# ECEN 615
# Methods of Electric Power Systems Analysis

## Lecture 25: Inertia Power Flow, GMD Modeling, Black Start

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# Announcements

- Problem Set 6 is due on Dec 10 (I'll actually accept it up until  Dec 11 at 1245pm)
  - It counts as two problem sets, with problems 1-4 as one set, and problem 5 as a second

# Inertia and Governor Power Flows

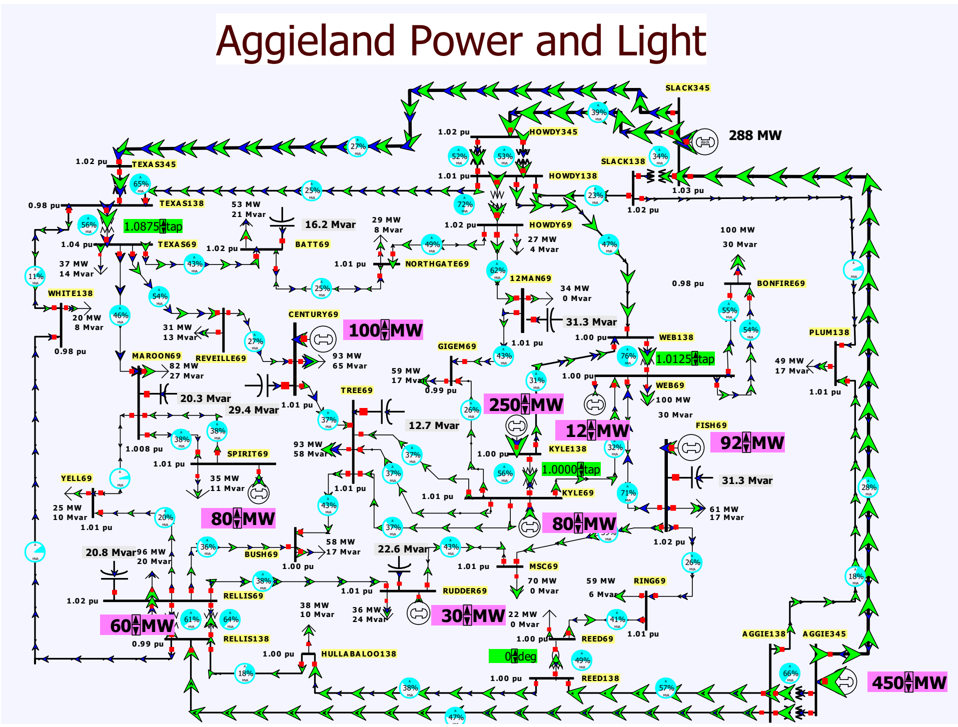
- In the regular power flow a single slack bus is used so total load + losses = total generation
- The slack bus is characterized by having a fixed voltage magnitude and angle
  - A slack bus is needed for each island though nothing precludes having multiple slack buses in an island
- If an area is on AGC then the outputs for the other generators can be changed either before or during the power flow solution
- This does not match the initial change in the generator output following a contingency

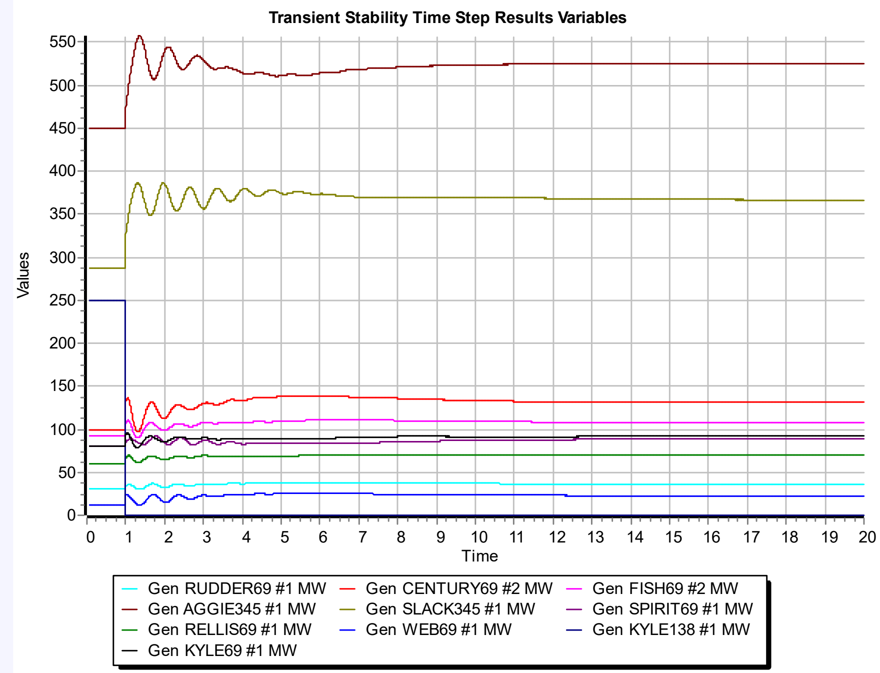
# Inertia and Governor Power Flows

- Following a generation and/or load contingency the changes in the generator outputs will be
  - Initially determined by the generator's inertia
  - After several seconds the output will be determined by the generator's governor response, which takes into account limits
  - After dozens of seconds to minutes the AGC will respond
- A governor or an inertia power flow seeks to match this initial response
  - A useful reference is M. Lotfalian, R. Schlueter, et. al., "Inertial, Governor and AGC/Economic Dispatch Load Flow Simulations of Loss of Generation Contingencies," IEEE Trans. Power Apparatus and Systems, Nov. 1985

# Generator Output Example

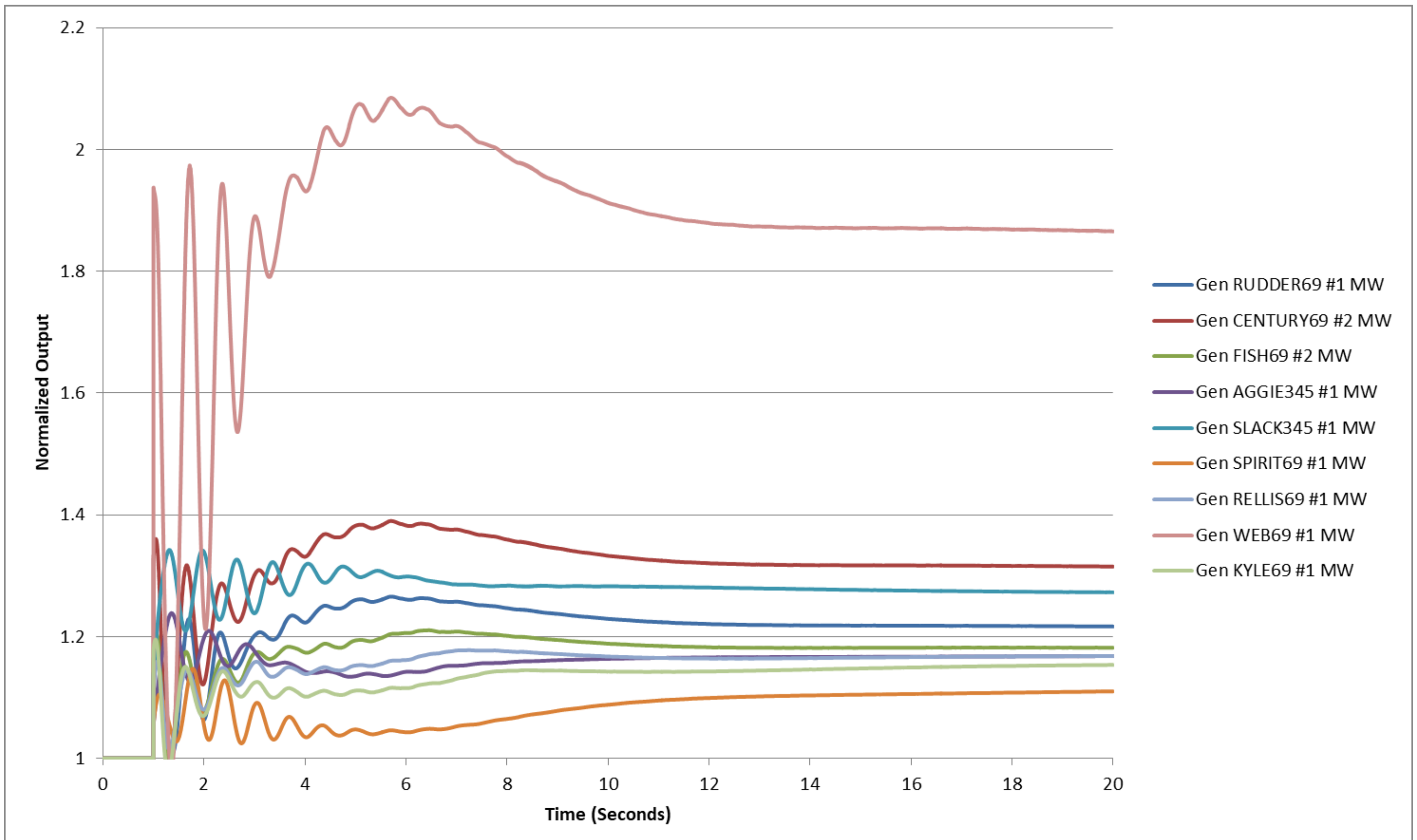
- Example shows the generator outputs following the loss of a 250 MW generator (at Kyle138)



