The Impact of Corona Mass Ejections on the High Voltage Electric Grid

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Presentation to TAMU Astronomy Department
October 2, 2017

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Overview

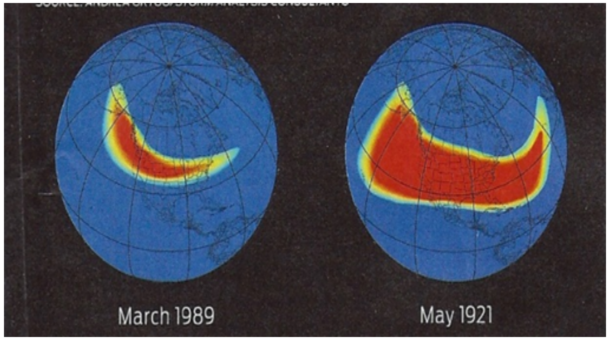
- The electric grid is the lifeblood of our modern society
- The grid reliability is high, but there are some events that could cause large-scale, long duration blackouts
  - These include what the North American Electric Reliability Corporation (NERC) calls High-Impact, Low-Frequency Events (HILFs); others call them black swan events
  - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) high altitude electromagnetic pulses
- Presentation covers impact of GMDs

Geomagnetic Disturbances (GMDs)

- GMDs are caused by corona mass ejections (CMEs)
- 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

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; 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

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 field at the surface is dependent on deep earth (hundreds of km) conductivity
  - 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 volts/km
- 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 electric field is 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 150 years
- There is still lots of uncertainly about how large a storm is reasonable to consider in electric utility planning

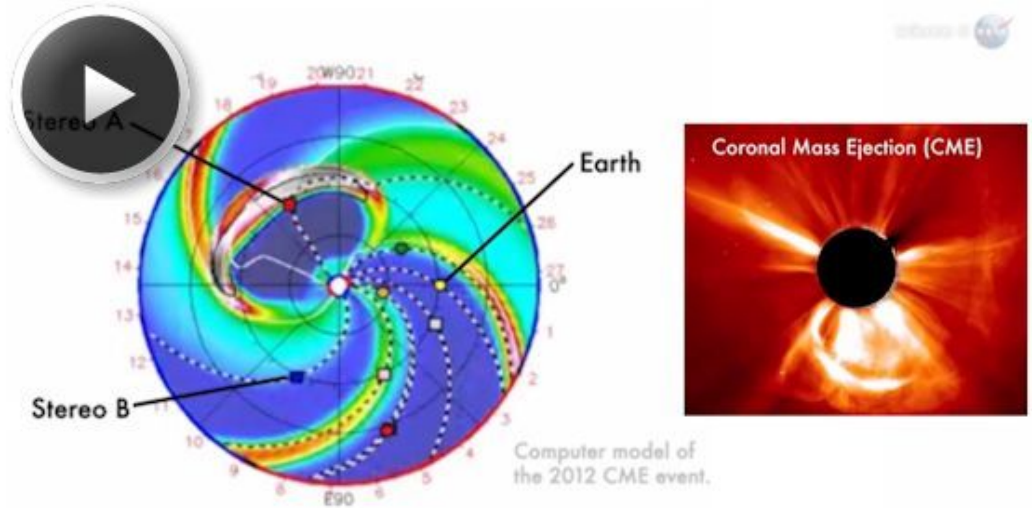
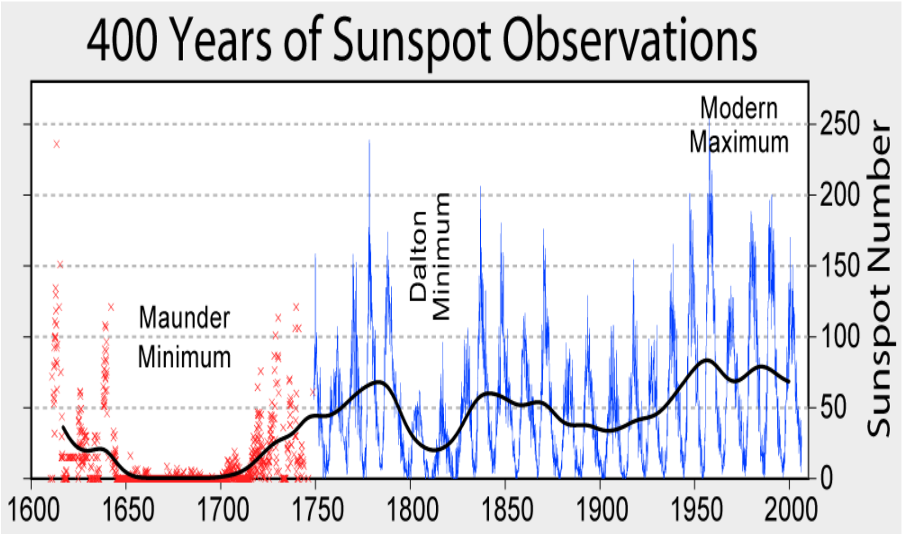
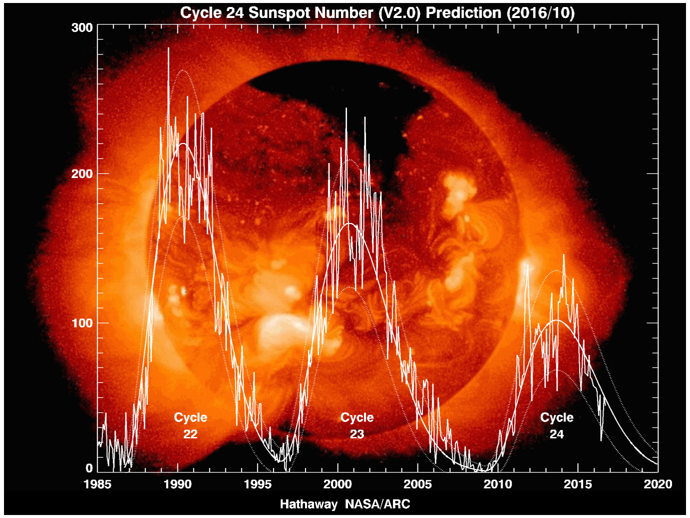


Image Source: science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/

Solar Cycles

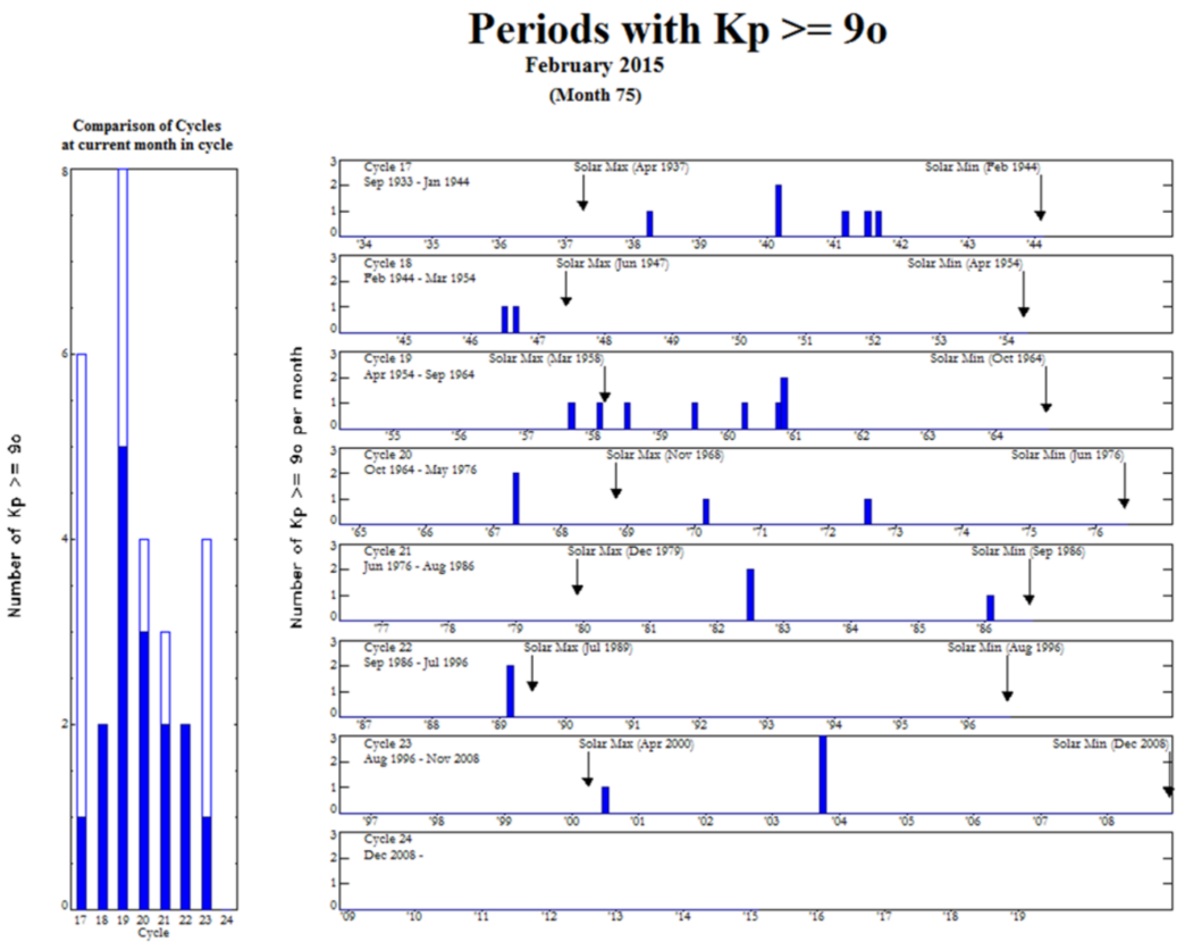
- Sunspots follow an 11 year cycle, and have been observed for hundreds of years
- We're in solar cycle 24 (first numbered cycle was in 1755); minimum was in 2009, maximum in 2014/2015





