Enhancing the Resilience of Large-Scale Electric Grids

Tom Overbye
TEES Eminent Professor
Electrical and Computer Engineering
overbye@tamu.edu

University of Toronto

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TEXAS A&M UNIVERSITY

A Vision for an Electric Future

- In 2000 the NAE named Electrification (the vast networks of electricity that power the developed world) as the top engineering technology of the 20th century
  - Beating automobiles (2), airplanes (3), water (4), electronics
- My vision is to help us win the 21th century as well!
  - "Development of a sustainable and resilient electric infrastructure for the entire world"
  - We will need to leverage a wide range of technologies and generation sources for the "smarter grid" of the future

Overview

- Interconnected electric grids are going to play a key role in the development of a sustainable energy future
  - In the North America about 40% of our energy transported as electricity, a value that should be increasing as transportation becomes more electrified
- In order to achieve this vision of a bright future, we need to increase the reliability and resiliency of the electric grid
  - Consideration of blackouts, both large and small, and of all durations

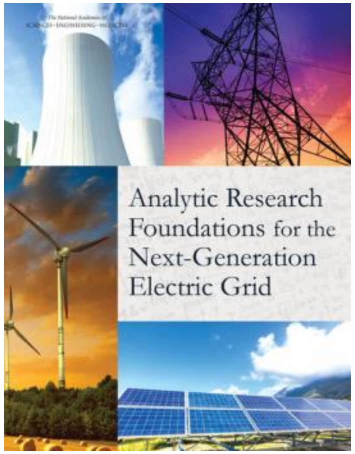
My favorite 8/14/03 blackout hoax picture

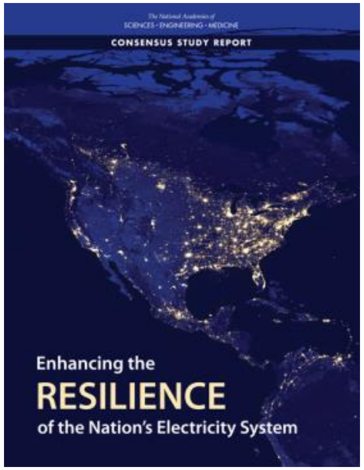
Reliability and Resiliency

- 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

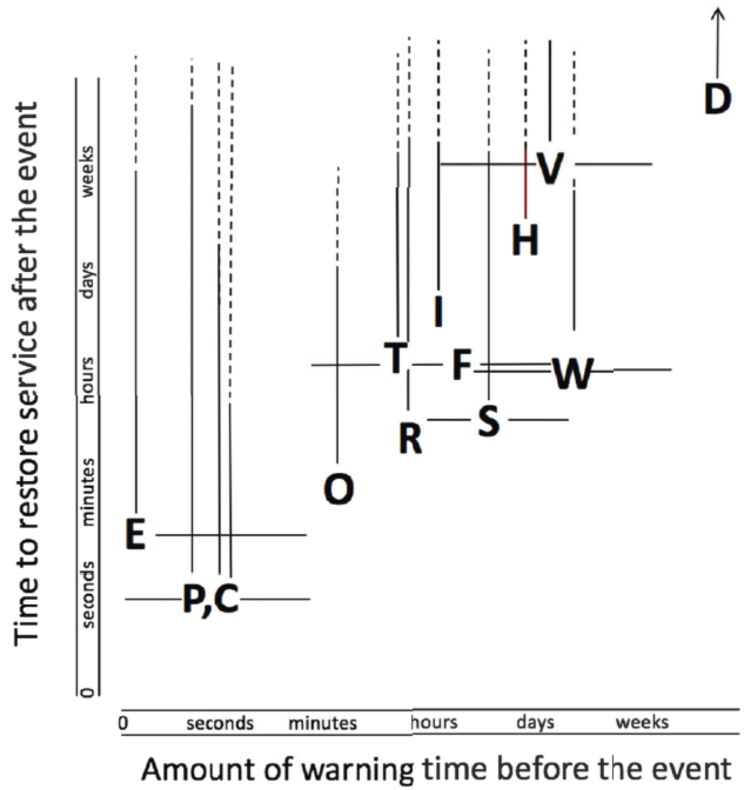
Two New US National Academies Reports

- 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”
- Focus here is on resiliency





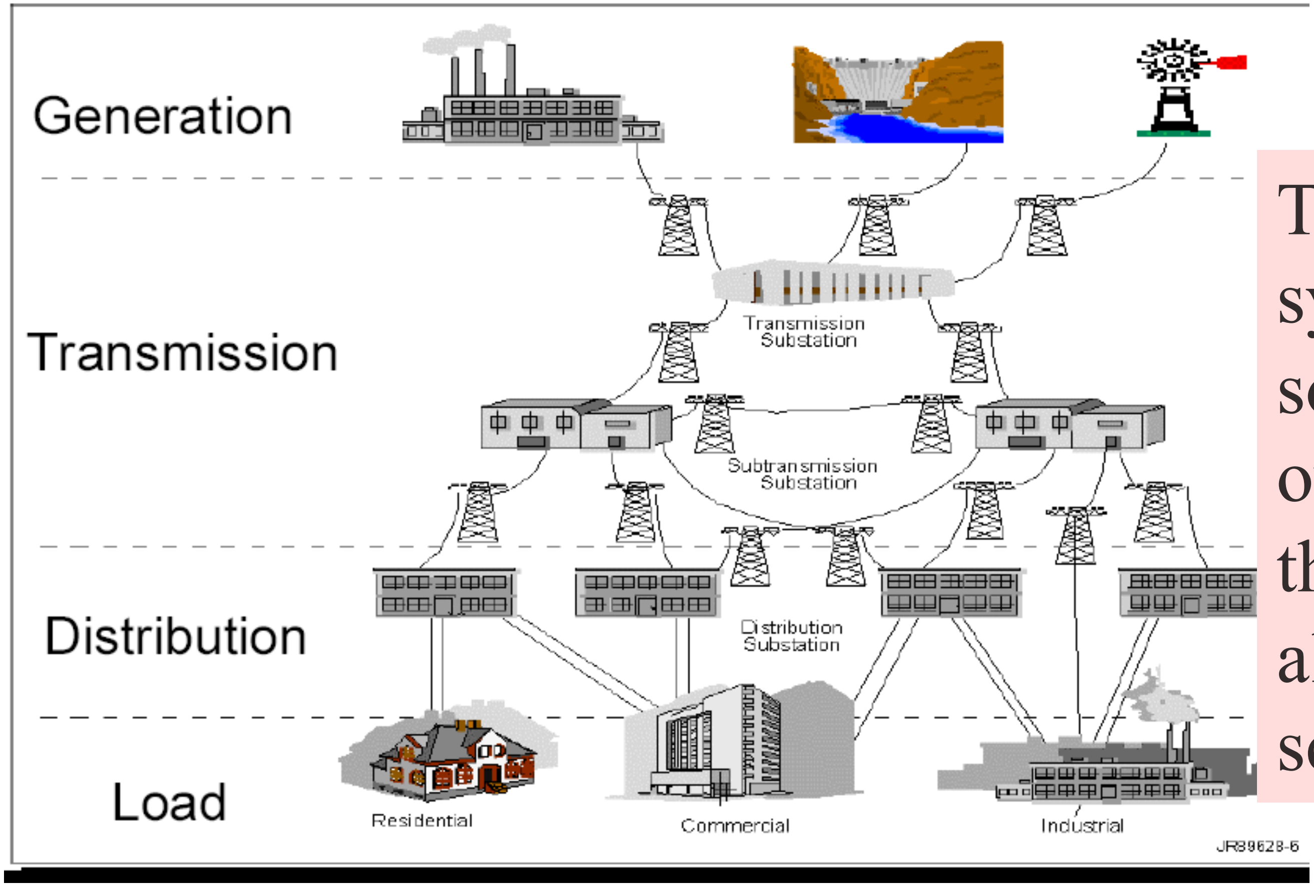
Some Electric Grid Risks



C = cyber attack (ranging from state/pro on left to good hacker on right)
D = drought and associated water shortage
E = earthquake (in some cases with warning systems)
F = flood/storm surge
H = hurricane
I = ice storm
O= major operations error
P = physical attack
R = regional storms and tornados
S = space weather
T = tsunami
V = volcanic events
W= wild fire

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

Major Power Grid Components



The distribution system is the source of most outages, but these are almost always small-scale events

The Real Cause of Most Blackouts!

