# New Developments in the Visualization of Wide-Area Electric Grid Information with Application to Grid Interconnection Studies

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TEXAS A&M UNIVERSITY

# Acknowledgments


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- Slides contain contributions from many of my students, postdocs, staff and colleagues

- These slides and the associated papers are available at **overbye.engr.tamu.edu/**
- Visualizations and simulations were done using PowerWorld Simulator Version 22; a free 42 bus educational version is available at **www.powerworld.com/gloveroverbyesarma**

# Our Energy Future Could be Quite Bright!

- My professional goal is to help in the development of a sustainable and resilient electric infrastructure for the entire world.
- Electric grids are in a time of rapid transition, with lots of positive developments. It is a great time to be in the electric energy field or entering it!!
- I think our electric energy future could be quite bright! But there are lots of challenges with this transition, including maintaining human situational awareness, particularly during times of stress.

# Overview

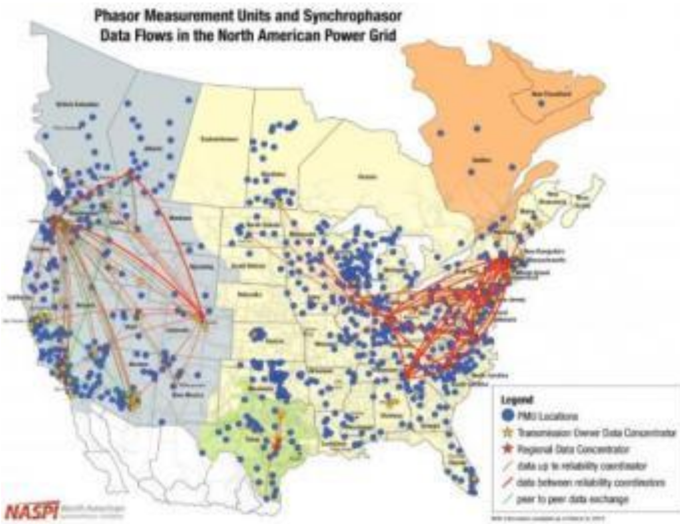
- Presentation focuses on how wide-area electric grid visualization can help
- Grids are getting increasingly complex, particularly with many more automatic controls, and there is a concern about whether anybody fully really knows what's going on
- How data is transformed into actionable information is a crucial, yet often unemphasized, part of the software design process
- Focus here is more on visualization for engineers, as opposed to operators

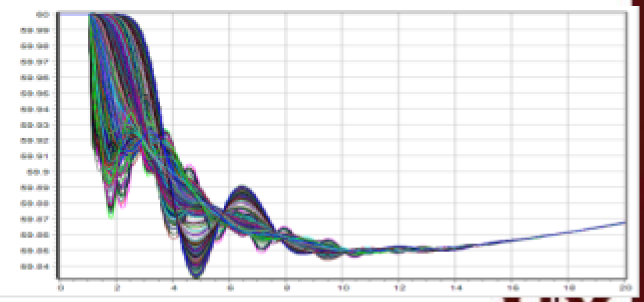
# 53rd NAPS, Nov 14-16, 2021, In Person

- The 53rd North American Power Symposium (NAPS) will be held in person on Nov 14-16, 2021 at Texas A&M, College Station, TX
- Papers are due July 15, 2021, with the paper submission website now open!
- See **na.eventscloud.com/website/22926/home/**

# Examples of Power System "Big Data"

- Power system operations and planning are a rich source of data
  - SCADA has traditionally provided a grid data at scan rates of several seconds
  - Thousands of PMUs are now deployed providing data at 30 times per second
  - In planning many thousand of studies are now routinely run, with a single transient stability run creating gigabytes



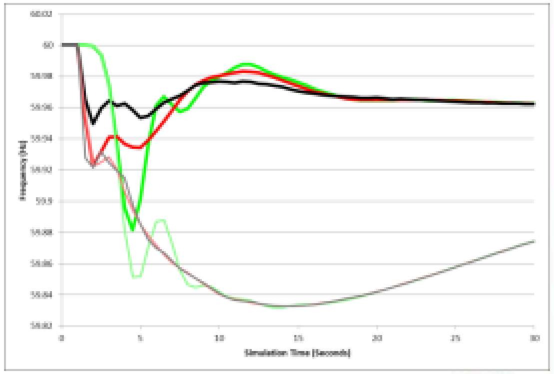



# A Specific Example: One Stability Study

- One of our 2020 projects was looking at dynamic aspects of an ac interconnection of the Eastern Interconnect and the WECC
- We did lots of dynamic simulations (some 30 seconds, some up to six minutes)
- The Model contained 110,000 buses, 244 different types of dynamic models, 48,000 model instances and 194,000 states
- A human factors challenge in doing such a study is for the engineer to know what happened