Images from NASA

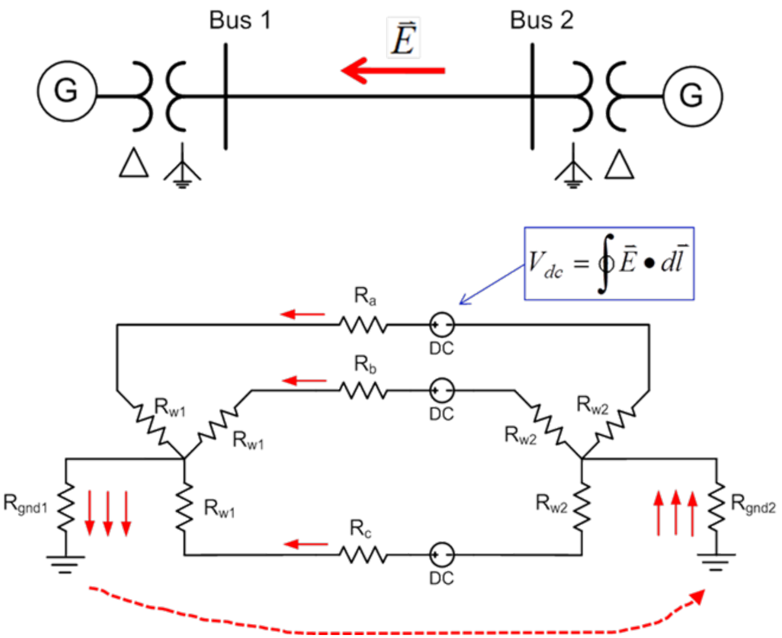
But Large CMEs Are Not Well Correlated with Sunspot Maximums



The large 1921 storm occurred four years after the 1917 maximum

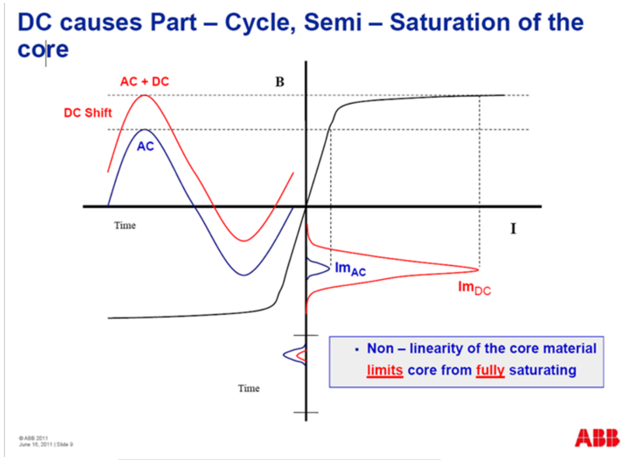
Geomagnetically Induced Currents (GICs)

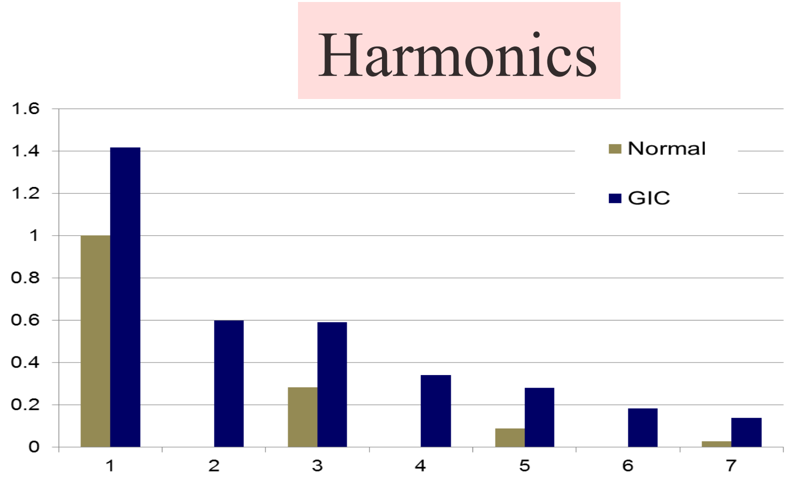
- GMDs cause slowly varying electric fields
- Along length of a high voltage transmission line, electric fields can be modeled as a dc voltage source superimposed on the lines
- These voltage sources produce quasi-dc geomagnetically induced currents (GICs) that are superimposed on the ac (60 Hz) flows



Transformer Impacts of GICs

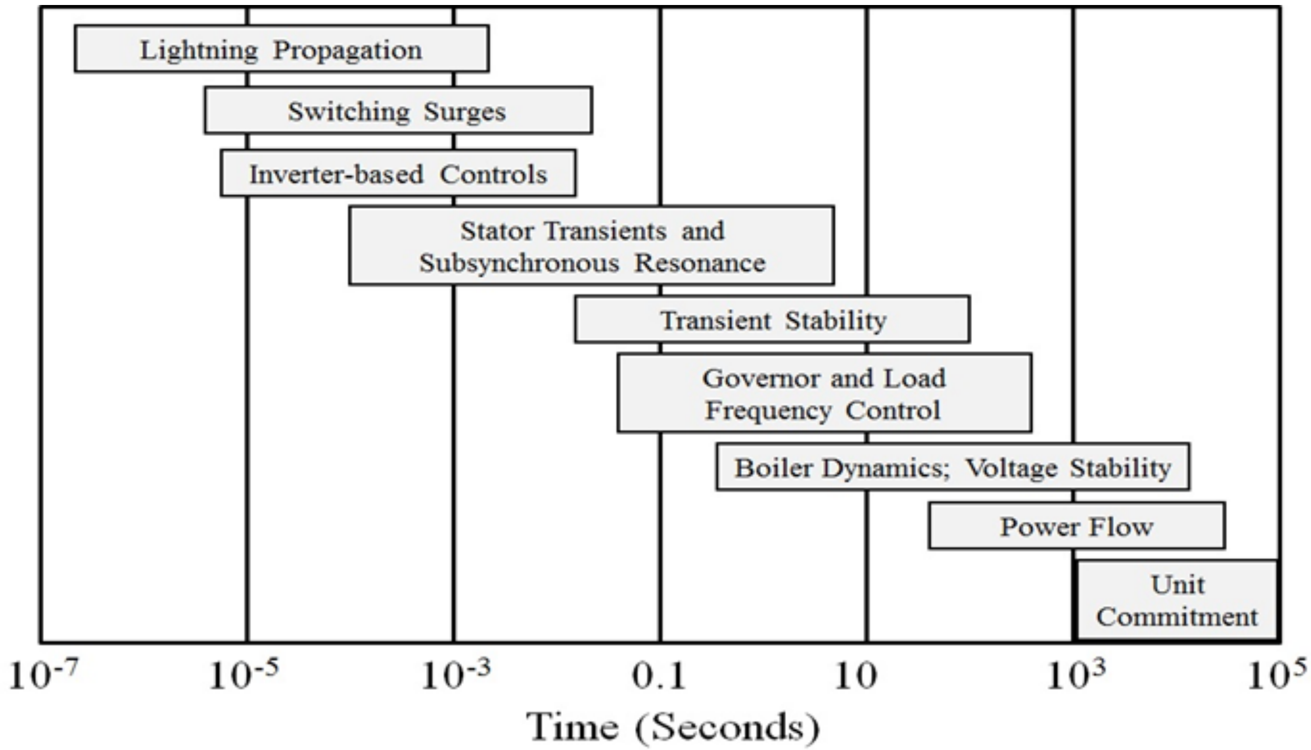
- The superimposed dc GICs can push transformers into saturation for part of the ac cycle
- This can cause large harmonics; in the positive sequence (e.g., power flow and transient stability) these harmonics can be represented by increased reactive power losses in the transformer