# Generator Output Example, cont.

- Graph shows the normalized change in output, with the initial value based on the inertia then on the governor



# Inertia and Governor Power Flows

- The inertia and governor power flows seek to match this response by including in each real power balance equation an additional term that the allocates this power mismatch to each generator in proportion to its relative percentage inertia or relative percentage governor response
- This is a distributed slack approach since the allocation occurs inside the power flow iteration
- There is still a slack bus to provide an angle reference

# Inertia Power Flow

- In an inertia power flow let α be the accelerating power. Then at each generator bus i the generator output is

$$P_{Gi} = P_{0,Gi} + \frac{H_i}{H_T}\alpha$$

where $P_{0,Gi}$ is the initial power output for the bus i generators,
$H_i$ is the inertia constant for all the generators at bus i and
$H_T$ is the total inertia constant for all the generators
(both values are per unit on the system MVA base)

- The accelerating power can just be included as a solution variable
- Real power flow equations are then written for all the buses, but the slack angle is not a solution variable

# Two Bus DC Power Flow Example

- Assume a two bus system with the buses connected with a lossless line with X=0.1. Let bus 2 be the slack with $\theta_2$=0, generators at both buses with $P_{G1}$ =1 and a single load (at bus 1) with $P_{L1}$=3. Assume equal inertia for the generators
- In a traditional dc power flow there is one equation

$$P_{G1} - P_{L1} = 1 - 3 = 10\theta_1$$

# Two Bus DC Power Flow Example

- With the inertia approach there would be two equations and the power is specified at both buses (say $P_{G2}$=1.5)

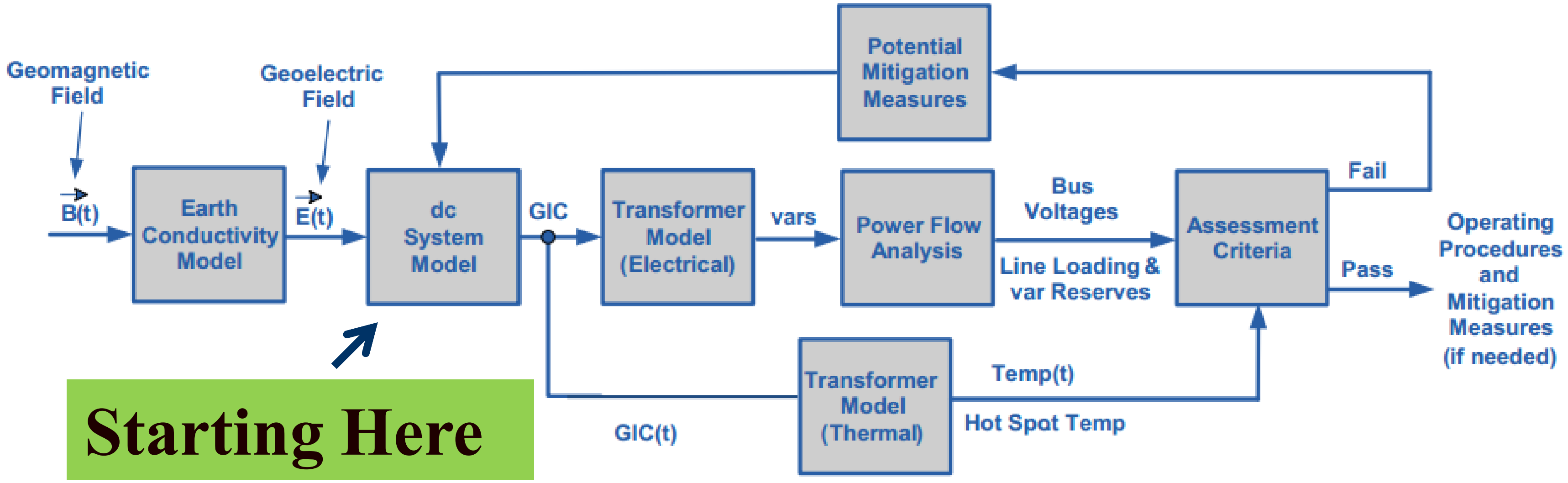
$$P_{G1} - P_{L1} + 0.5\alpha = 10\theta_1$$
$$P_{G2} + 0.5\alpha = 10\theta_1$$

- Solving gives

$$\begin{bmatrix} 10 & -0.5 \\ -10 & -0.5 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \alpha \end{bmatrix} = \begin{bmatrix} -2 \\ 1.5 \end{bmatrix} \rightarrow \begin{bmatrix} \theta_1 \\ \alpha \end{bmatrix} = \begin{bmatrix} -0.175 \\ 0.5 \end{bmatrix}$$

# Back to GMD: The Assessment

In is a quite interdisciplinary problem

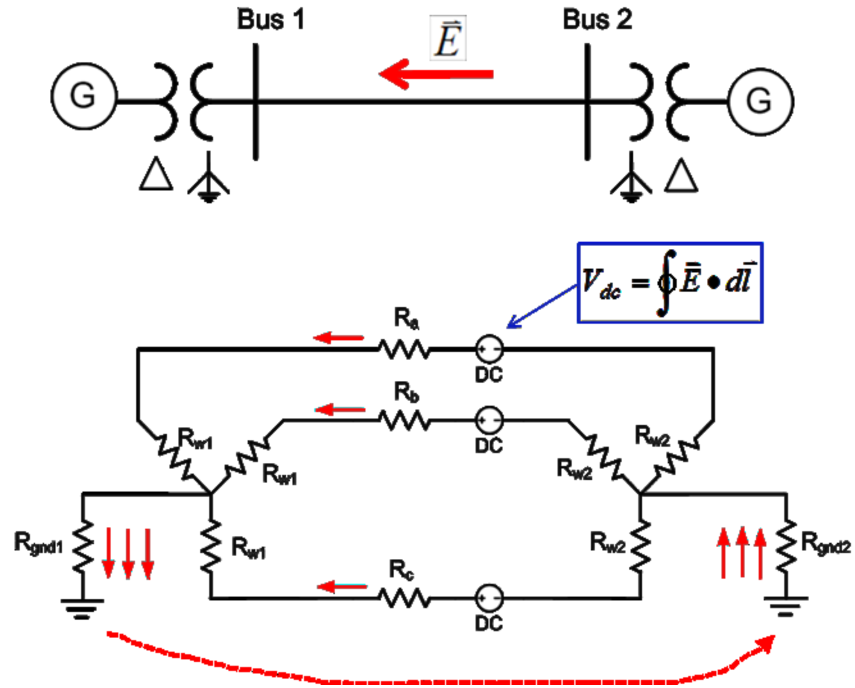



The two key concerns from a big storm are 1) large-scale blackout due to voltage collapse, 2) permanent transformer damage due to overheating