# Aside: East-WECC Interconnect Study

- The project, which ran most of 2020, looked primarily at the stability aspects of an ac interconnection of the EI and WECC
- Nine connections were modeled, from Montana to New Mexico
- The stability of the combined current is good, and has some nice frequency response benefits
- Cost to connect is relatively low and such an interconnection certainly merits further study!



# Visualization Software Design

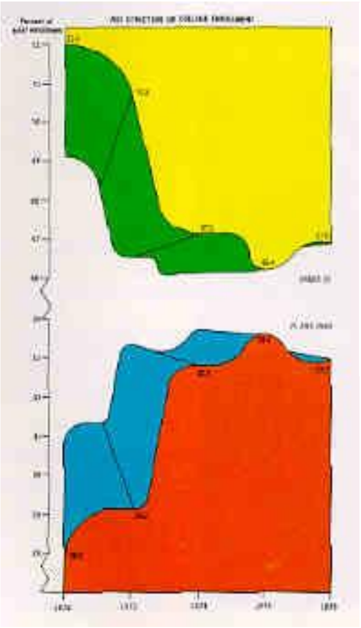
- Key question: what are the desired tasks that need to be accomplished?
  - Needs for real-time operations might be quite different than what is needed in planning
- Understanding the entire processes in which the visualizations are embedded is key
- Software should help humans make the more complex decisions, i.e., those requiring information and knowledge
  - Enhance human capabilities
  - Alleviate their limitations (adding up flows into a bus)

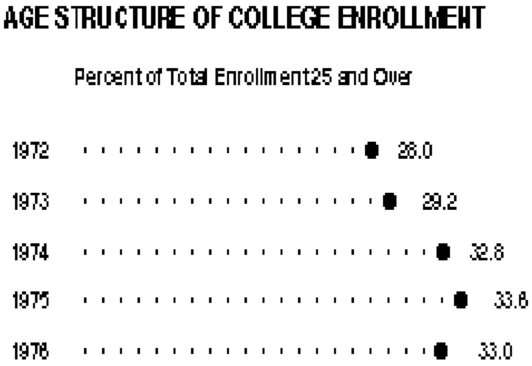
# Some Useful General References

- Colin Ware, *Information Visualization: Perception for Design*, Fourth Edition, 2021
- Edward Tufte, *Envisioning Information*, 1990
- Edward Tufte, *Visual Explanations: Images and Quantities*, 1997
- Edward Tufte, *The Visual Display of Quantitative Information*, 2001
- Edward Tufte, *Beautiful Evidence*, 2006
- Claus Wilke, *Fundamentals of Data Visualization*, 2019

# Visualization Cautions!

- Just because information can be shown graphically, doesn't mean it should be shown
- Three useful design criteria from 1994 EPRI visualization report:
  1. Natural encoding of information
  2. Task specific graphics
  3. No gratuitous graphics






Tufte: "may well be worst graphic ever"

Source: E. Tufte, The Visual Display of Quantitative Information, Graphics Press, Cheshire, CT, 1983.

# Visualization and User Familiarity

- Visualizations do not exist in a vacuum; the prior experience of the users is a key consideration
  - QWERTY keyboard arrangement is a classic example, in which a design originally setup in 1870’s (perhaps to prevent mechanical problems) is still used today
- Using existing visual metaphors in new designs help them seem more familiar (like a folder)
  - A skeuomorphic design retains no longer needed structures that were inherent in the original, usually to make them more familiar (using gauges, sliders, buttons and analog clocks in visualizations are examples)

# Synthetic Models and Visualization

- Access to actual power grid models is often restricted (CEII), and this can be a particular concern with data analysis and visualization since its purpose is to provide insight into the model, including weaknesses
  - Models cannot be freely shared with other researchers, and even presenting results can be difficult
- A solution is to create entirely synthetic (fictitious) models the mimic characteristics of actual models
  - Kudos to the US DOE ARPA-E for funding work over the last six years in this area