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

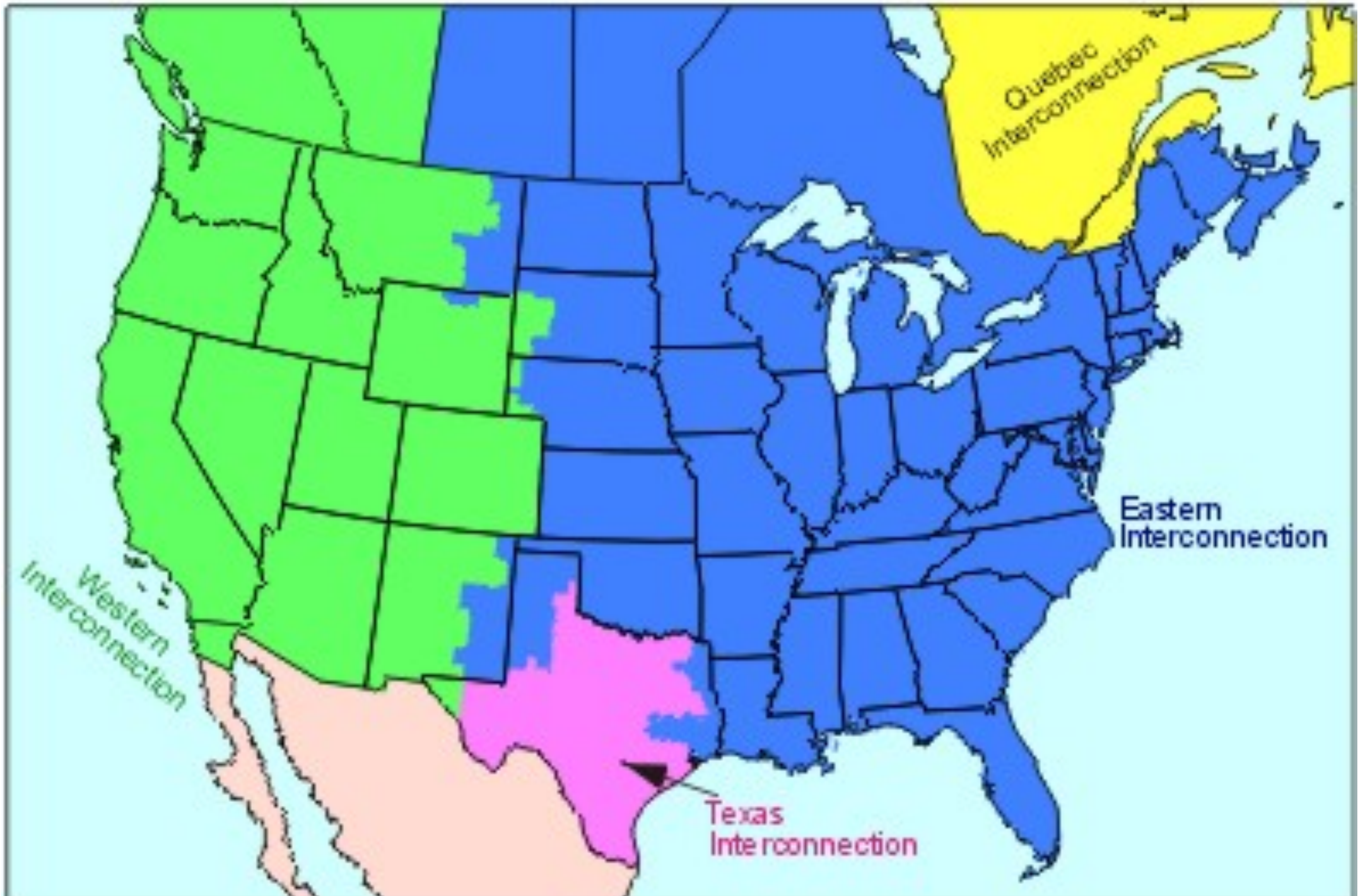
Electric Grid Time Frames



GMDs impact grid on time scale of many seconds to hours; this is considered quasi-steady state analyzed by power flow

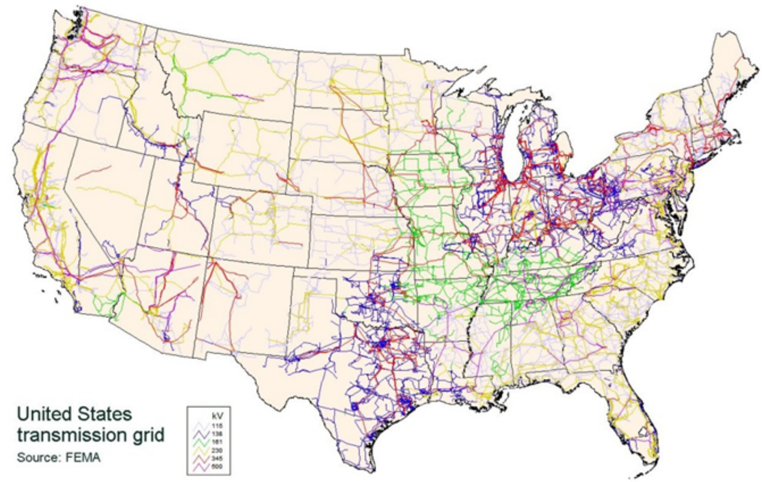
Image: Sauer, P.W., M. A. Pai, *Power System Dynamics and Stability*, Stripes Publishing, 2007

North America Electric Interconnects



Electric Grid Considerations in Power Flow (GMD) Time Frame

- Electricity cannot be economically stored
  - Generation must be continually adjusted to match changes in electric load and losses
- Electric power flows on high voltage transmission lines cannot usually be directly controlled
  - Control is mostly indirect, by changing generation

