Assessment of an AC Interconnection of the North American Eastern and Western Electric Grids

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Acknowledgments

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- Slides also include contributions from many of my students, postdocs, staff and colleagues at TAMU
- Special thanks to SPP and the electric utilities which provided us with technical guidance
- The studies and visualizations were done using PowerWorld Simulator version 22
- The views expressed here are my own, and do not necessarily represent the views of any other person or organization.

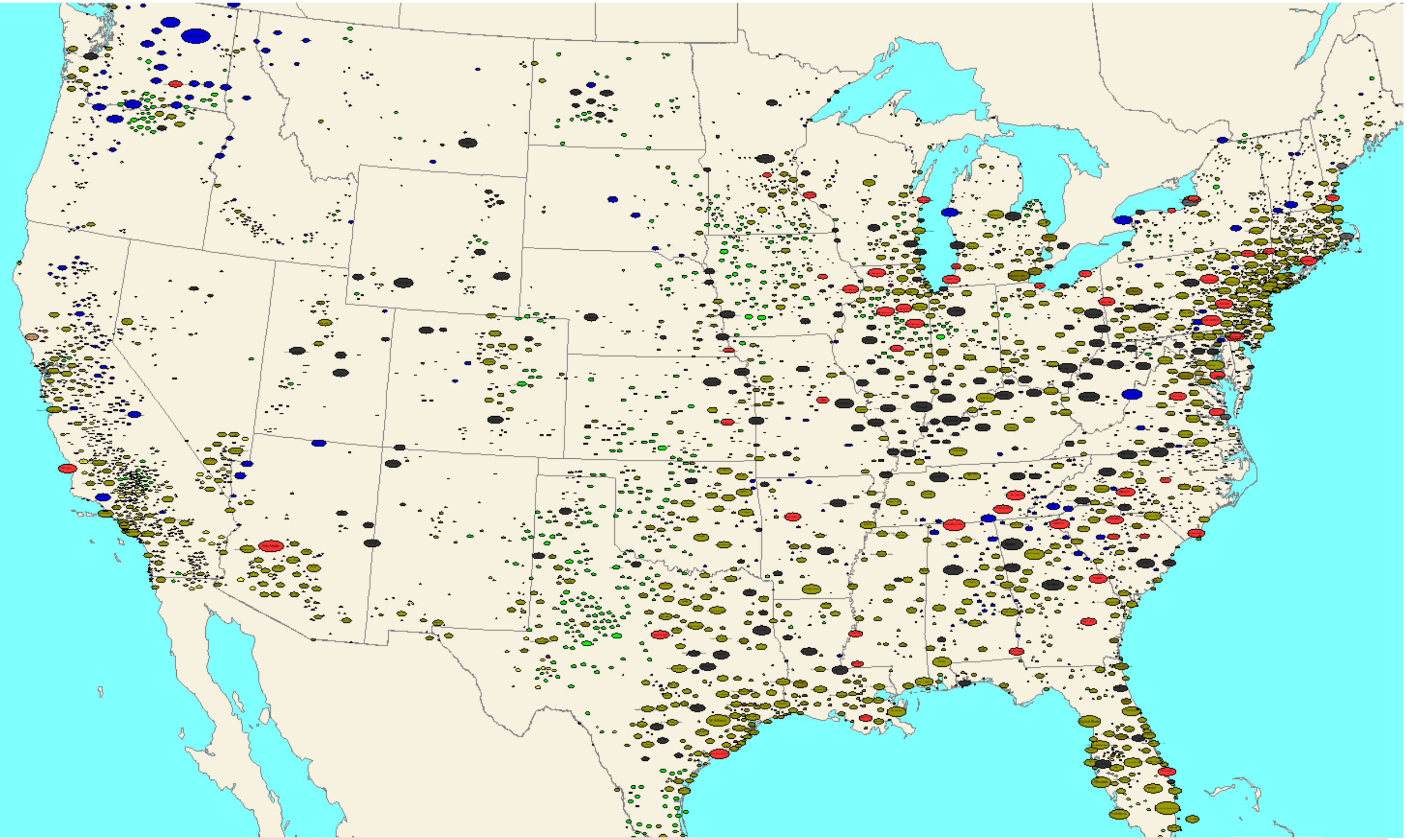
Overview

- Interconnected electric grids world-wide are in a period of rapid transition. Examples include
  - Integration of large amounts of renewable generation
  - Changing load, including more electric vehicles
  - Customers having more choice in their electric service
  - Inclusion of new technologies for sensing and control, such as phasor measurement units with “big data”
- There are lots of opportunities for innovation and changes in how the grid is operated
- This presentation discusses one potential change, the integration of the North American Eastern and Western electric grids

Background: Major North America Interconnects

Image Source: North American Electric Reliability Corporation

2019 US Generation by Capacity and Fuel



Oval size is proportional to the substation generation capacity, and color indicates primary fuel type (red nuclear, black coal, brown natural gas, blue hydro, green wind, yellow solar). Image shows public data from EIA Form 860; image created using PowerWorld Simulator.

2019 US Generation by Capacity and Fuel Type (Zoomed on Texas)

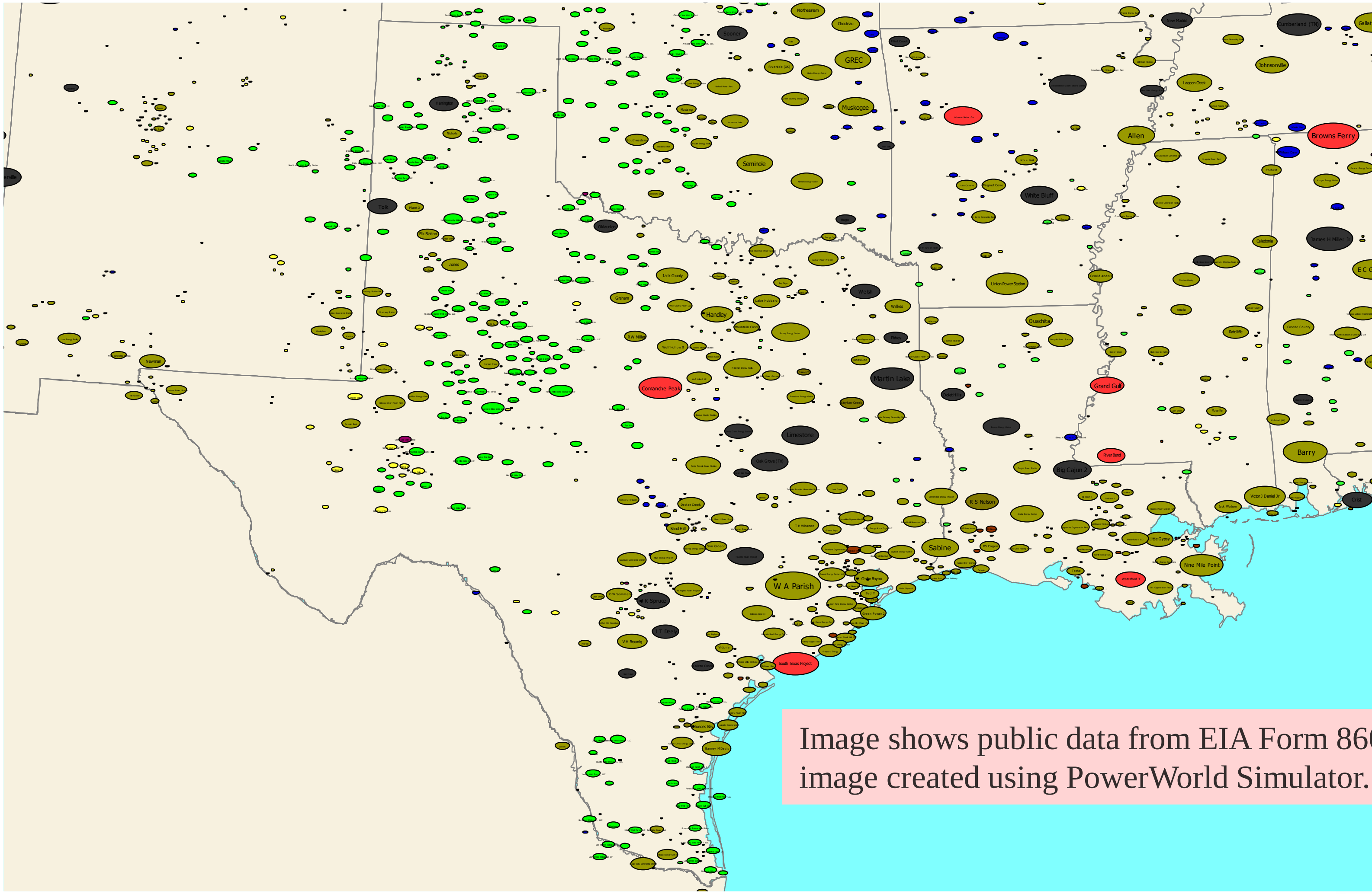


Image shows public data from EIA Form 860; image created using PowerWorld Simulator.

Comments on the Texas Cold Wave

- Starting on Feb. 14, 2021 statewide Texas had temperatures much below average
- In College Station, TX (between Dallas and Houston)
  - On Feb 14 the average high is 65°F and average low 45°F
  - Our coldest ever recorded temp was -3°F (1/31/1949)
  - Coldest February temp was 5°F (on 2/5/1951), last single digit was 9°F (12/22/1989)
- On 2/15/21 it was 9°F and very windy (and 5°F on 2/16)
- Across the state there were near all time coldest temperatures

A Few Comments on Texas Cold Wave

- On Sunday 2/14 between 6-7pm ERCOT set an all time peak winter demand of 69,150 MW (summer peak is 74,820 MW), previous winter peak was from 1/17/2018 (Wed) of 65,915 MW
- At 1:25am on 2/15 ERCOT had 10,500MW of load shed and had more than 30,000 MW of generation forced off the system
- They went to an EEA3 emergency conditions, which ended on Friday Feb 19 (with much warmer temperatures)

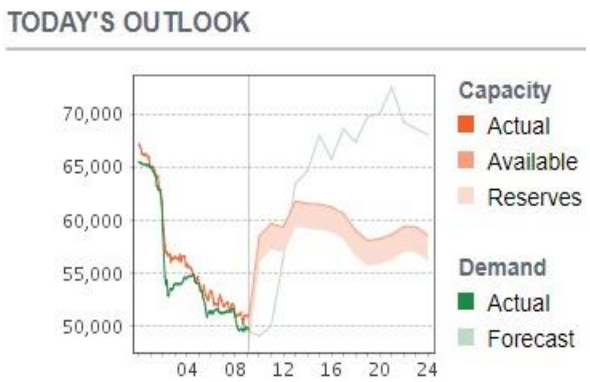


Image source: ERCOT website, February 15, 2021

It was Bad and Could Have Been Worse

- Many, many Texans lost power and water for days during record low temperatures and had large amounts of damage (e.g. from burst pipes)
- Others did not lose power and only lost water after the worst of the temperatures were past
- Much load was lost, but the ERCOT system continued to operate. However, ERCOT reported they were seconds and minutes from total collapse, a catastrophic scenario!!
- I think there are heroes among ERCOT and utility operators, engineers and field personnel who kept at least the majority of the heat and lights on