Photo source: http://save-the-squirrels.com

But mostly only the small ones in the distribution system

And Sometimes It's the Trees

Same Trees After “Trimming”

High-Impact, Low-Frequency Events

- In order to enhance electric grid resiliency we need to consider the almost unthinkable events
- These include what the North American Electric Reliability Corporation (NERC) calls High-Impact, Low-Frequency Events (HILFs); others call them black sky days

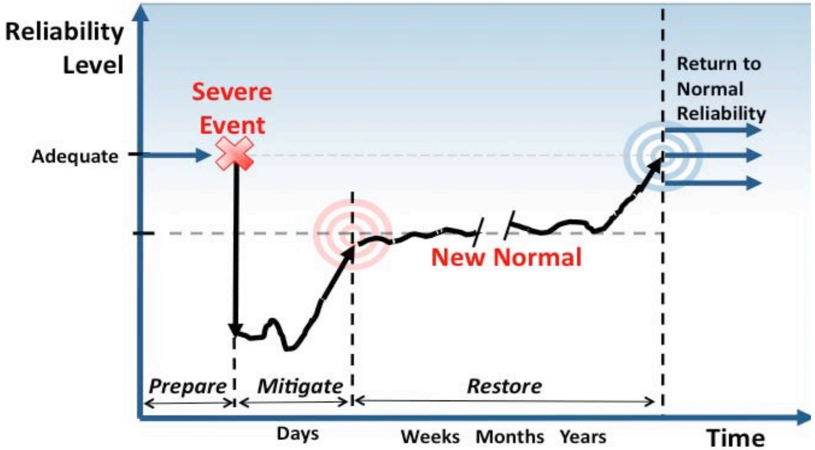
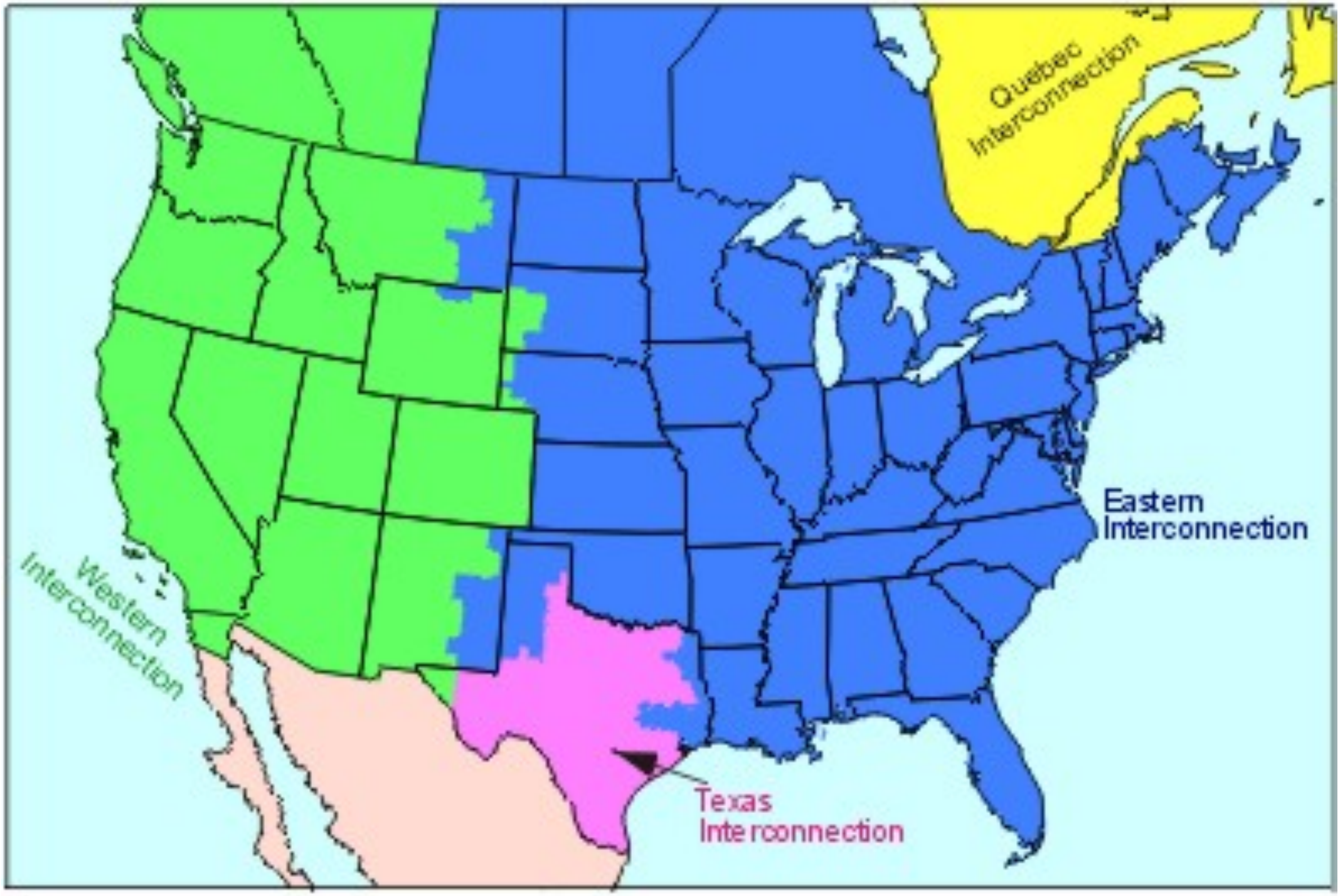


Image Source: NERC, 2012

  - Large-scale, potentially long duration blackouts
  - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) HEMPs

