ECEN 615
Methods of Electric Power Systems Analysis

Lecture 24: Power Markets, GMD Modeling

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Announcements

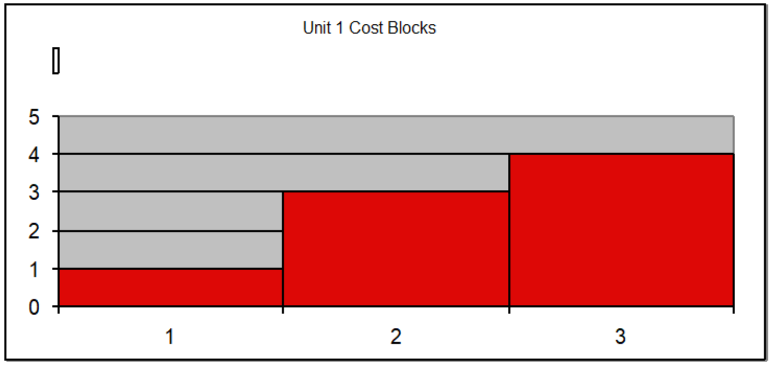
- Read Chapters 3 and 8 from the book
- Second exam is in class on November 21
  - Same format as with the first exam except you can bring in two note sheets (e.g., your sheet from the last exam and a new one)
  - Exam covers up to the end of today's material

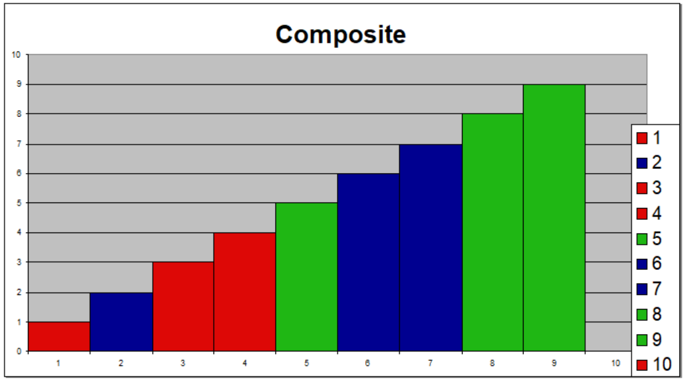
LMP Energy Markets

- In an LMP energy market the generation is paid the LMP at the bus, and the loads pay the LMP at the bus
  - This is done in both the day ahead market and in the real-time market (which makes up the differences between actual and the day ahead)
- The generator surplus (profit) is the difference between the LMP and the actual cost of generation
- Generators that offer too high are not selected to run, and hence make no profit
- A key decision for the generation owners is what values to offer

Generator Offers

- Generator offers are given in piecewise linear curves; that is, a fixed $/MWh for so much power for a time period
- In the absence of constraints (congestion) the ISO would just select the lowest offers to meet the anticipated load
- Actual dispatch is determined using an SCOPF





General Guidelines

- Generators with high fixed costs and low operating costs (e.g., wind, solar, nuclear) benefit from running many hours
  - Usually they should submit offers close to their marginal costs
  - Wind (and some others) receive a production tax credit for their first ten years of operation
    - $23/MWh for systems starting construction before 1/1/2017
    - $18.4/MWh for systems starting construction in 2017 (a 20% reduction)
    - In 2018 the reduction is 40% and 60% in 2019; after that it is zero (unless, of course, changed by Congress)
- Generators with low fixed costs and high operating cost can do fine operating fewer hours (at higher prices)

Auctions

- In its simplest form, an auction is a mechanism of allocating scarce goods based upon competition
  - a seller wishes to obtain as much money as possible, and a buyer wants to pay as little as necessary.
- An auction is usually considered efficient if resources accrue to those who value them most highly
- Auctions can be either one-sided with a single monopolist seller/buyer or a double auction with multiple parties in each category
  - bid to buy, offer to sell
- Most people's experience is with one-side auctions with one seller and multiple buyers

Auctions, cont.

- Electricity markets can be one-sided, with the ISO functioning as a monopolist buyer, while multiple generating companies make offers to sell their generation, or two-sided with load participation
- Auction provides mechanism for participants to reveal their true costs while satisfying their desires to buy low and/or sell high.
- Auctions differ on the price participants receive and the information they see along the way

Types of Single-Sided Auctions with Multiple Buyers, One Seller

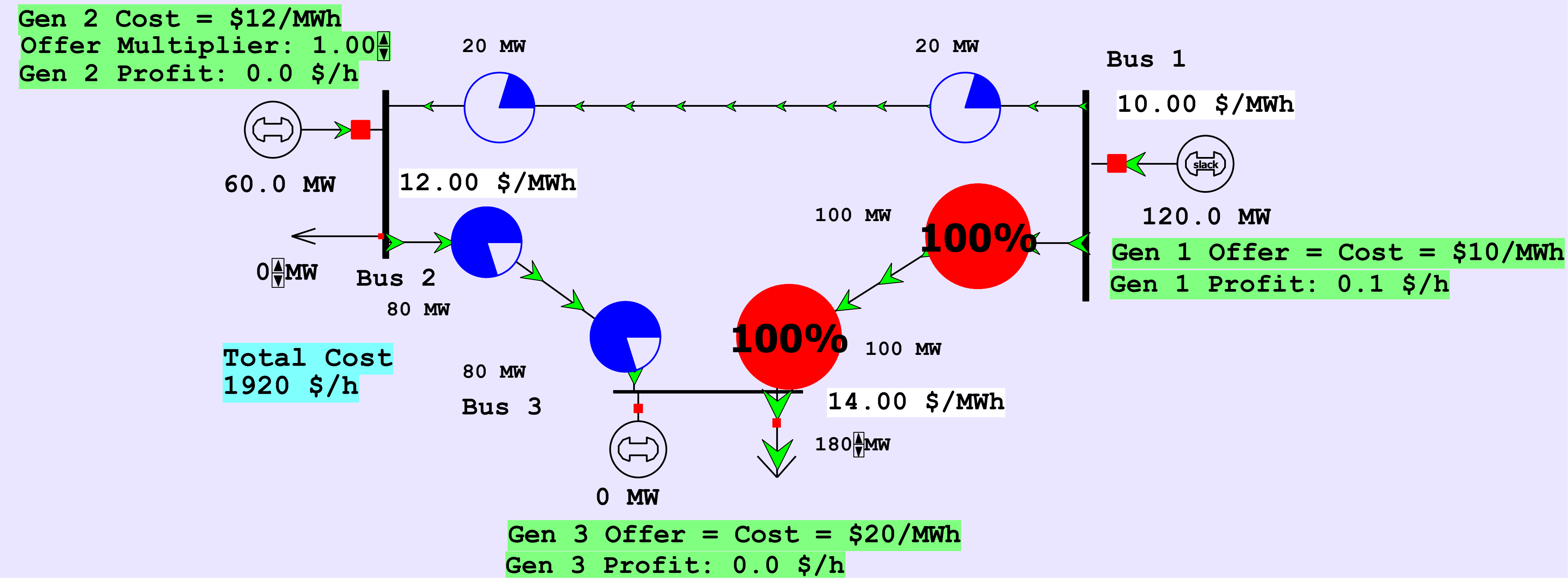
- Simultaneous auctions
  - English (ascending price to buy)
  - Dutch (descending price to buy)
- Sealed-bid auctions (all participants submit offers simultaneously)
  - First price sealed bid (pay highest price if one, discriminatory prices if multiple)
  - Vickrey (uniform second price) (pay the second highest price if one, all pay highest losing price if many); this approach gives people incentive to bid their true value

Uniform Price Auctions: Multiple Sellers, One Buyer

- Uniform price auctions are sealed offer auctions in which sellers make simultaneous decisions (done when submitting offers).
- Generators are paid the last accepted offer
- Provides incentive to offer at marginal cost since higher values cause offers to be rejected
  - reigning price should match marginal cost
- Price caps are needed to prevent prices from rising up to infinity during shortages
- Some generators offering above their marginal costs are needed to cover their fixed costs

What to Offer Example

- Below example shows 3 generator case, in which the bus 2 generator can vary its offer to maximize profit



Note, this example makes the unrealistic assumption that the other generators do not vary their offers in response

Horizontal Market Power

- One issue is whether a particular group of generators has market power
- Market power is the antithesis of competition
  - It is the ability of a particular group of sellers to maintain prices above competitive levels, usually by withholding supply
- The extreme case is a single supplier of a product (i.e., a monopoly)
- In the short run what a monopolistic producer can charge depends upon the price elasticity of the demand
- Sometimes market power can result in decreased prices in the long-term by quickening the entry of new players or new innovation

Market Power and Scarcity Rents

- A generator owner exercises market power when it is unwilling to make energy available at a price that is equal to that unit's variable cost of production, even thought there is currently unloaded generation capacity (i.e., there is no scarcity).
- Scarcity rents occur when the level of electric demand is such that there is little, if any, unused capacity
- Scarcity rents are used to recover fixed costs