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

# Geomagnetically Induced Currents (GICs

- 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

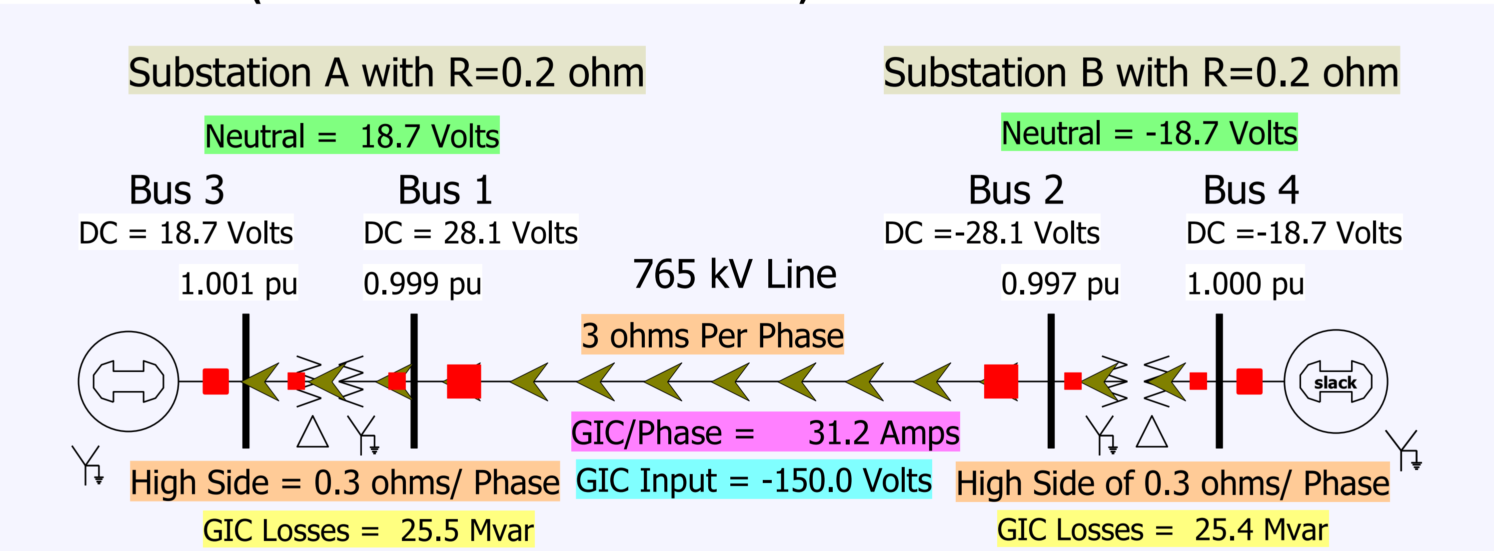
- With knowledge of the pertinent transmission system parameters and the GMD-induced line voltages, the dc bus voltages and flows are found by solving a linear equation **I** = **G V** (or **J** = **G U**)
  - **J** and **U** may be used to emphasize these are dc values, not the power flow ac values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

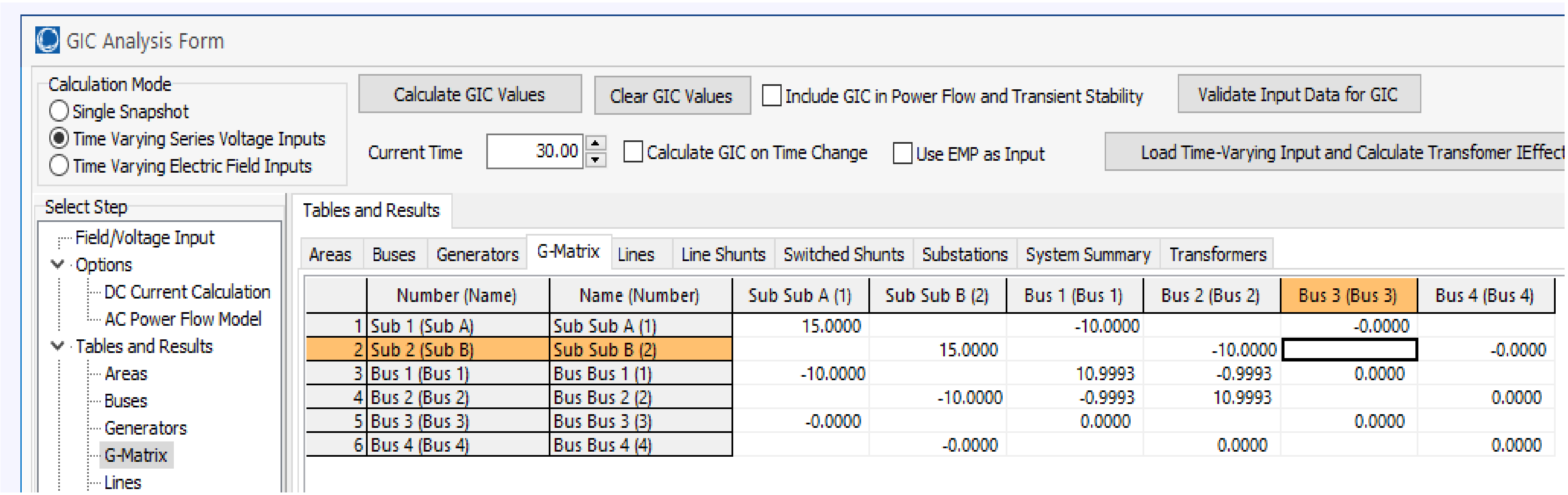
$$I_{GIC,3Phase} = \frac{150\,\text{volts}}{(1+0.1+0.1+0.2+0.2)\Omega} = 93.75\text{ amps or }31.25\text{ amps/phase}$$