North America Electric Interconnects



Electric Grid Time Frames

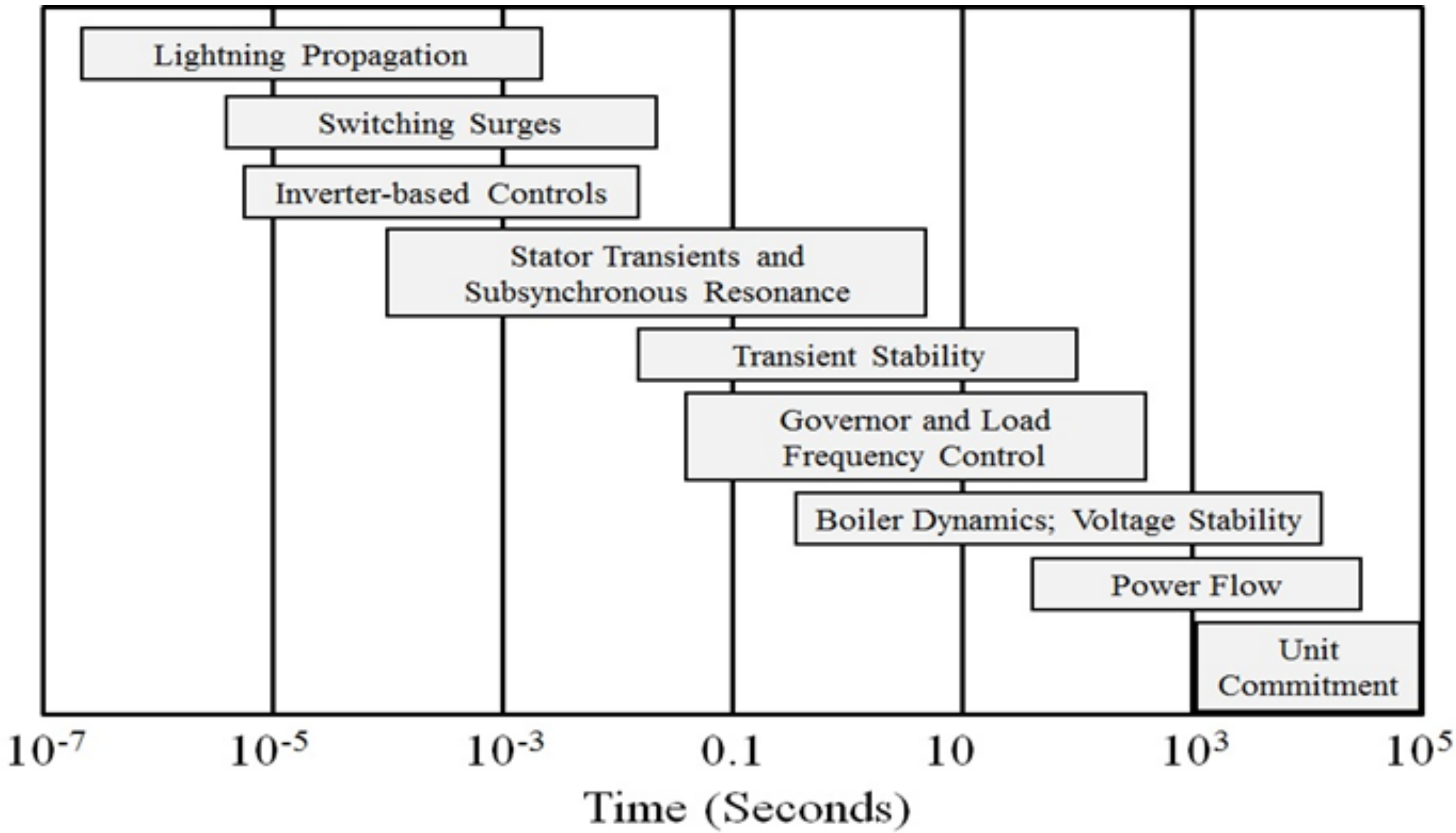


Image: Sauer, P.W., M. A. Pai, *Power System Dynamics and Stability*, Stripes Publishing, 2007

Modeling Cautions!

- "All models are wrong but some are useful," George Box, *Empirical Model-Building and Response Surfaces*, (1987, p. 424)
  - Models are an approximation to reality, not reality, so they always have some degree of approximation
  - Box went on to say that the practical question is how wrong to they have to be to not be useful
- A good part of engineering is deciding what is the appropriate level of modeling, and knowing under what conditions the model will fail
- Always keep in mind what problem you are trying to solve!

Important Electric Grid Considerations

- 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; often operated close to its limit for economic reasons

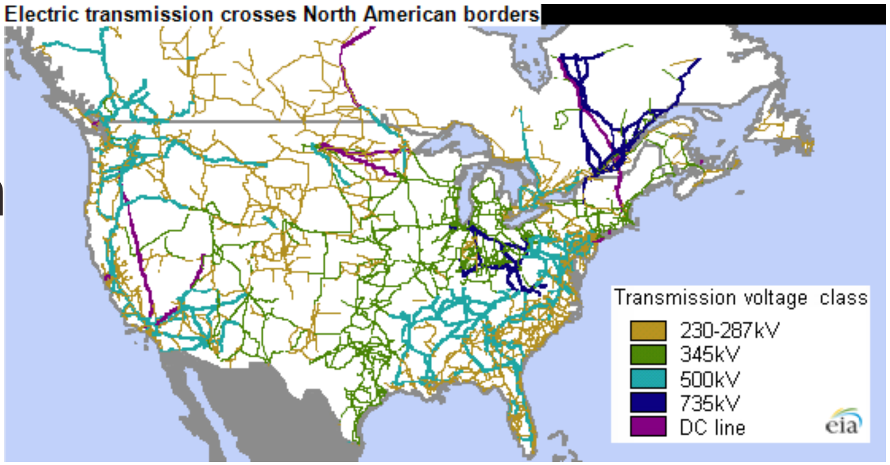
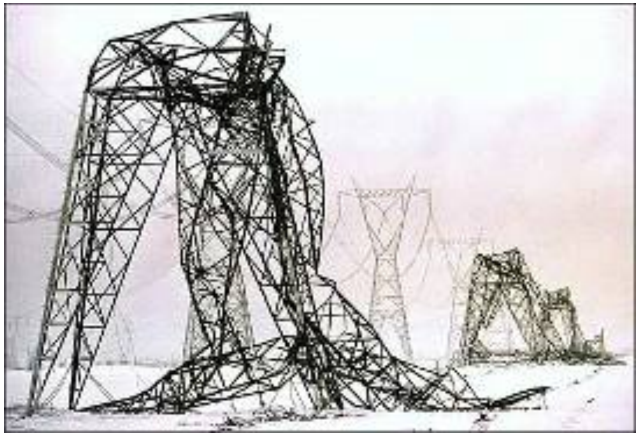


Image: US Energy Information Administration

The Grid Needs to Be Resilient to Lots of 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 operating conditions



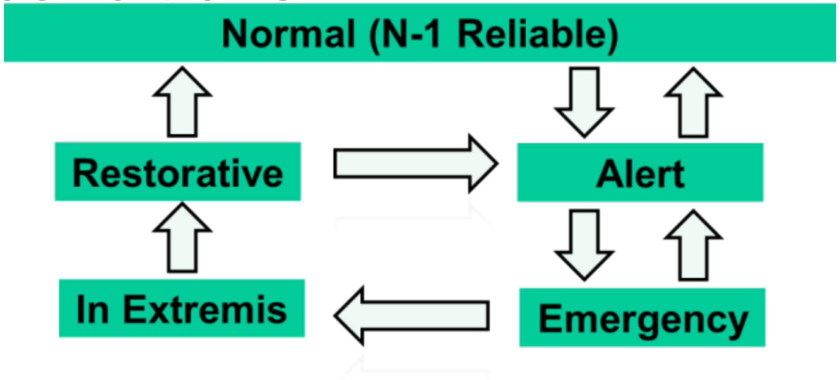
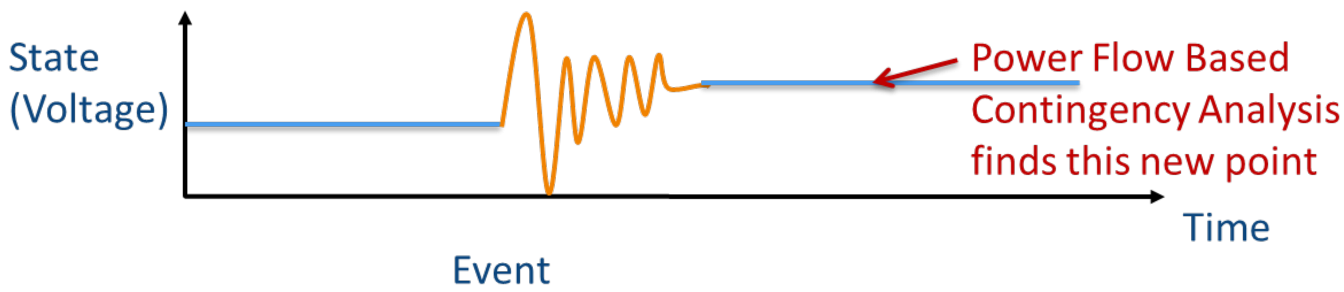


Image Derived From L.H. Fink and K. Carlsen, Operating under stress and strain, *IEEE Spectrum*, March 1978, pp. 48-53

Electric Grid Modeling: Quasi Steady-State with Power Flow

- The power flow is used to determine a quasi steady-state operating condition for a power system
  - Goal is to solve a set of algebraic equations
    - **g(y)** = **0** [**y** variables are bus voltage and angle]
  - Models employed reflect the steady-state assumption
- Using a power flow, after a contingency occurs (such as opening a line), the algebraic equations are solved to determine a new equilibrium