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

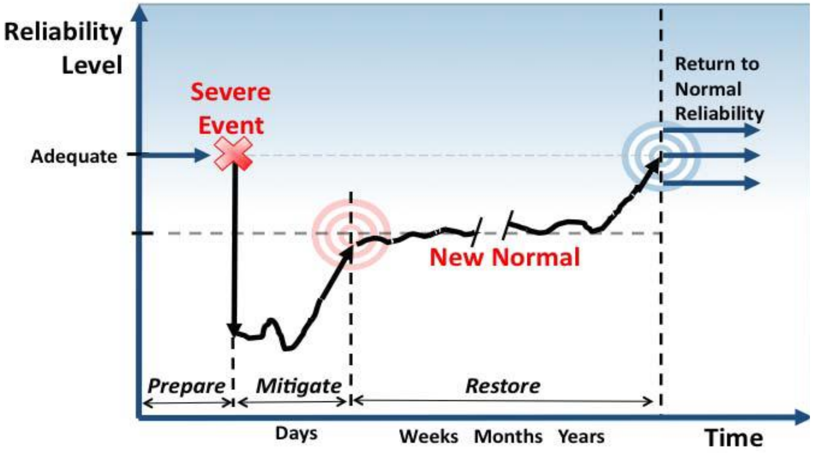


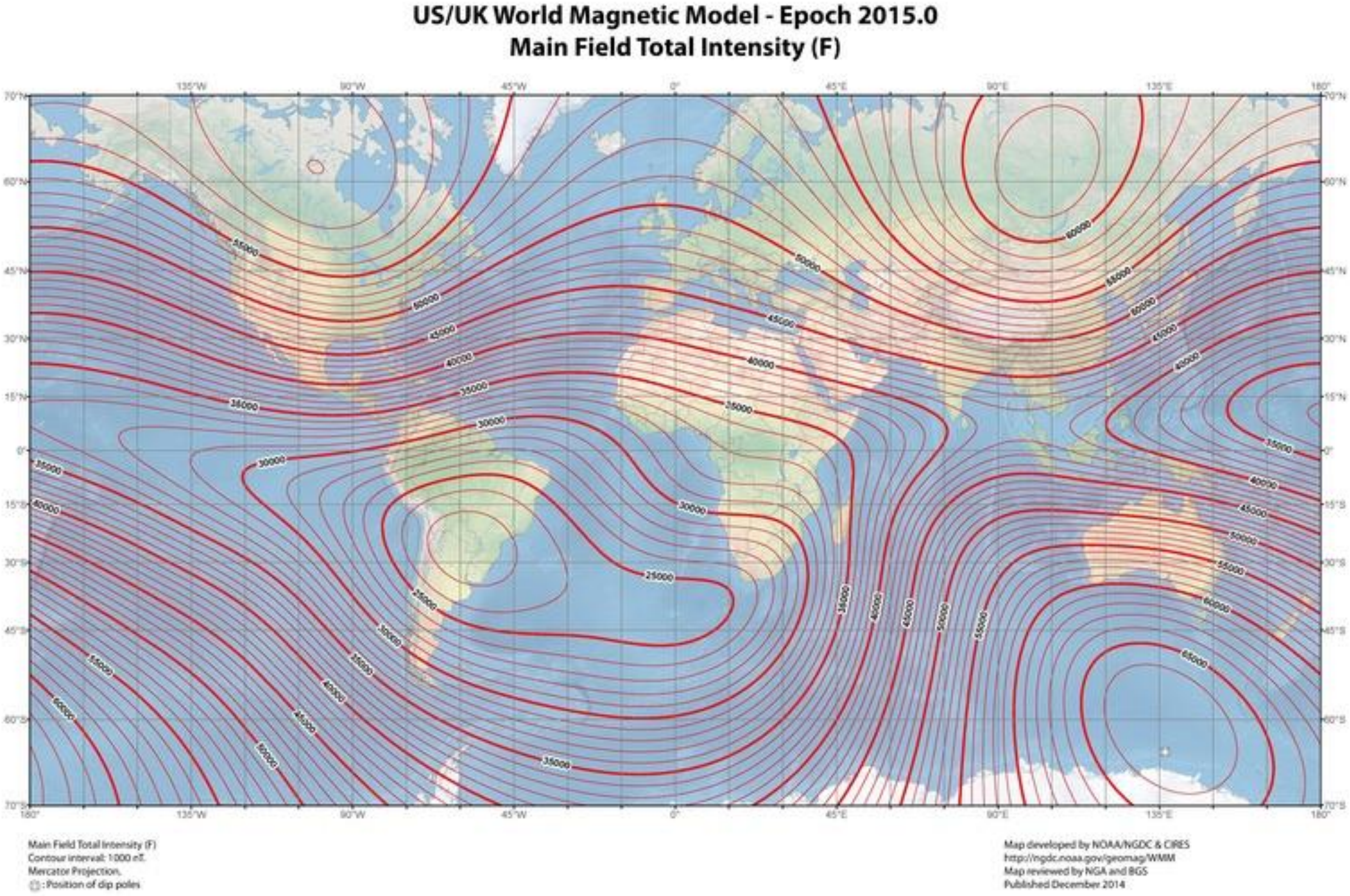
Image Source: NERC, 2012

- The next several slides will consider GMDs and HEMPs

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



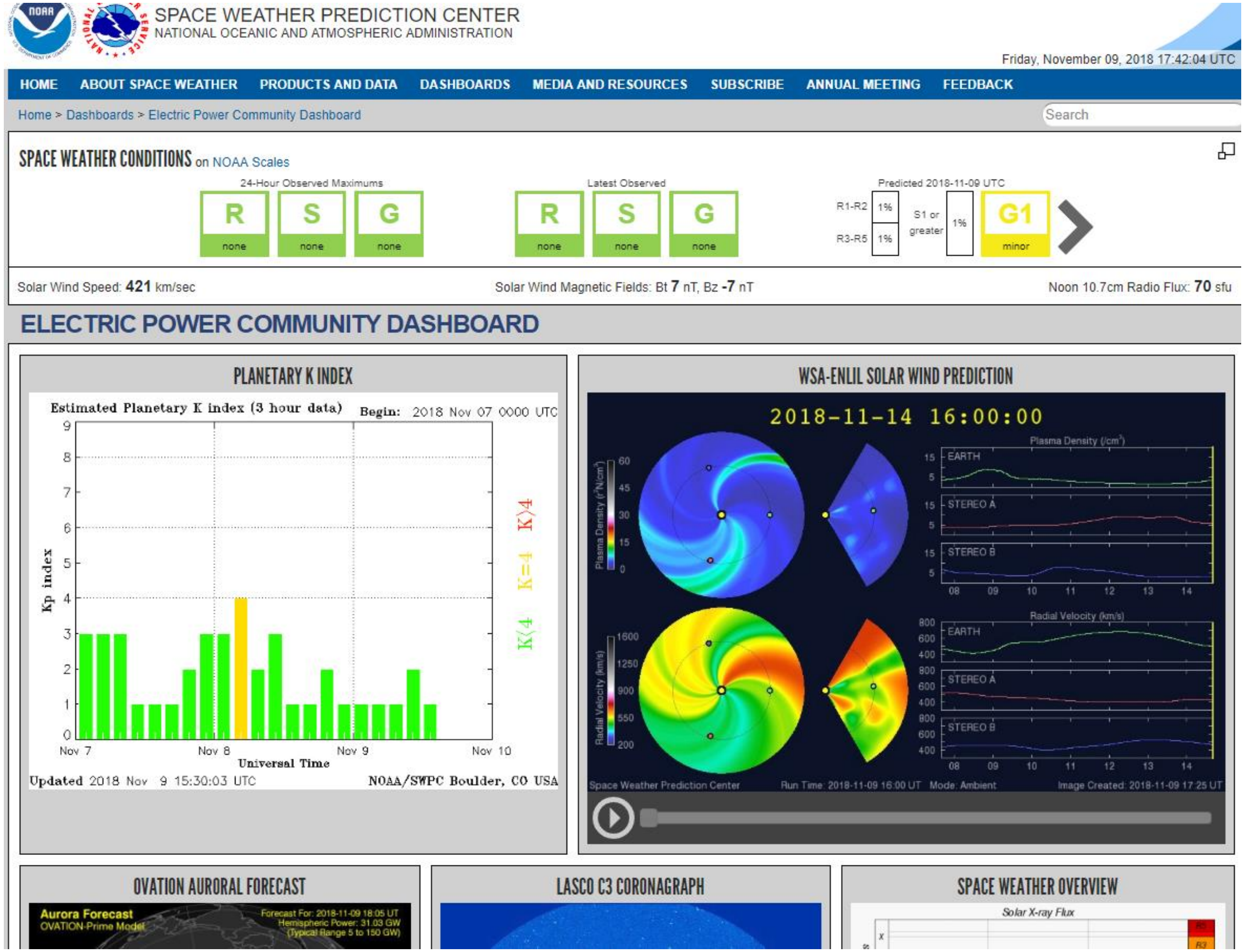
The earth's magnetic field is usually between 25,000 and 65,000 nT