Background: Why is ERCOT Separate

- ERCOT operates asynchronous from the rest of North America, but has high voltage dc (HVDC) ties with the Eastern Interconnect and Mexico
- The advantage is ERCOT avoids some federal regulation. The legal basis for this is complex, based on the US Constitution, the Federal Power Act, the 5/4/76 midnight connection, other legislation, court rulings, and FERC decisions

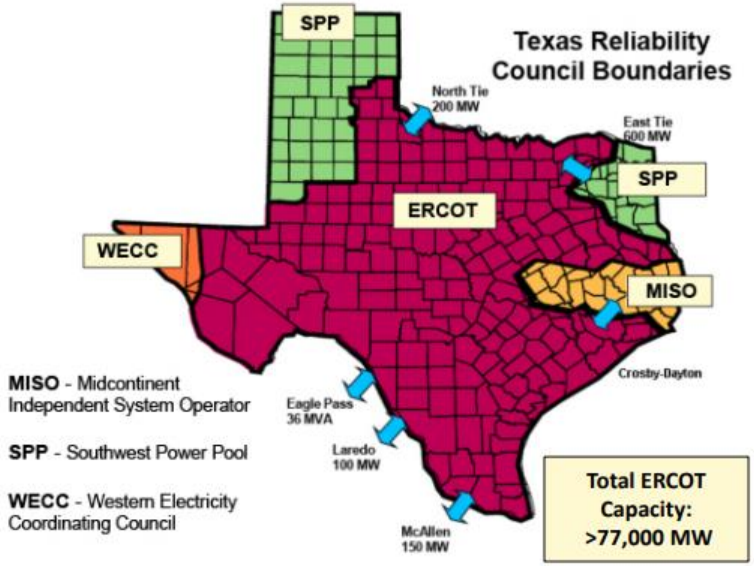


Image Source: aect.net/documents/2017/AECT%20LSB%20012617.pdf

High Voltage Direct Current (HVDC) Transmission

- Most electricity is transmitted in ac form, at either 60 or 50 Hz (with 60 Hz in North America)
- HVDC is sometimes used to transmit electricity either within an interconnect or between interconnects (back-to-back HVDC)
  - Within an interconnect, HVDC is usually used for long distance transfer, or in underground or undersea cables
- HVDC avoids issues with reactive power, but incurs the costs associated with the rectification (ac to dc) and inversion (dc to ac)
- HVDC power flow can be quickly controlled (milliseconds)

Southern Cross HVDC Transmission Project

- The Texas Public Utility Commission has approved an application to build a 38 mile, 345 kV ac transmission line to connect to a 400 mile long, 500 kV HVDC between the Mississippi/Alabama and the Louisiana/Texas borders
  - As planned it would have a capacity of 2000 MW
  - It could be operational in 2022 with a cost that might be more than $1 billion
  - Up-to-date information on the project is available at www.ercot.com/mktrules/puctDirectives/southernCross

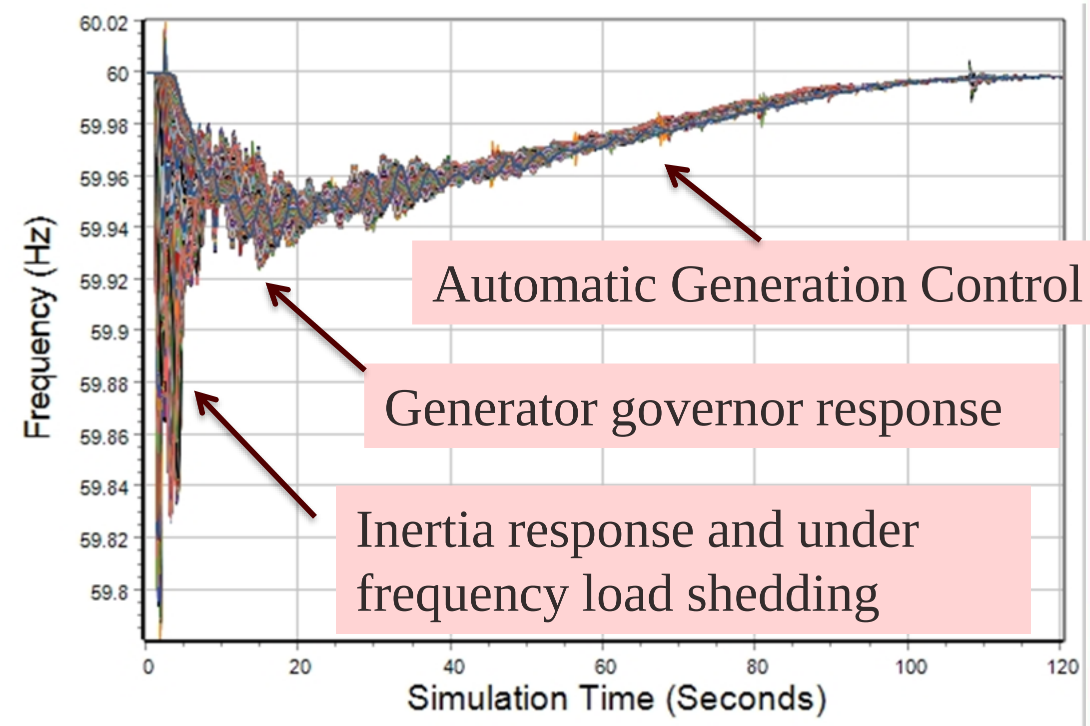
Image source: southerncrosstransmission.com/louisiana/

Electric Grid Resiliency

- The ability of electric grids to resiliently respond to high impact, low frequency events is an important but often overlooked aspect of operation, design and research
  - There is always a tradeoff between risk and mitigation cost
- The best reference I know of is the free 2017 report from the US National Academies titled, “Enhancing the Resilience of the Nation’s Electricity System”
  - It does mention the threat of cold weather, and specifically mentions the February 2011 Texas cold snap

Quick Aside: Power System Dynamic Response to Load/Gen Mismatch

- An electric grid frequency is constantly changing, but it usually within a few mHz of desired (e.g., 60 Hz)
- Too much generation increases the frequency and and too little decreases it
- All grid elements have the same average frequency but during disturbances the frequency can oscillate



Background: East-West History

- The East and the West have been joined in the past, at least from 1967 to the 1970's
  - In the [a] (from 1970), the authors say,

    "The nation's largest synchronized network now extends from coast to coast and includes 94 percent of United States generating capacity."
  - In a 2018 IEEE Proceedings article Julie Cohen says they were joined from 1967 to 1975; they separated because of problems with maintaining synchronism and the introduction of HVDC
- A 1994 WAPA report looked at the reconnection

[a] Cohn, Biddle, Lex, Preston, Ross, Whitten, "On-line Computer Applications in the Electric Power Industry," IEEE Proc., January 1970, pp. 78-87

Background: Grid in 1970 (From [a])

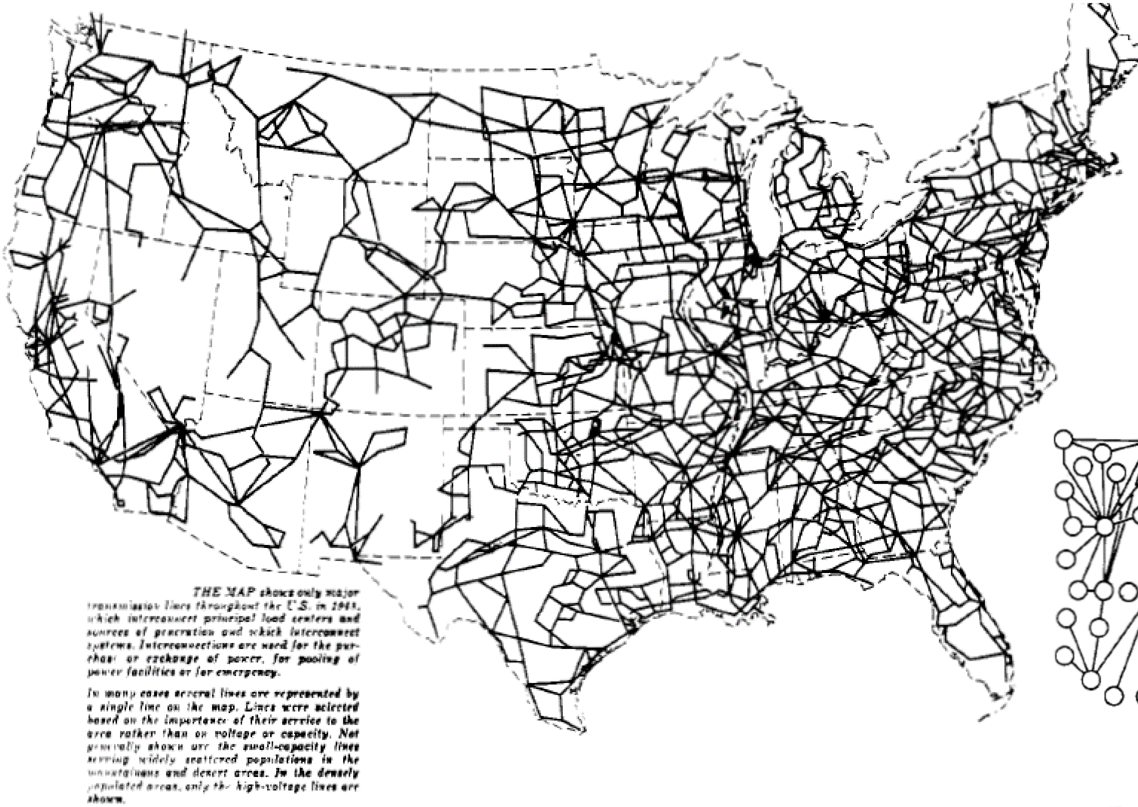


Fig. 2. Schematic backbone transmission map illustrating the major interconnecting tie lines in the United States as of the end of 1969 (courtesy of Edison Electric Institute).

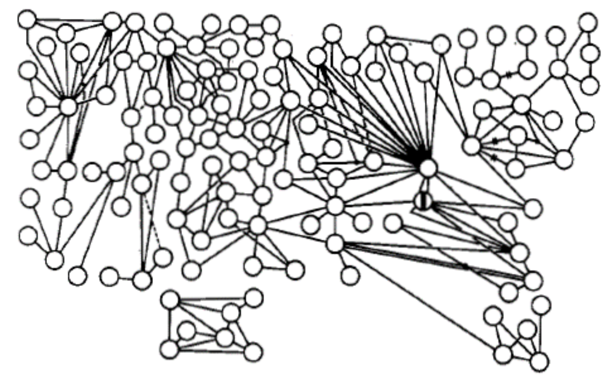


Fig. 3. Interconnected control areas of the continental United States and Canada.