Grid Failure Example
August 14th 2003 Blackout Longer Term

Figure 5.13. Timeline Phase 4

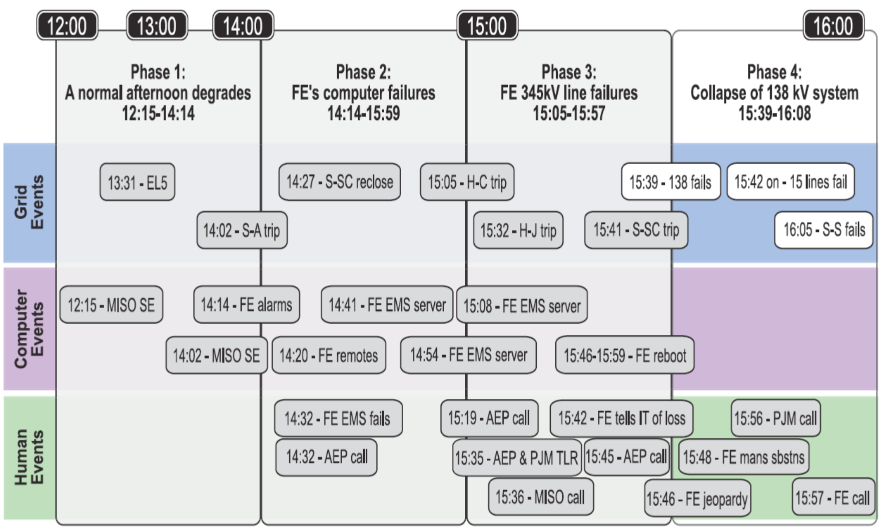


Figure 5.12. Cumulative Effects of Sequential Outages on Remaining 345-kV Lines

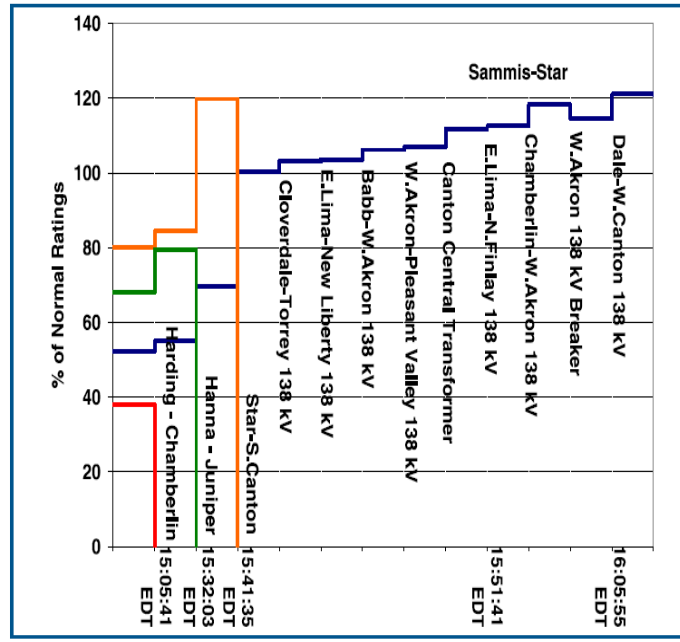
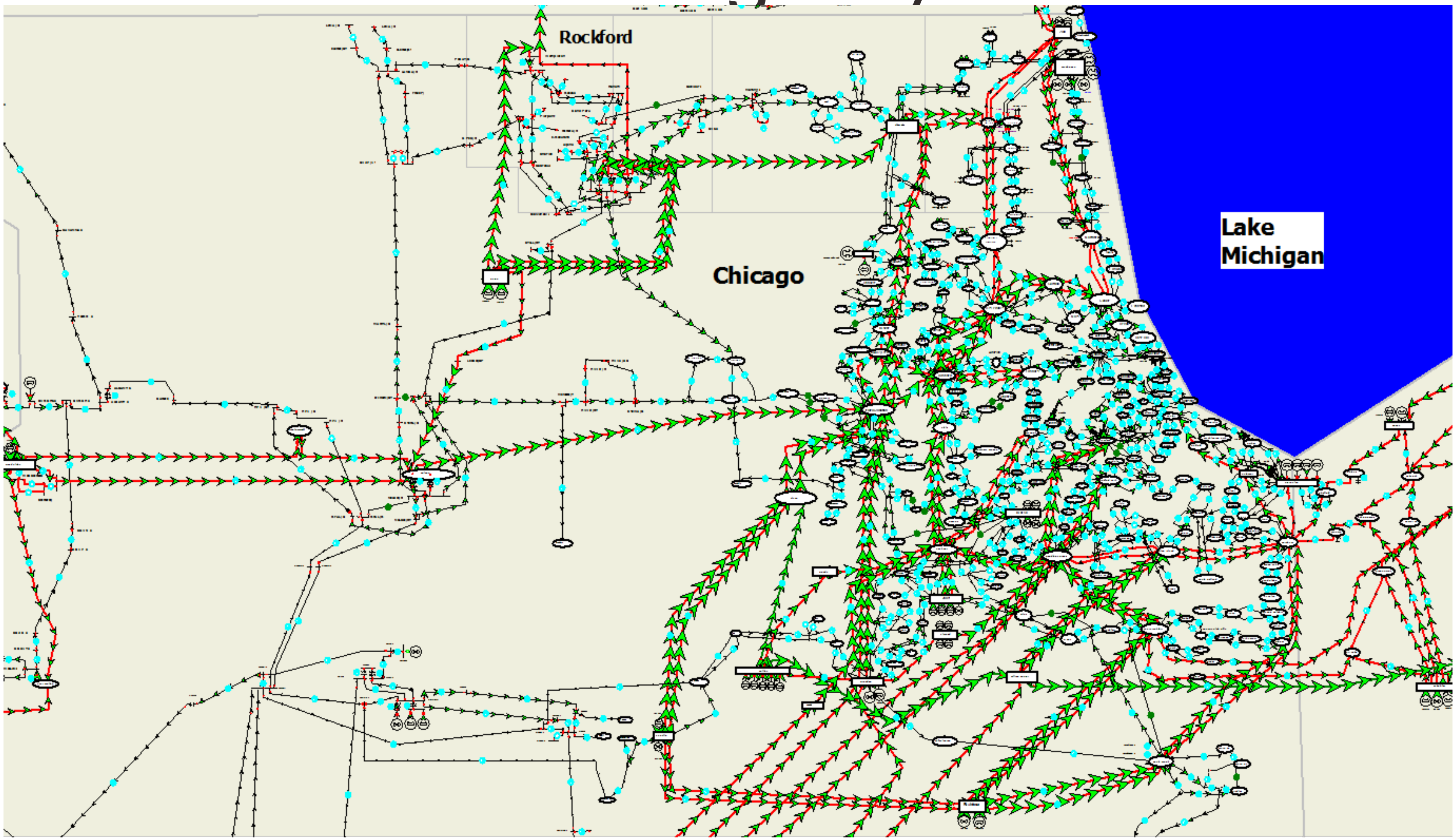


Image Sources: August 14, 2003 Blackout Final Report

Steady-State Electric Grid Operations Demo: Large System



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

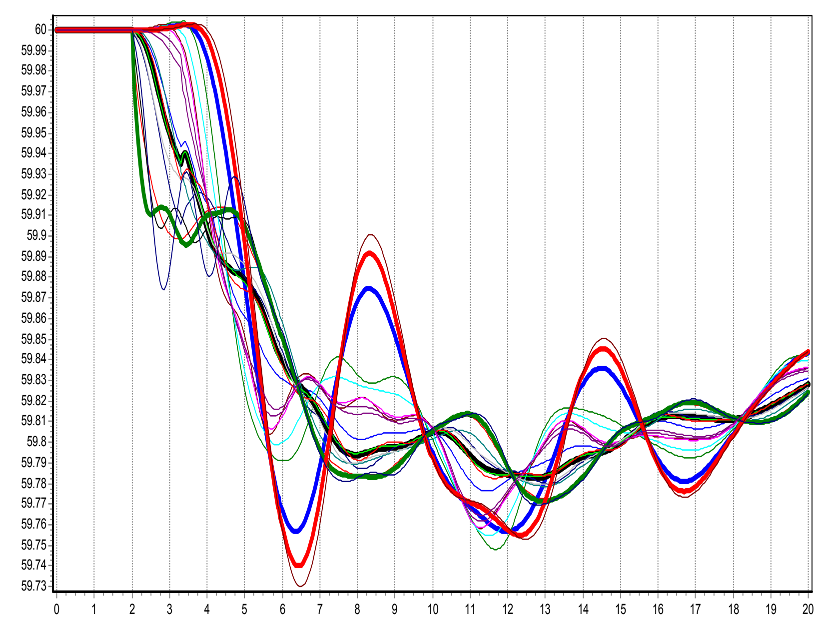
Power Flow vs. Transient Stability

- Transient stability is used to determine whether following a contingency the power system returns to a steady-state operating point
  - Goal is to solve a set of differential and algebraic equations,
    - $d\mathbf{x}/dt = \mathbf{f}(\mathbf{x},\mathbf{y})$ [**y** variables are bus voltage and angle]
    - $\mathbf{g}(\mathbf{x},\mathbf{y}) = \mathbf{0}$ [**x** variables are dynamic state variables]
  - Starts in steady-state, and hopefully returns to a new steady-state.
  - Models reflect the transient stability time frame (up to dozens of seconds)
    - Slow Values → Treat as constants
    - Ultra Fast States → Treat as algebraic relationships

