Transportable Array (TA) stations (red), Flexible Array (FA) stations (blue), and Magnetotelluric (MT) array (green) operated at different scales from 2004–2018. MT stations are subdivided between MT-TA (green triangles) and MT-FA (tight cluster of green diamonds in the Pacific Northwest and dense line across the Mid-Atlantic). Backbone stations (white) were used as part of the TA at its outset and in Canada. Over 200 TA stations have been permanently adopted across the country, and there are active efforts across the federal government to complete the MT-TA across the southern one-third of the U.S.
Source: https://www.earthscope.org/articles/Reflections_on_USArray.html

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

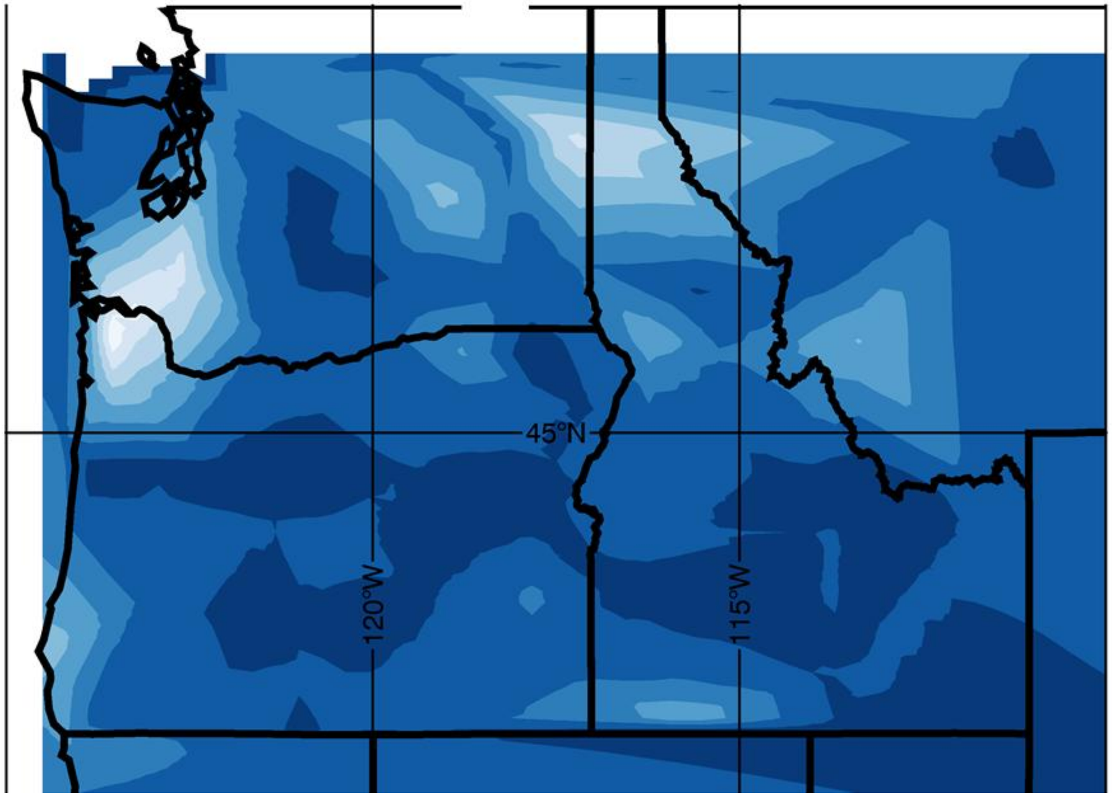
$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} \xi_{xx} & \xi_{xy} \\ \xi_{yx} & \xi_{yy} \end{bmatrix} \cdot \begin{bmatrix} Bx \\ By \end{bmatrix}$$