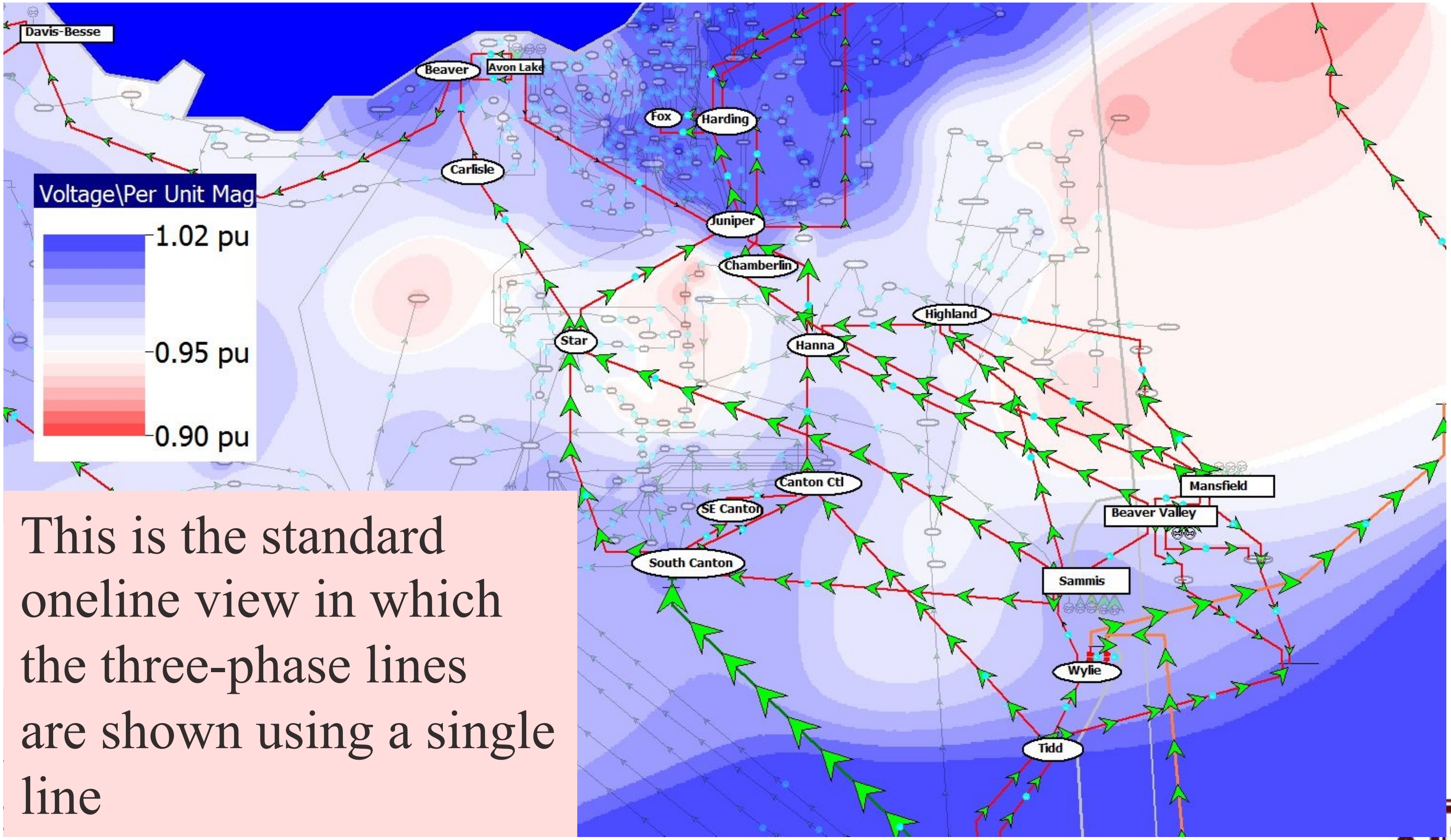


- Customers have been in control of their load
- Transmission system has finite limits including voltage magnitude constraints

Power System Voltage Collapse

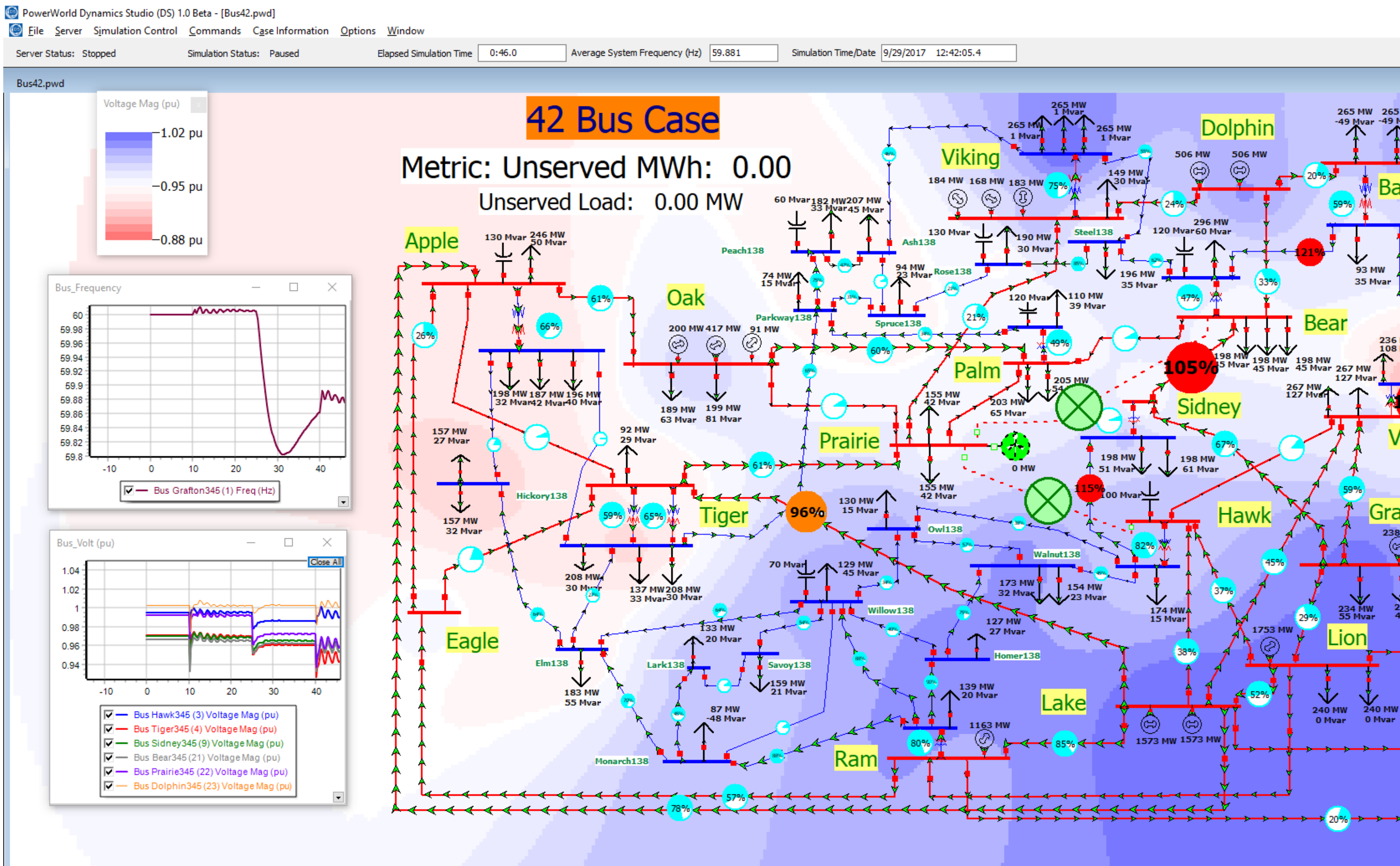
- At constant frequency (e.g., 60 Hz) the complex power transferred down a transmission line is $S=VI^*$
  - V is phasor voltage, I is phasor current
  - This is the reason for using a high voltage grid
- Line real power losses are given by RI^2 and reactive power losses by XI^2
  - R is the line's resistance, and X its reactance; for a high voltage line X >> R
- Increased reactive power tends to drive down the voltage, which increases the current, which further increases the reactive power losses

Demo of How the Grid Can Fail in the Power Flow Time Frame

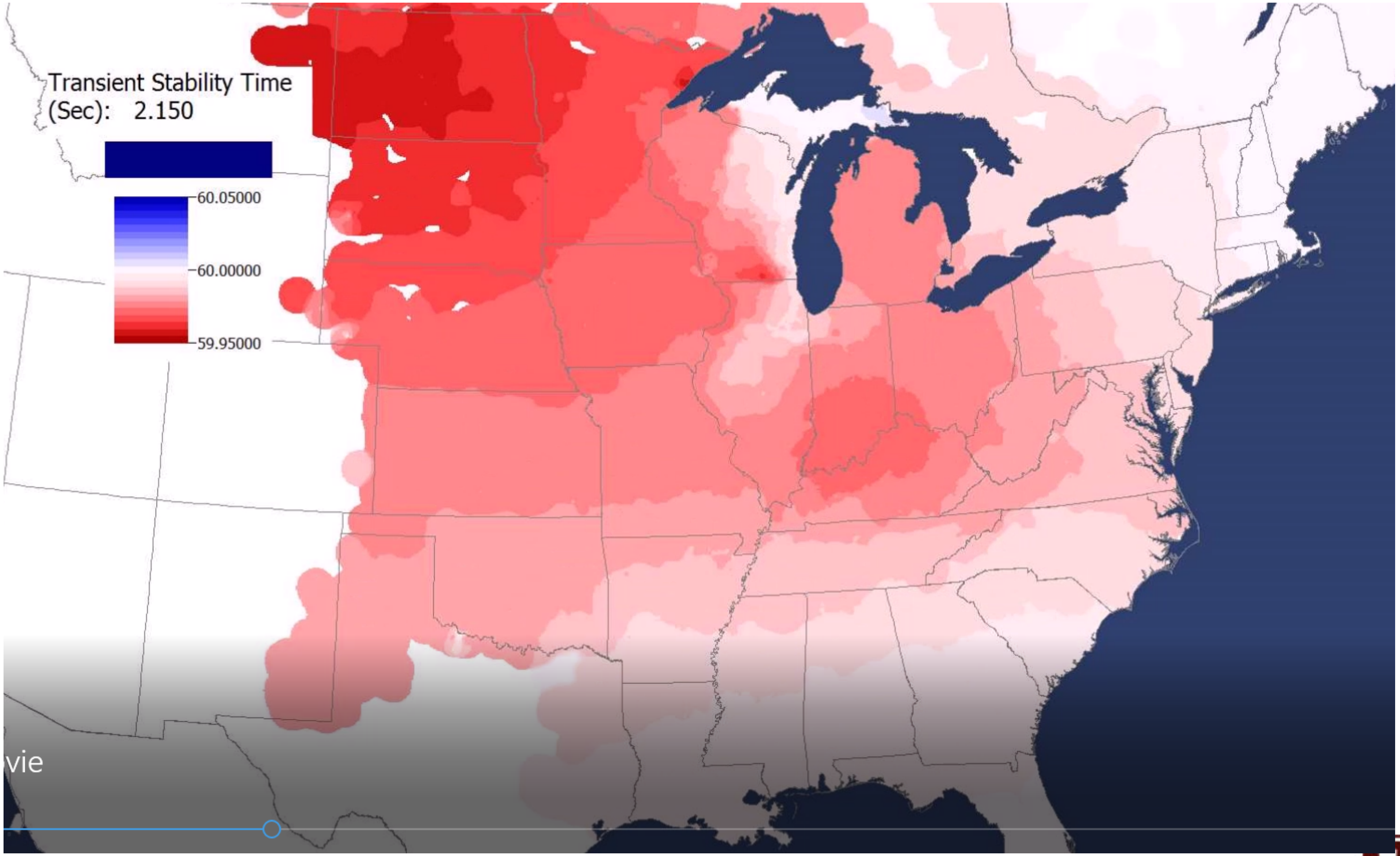


This is the standard oneline view in which the three-phase lines are shown using a single line