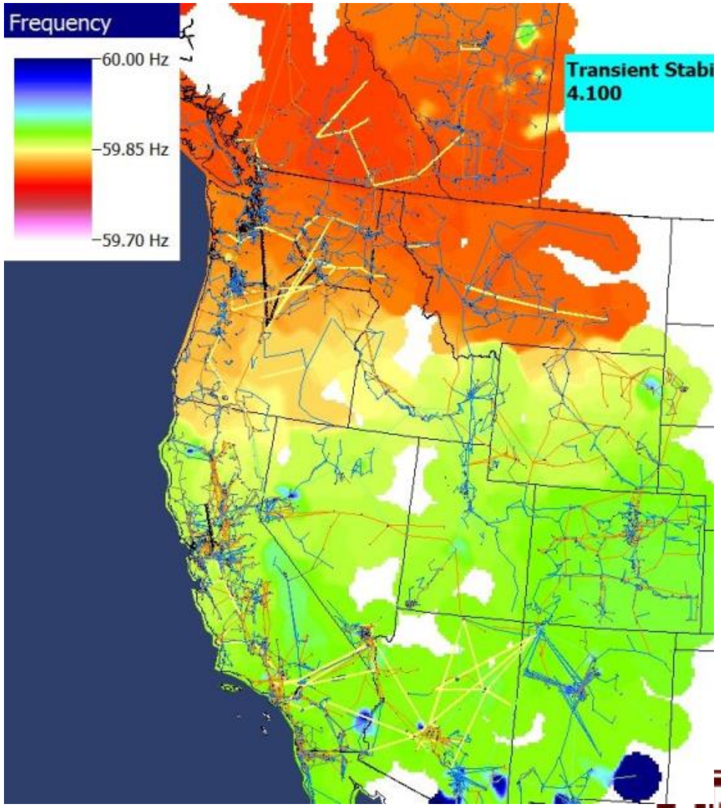
Grid Dynamics Disturbance Example

- Figures show the frequency change from the sudden loss of a large amount of generation in a North American Grid

Freq. Hz)



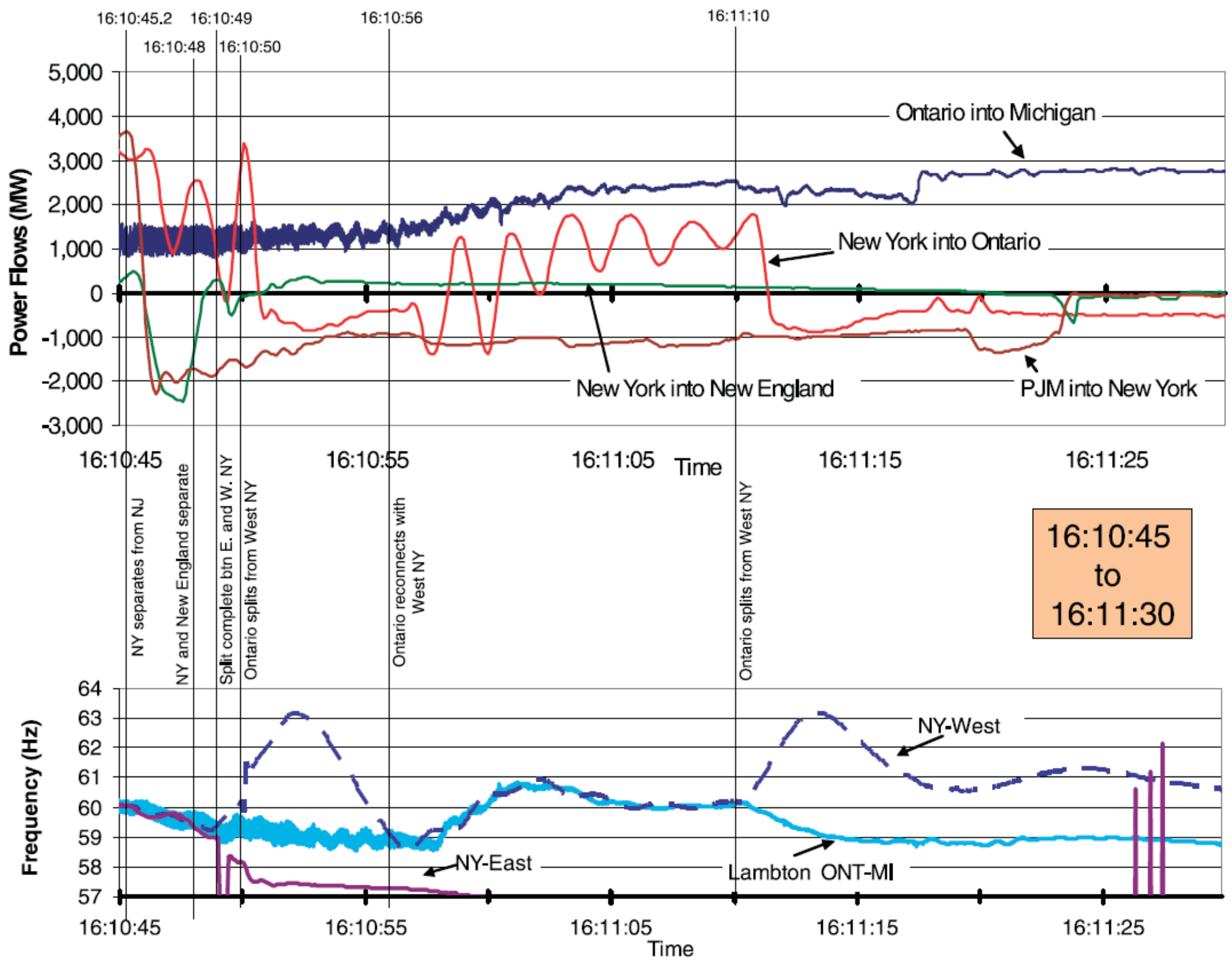
Time in Seconds



Grid Dynamics Example

WECC Large
Generation Drop
Simulation Using
PowerWorld version 16
(1/3 real-time
playback)

Grid Failure Example: August 14th 2003 Blackout Shorter Term



HILF Event: Geomagnetic Disturbances (GMDs)

- GMDs are caused by solar 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

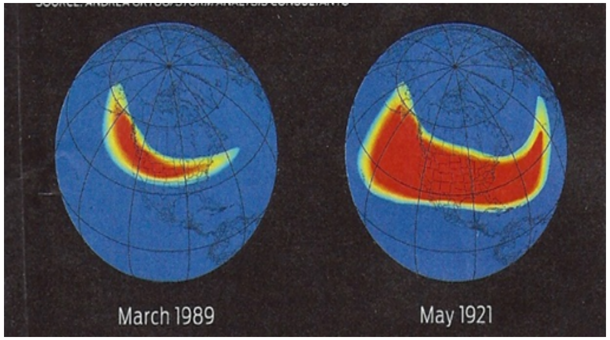


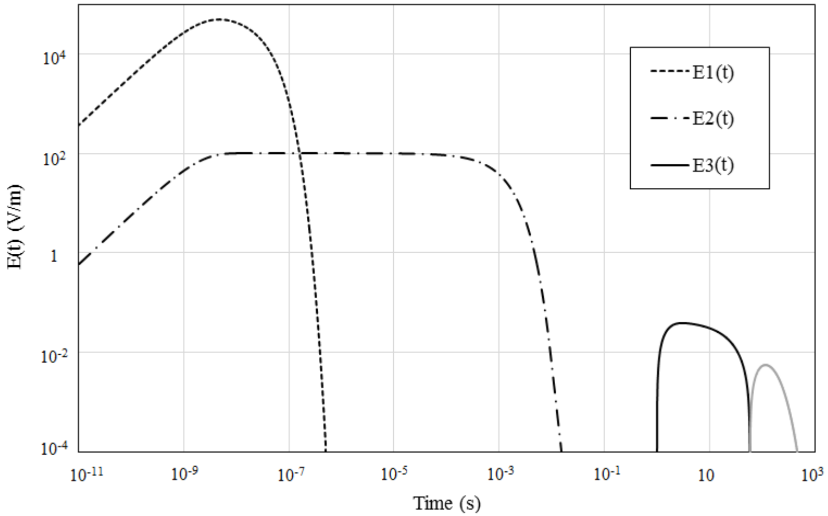
Image source: J. Kappenman, "A Perfect Storm of Planetary Proportions," *IEEE Spectrum*, Feb 2012, page 29