[a] Cohn, Biddle, Lex, Preston, Ross, Whitten, “On-line Computer Applications in the Electric Power Industry,” IEEE Proc., January 1970, pp. 78-87

Another good background article is by Julie Cohn in the January 2019 *IEEE Proceedings*, titled, “When the Grid Was the Grid: The History of North America’s Brief Coast-to-Coast Interconnected Machine”

Background: Critical Energy/Electric Infrastructure Information (CEII)

- Some of the information associated with the US electric grid is considered to be CEII, which restricts its public disclosure
  - For those interested, some background on CEII is provided at https://www.ferc.gov/enforcement-legal/legal/major-orders-regulations/critical-energyelectric-infrastructure-information
  - Based on FERC 683 (9/2006) the general location of critical infrastructure is not CEII; also much of the information about US electric generators is publicly available via Form EIA-860 (eia.gov/electricity/data/eia860/)
- This project used CEII but this presentation contains no CEII

Summary of Presentation

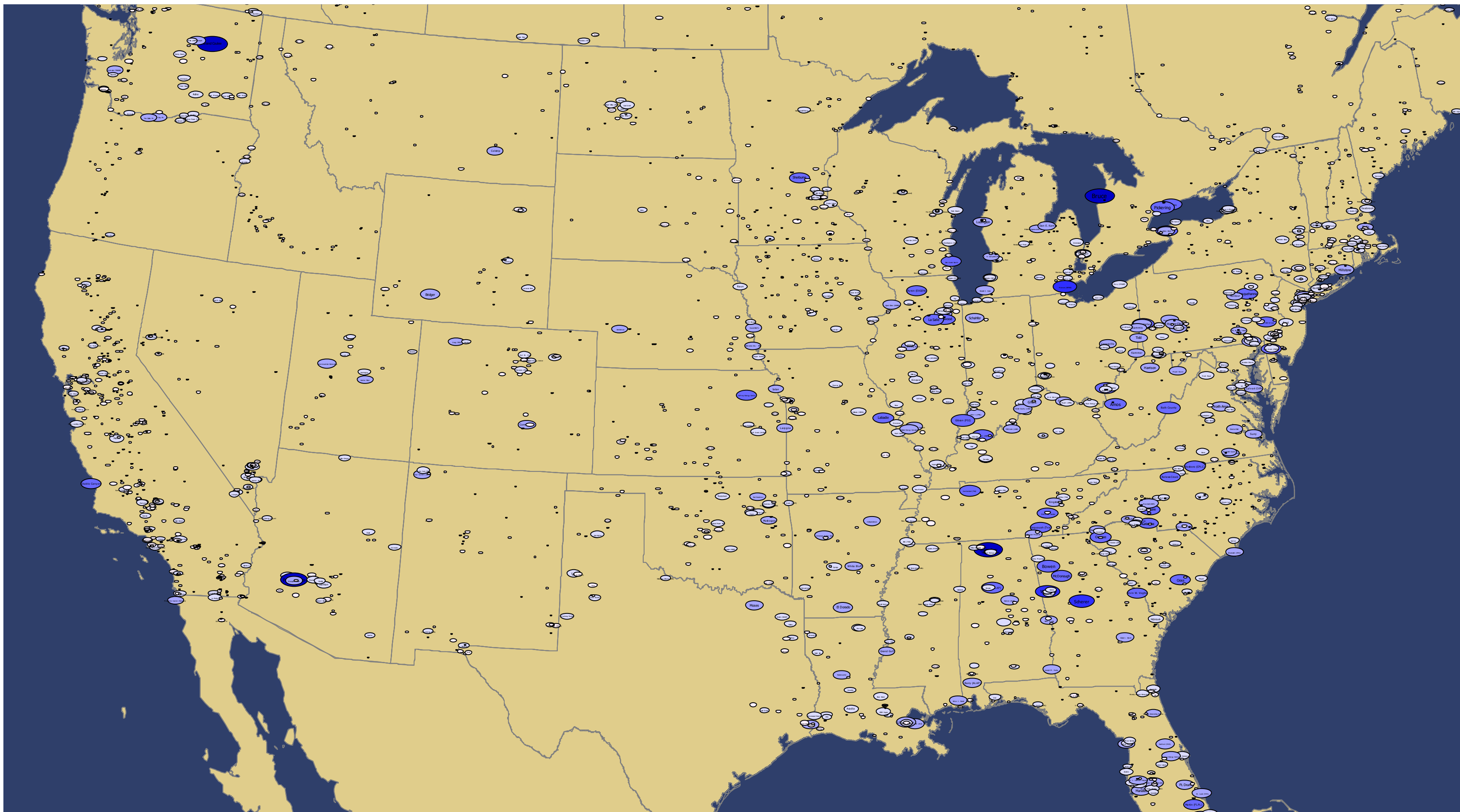
- The presentation covers primarily the dynamic aspects of interconnecting two large electric grids
- For the project we mostly used a 110,000 bus dynamic (transient stability level) model of a combined North America East and West grid
- The grids were combined using nine short ac interconnections at voltages from 161 to 345 kV
- There are no showstoppers with doing such an interconnection with the key constraint that during dynamic disturbances with lost generation in the West, about 75-80% of the lost generation will flow East to West; modelling the AGC response is important
- Some results will be shown with synthetic grids

More Details on Combining the Models

- The input data for the project was high and low demand power flow and dynamics cases for the Eastern Interconnect and the WECC (West)
  - These are the best electric grid models available
- Power flow and dynamic data were provided for the East in PSSE format and for the West in PowerWorld format, based on PSLF
  - Not all the models are compatible between PSSE and PSLF, but PowerWorld supports both
- To avoid overlapping bus numbers the West was renumbered by adding 2 million to the West
- A combined case was created in PowerWorld with 110,000 buses