Or On a Slightly Shorter Time-Scale

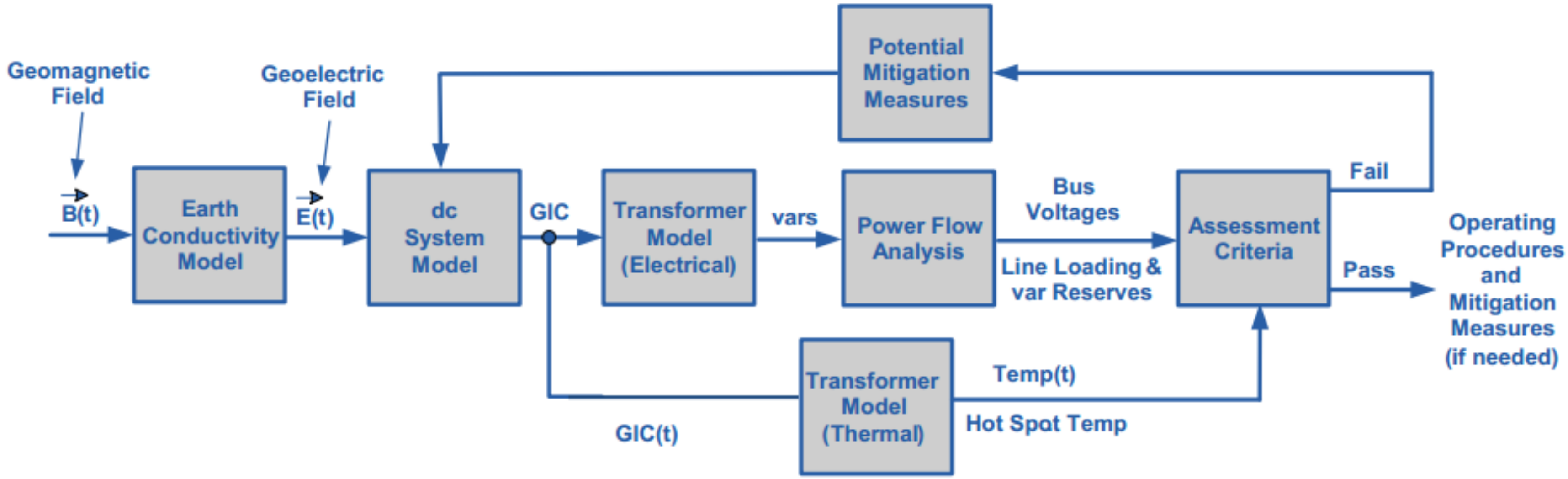


Frequency Response in Eastern Interconnect to Generator Outage



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

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

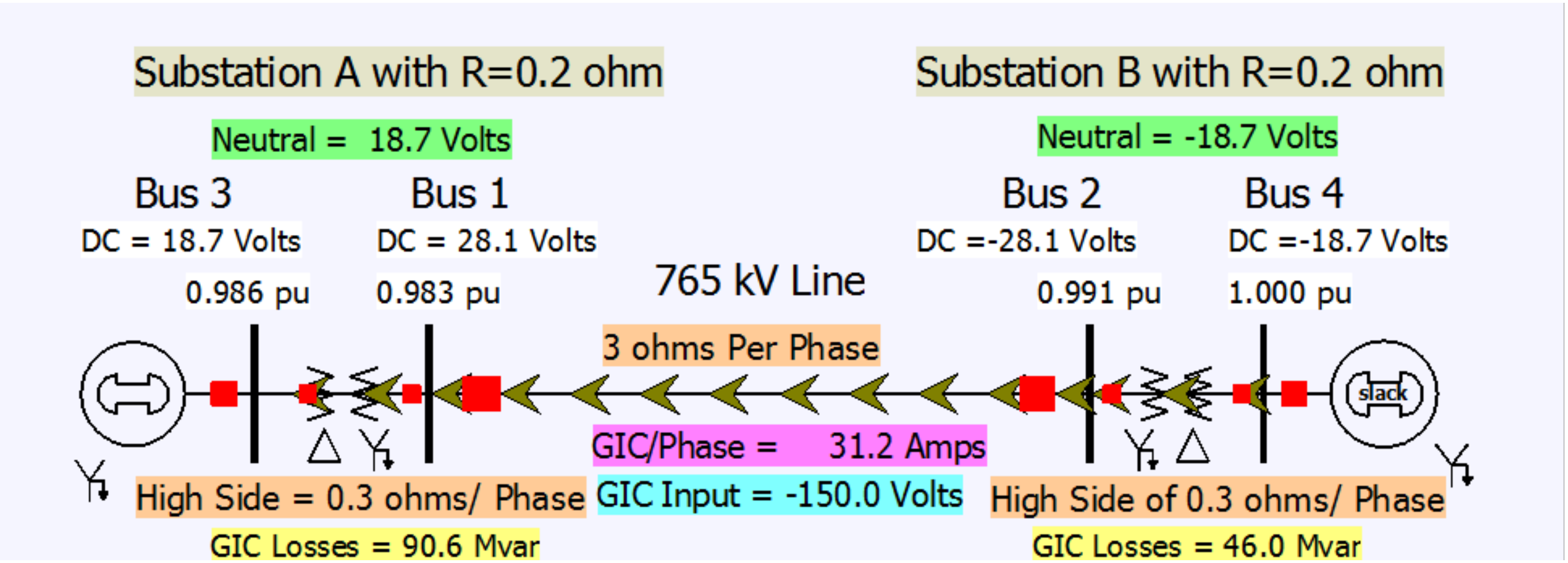
- Reactive power loadings on hundreds of high voltage transformers could rapidly rise

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 might not be a good idea!

Four Bus Example

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



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.

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
  - Various transformer parameters
  - generator step-up transformer parameters

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 (issue is ongoing as of September 2017)