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**

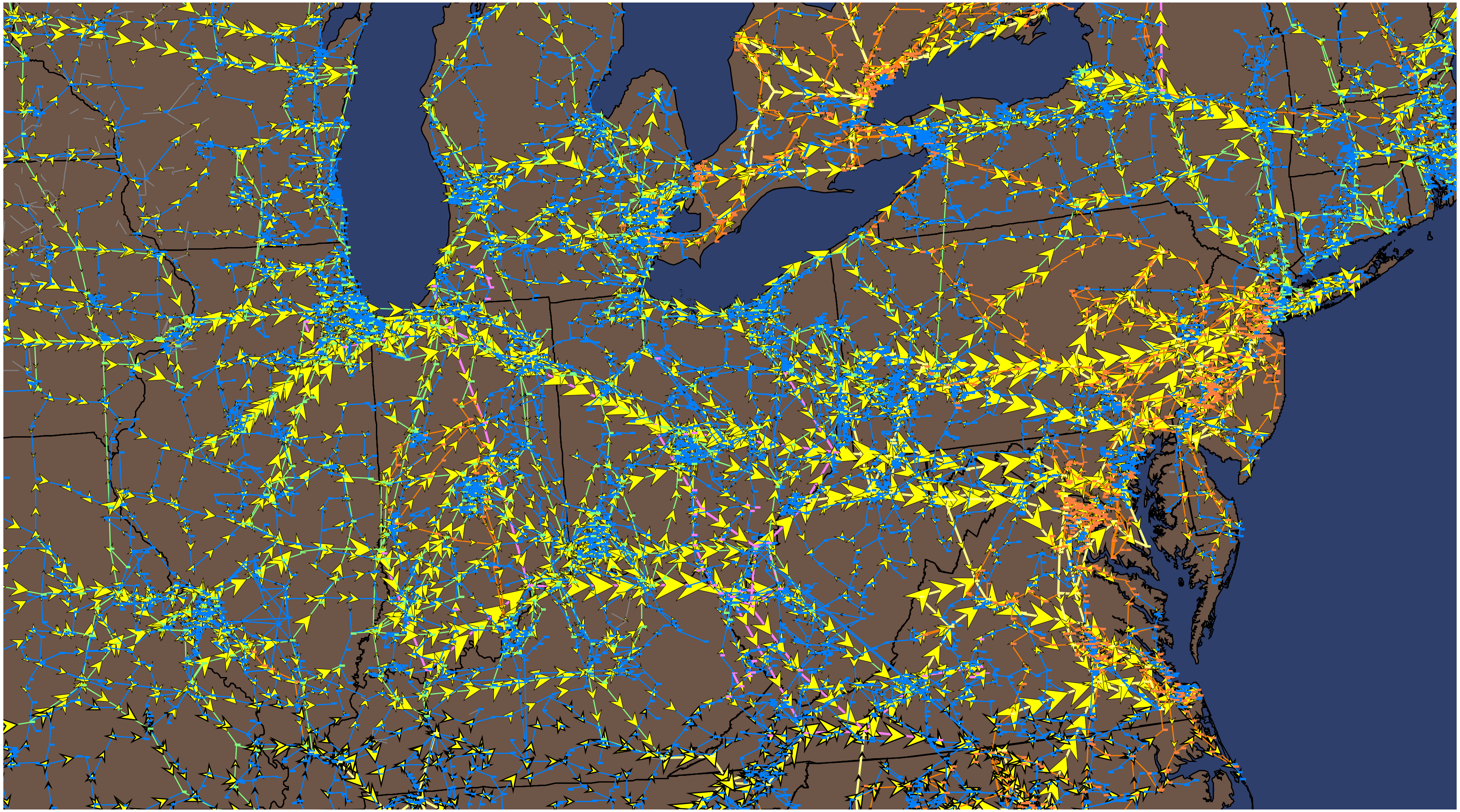
# Four Bus Example GIC G Matrix



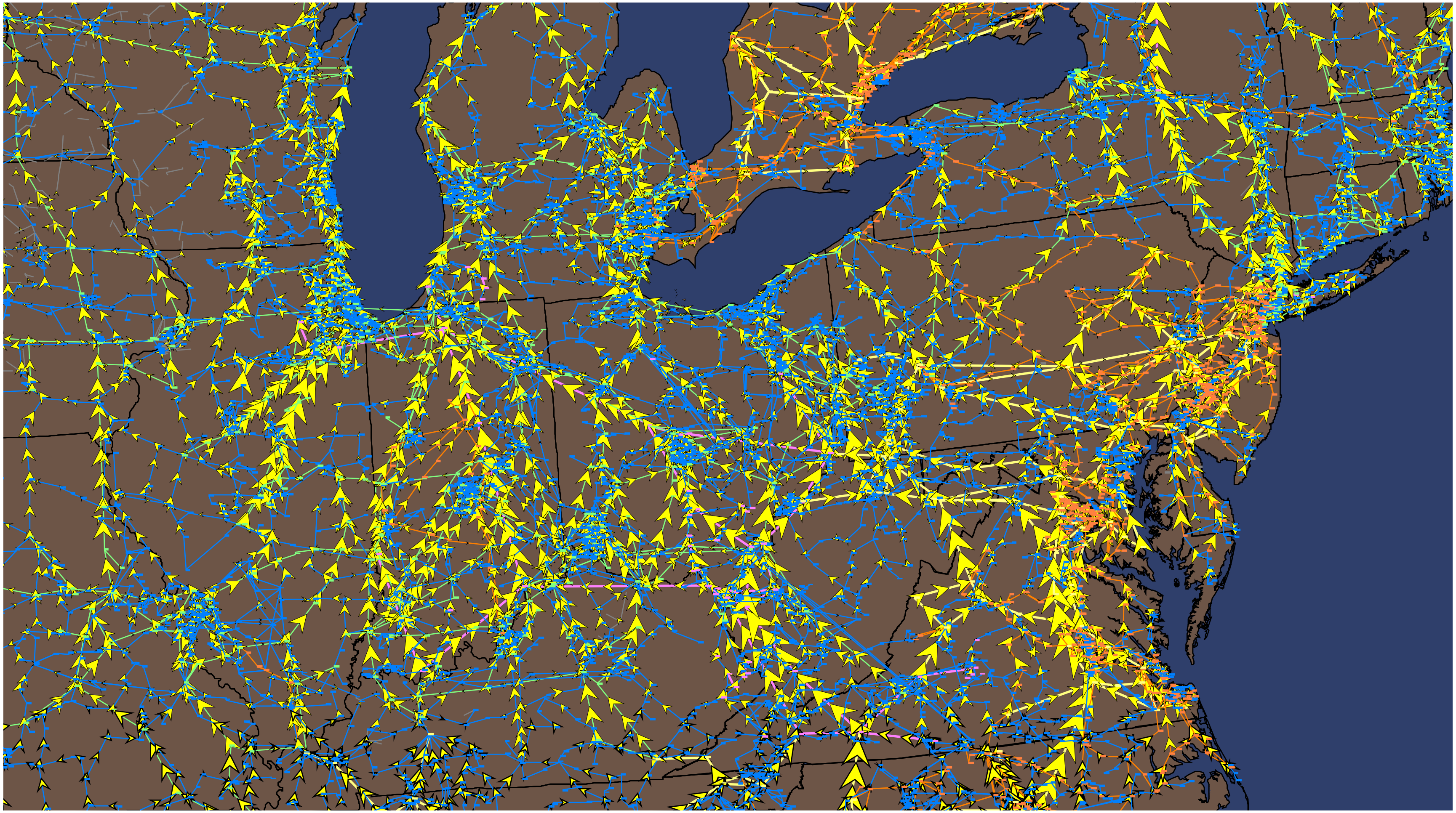

$$\mathbf{U} = [\mathbf{G}]^{-1}\mathbf{J}$$

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

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



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



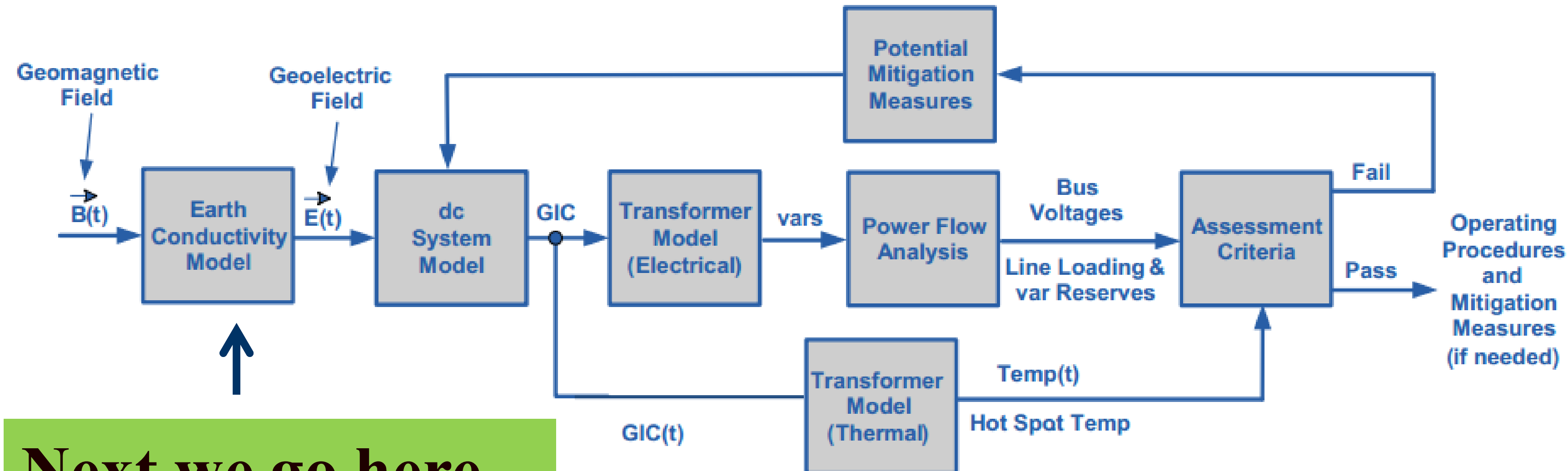
# Determining GMD Storm Scenarios

- 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

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

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

# 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

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

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

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

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

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

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

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

A more resistive earth gives higher electric fields

# Typical Conductance and Resistivity Values

- Soil conductance is often expressed in its inverse of resistivity in 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

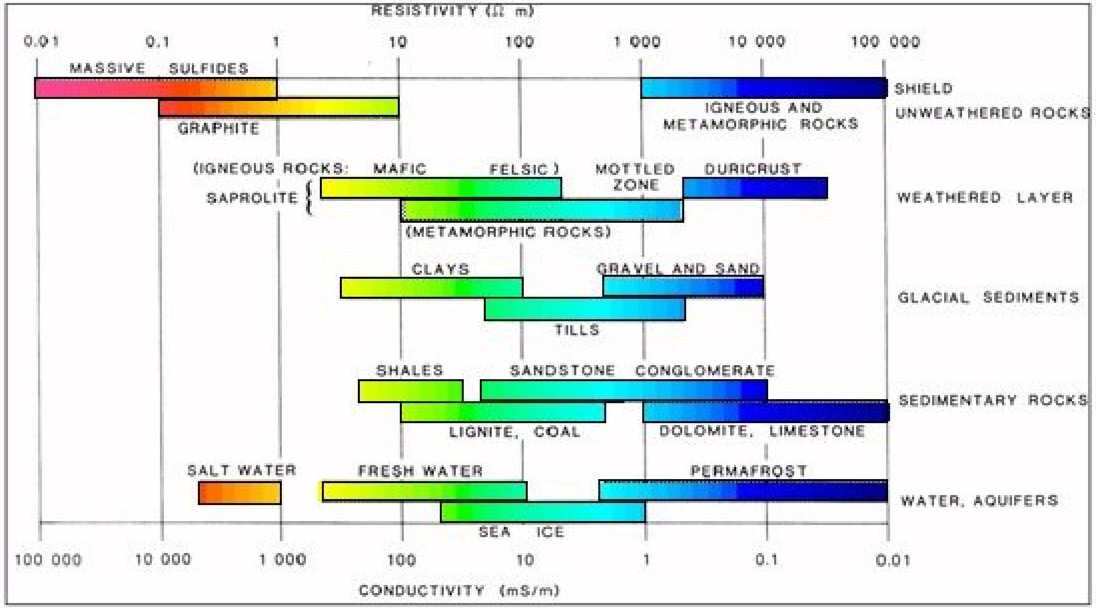



Image source: https://www.eoas.ubc.ca/courses/eosc350/content/foundations/properties/resistivity.htm