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 2500 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

Nuclear EMPs

- Broadly defined, an electromagnetic pulse (EMP) is any transient burst of electromagnetic energy
- High altitude nuclear explosions can produce continental scale EMPs; called HEMPs
- The impacts of an HEMP are typically divided into three time frames: E1, E2 and E3
  - E1 impacts electronics, E2 is similar to lightning, E3 is similar to a very large, but short duration GMD



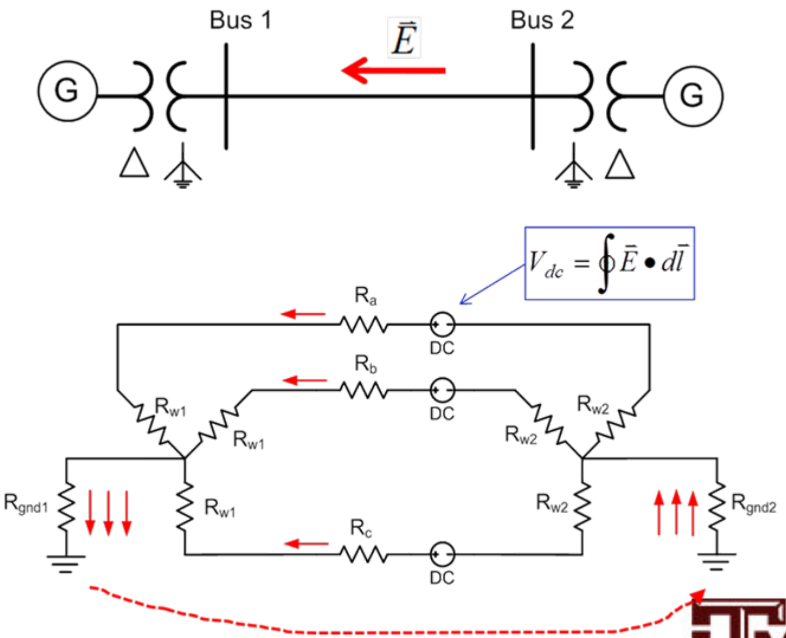
Nuclear EMP History: Starfish Prime

- HEMPs were theorized from the beginning; much of the public data is from tests in early 1960's
- Starfish Prime was an explosion of a 1.44 megaton nuclear weapon at an altitude of 400 km over the Pacific Ocean in July 1962
  - Part of series of tests known as Operation Fishbowl
  - The HEMPs were large, driving instruments off scale
  - Impacts seen in Honolulu (1445 km away), including knocking out about 300 street lights, setting off alarms, and damaging a microwave link; some satellites were also damaged

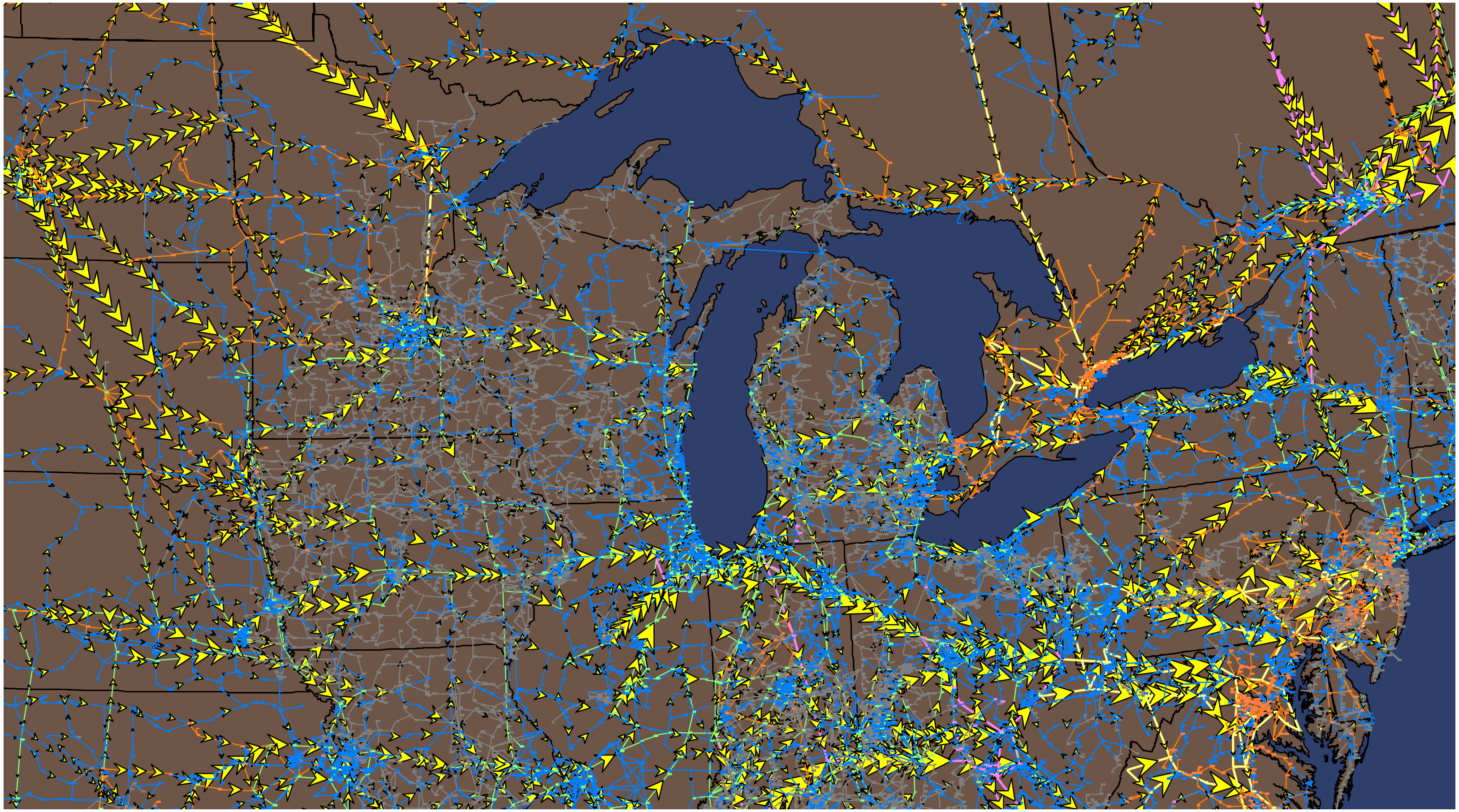
Starfish Prime flash seen in Honolulu; source: Wikipedia

Geomagnetically Induced Currents (GICs)

- Both GMDs and HEMPs cause electric fields, with values dependent on the deep earth conductivity
- 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