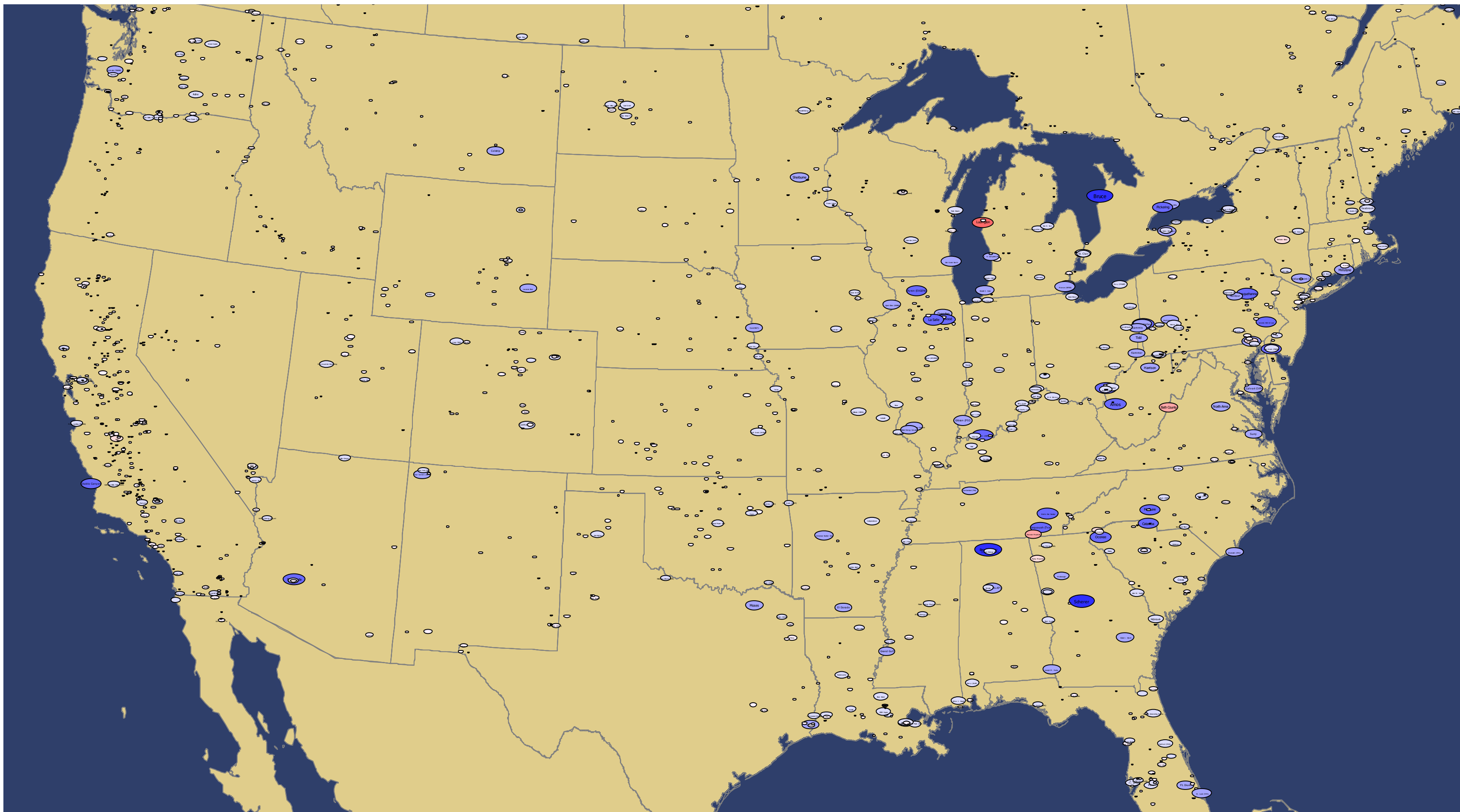
Base Model 1: Heavy Load Conditions

Substation Generation Sized and Colored by MW Value

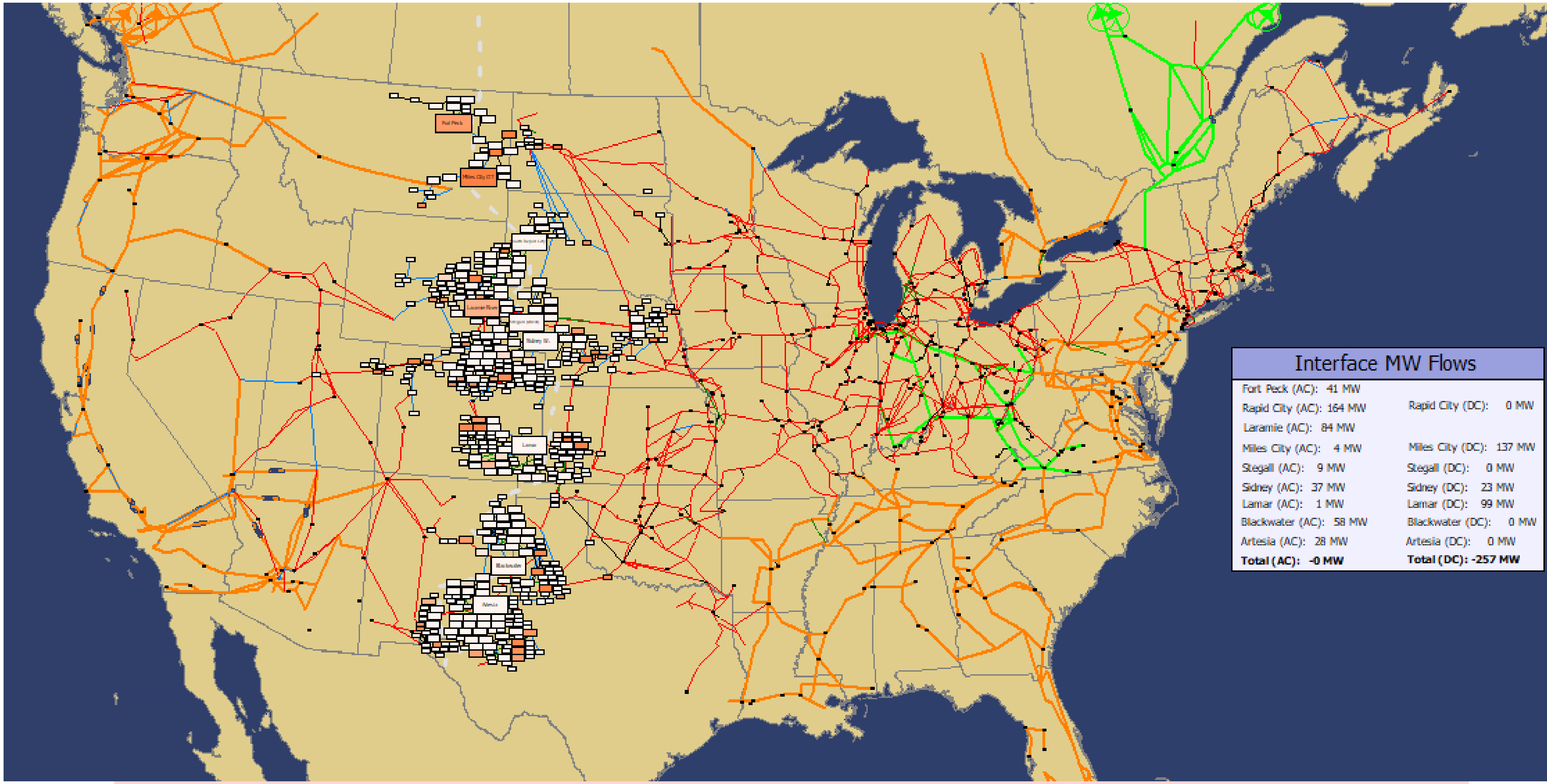


Base Model 2: Light Load Conditions

Substation Generation Sized and Colored by MW Value



The Combined Grid Overview



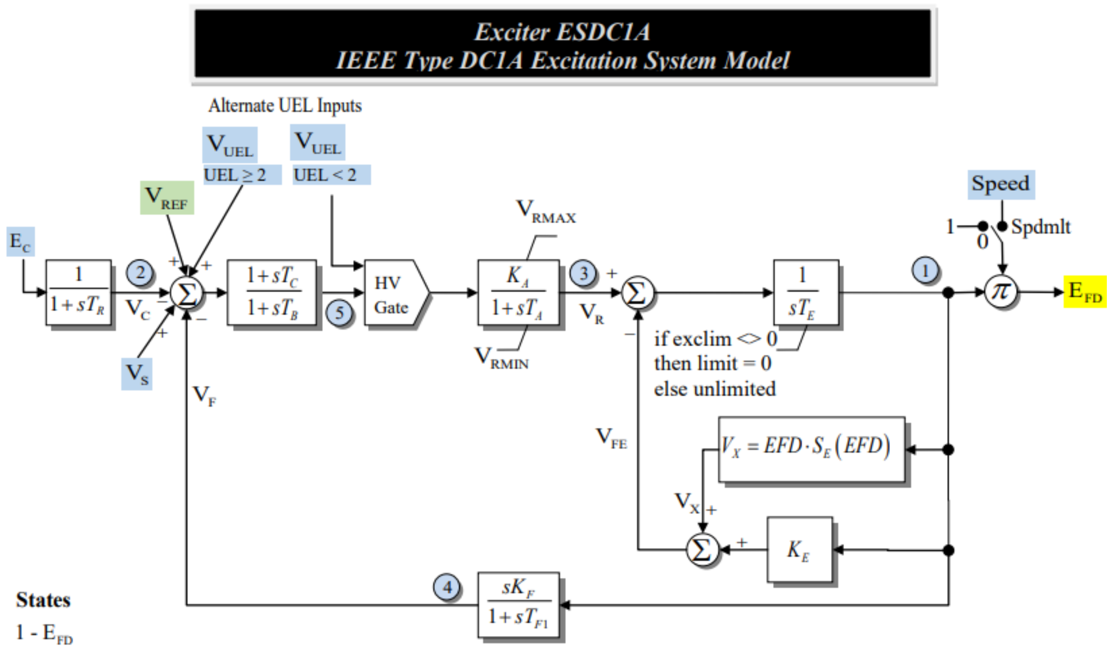
The study included Canada but we did not consider any ac interconnections between the grids in Canada

Dynamic Model Setup

- A primary project task was to perform dynamic (transient stability level) studies on the combined grid, and to compare the results with the separate grids
  - Key dynamic contingencies were the loss of a large amount of generation (greater than 5000 MW in the East)
  - The model has 110,000 buses, 14,000 generators, 37,000 dynamic model devices with 243 different model types
  - The Integrations were solved using a ½ cycle time step

Modeling Considerations

- While many of the dynamic models used in the East and West are similar (or identical), there are sometimes subtle differences
  - Example is with an ESDC1A exciter in which the KE value is auto determined by the software when it is set to zero

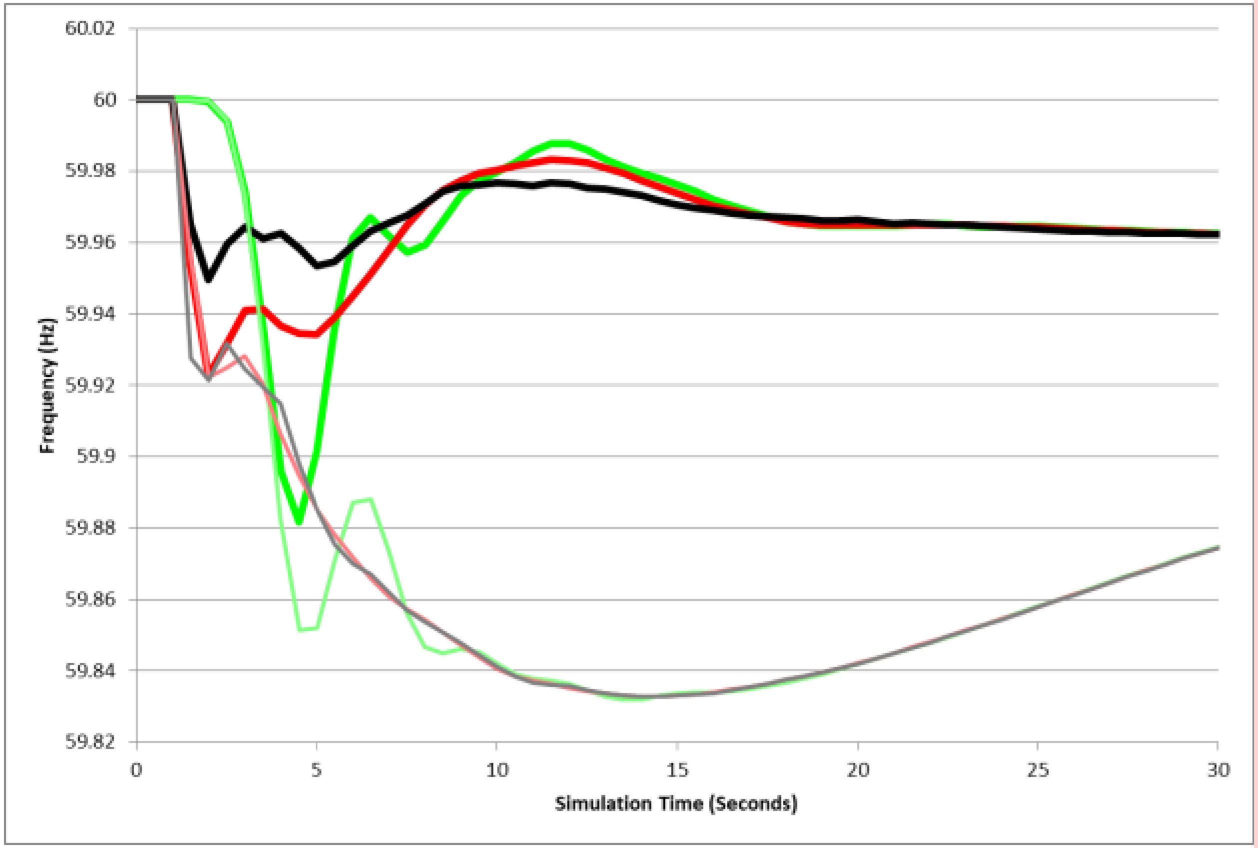


How this adjustment occurs differs between software packages, and changing the approach can result in unstable simulation results.

Dynamic Studies

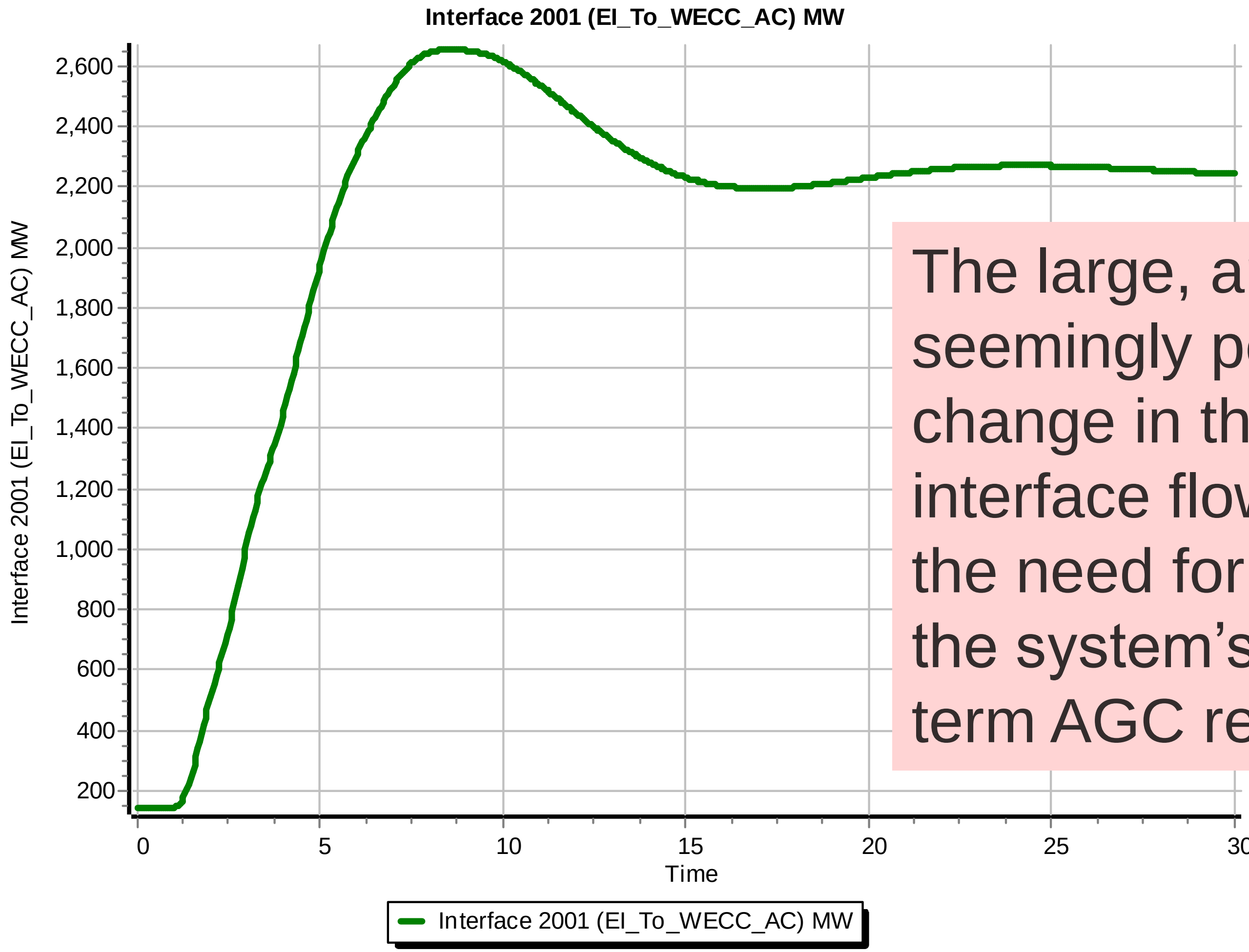
- Over the course of the project we did a large number of simulations, ranging for short (10 second) fault studies to longer (six minute) automatic generation control (AGC) response scenarios
- Even for severe events (> 5 GW losses in the East) the interconnected grid maintained synchronism
- However, a key issue is for the loss of generation in the West about 80% of the makeup power flows across the interface from East to West
  - The converse is true for generation loss in the East, about 20% of the makeup power flows across the interface from West to East

WECC Frequency Response Comparison: With and Without the AC Interconnection



The graph compares the frequency response for three WECC buses for a severe contingency with the interface (thick lines) and without (thin lines)

AC-Tie Interface, Severe Contingency



The large, and seemingly persistent, change in the interface flow required the need for modeling the system's longer term AGC response.