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



SPACE WEATHER PREDICTION CENTER
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Friday, November 09, 2018 17:42:04 UTC

Home > Dashboards > Electric Power Community Dashboard

SPACE WEATHER CONDITIONS on NOAA Scales

Solar Wind Speed: **421** km/sec

Solar Wind Magnetic Fields: Bt **7** nT, Bz **-7** nT

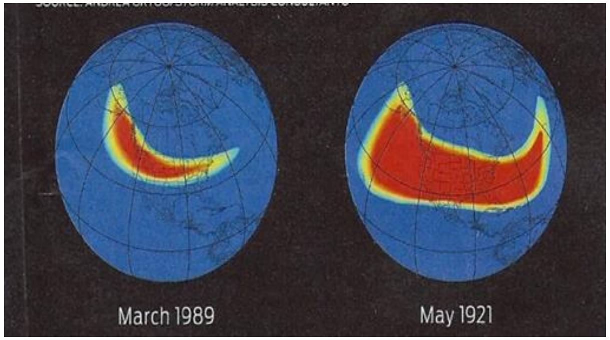
Noon 10.7cm Radio Flux: **70** sfu

ELECTRIC POWER COMMUNITY DASHBOARD

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

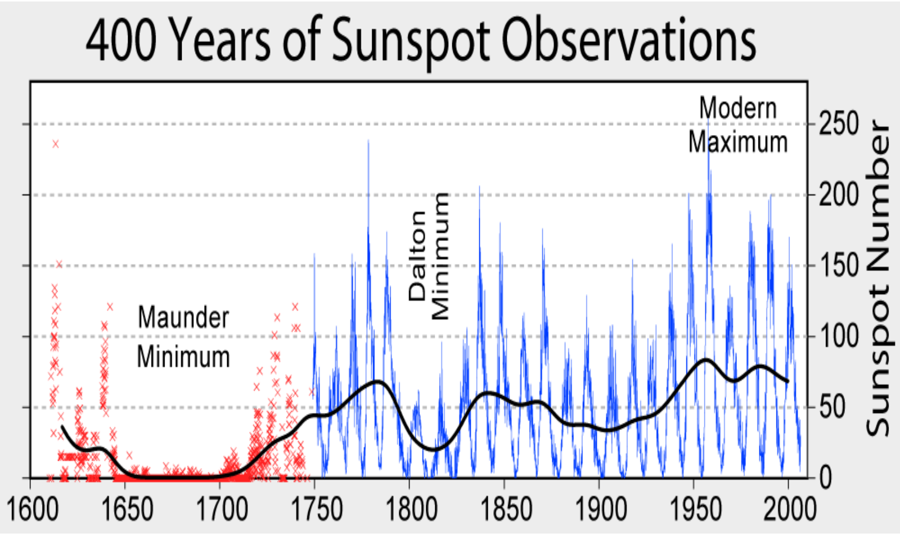
GMD and the Grid

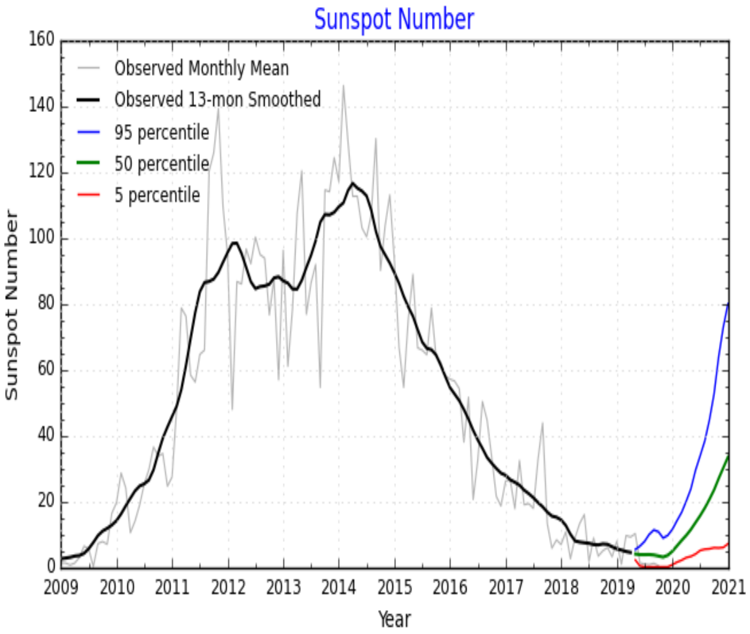
- Large solar corona mass ejections (CMEs) can cause large changes in the earth’s magnetic field (i.e., dB/dt). These changes in turn produce a non-uniform electric field at the surface
  - Changes in the magnetic flux are usually expressed in nT/minute; from a 60 Hz perspective they are almost dc
 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

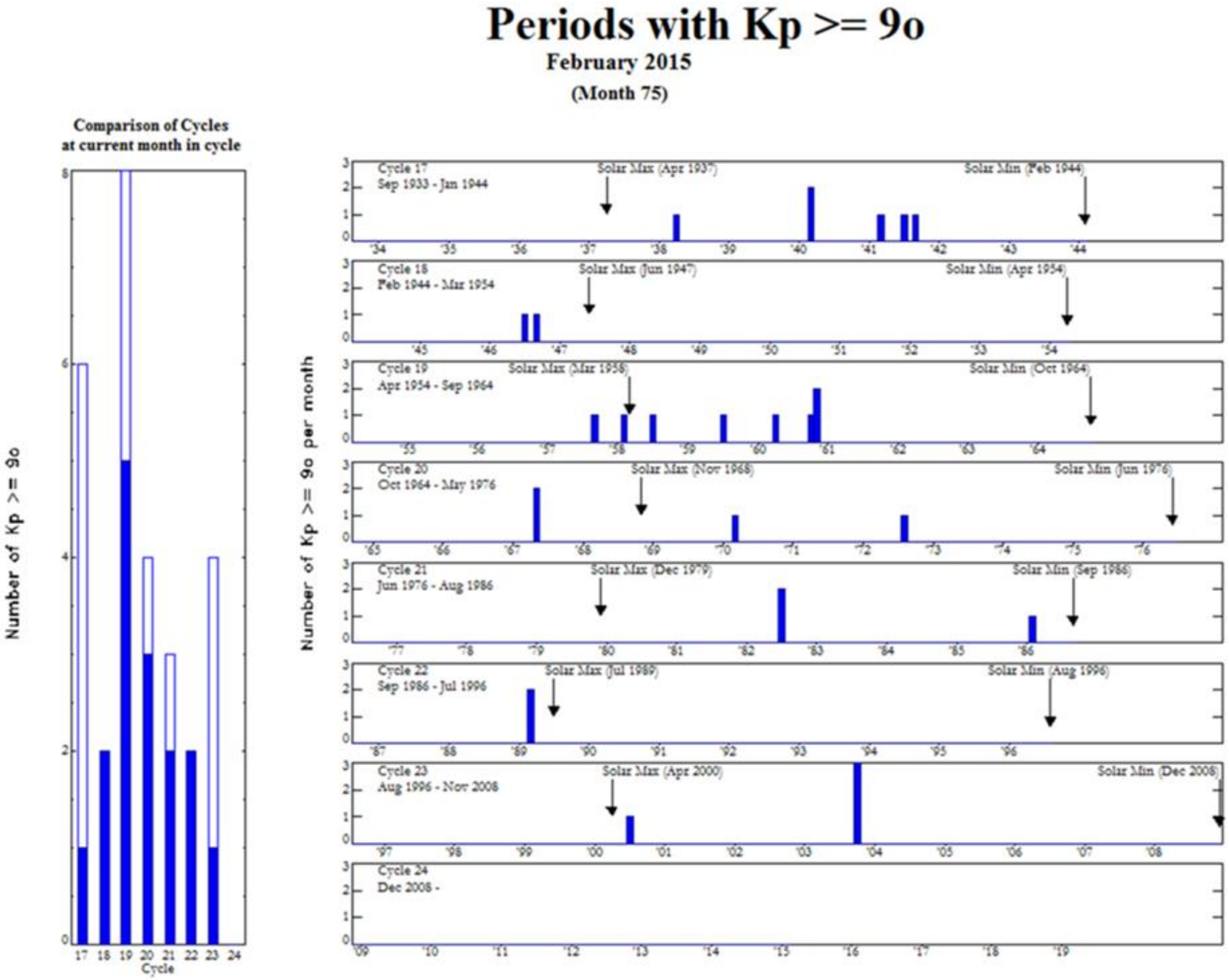
- Sunspots follow an 11 year cycle, and have been observed for hundreds of years
- We're in solar cycle 24 (first numbered cycle was in 1755); minimum was in 2009, maximum in 2014/2015