Large-Scale Studies Require Geo-mapped Buses

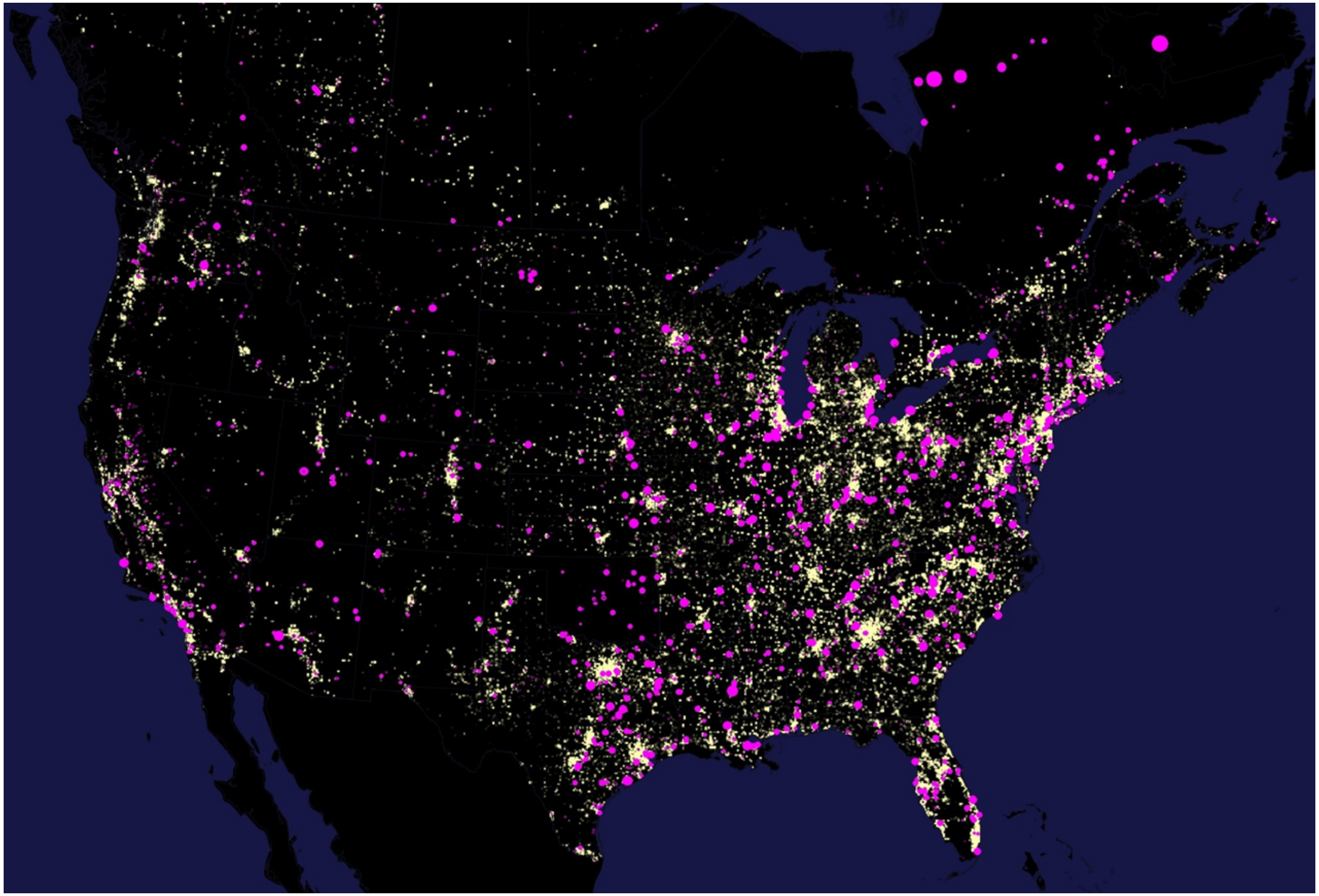
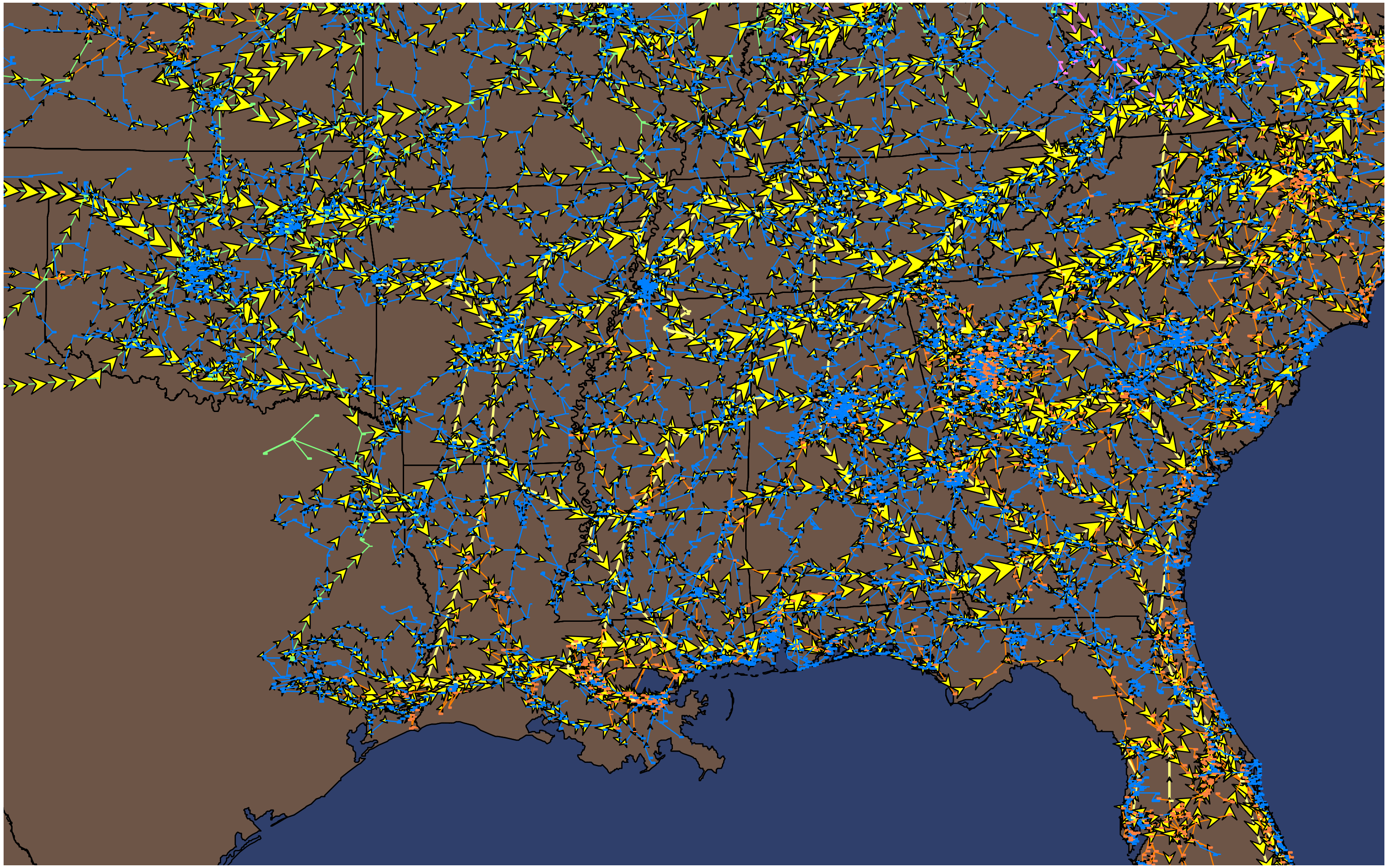
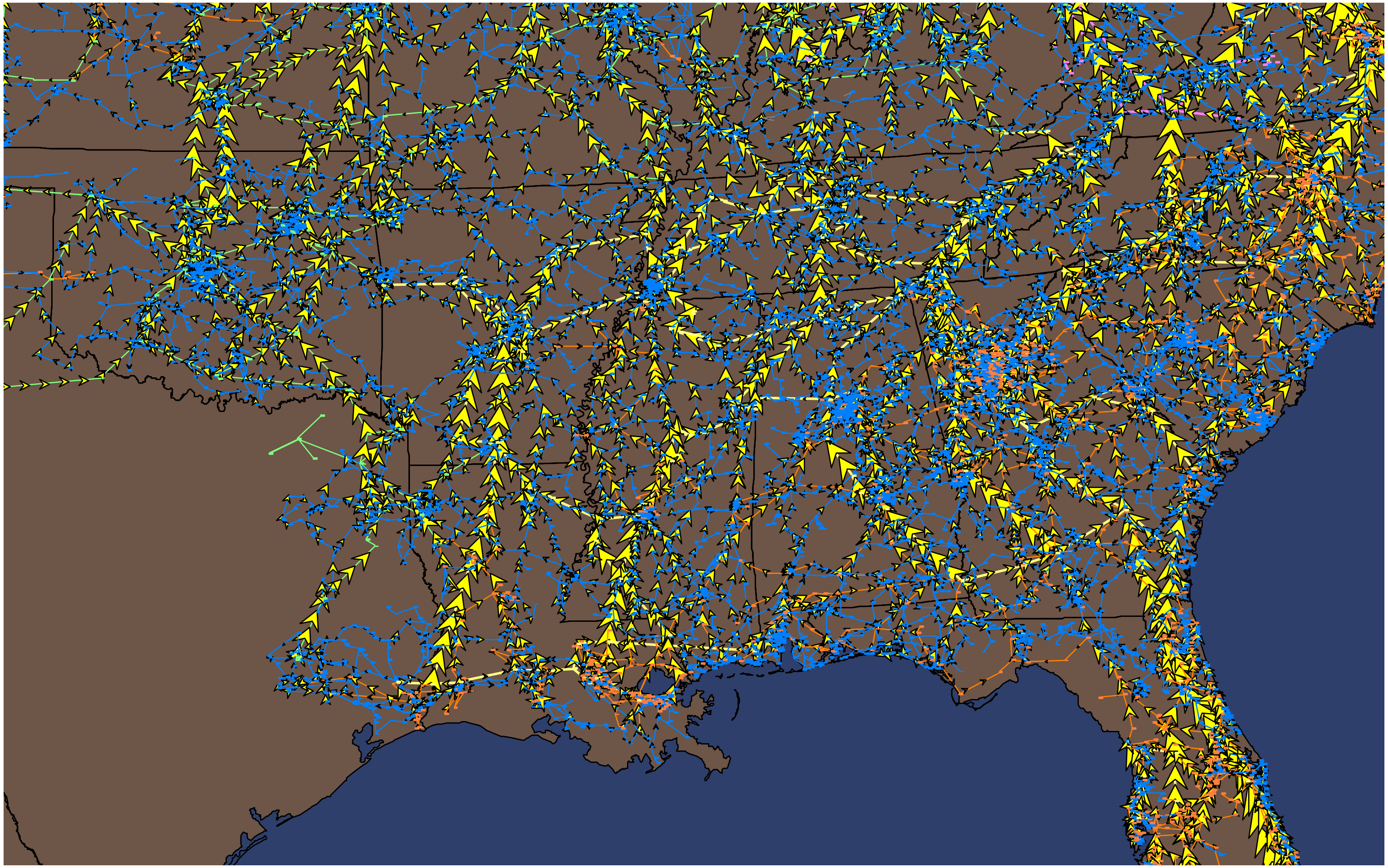