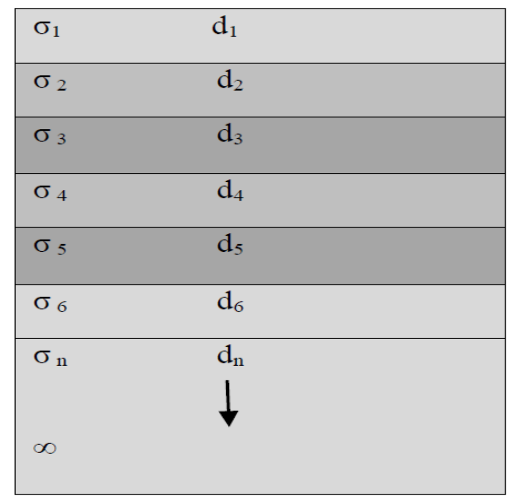
# 1-D Earth Models

- 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

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

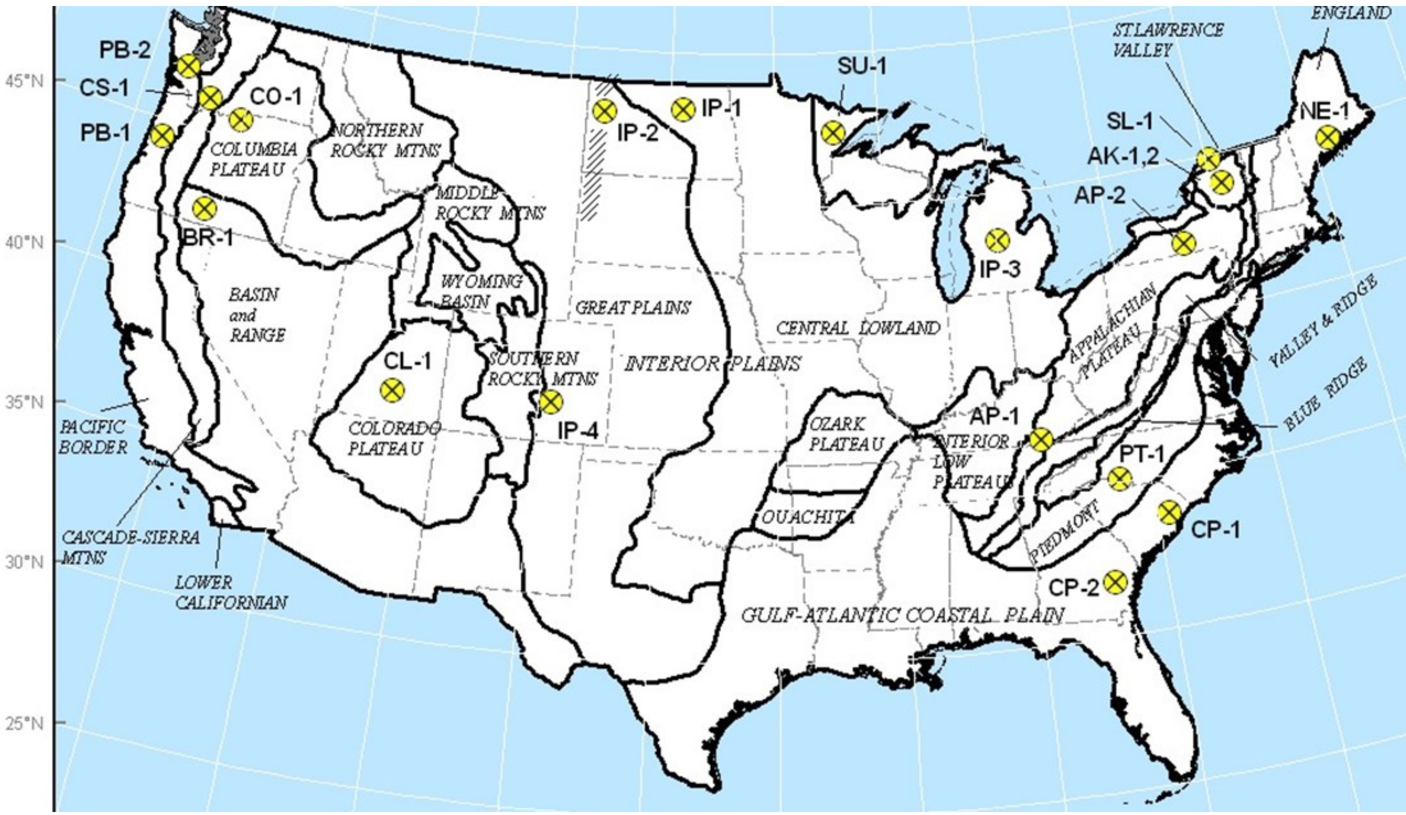
- With the impedance at the top of layer m given as

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

- 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

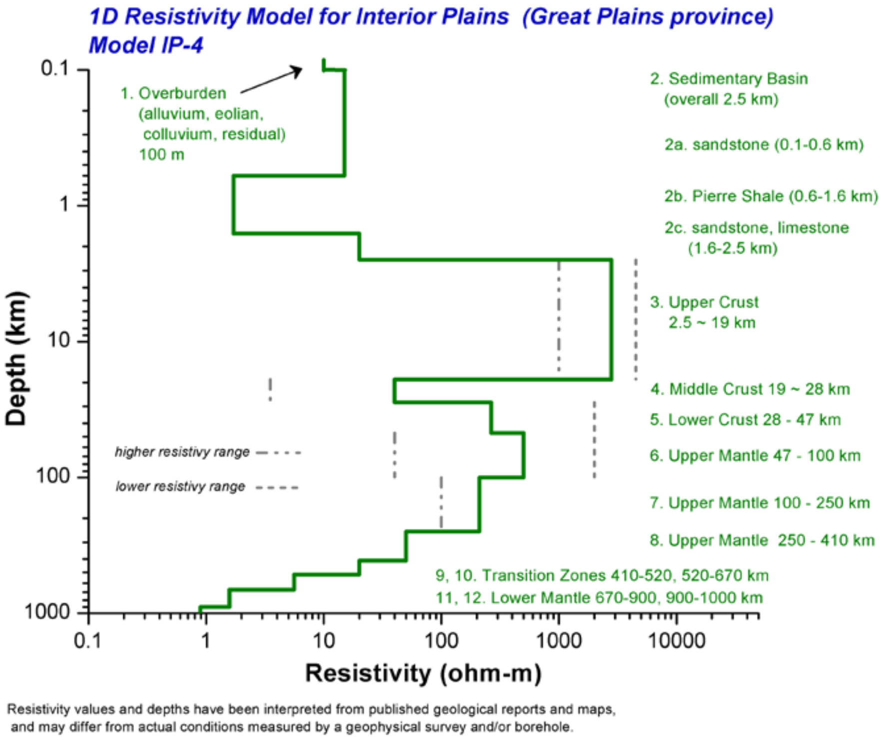
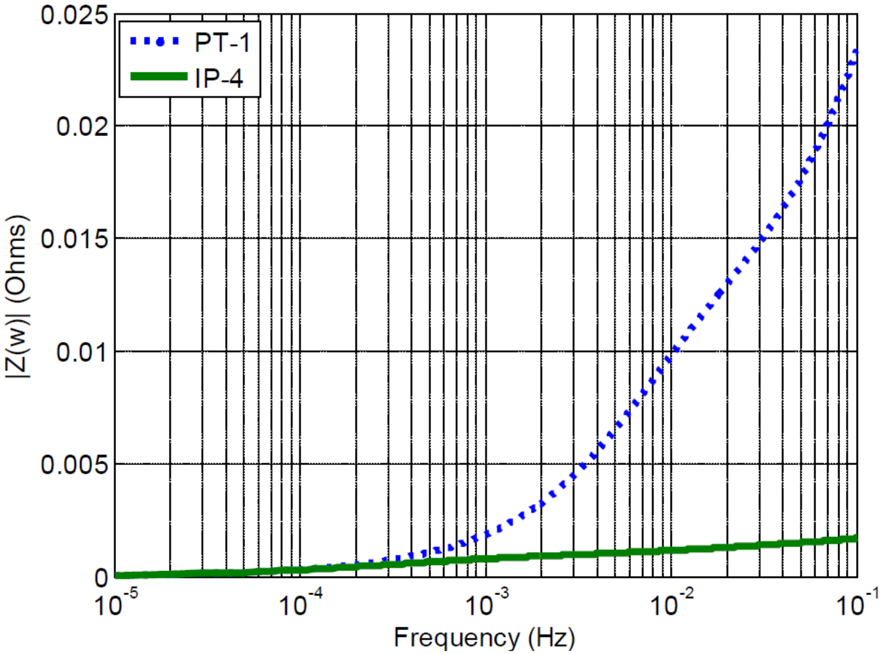
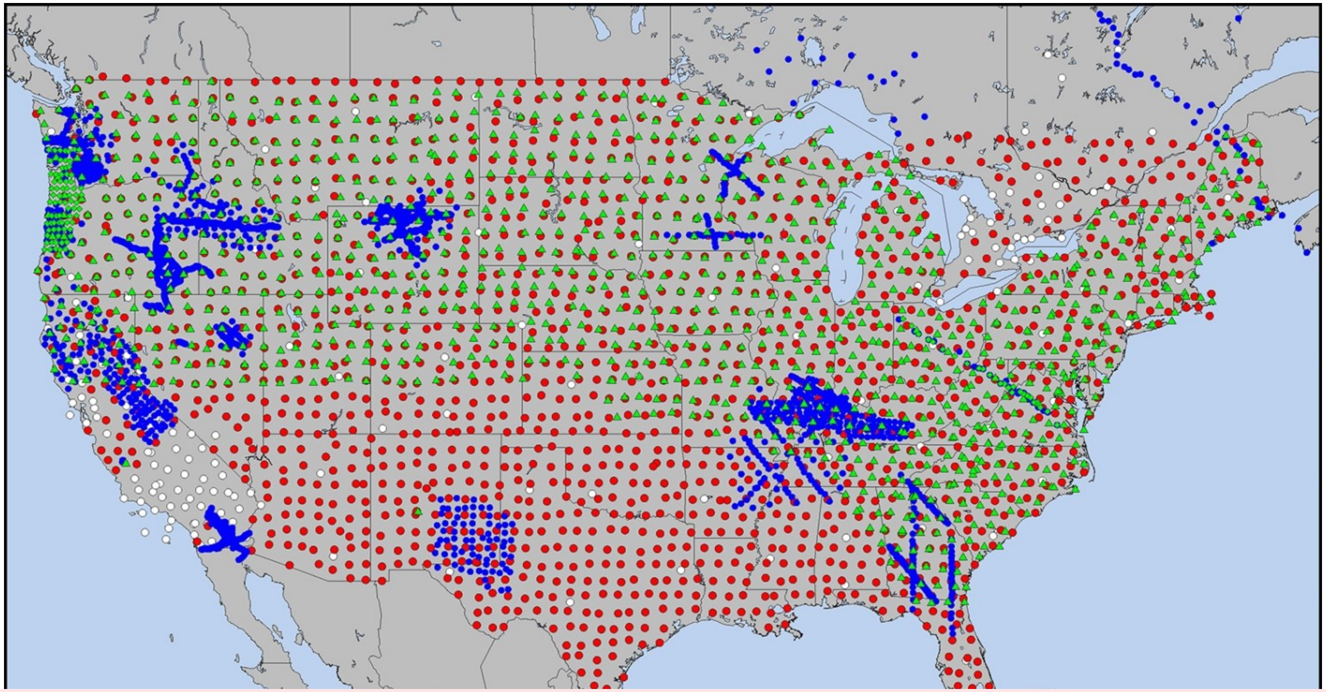