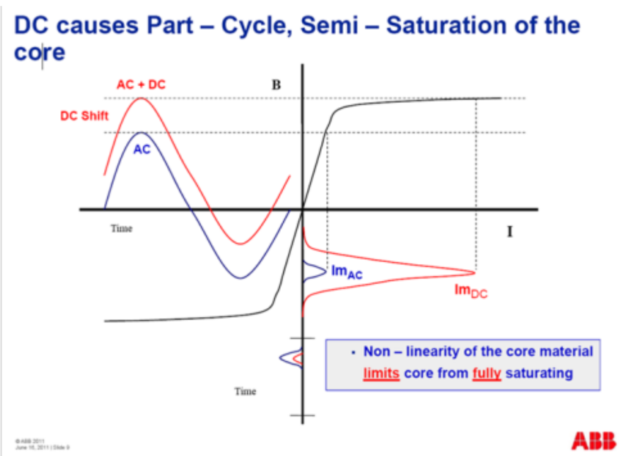


Simulated GICs in High Voltage Transmission Grid

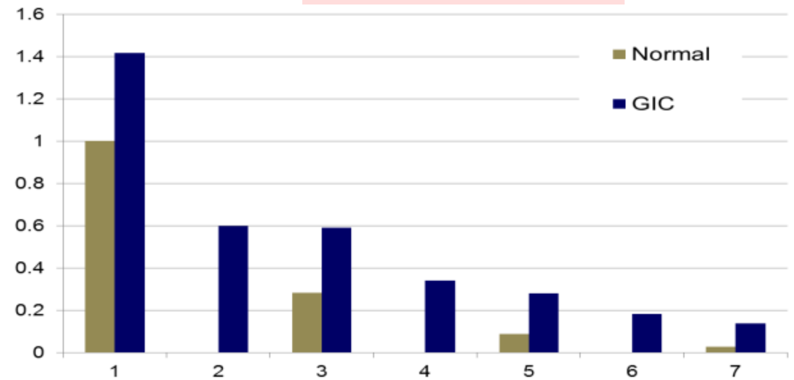


Transformer Impacts of GICs

- 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



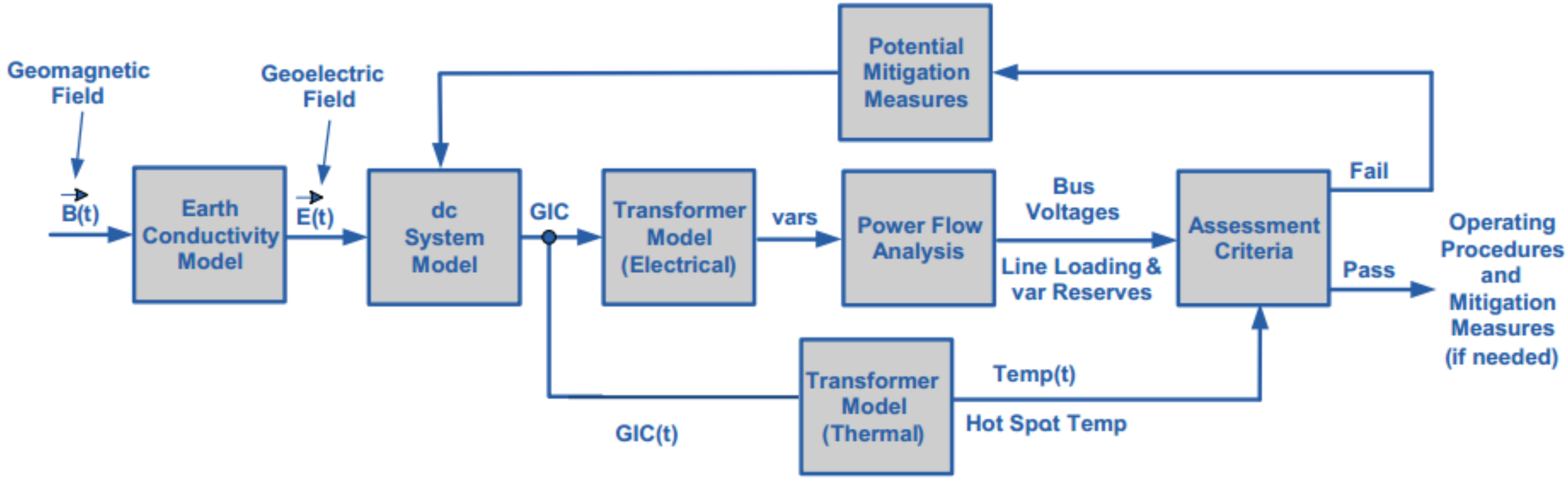
Harmonics



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

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; similar concerns due to HEMPs

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 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"

Example: Synthetic Electric Grids

- Enhanced resilience requires in-depth, mulit-discipline simulation but and access to information about the actual power grid is often restricted
  - Critical energy/electricity infrastructure information [CEII])
- For broad electric grid community to engage in research that adheres to the scientific principle of reproducibility of results, we need common access to models the mimic the complexity of actual grid
  - This is extremely important to drive the big data research we are discussing in this workshop
  - Lack of transparency can lead to ineffective research!
- Solution is to create synthetic electric grids

Synthetic Electric Grids

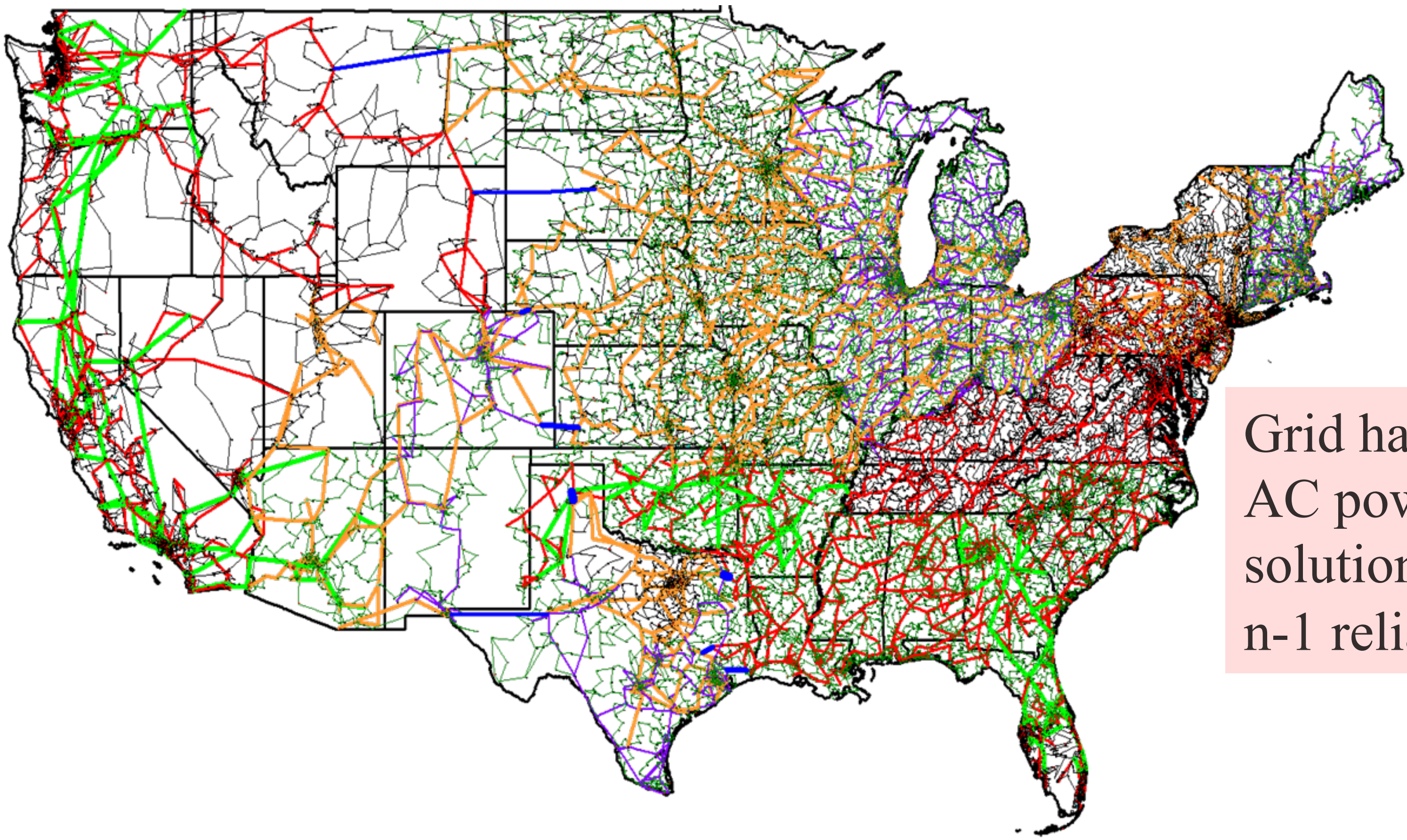
- The overall focus is the creation and dissemination of synthetic (fictional) high voltage power grids and associated scenarios
  - The systems will be of varying size and complexity, ranging from 200 buses up to 100,000 buses; they will also include contingencies and extra parameters for transient stability time frame dynamics and GMD analysis
  - All systems have geographic coordinates
  - Scenarios will be hourly for a year, SCOPF solved
  - Validation metrics are also a key consideration
- This will allow easy access to large-scale systems;
  - we're using a 2000 bus system in a TAMU undergrad lab

Approach

- Make the electric grids look real and familiar by siting them on an existing geography
  - Approach is general and could be used anywhere; so far all models are sited in North American serving a load that mimics the actual population density
  - The transmission grid is, however, totally fictitious, and the models contain no CEII by design
- This approach is predicated on gathering statistics associated with actual grids
  - Actual grids have idiosyncratic characteristics that need to be considered; outlier characteristics can be quite important!