Image is based on power flow data (summer 2015) for the four North American grids

GICs, Generic EI, 8 V/km East-West



GICs, Generic EI, 8 V/km North-South



FERC and NERC Actions

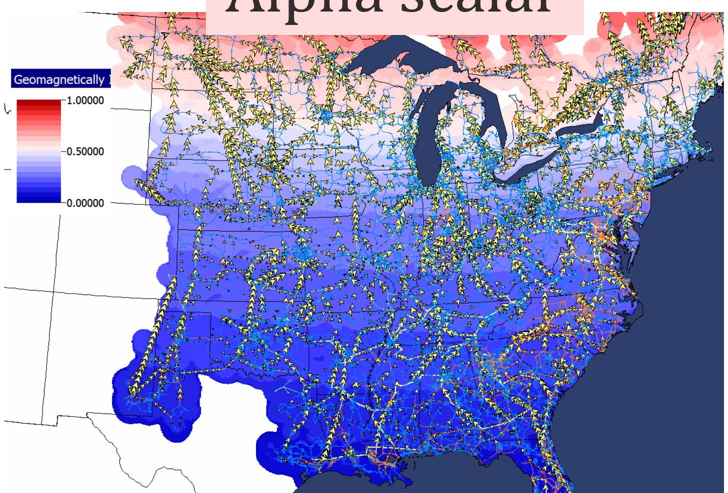
- May 2013: FERC Order 779 issued to NERC to develop Operations Standards and Planning Standards
- November 2013: NERC files EOP-010-1, Geomagnetic Disturbance Operations
- Ongoing: NERC TPL-007-1 Transmission System Planned Performance During Geomagnetic Disturbances
  - Several requirements, including study of “Benchmark GMD Event”
  - NERC is working on a non-uniform electric field magnitude model with potential "hotspot" analysis

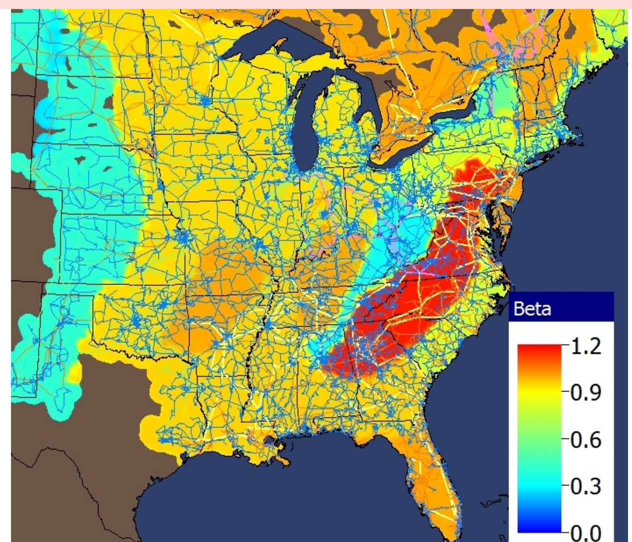
NERC Benchmark GMD Scenario

- Time varying, derived from the March 1989 event
- Peak electric field is 8 V/km for a reference location (60 deg. N, resistive Earth)
- Electric field for other regions scaled by two factors
  - $E_{peak} = 8 * \alpha * \beta$ V/km
  - "1 in a 100 year" event

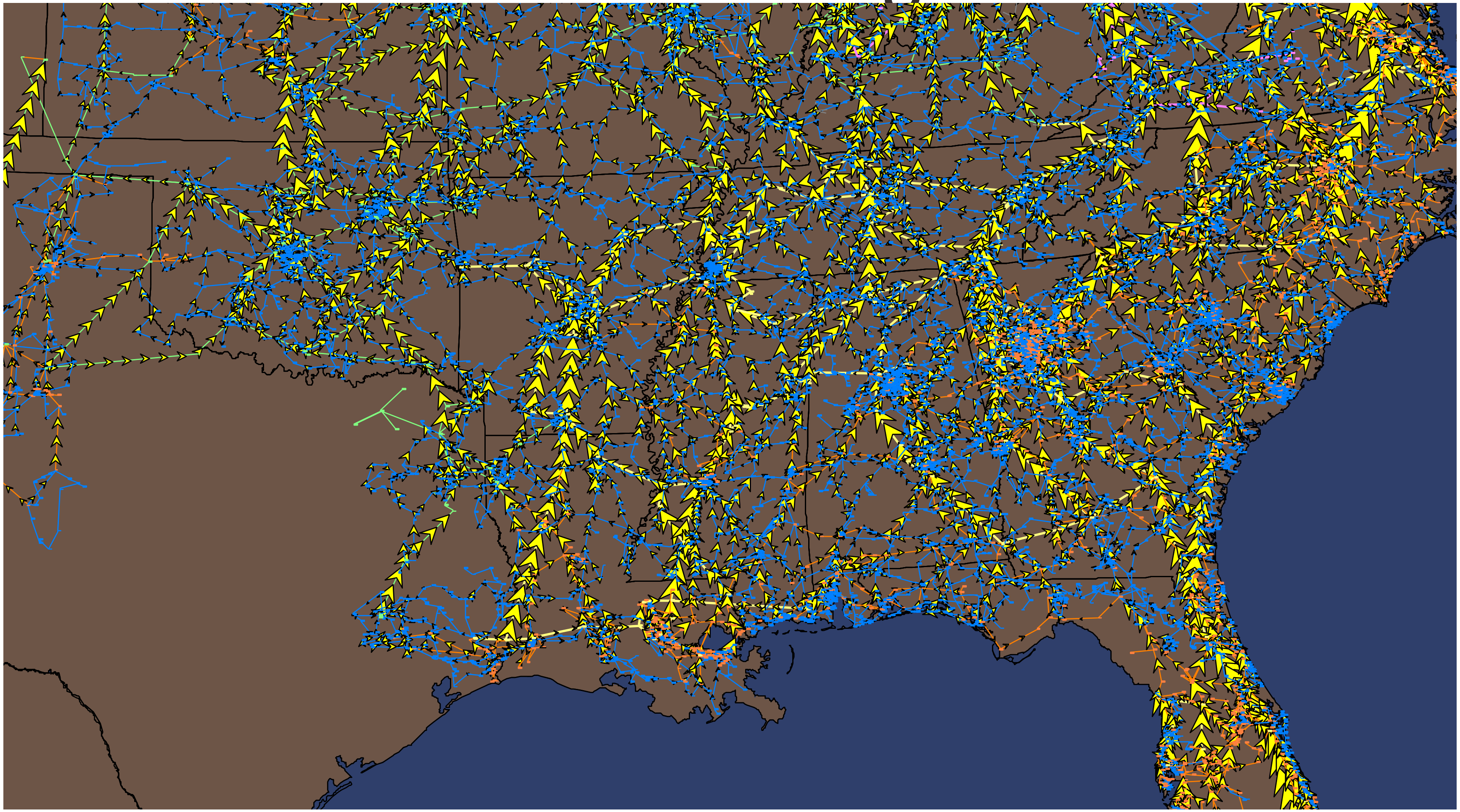
The beta scalars depend on an assumed deep earth model