Figure 9: Frequency response of two layered Earth conductivity models.



# 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

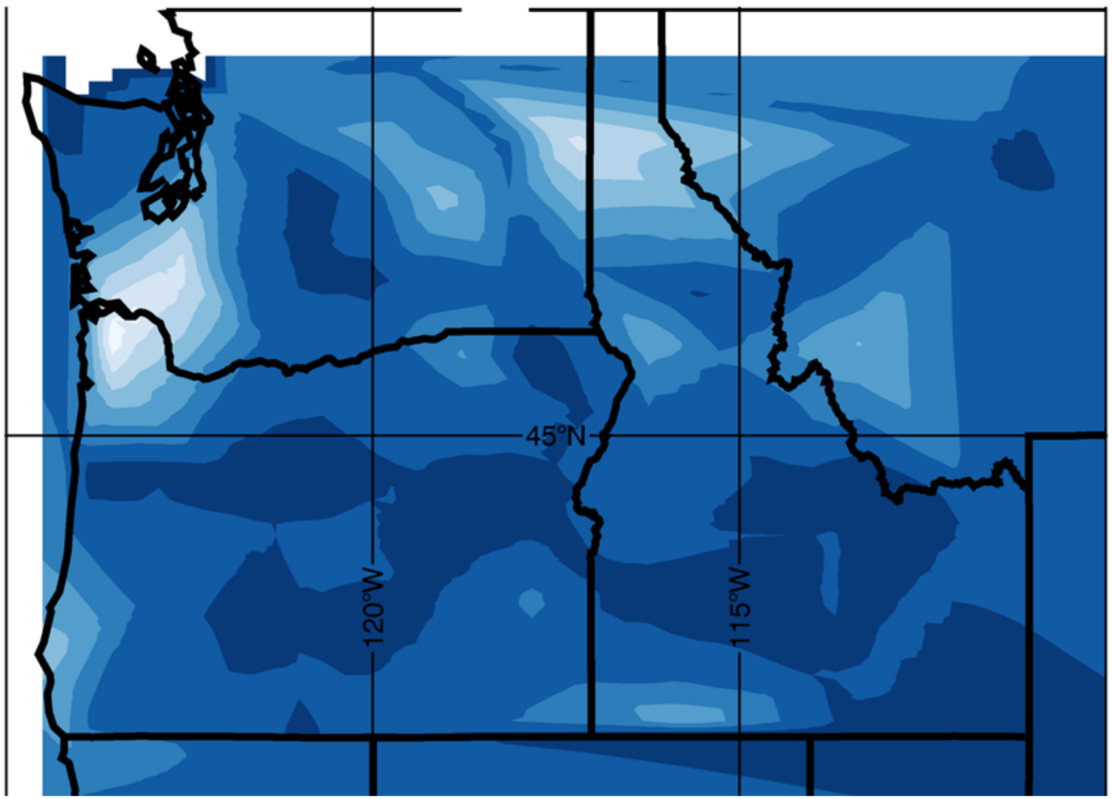
$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} \xi_{xx} & \xi_{xy} \\ \xi_{yx} & \xi_{yy} \end{bmatrix} \cdot \begin{bmatrix} Bx \\ By \end{bmatrix}$$