Adding AGC Modeling

- As noted following any disturbance about 80% of the governor response will occur in the East, with the change in flow going across the new ac interface if the disturbance is in the West.
- The governors don't restore the system frequency to its setpoint value; rather this is done by the automatic generation control (AGC) utilizing the balancing authority area control error (ACE) signal
- The ACE has a frequency component

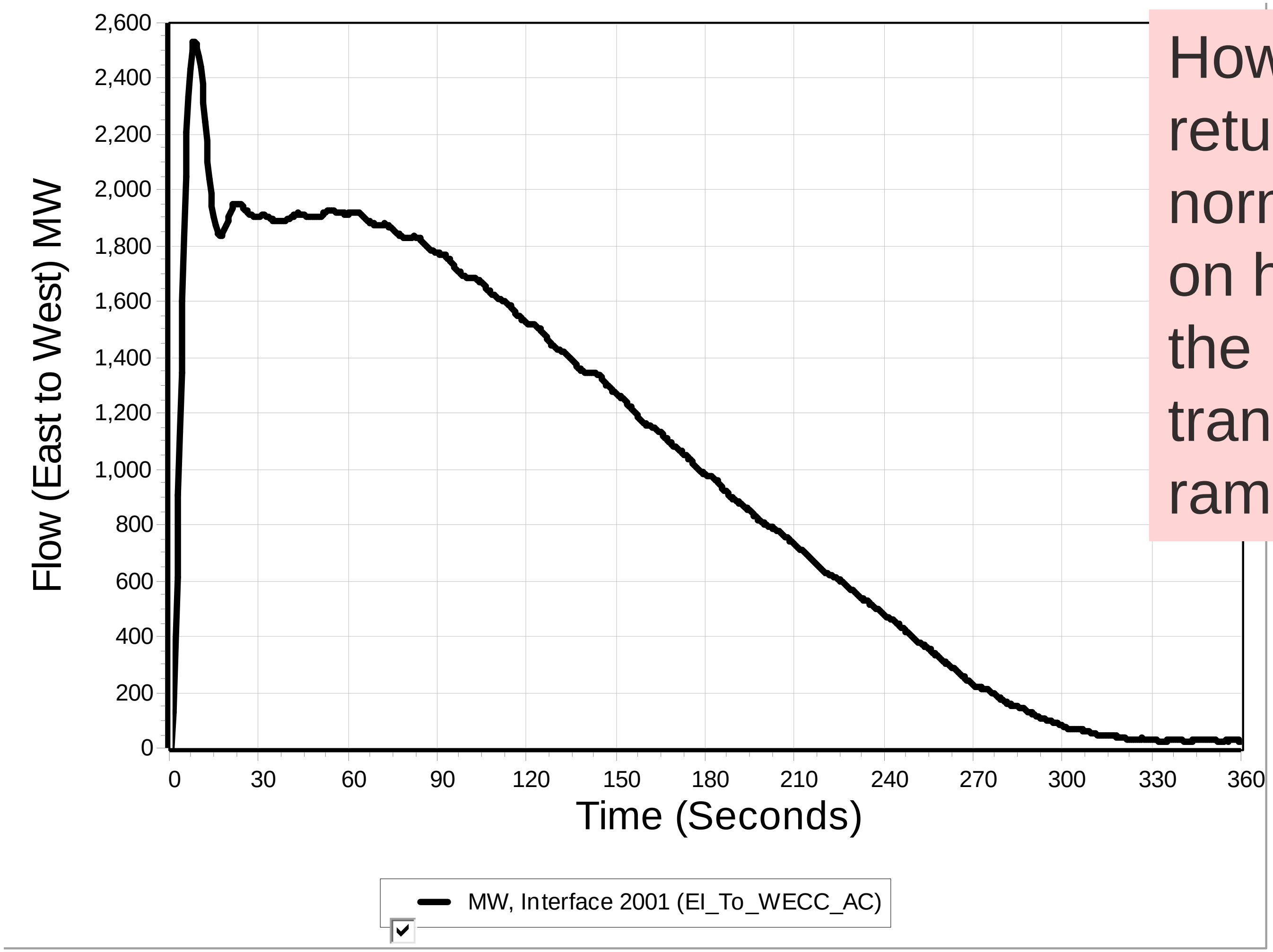
  $ACE = P_{actual} - P_{sched} - 10\beta(freq_{act} - freq_{sched})$

  β is the frequency bias; it has a negative sign, units of MW/0.1 Hz and is about 1% of the peak load/generation

Example AGC Response

- Six minute simulation with severe generator loss, with emergency transactions implemented between several of the utilities
- These transactions were initiated and ramped faster than normal to keep the simulation length reasonable (starting at 30 seconds and ramping over four minutes)
- Initially much of the makeup generation flowed through the interface, but it ramped down to zero

New Interface Flow



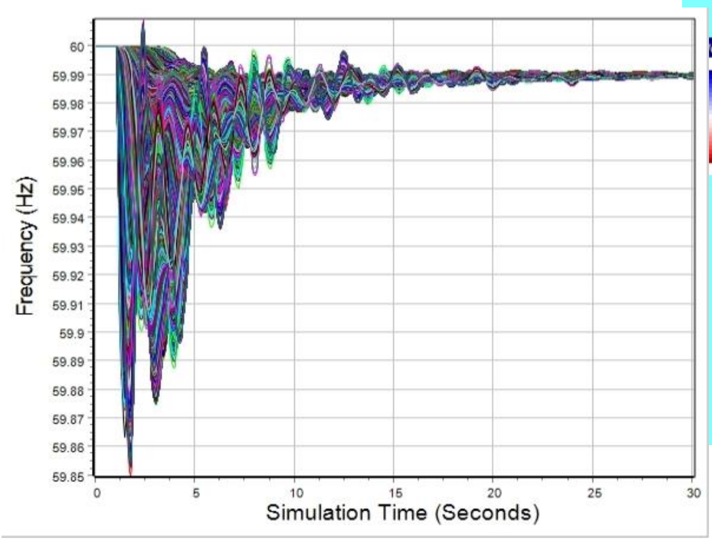
How fast it returns to normal depends on how fast the MW transactions ramp

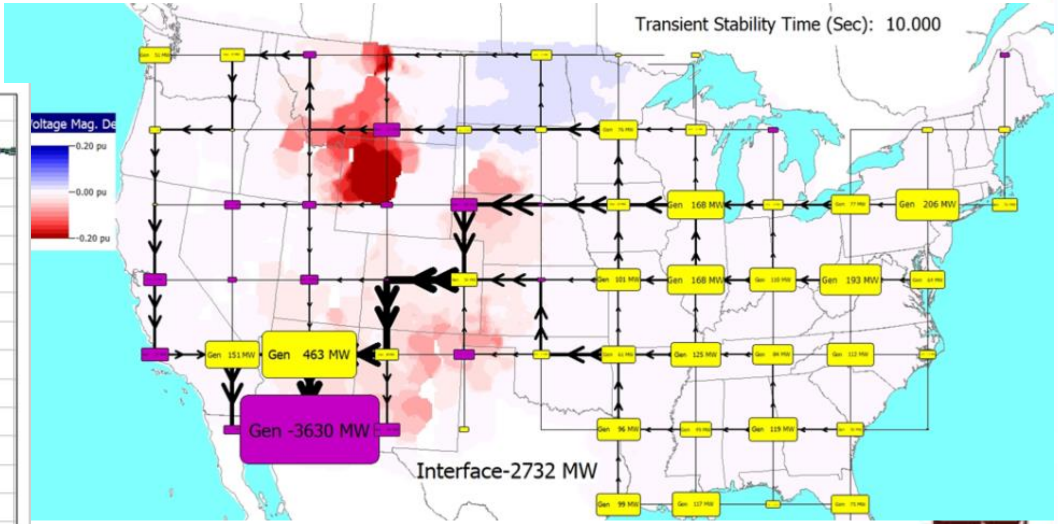
Situational Awareness

- A key challenge with this project was understanding the results of these dynamic studies
  - Even a 30 second study produced many GBs of results
- Situational awareness (SA) is defined informally as "knowing what's going on" and more formally as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future"
- In this study we wanted to have good SA to make sure we didn't miss something