Images from NASA, NOAA

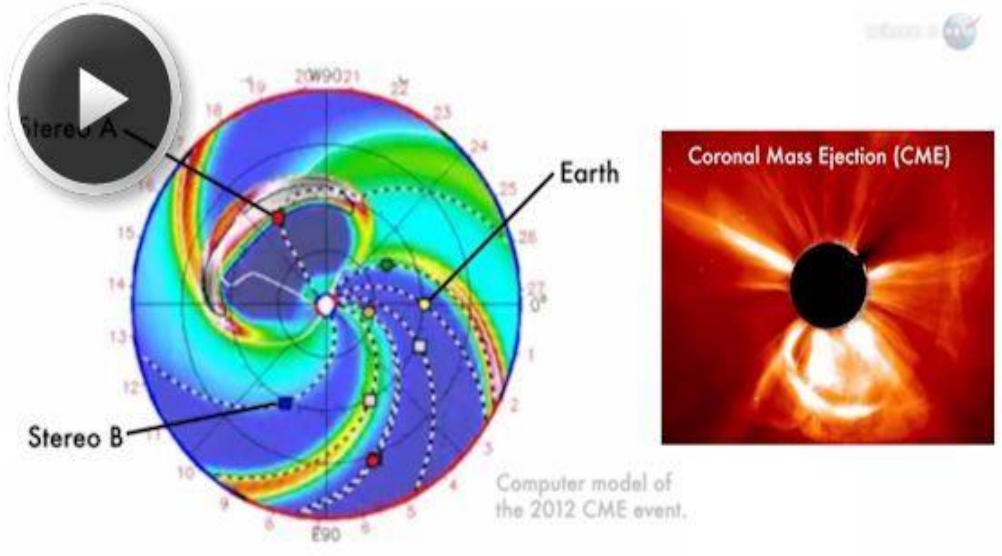
But Large CMEs Are Not Well Correlated with Sunspot Maximums



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

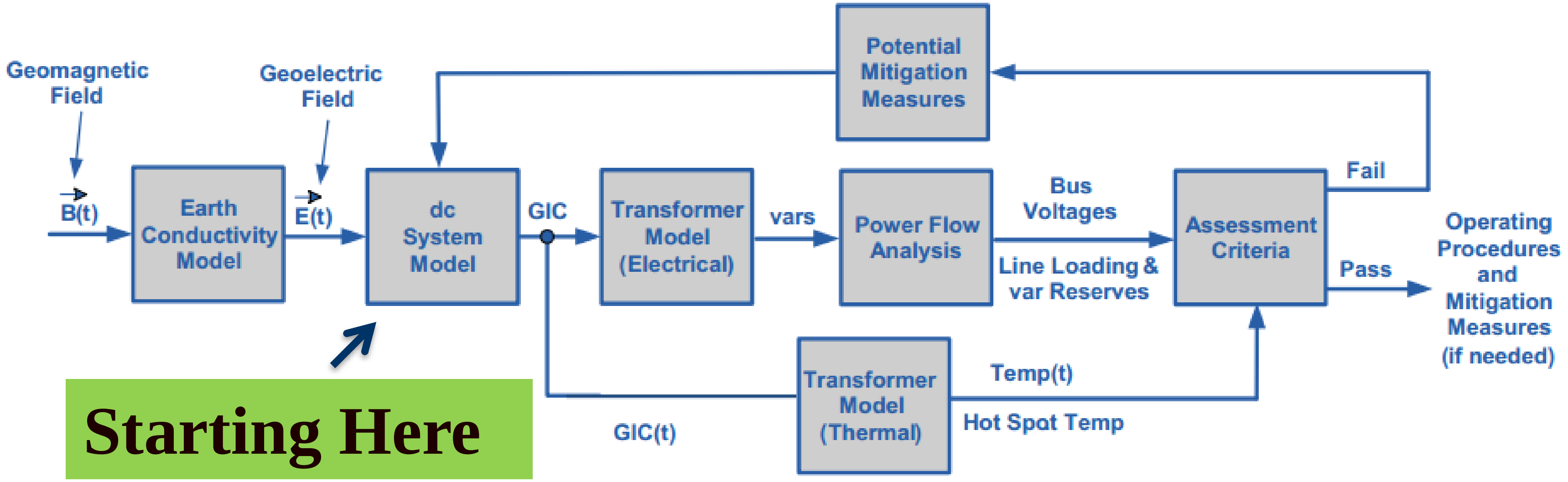


Computer model of the 2012 CME event.

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

Overview of GMD Assessments

In is a quite interdisciplinary problem



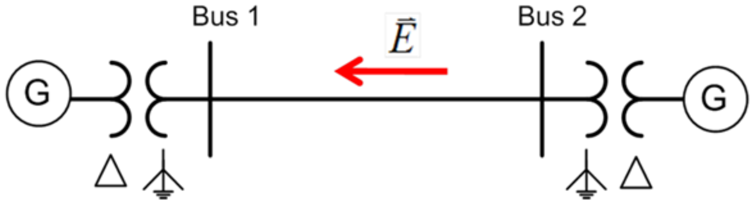
Starting Here

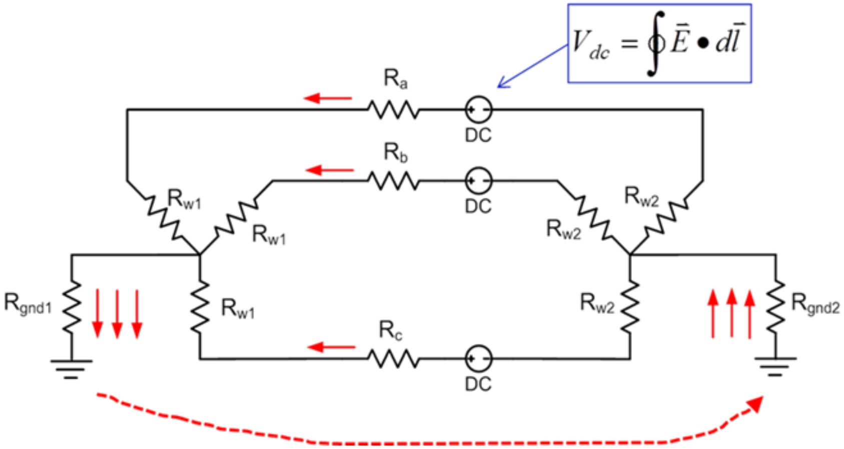
The two key concerns from a big storm are 1) large-scale blackout due to voltage collapse, 2) permanent transformer damage due to overheating

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

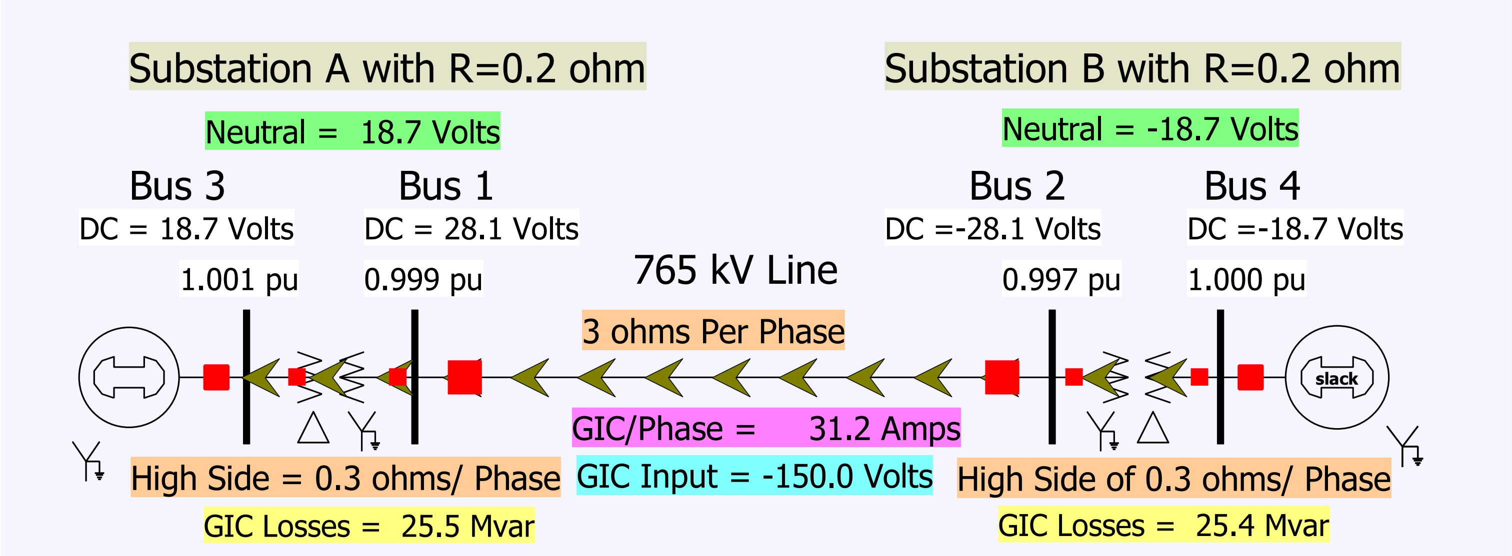
- With knowledge of the pertinent transmission system parameters and the GMD-induced line voltages, the dc bus voltages and flows are found by solving a linear equation $\mathbf{I} = \mathbf{G}\,\mathbf{V}$ (or $\mathbf{J} = \mathbf{G}\,\mathbf{U}$)
  - **J** and **U** may be used to emphasize these 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)