Current Status: Large-Scale Grids are Now Available

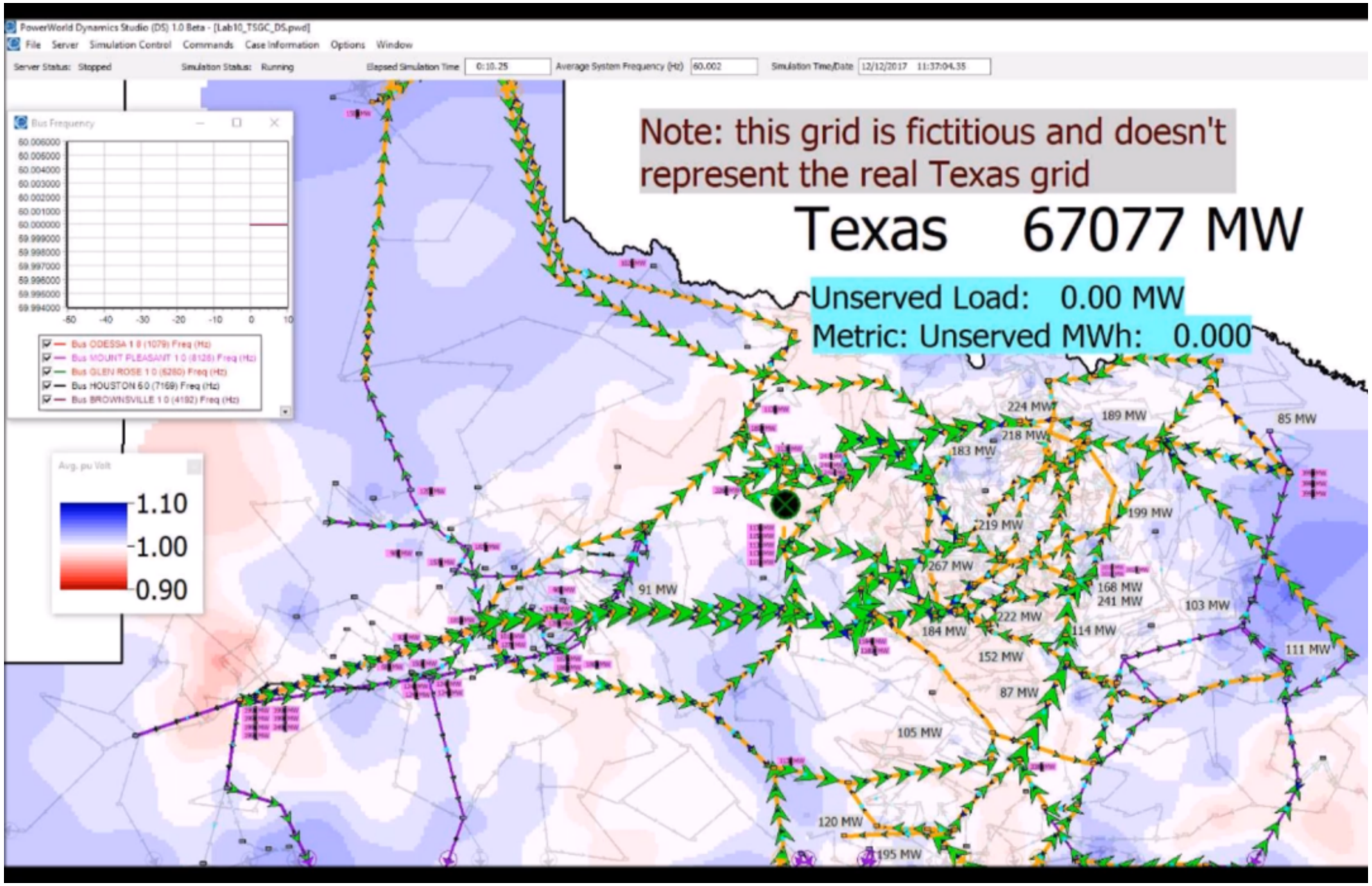
This is an 82,000 bus synthetic model that we publicly released this summer at electricgrids.engr.tamu.edu; we do hope to eventually add in Canada!



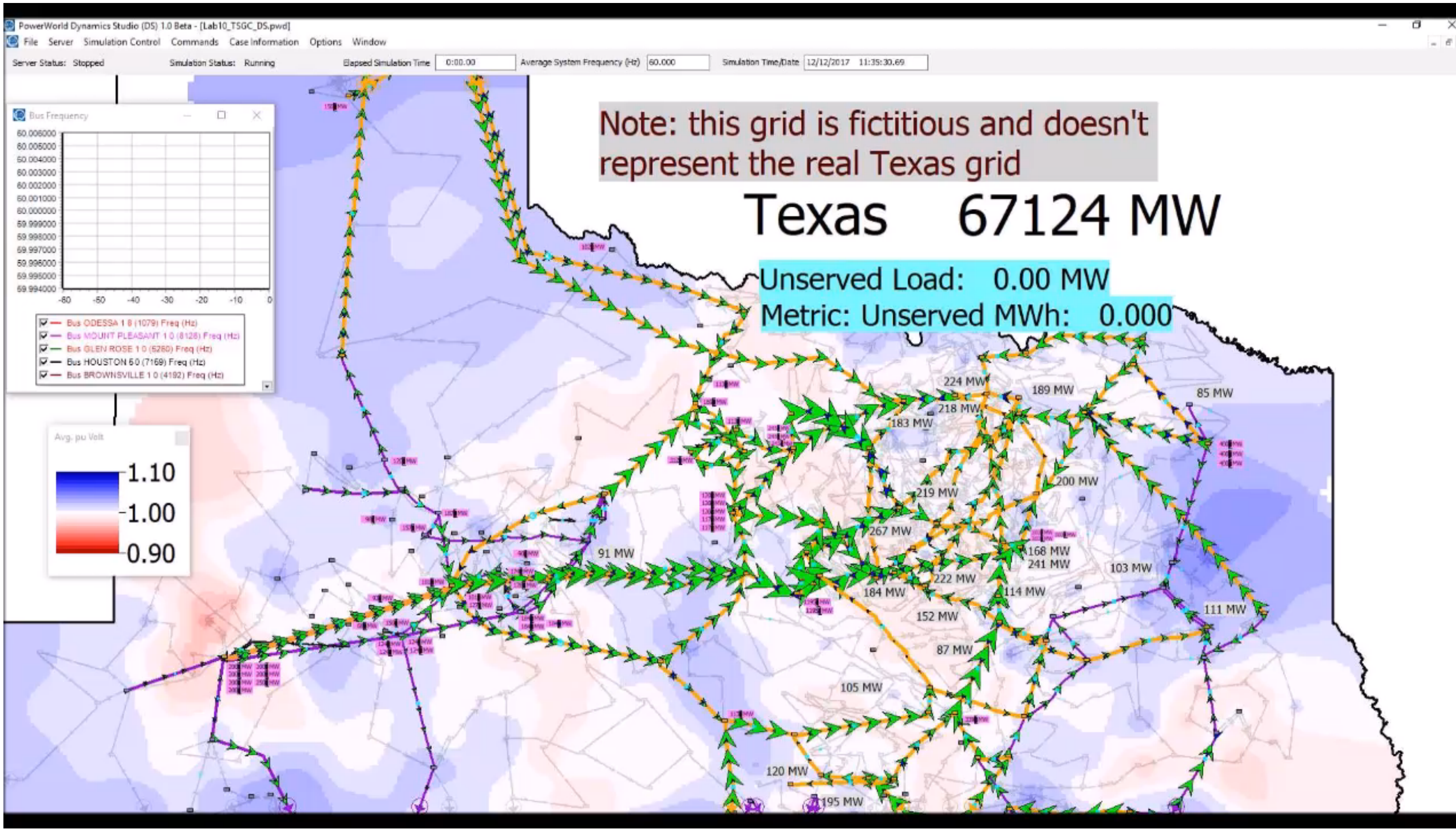
Grid has an AC power flow solution with n-1 reliability

Use of 2K Bus Grid in Undergrad Education

- Used in four experiments for TAMU ECEN 460 in Fall 2017, Spring 2018 and now Fall 2018



Innovative Electric Power Education



Conclusion

- The electric grid is crucial to our society, and for decades into the future we will be relying on it
- A perfect electric grid is impossible, and we need to be prepared for long-term, wide-area blackouts
- However, much can and should be done to reduce to reduce this risk
- A broad, sustained effort is needed in this area including the entire electric grid sector
- Synthetic electric grids will play a crucial role in this effort

Thank You!

Questions?