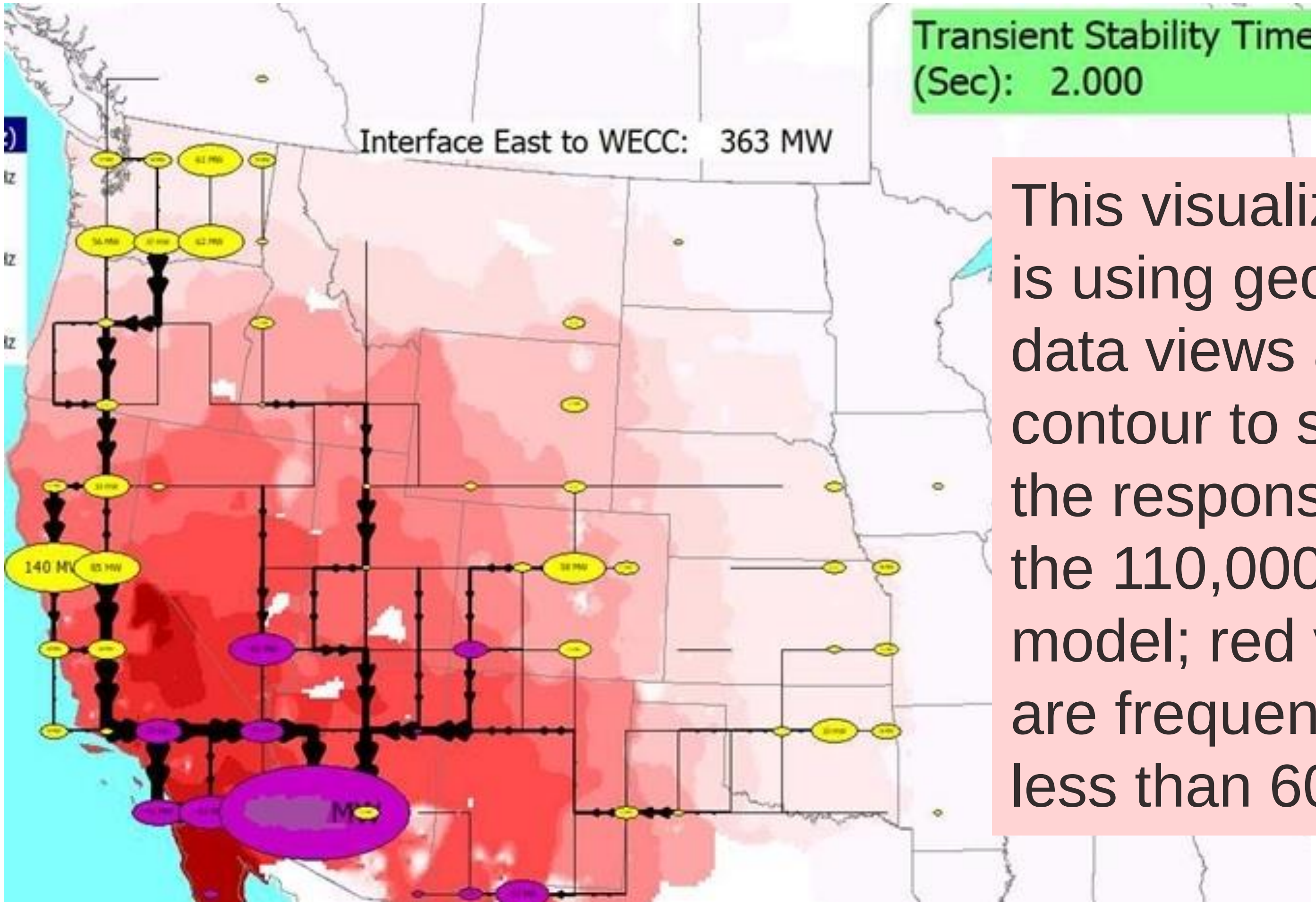
SA Techniques

- For this project we leveraged a number of different techniques including
  - Time-domain graphs
  - Geographic data views including planar flow visualizations
  - Contours
  - Animation (movies)





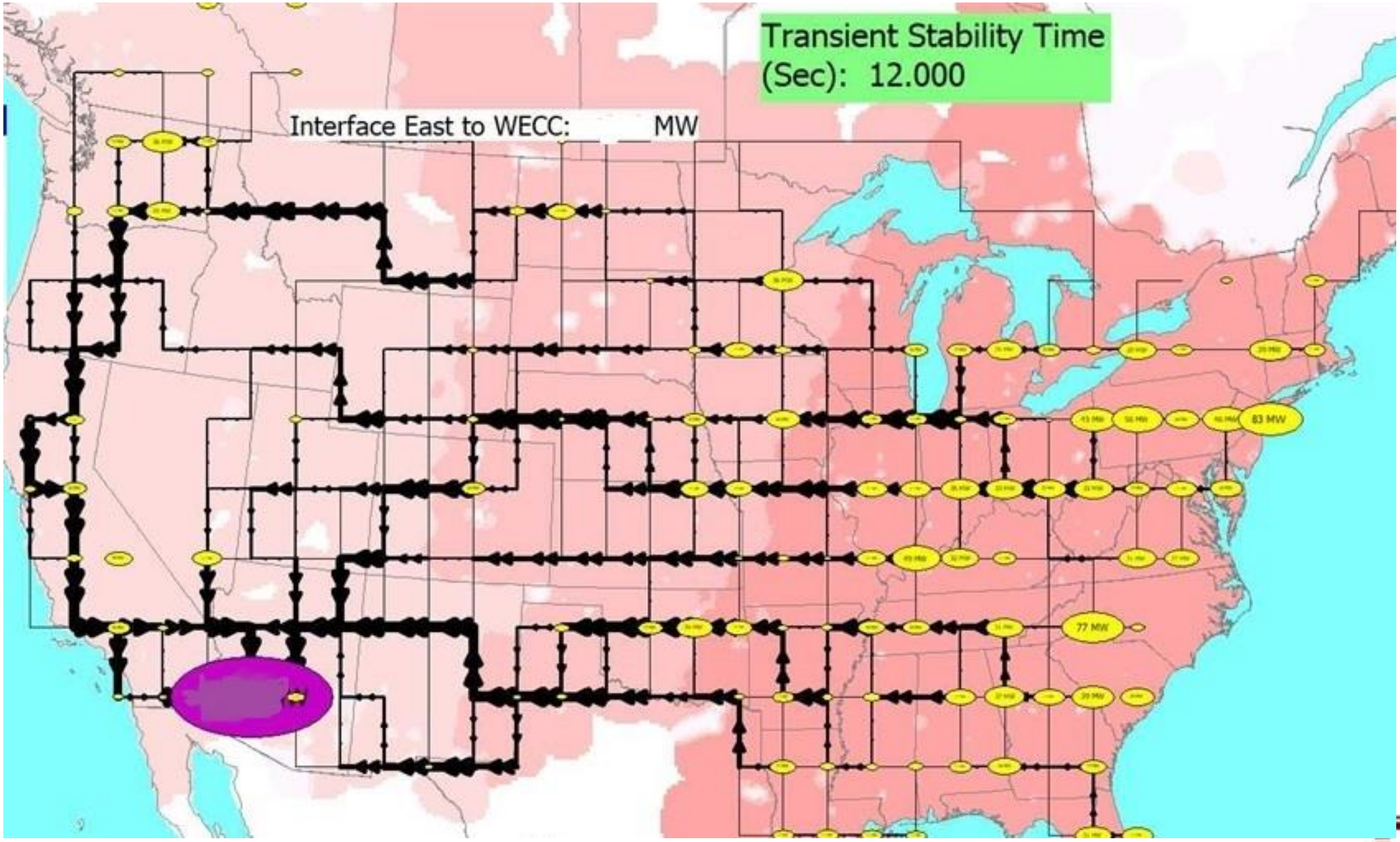
Results Example at 2.0 Seconds



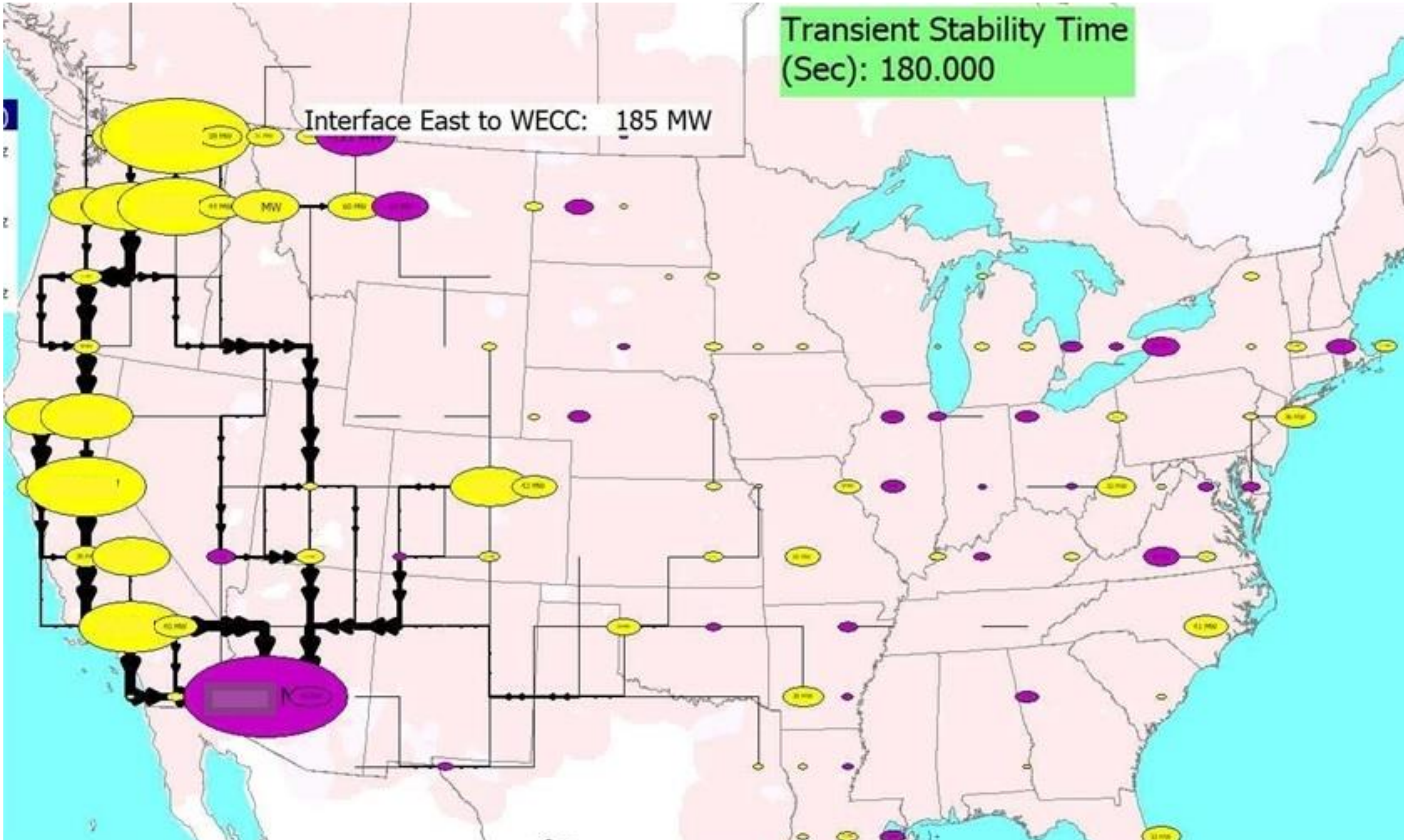
This visualization is using geographic data views and a contour to show the response of the 110,000 bus model; red values are frequencies less than 60 Hz

These visualization techniques are presented in the paper by T.J. Overbye, J.L. Wert, K.S. Shetye, F. Safdarian, A.B. Birchfield, "The Use of Geographic Data Views to Help With Wide-Area Electric Grid Situational Awareness," 2021 IEEE Texas Power and Energy Conference (TPEC), College Station, TX, USA, Feb. 2021; available at overbye.engr.tamu.edu/publications/