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



Substantion A with R=0.2 ohm

Neutral = 18.7 Volts

Substation B with R=0.2 ohm

Neutral = -18.7 Volts

Bus 3

DC = 18.7 Volts

1.001 pu

Bus 1

DC = 28.1 Volts

0.999 pu

765 kV Line

3 ohms Per Phase

Bus 2

DC =-28.1 Volts

0.997 pu

Bus 4

DC =-18.7 Volts

1.000 pu

GIC/Phase = 31.2 Amps

GIC Input = -150.0 Volts

High Side = 0.3 ohms/ Phase

GIC Losses = 25.5 Mvar

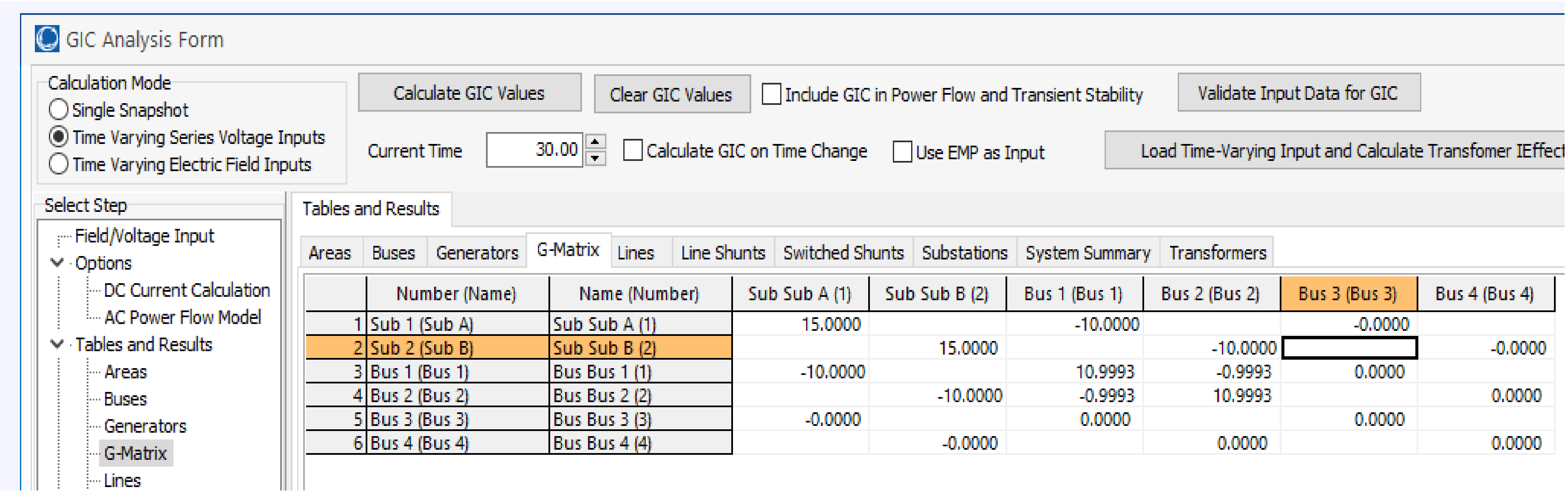
High Side of 0.3 ohms/ Phase

GIC Losses = 25.4 Mvar

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



Calculation Mode
○ Single Snapshot
● Time Varying Series Voltage Inputs
○ Time Varying Electric Field Inputs