- Are provided in 2x2 impedance tensors by USArray

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

Example 3-D Earthscope Model Results

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

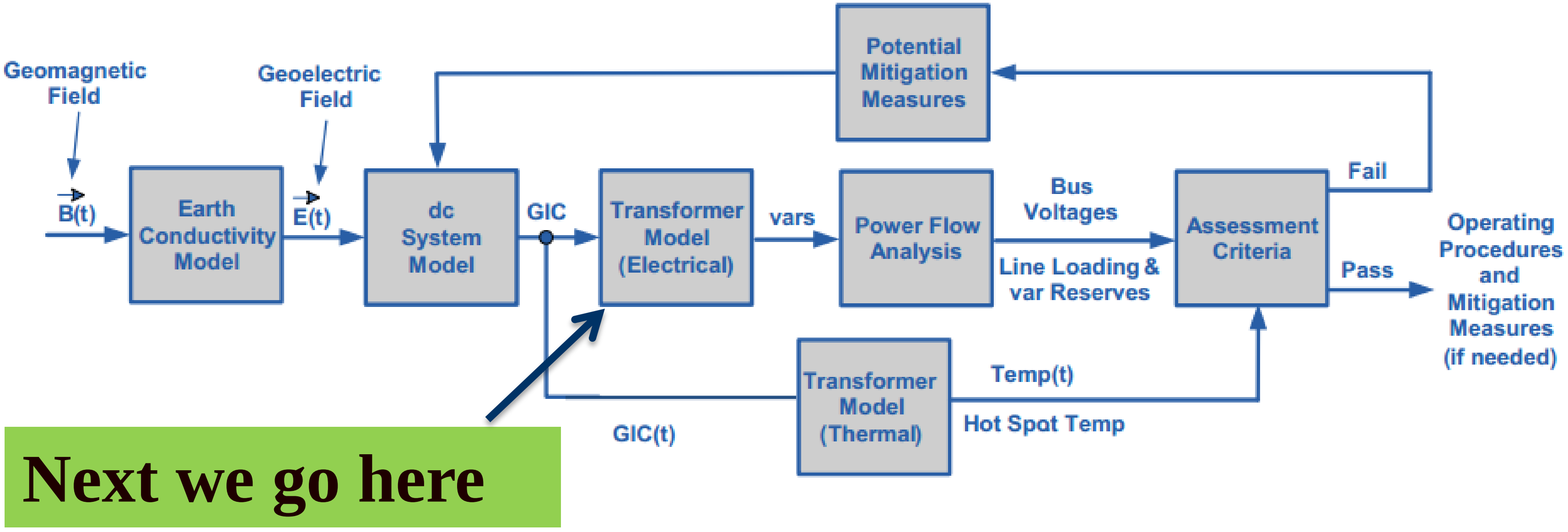


White ~ 10 V/km
Image Provided by
Jenn Gannon

Input Electric Field Considerations

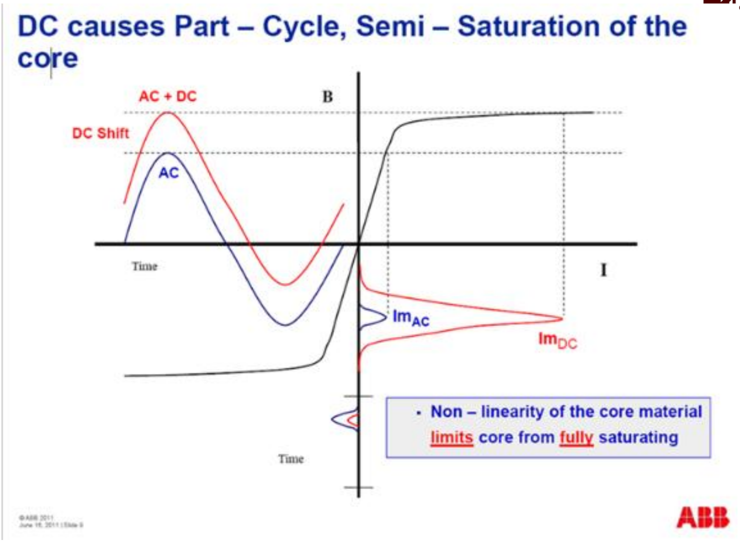
- The current vector (**I**) depends upon the assumed electric field along each transmission line
- With a uniform electric field determination of the transmission line's GMD-induced voltage is path independent
  - Just requires geographic knowledge of the transmission line's terminal substations
- With nonuniform fields an exact calculation would be path dependent, but just a assuming a straight line path is probably sufficient (given all the other uncertainties!)

Overview of GMD Assessments

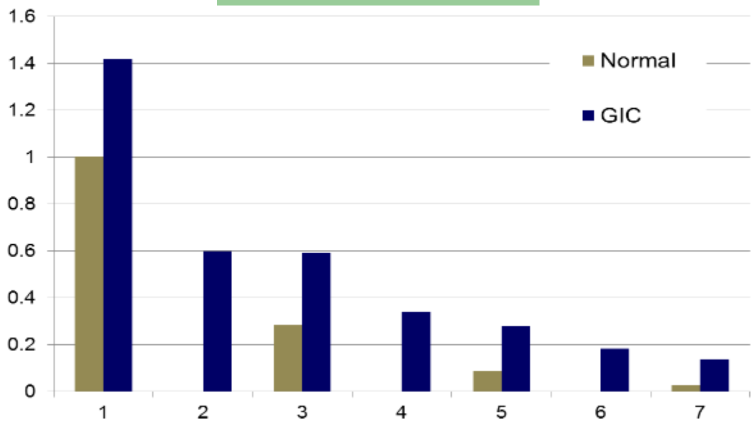


Transformer Impacts of GICs

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



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 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

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

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 with less than 30 minutes lead time
  - Could strike quickly; rise time of minutes, rapidly covering a good chunk of the continent

- Reactive power loadings on hundreds of high voltage transformers could rapidly rise

The Impact of a Large GMD From an Operations Perspective

- Increased transformer reactive loading causes heating issues and potential large-scale voltage collapses
- 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 would not be a good idea!

GIC Mitigation

- Tools are needed to determine mitigation strategies
  - Cost-benefit analysis
- GIC flows can be reduced both through operational strategies such as opening lines, and through longer term approaches such as installing blocking devices

- Redispatching the system can change transformer loadings, providing margins for GICs
- Algorithms are needed to provide real-time situational awareness for use during GMDs

Some Specific Recommendations to Enhance Resilience

- A "visioning" process is needed to imaging and assessing plausible high impact events
- The electric grid operators need to do exercises to better simulate high impact scenarios
- More physical components are needed, including replacement transformers and backup power
- More research, development and demonstration is needed, including a focus on cyber and HILFs
- Resilience groups are needed throughout the industry and government to raise awareness

Source: National Academies 2017 "Enhancing the Resilience of the Nation's Electricity System"