Results Example at 12.0 Seconds



Results Example With AGC Response



Synthetic Electric Grids Models

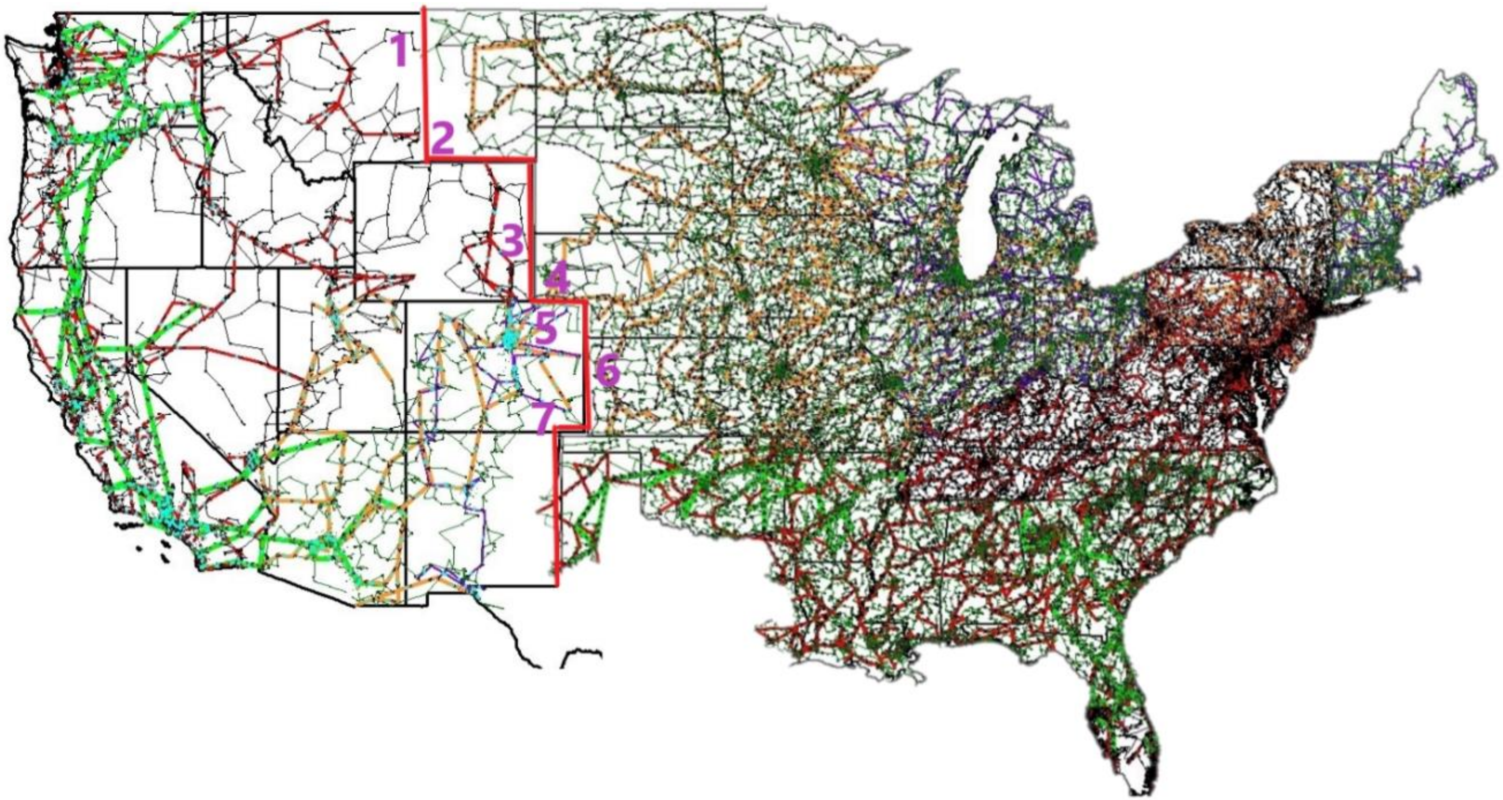
- The project had a synthetic grid component in order to provide access to detailed results while not disclosing any CEII.
- Synthetic electric grids and associated datasets are fictional electric grids that are designed to be statistically similar to actual systems
  - “Realistic but not real”
- Synthetic grids are particularly helpful for visualization research
- Kudos to the US DOE ARPA-E for funding work over the last five years in this area

Our Synthetic Grid Approach

- Make grids that look real and familiar by siting them geographically (North America for us) and serving a population density the mimics actual
- Goal is to leverage widely available public data
  - Geography
  - Population density (easily available by post office)
  - Load by utility (US FERC 714), state-wide averages
  - Existing and planned generation (Form US EIA-860, which contains lots of generator information)
- Substation locations and transmission system is entirely fictional (but hopefully good fiction!)

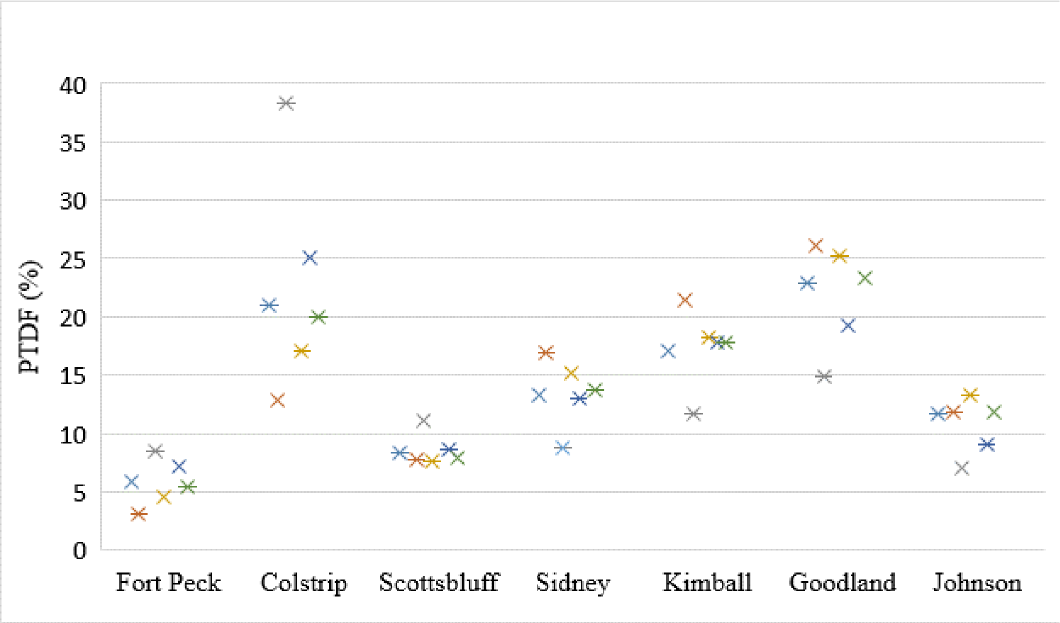
Synthetic Grid Component

- We're using an 80,000 bus model that can be freely shared that has a synthetic East grid joined to a synthetic West grid at seven points



Synthetic Grid Interconnection Points and PTDF Analysis

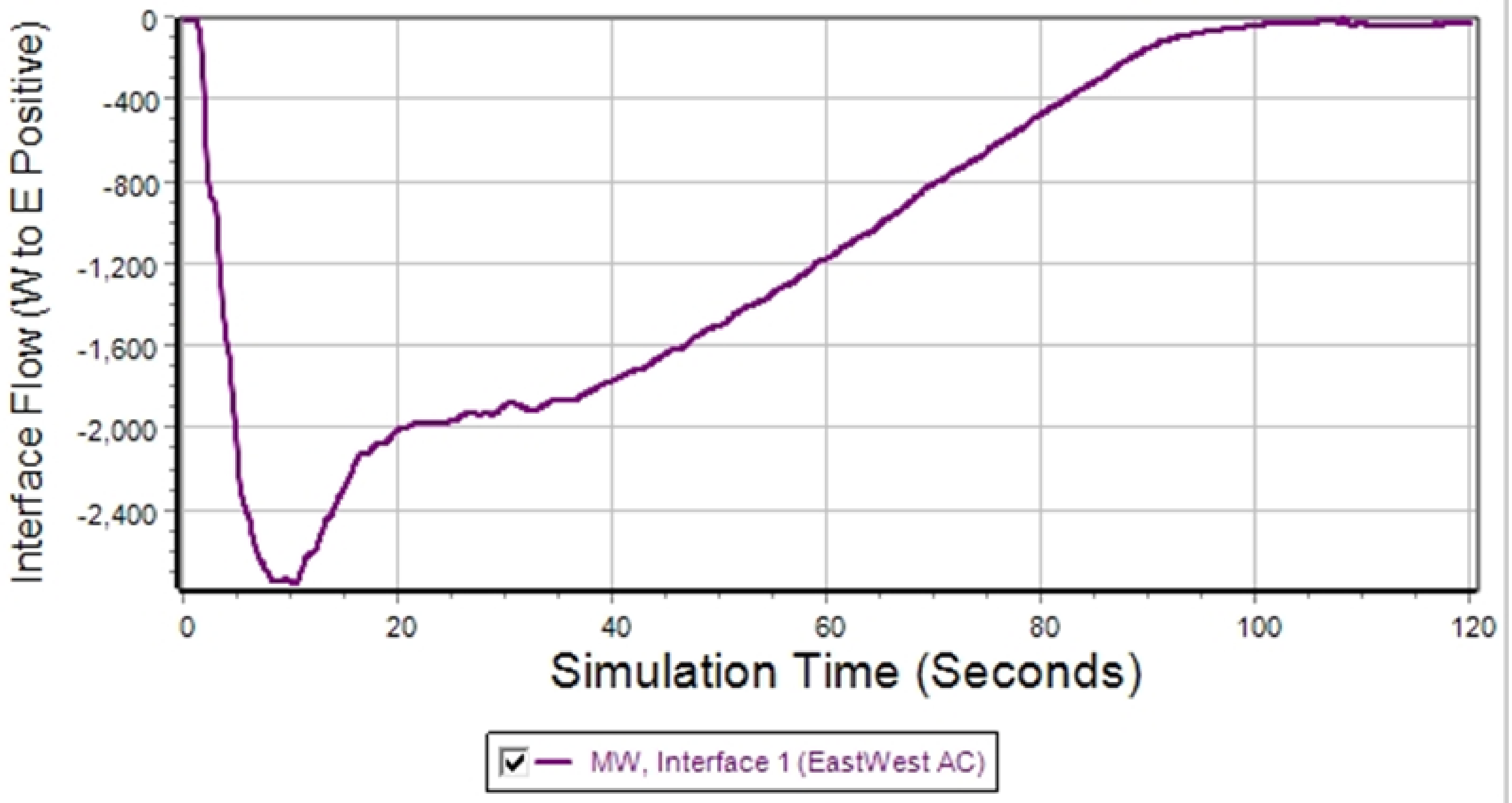
No.	From Bus (kV)	To Bus (kV)	X (p.u.)	Lim (MVA)
1	Glasgow (138)	Fort Peck (500)	0.055	600
2	Hardin (345)	Colstrip (500)	0.06	1200
3	Wheatland (345)	Scottsbluff (500)	0.07	1400
4	Peetz (500)	Sidney (500)	0.03	2000
5	New Raymer (500)	Kimball (500)	0.02	2000
6	Burlington (500)	Goodland (500)	0.03	2000
7	Lamar (500)	Johnson (161)	0.04	800



The power transfer distribution factors (PTDFs) tell how different transactions impact the interface flows