☐ Include GIC in Power Flow and Transient Stability

Current Time 30.00

☐ Calculate GIC on Time Change

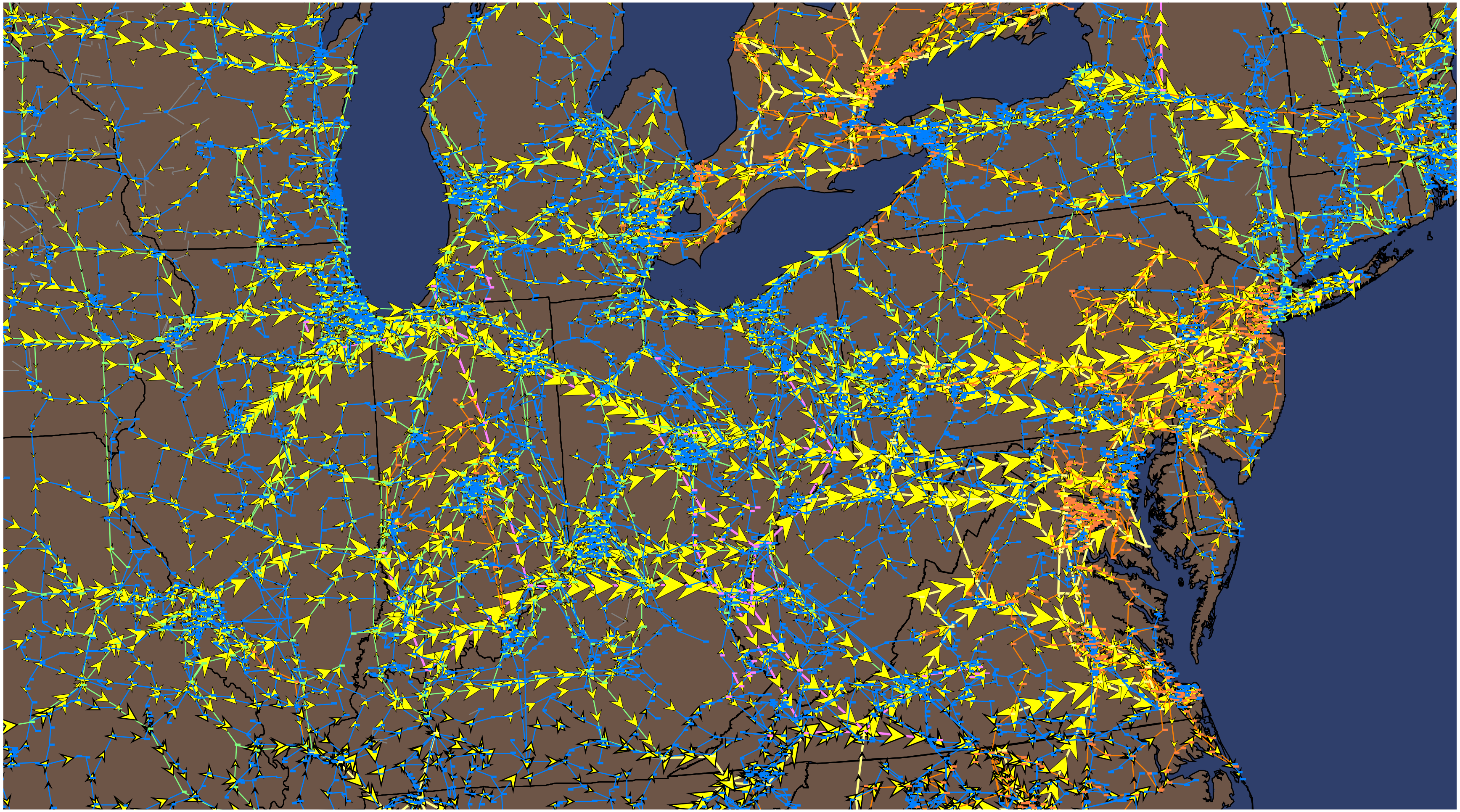
☐ Use EMP as Input

	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

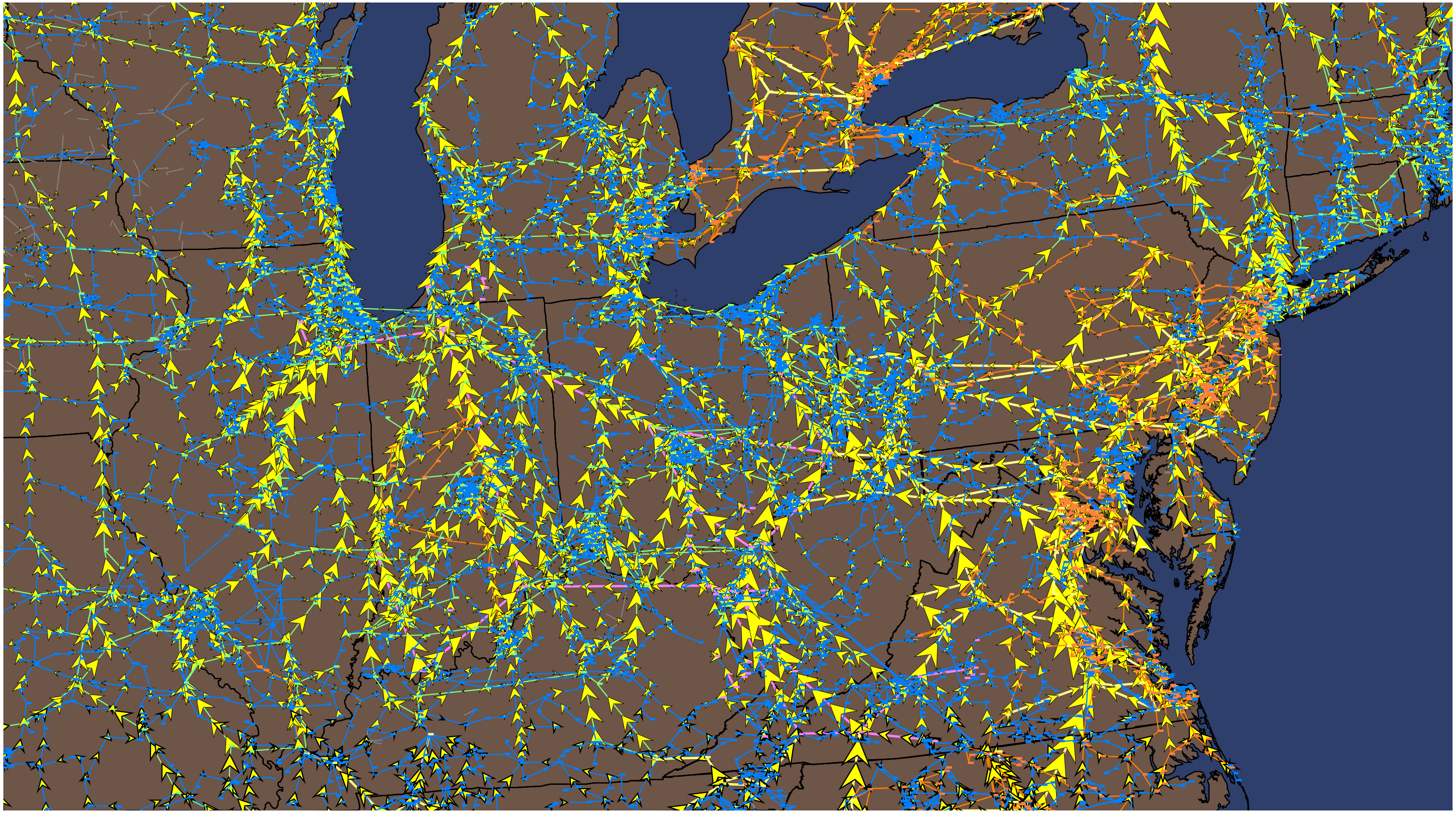
$$\mathbf{U} = [\mathbf{G}]^{-1}\mathbf{J}$$

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

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



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



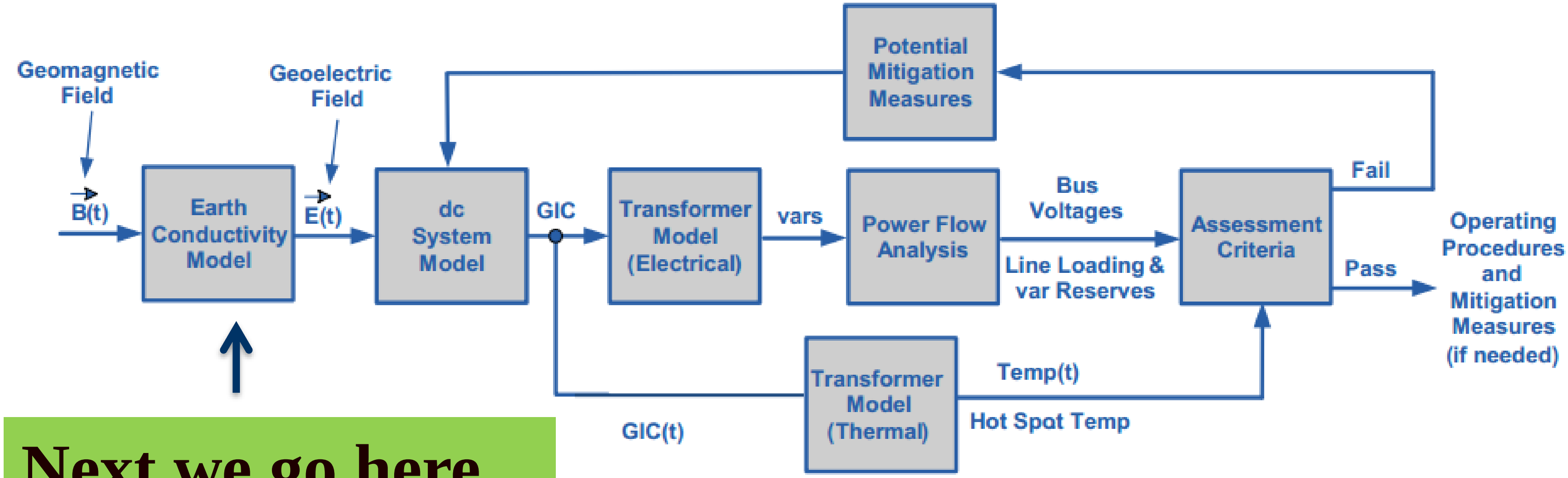
Determining GMD Storm Scenarios

- 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



Next we go here

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

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

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

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

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

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

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

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

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

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

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

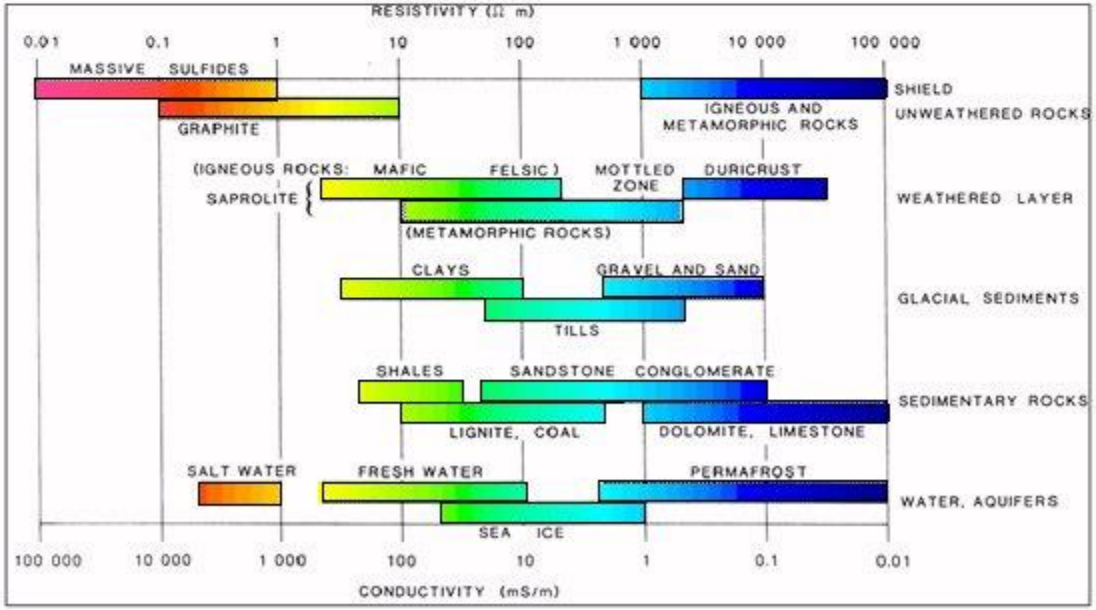


Image source: https://www.eoas.ubc.ca/courses/eosc350/content/foundations/properties/resistivity.htm