- 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

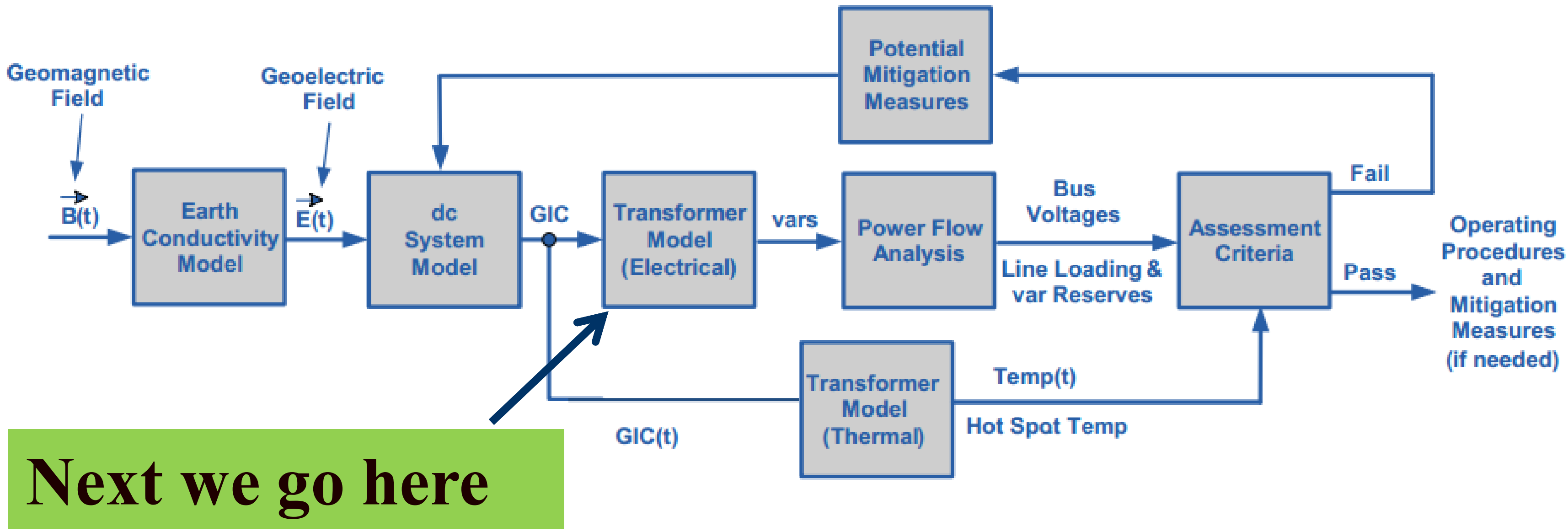



White ~ 10 V/km
Image Provided by Jenn Gannon

# Input Electric Field Considerations

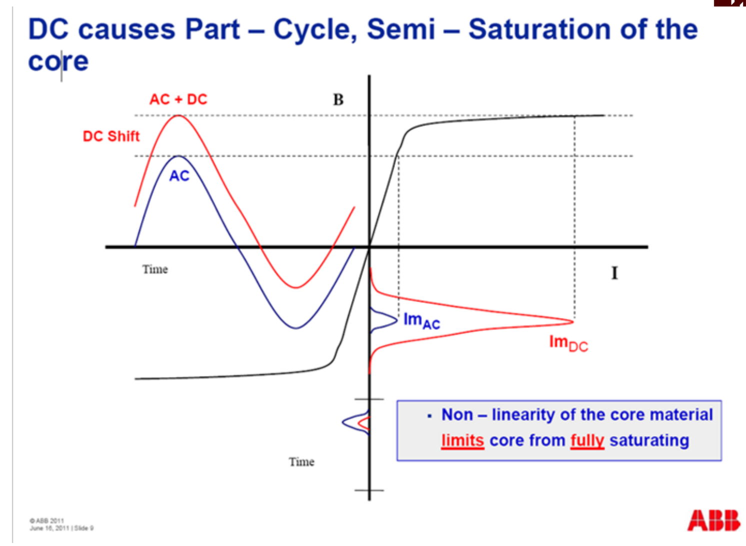
- The current vector (**I**) depends upon the assumed electric field along each transmission line
- With a uniform electric field determination of the transmission line's GMD-induced voltage is path independent
  - Just requires geographic knowledge of the transmission line's terminal substations
- With 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!)

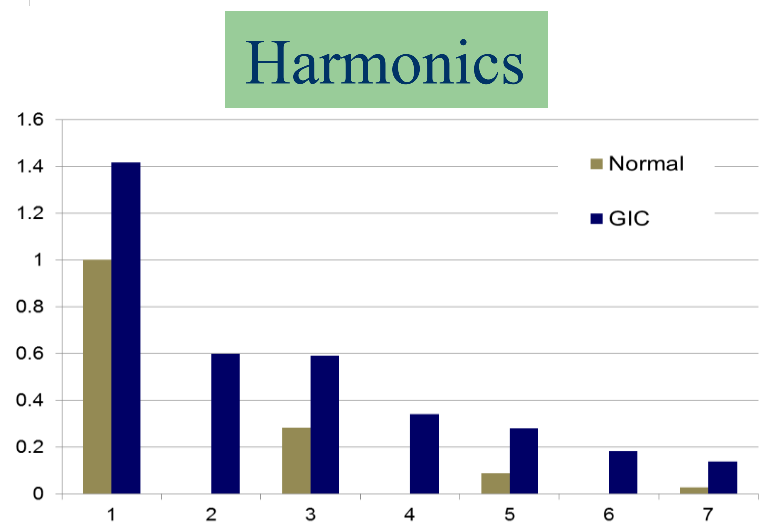
# Overview of GMD Assessments



# 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




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

$$Q_{loss} = K V_{pu} I_{GIC,Eff}$$

- 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 $S_{base,xf}$

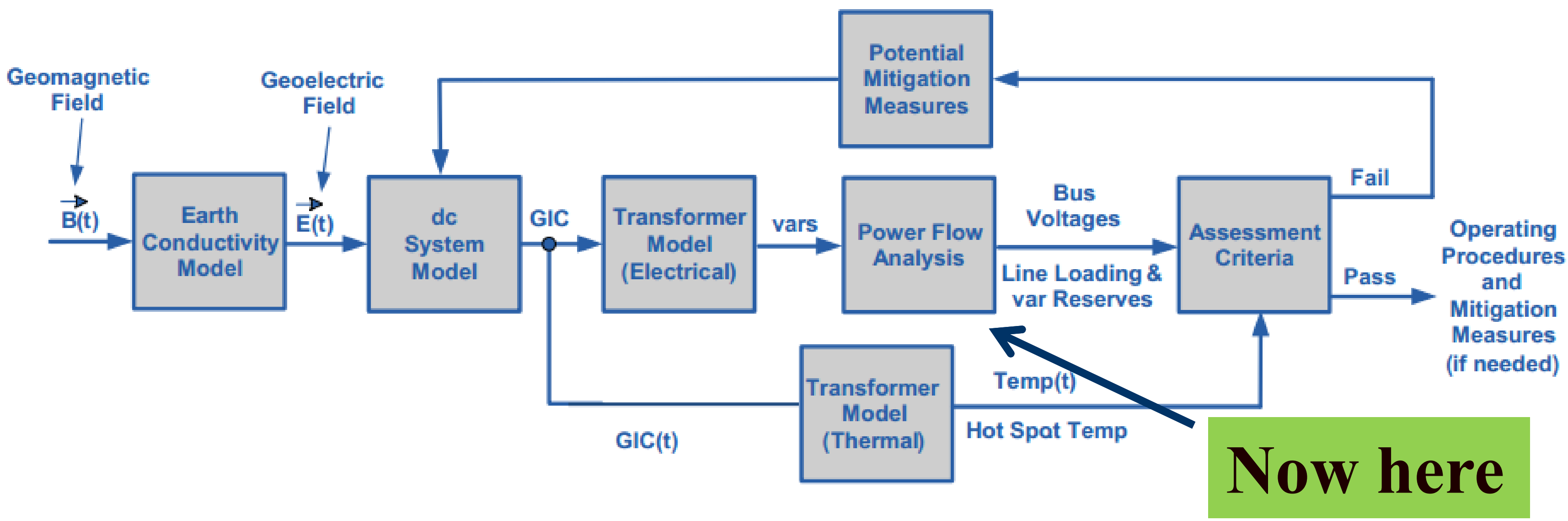
$$\frac{Q_{loss}}{S_{base,xf}} = \frac{V_{pu} K_{old} \frac{V_{base,highkv}}{500} 1000 I_{GIC,Eff} \sqrt{2}}{V_{base,highkv} I_{base,highkv,peak} \sqrt{3}}$$

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

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

$K_{old}$ based on an assumed 500 kV

# Overview of GMD Assessments



# 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
  - transformer coil resistance
  - whether auto-transformer, three-winding transformer

# Power System Restoration

- Power system restoration or black start (or blackstart)
  - A procedure to restore power in the event of a partial or total shutdown of the power system
  - A highly complex decision problem
- Object is to serve the load as soon as possible without violating operating constraints
  - Actions are time critical
- Primarily manual work by operators
- Offline restoration planning usually based on simulations

# Power System Restoration

- Common characteristics of restoration (even though strategies are different)
  - Immediate resupply of station service
  - Time consuming nature of switching operation
  - Start-up timings of thermal units
  - Voltage rise problems of energizing unloaded transmission lines
  - Frequency response of prime movers to a sudden load pickup
  - Cold load inrush, power factors and coincident demand factors

# System Restoration Efforts - IEEE

- After 1977 New York City blackout, DOE required operating companies to develop a power system restoration plan, train personnel, regularly update and maintain the plan.
- In response to this requirement in 1978, the Power System Operation Committee established the Power System Restoration (PSR) Task Force (TF) within the System Operation Subcommittee of the Power System Engineering Committee.
- A few years later, the PSR TF was upgraded to PSR working group (WG)

# System Restoration Efforts - IEEE

- In 1993 a 110 page brochure was prepared by PSR WG and published by the IEEE PES
- Includes:
  - 14 IEEE Committee Reports
  - 5 SRWG member papers in IEEE publication
  - 13 related IEEE transaction papers