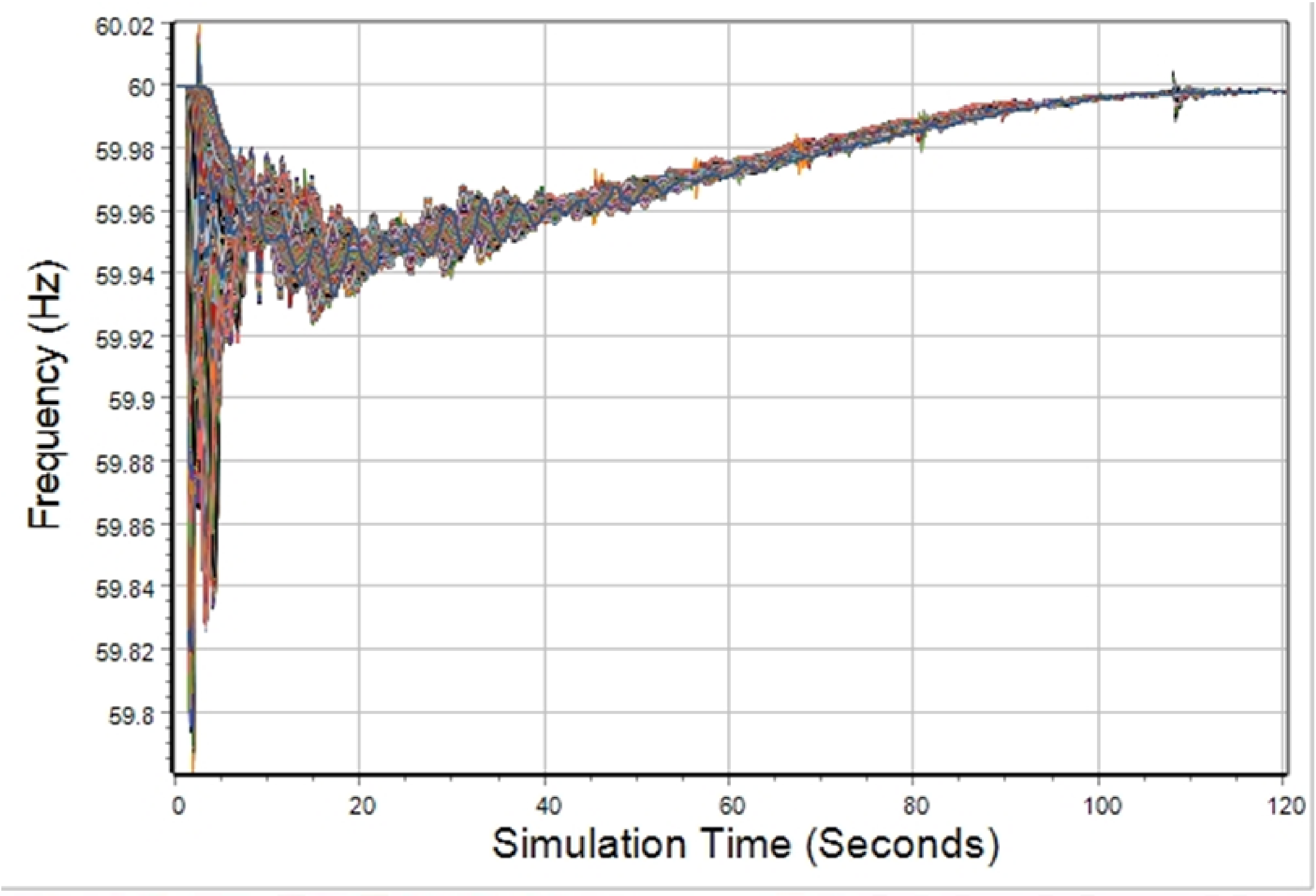
The maximum transfer capacity is about 5000 MW West to East and 3500 East to West

Synthetic Grid Interface Response for a Generator Loss Contingency in the West

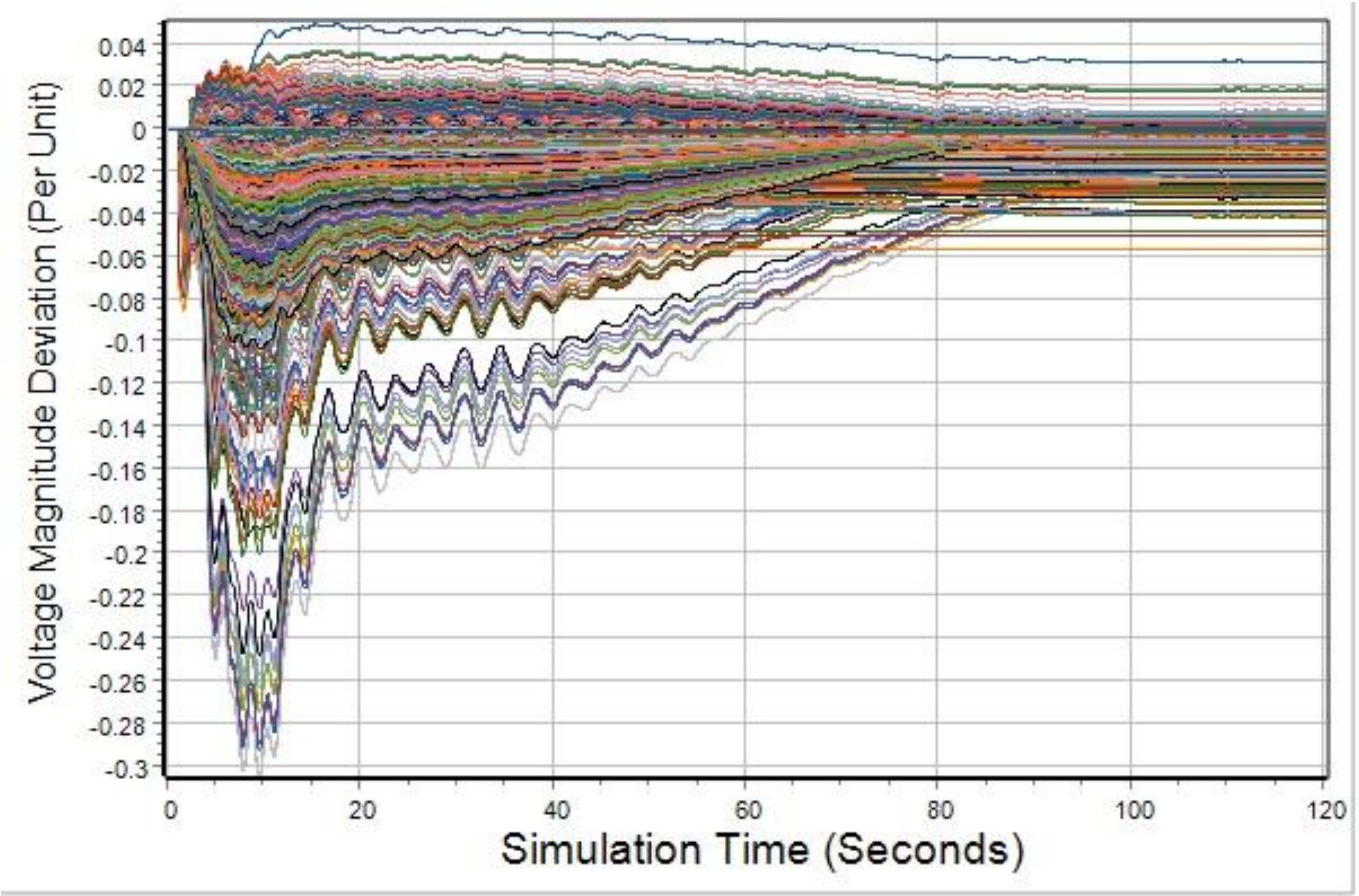


The sign convention on the interface is positive flow is from West to East; within seconds large amounts of power flow in!

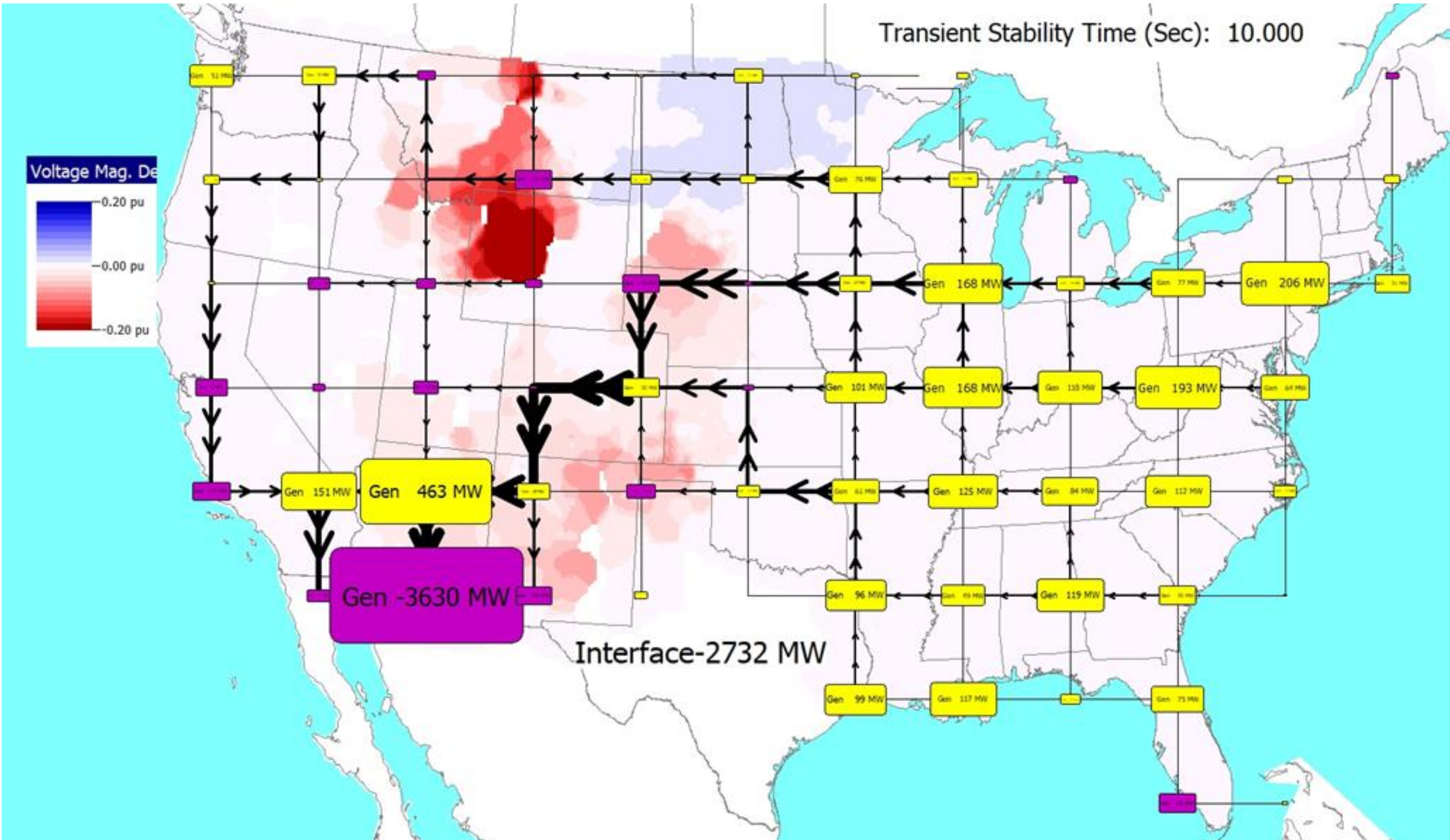
Synthetic Grid Frequency Response, All Locations



Synthetic Grid Voltage Deviation, All Locations



Synthetic Grid Voltage Contour



Summary

- The electric grid is rapidly changing and there are lots of engineering opportunities!!
- From a technical perspective we believe the North American Eastern and Western grids could be connected with a modest number of ac interties that would allow for stable operation under even quite severe contingencies
- A key constraint is that following a generation (or load) disturbance in the West, most of the makeup power would flow through the interface, potentially causing voltage or thermal issues
- Visualization of results for large systems is crucial

Thank You! Questions?