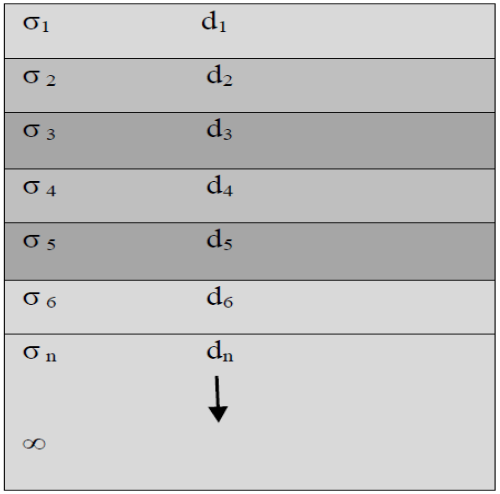
1-D Earth Models

- 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

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

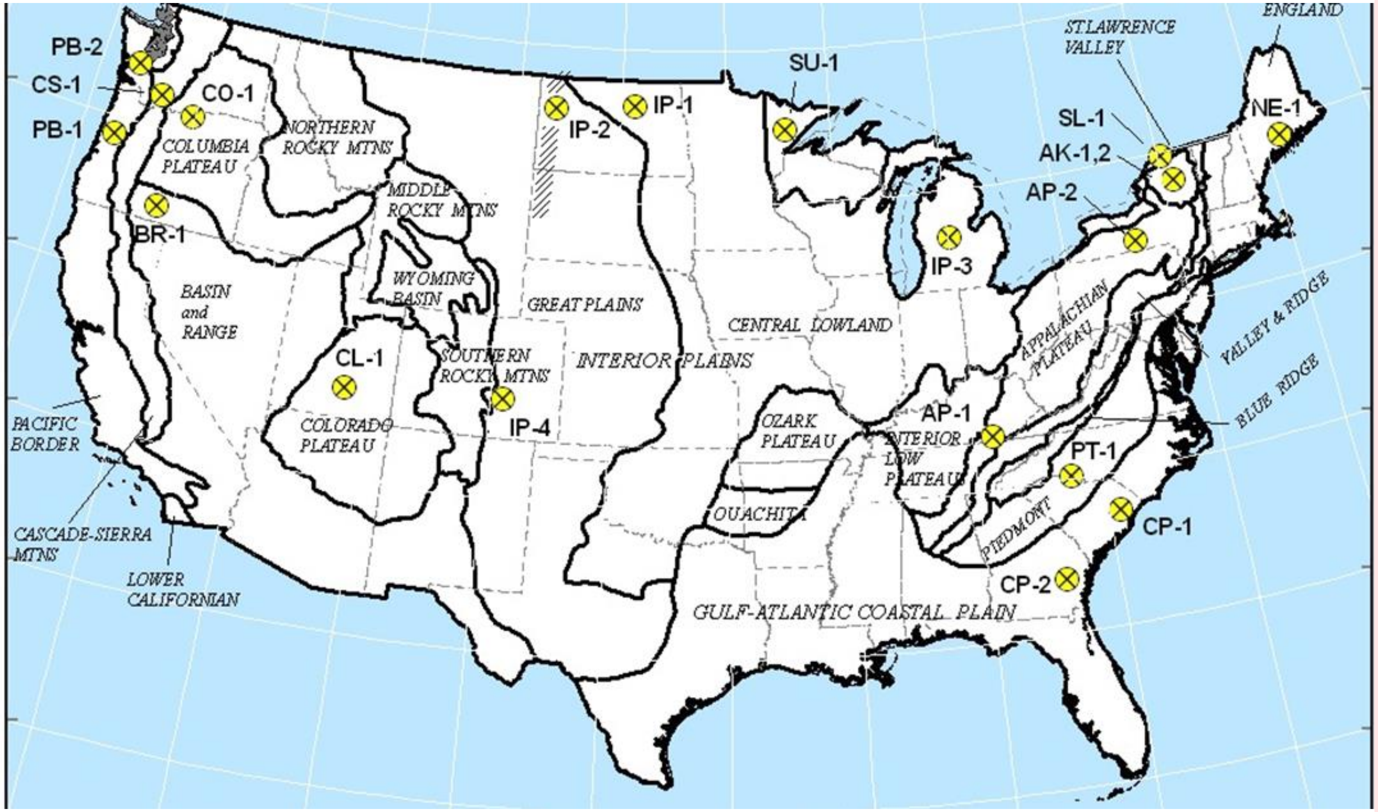
- With the impedance at the top of layer m given as

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

- 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

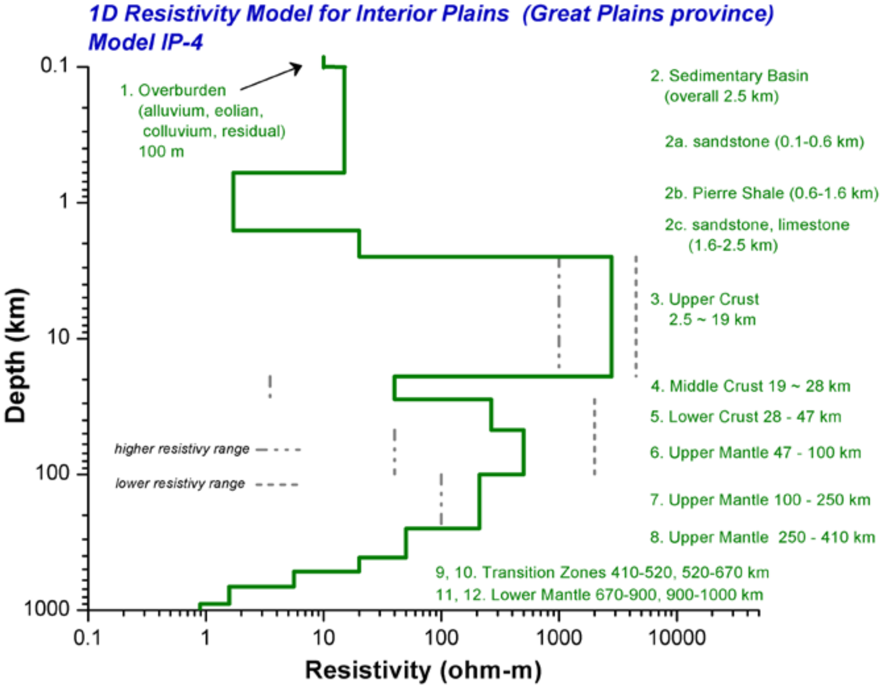


These regional scalings are now being used for power flow GMD analysis, and are being updated