IEEE Power Engineering Society

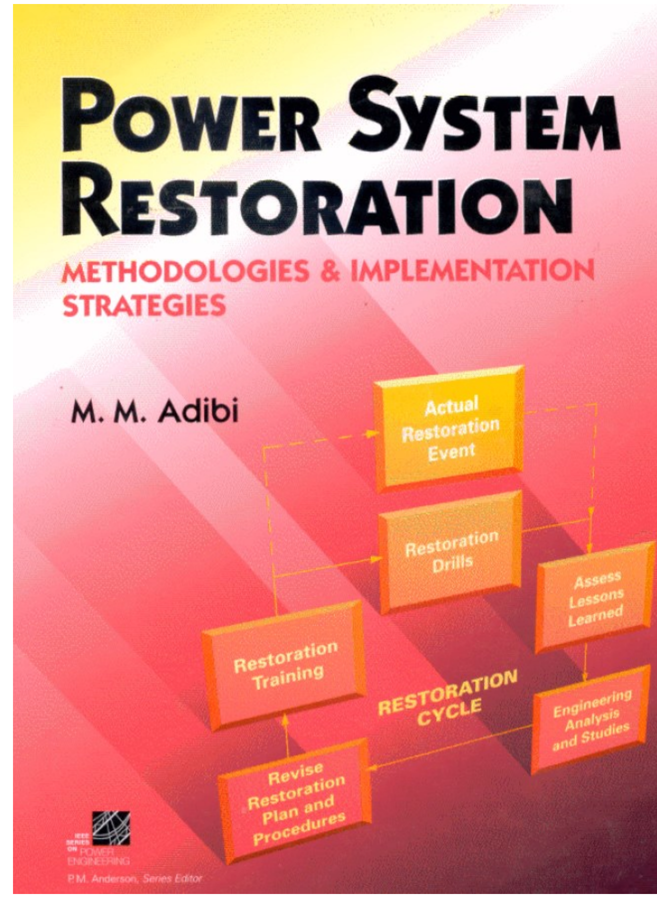
**POWER SYSTEM RESTORATION**

Prepared by the
Power System Restoration Working Group

Sponsored by the
System Operations Subcommittee

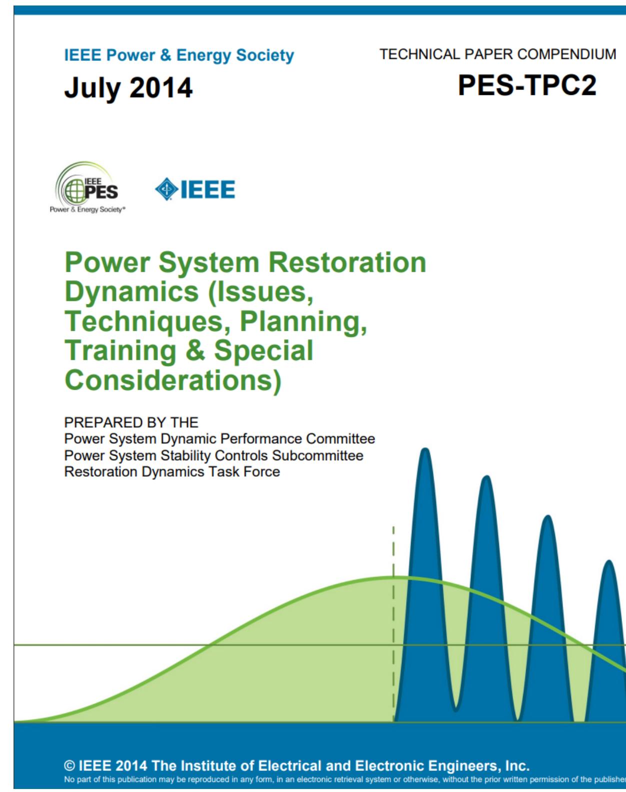
# System Restoration Efforts - IEEE

- In 2000 a 700 page book was prepared by PSRWG and published by Wiley-IEEE Press
- Includes 87 papers including 14 papers in the original 1993 collection

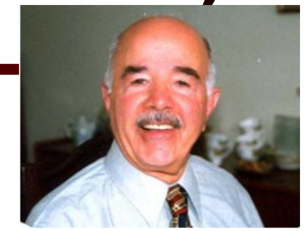


# System Restoration Efforts - IEEE

- In 2014 40 IEEE papers by 110 authors including 42 panelists of Restoration Dynamics Task Force
- Covers:
  - Real power balance and control of frequency
  - Reactive power balance and control of voltages
  - Critical tasks (time sensitive functions)
  - Analyses and simulations



# Mahmood Mike Adibi (1924 – 2018)



- The godfather of power system restoration
- B.S.E. in 1950 from University of Birmingham, U.K.
- M.S.E in 1960 from Polytech Institute of Brooklyn, NY
- IEEE Life Fellow
- Founder and chairman of the IEEE System Restoration Working Group in 1979
- Author of the book, "Power System Restoration – Methodologies and Implementation Strategies"
  - A great review book of IEEE papers between 1987 and 1999
- Developed restoration plans for over a dozen utilities

# Other Good References


- PJM Manual 36: System Restoration
- EPRI, "Development of Power System Restoration Tool Based on Generic Restoration Milestones," 2010.
- PSERC, "Development and Evaluation of System Restoration Strategies from a Blackout," 2009.
- IESO, "Part 7.8: Ontario Power System Restoration Plan," 2017.
- K. Sun et al., "Power System Control Under Cascading Failures: Understanding, Mitigation, and System Restoration," Wiley-IEEE Press. 2019.
- Yutian Liu, Rui Fan, and Vladimir Terzija, "Power system restoration: a literature review from 2006 to 2016," *J. Mod. Power Syst. Clean Energy*, 2016, 4(3), pp. 332-341

# NERC Standards on Restoration

- NERC System Restoration and Black Start standards
  - EOP-005-2 & EOP-005-3
    - System Restoration from Black Start Resources
    - Ensure plans, Facilities, and personnel are prepared to enable System restoration from Black Start Resources to assure reliability is maintained during restoration and priority is placed on restoring the Interconnection
  - EOP-006-2 & EOP-006-3
    - System Restoration Coordination
    - Ensure plans are established and personnel are prepared to enable effective coordination of the System restoration process to ensure reliability is maintained during restoration and priority is placed on restoring the Interconnection.

# Common Issues during Restoration

- Active power balance and frequency control
  - Need to maintain system frequency within limits by system stability and protection settings
  - Can be accomplished by picking up loads in increments
- Reactive power balance and overvoltage control
  - Energizing few high voltage lines
  - Operating generators at minimum voltage levels
  - Deactivating switched shunt capacitors
  - Connecting shunt reactors
  - Adjusting transformer taps
  - Picking up reactive loads

# Common Issues during Restoration

- Transient switching voltages
  - Switching surges occur when energizing equipment
- Self-excitation
  - When the charging current is high relative to the size of generators
  - When opening a line at the sending end but leaving the line connected to a large motor
  - This causes overvoltage and damages equipment
- Cold load pickup
  - When load has been de-energized for several hours or more
  - Inrush current can be as high as 8 – 10 times of the normal value

# Common Issues during Restoration

- System stability
  - Voltage should be within limits
  - Angle stability have to be maintained
  - Frequency is the main issue in stability assessment
- Protective systems and load control
  - Continuous change in system configuration and in operating conditions may trigger undesirable operation of relays
  - Load shedding can be useful in case of low frequency conditions

# Common Issues during Restoration

- Partitioning system into islands
  - Necessary to speed up the process, especially for large systems
  - NERC standards
    - Each islands must have sufficient black start capability
    - Each islands should have enough cranking paths to gens and loads
    - Each islands should be able to match generation and load within prescribed frequency limits
    - Each islands should have adequate voltage controls
    - All tie points must be capable of synchronization with adjacent subsystems
    - All islands should share information with other islands

# Generic Restoration Steps

- Preparation stage (1 – 2 hours)
  - Evaluate pre- and post-disturbance conditions
  - Define the target system
  - Restart generators and rebuild transmission network
- System restoration stage (3 – 4 hours)
  - Energize transmission paths
  - Restore load to stabilize generation and voltage
  - Synchronize islands and reintegrate bulk power system
- Load restoration stage (8 – 10 hours)
  - Load restoration is the governing control objective
  - Load pickup is scheduled based on generation availability
  - Load restoration is effected in increasingly larger steps

# System Restoration Tasks

- Know the status of the grid
- List and rank critical loads by priority
- List and rank initial sources of power by availability
  - Maximize generation capabilities with the available black start resources
- Determine the most effective ways of brining the two together
  - Schedule tasks and resources during restoration
  - Establish transmission capability and paths while meeting operating constraints

# Initial Power and Load

- Initial source of power

| Type | Time (min) | Success probability |
| --- | --- | --- |
| Run-of-the-River Hydro | 5-10 | High |
| Pump-Storage Hydro | 5-10 | High |
| Combustion Turbine | 5-15 | Medium |
| Tie-line with Adjacent Systems | Short | |

- Initial critical loads

| Type | Priorities |
| --- | --- |
| Cranking drum-type units | High |
| Pipe-type cables pumping plants | High |
| Transmission stations | High to Medium depending on location |
| Distribution stations | High to Medium depending on location |
| Industrial loads | Medium to low |