Alpha scalar

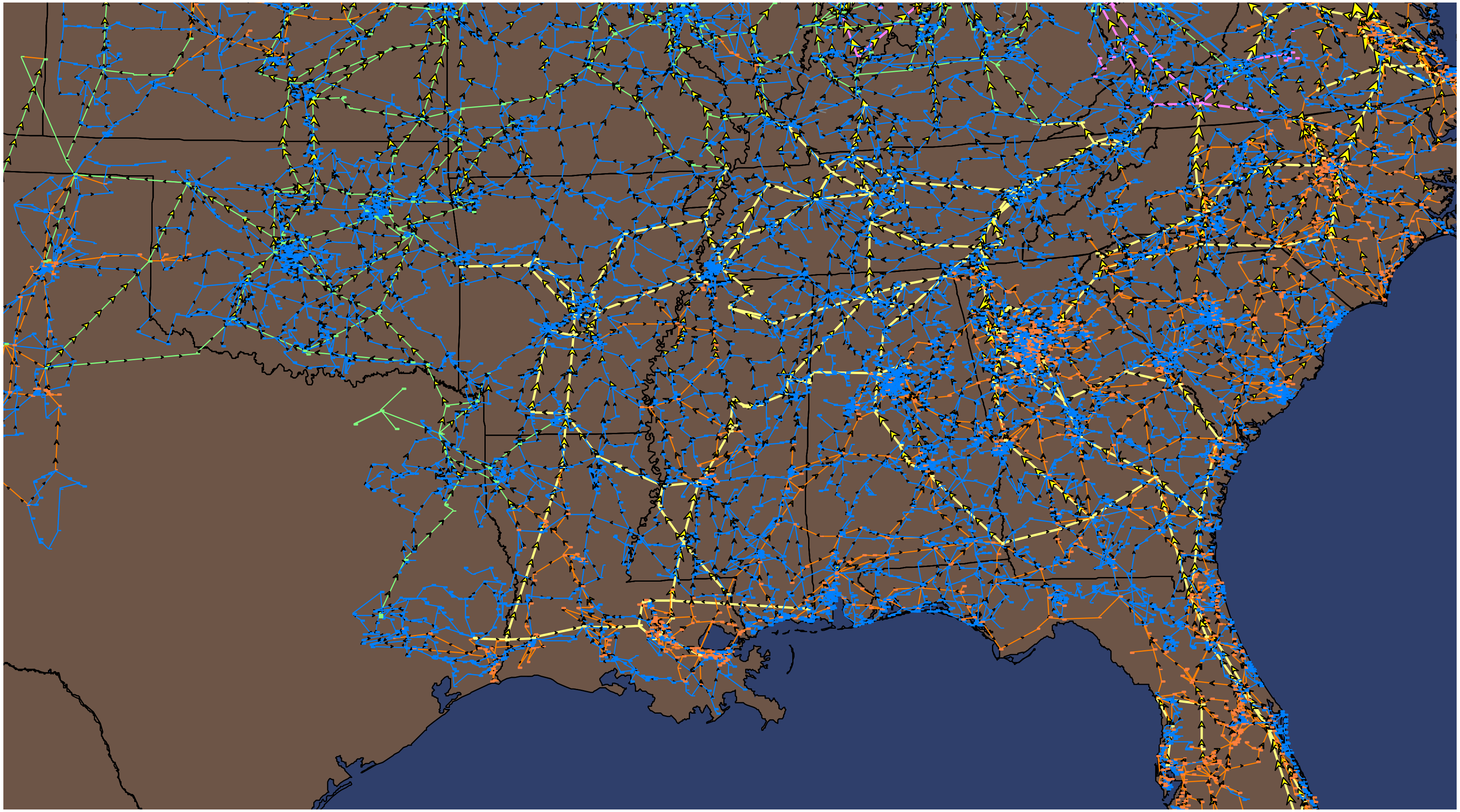




GICs, Generic EI, 8 V/km North-South No Scaling



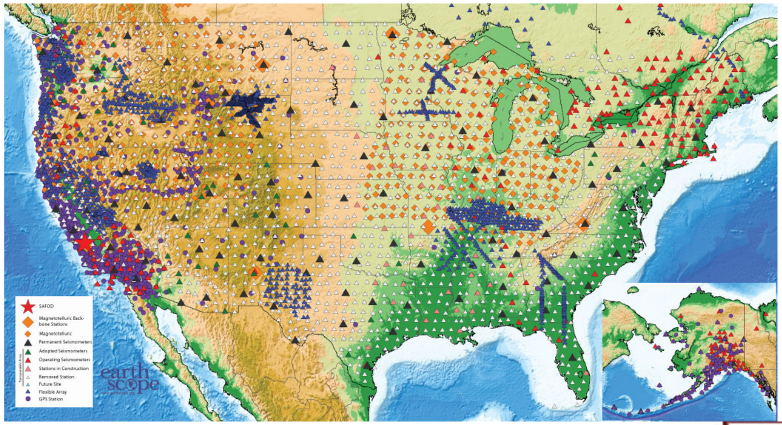
GICs, Generic EI, 8 V/km North-South Scaled



However, Research is Ongoing

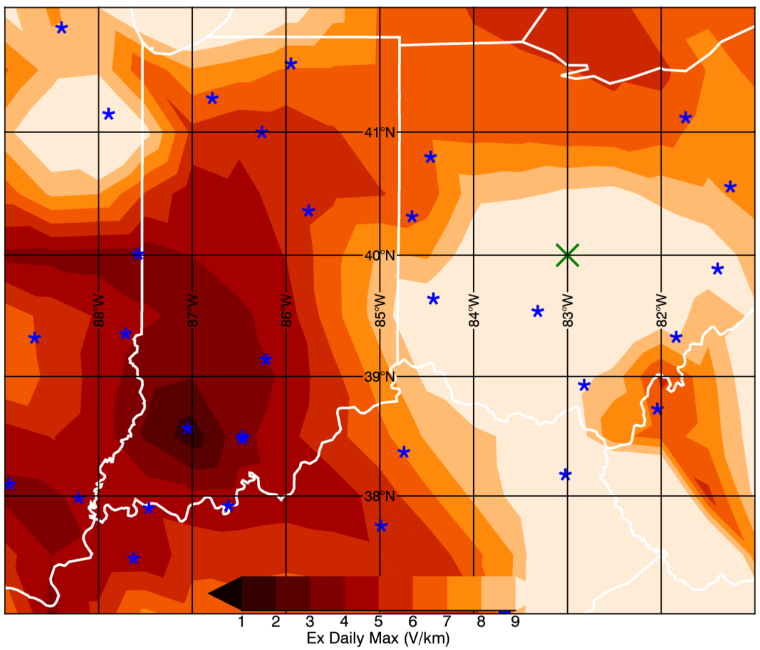
- There is not a consensus on how large a GMD we need to consider, or on how large GMDs are affected by magnetic latitude
- The deep earth conductivity model can be quite important, and we are just now starting to consider the impact of more complete 3D models
  - Data is becoming available from the NSF Earthscope
- TAMU is leading an NSF project to develop better models

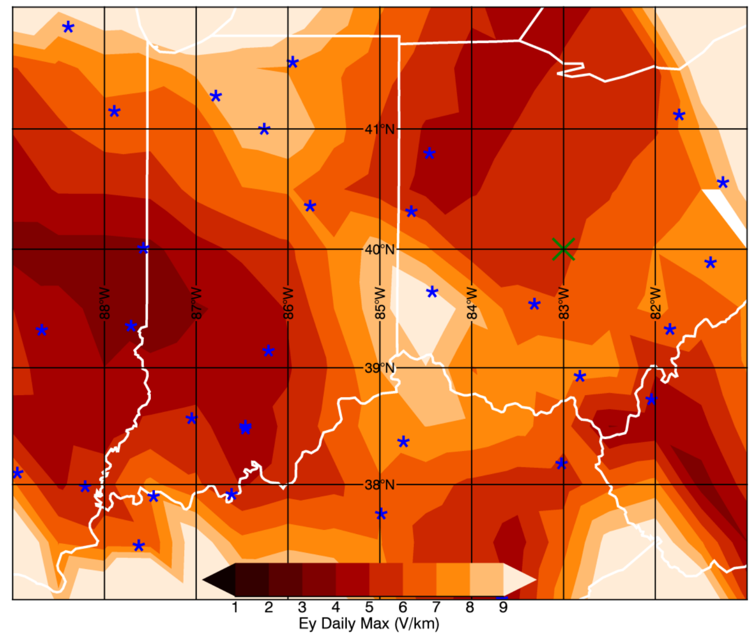
EarthScope Stations Status as of June 2015



Example of 3D Electric Field Models

Images show the electric field (in V/km) in the Indiana and Ohio area in the x and y directions





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

Thank You!

Questions?

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