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

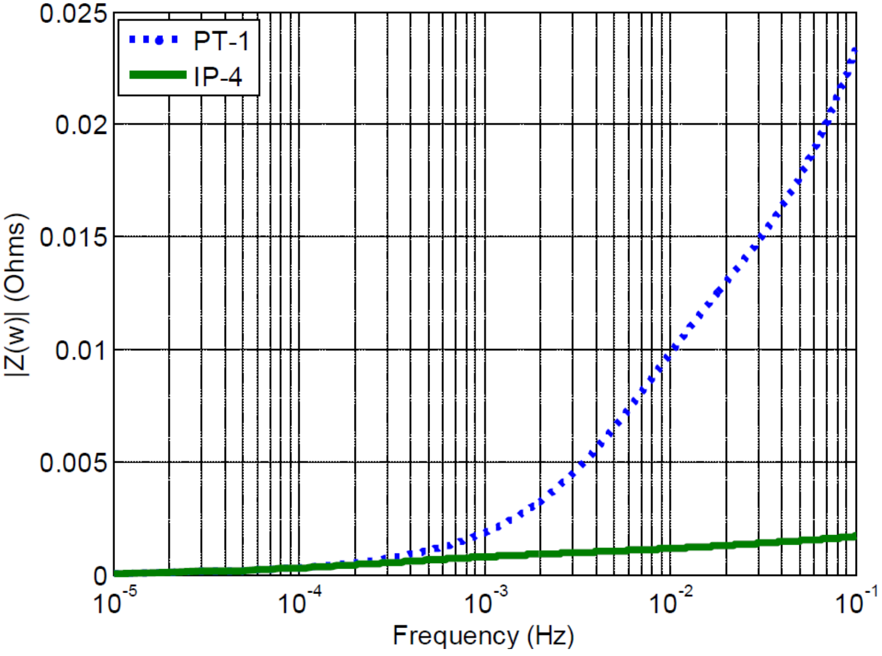
1-D Earth Models

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

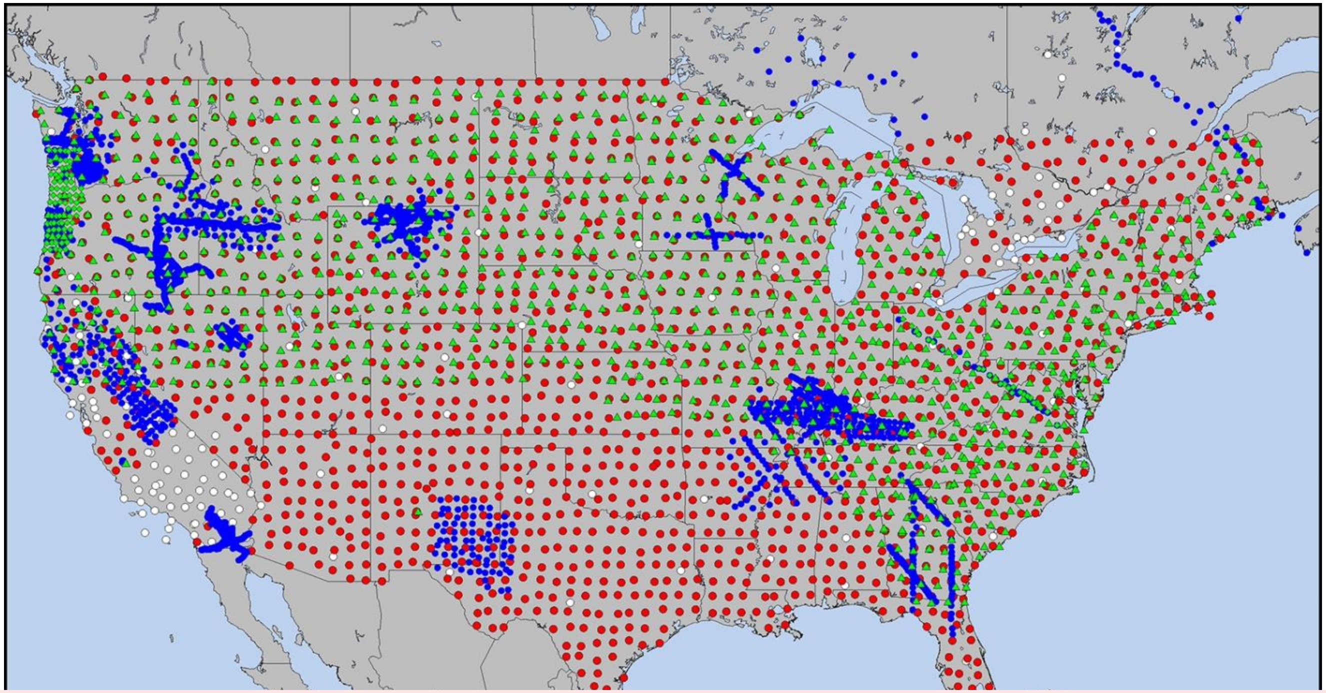


Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

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

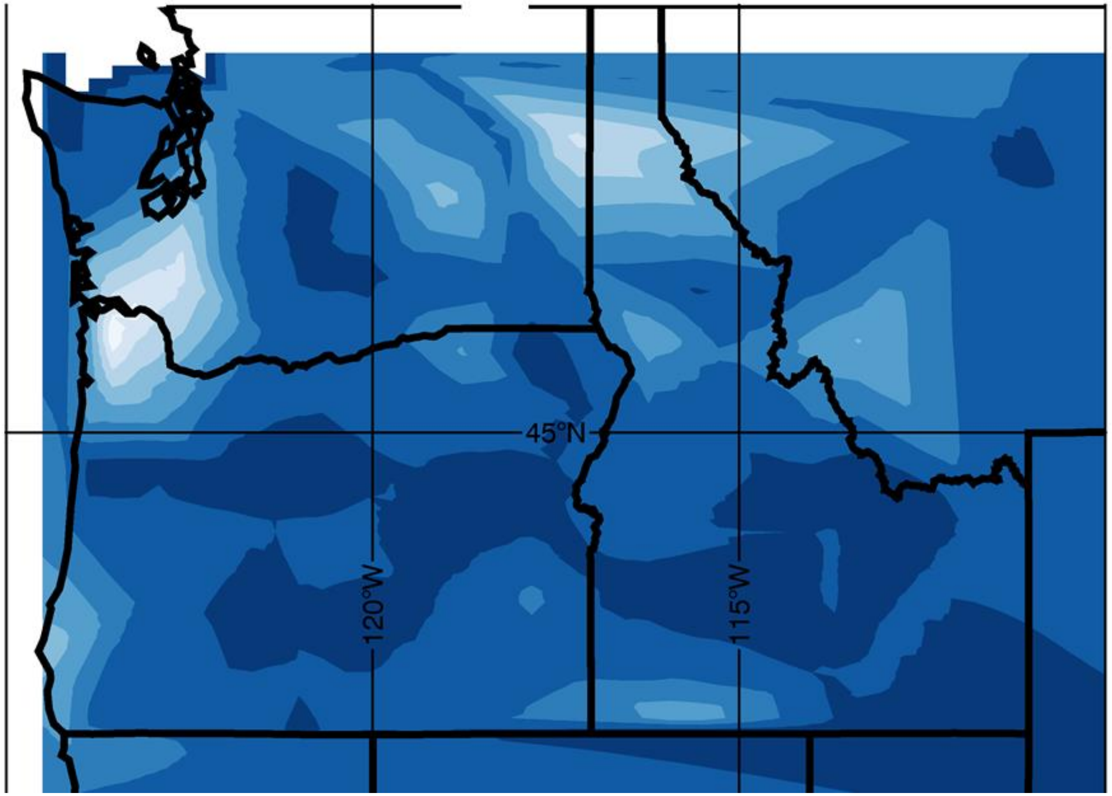
$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} \xi_{xx} & \xi_{xy} \\ \xi_{yx} & \xi_{yy} \end{bmatrix} \cdot \begin{bmatrix} Bx \\ By \end{bmatrix}$$

- 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

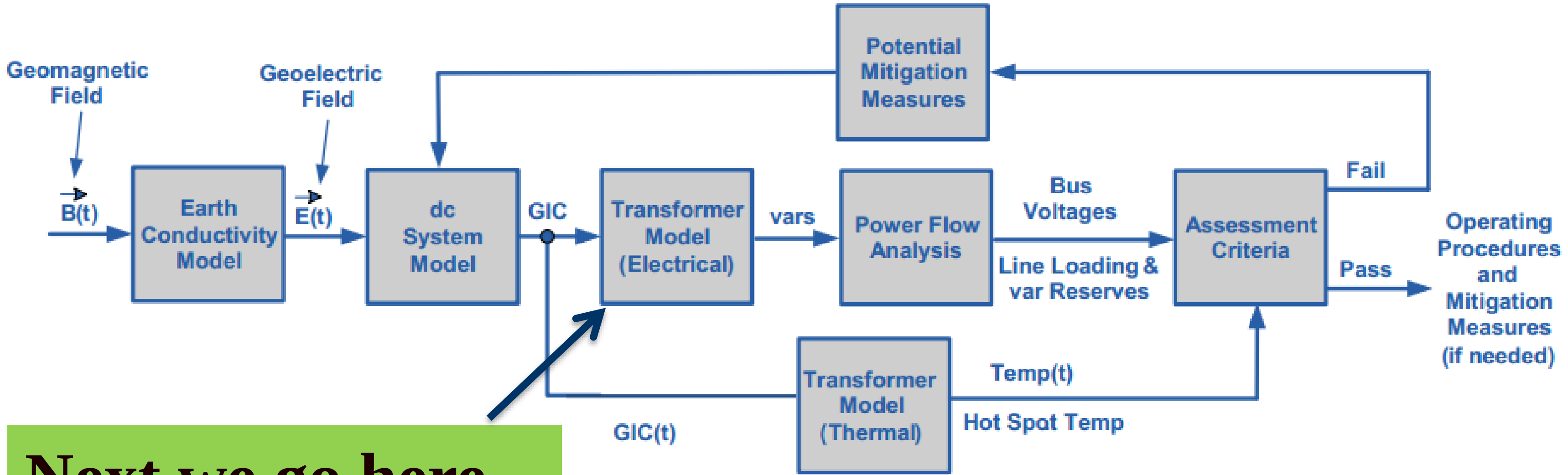


White ~ 10 V/km
Image Provided by
Jenn Gannon

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!)

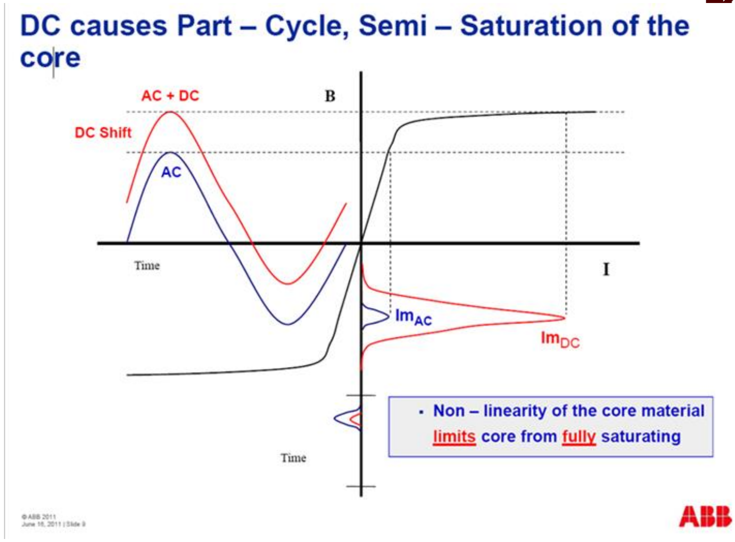
Overview of GMD Assessments



Next we go here

Transformer Impacts of GICs

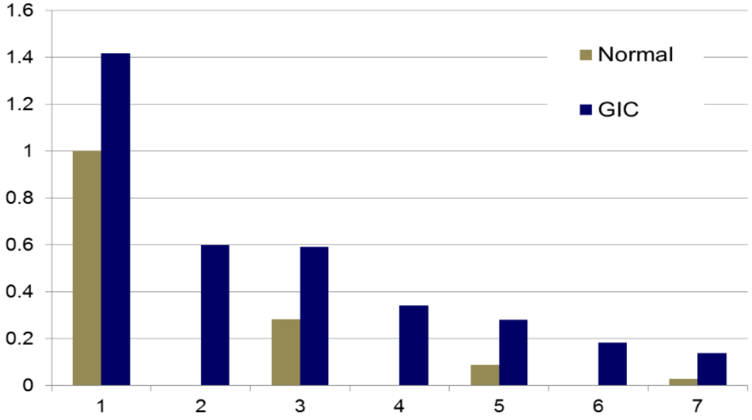
- The GICs superimpose on the ac current, causing transformers saturation for part of the ac cycle
- This can cause large harmonics; in the positive sequence these harmonics can be represented by increased reactive power losses in the transformer



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

- Non – linearity of the core material limits core from fully saturating

Harmonics



Images: Craig Stiegemeier and Ed Schweitzer, JASON Presentations, June 2011