# Early Synthetic Grids

- Synthetic electric grids are models of electric grids that do not represent any actual electric grid

A pseudo-geographic grid

A non-geographic grid

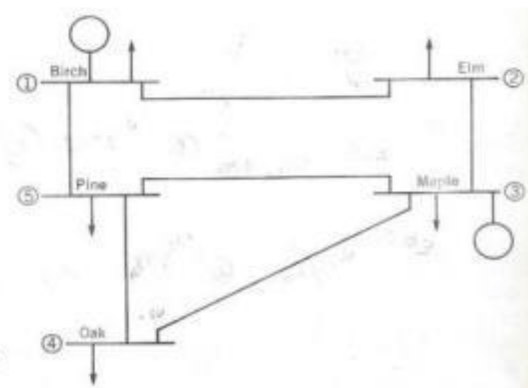
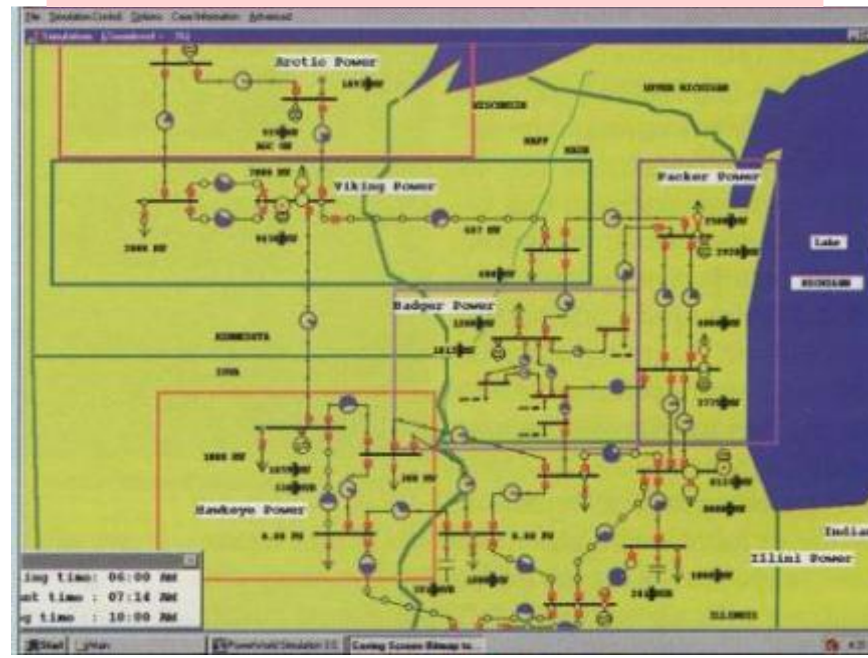



Figure 8.1 One-line diagram for Example 8.1.



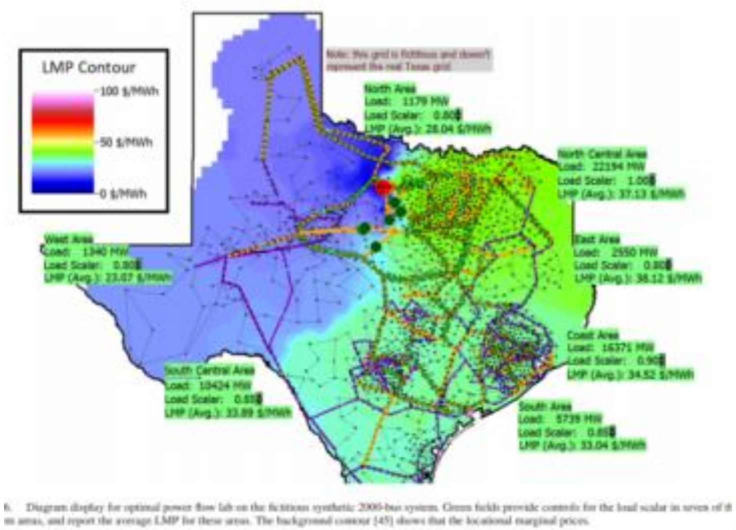

Left Image Source: W.D. Stevenson, *Elements of Power Systems*, Fourth Edition, McGraw-Hill Book Company New York, 1982 (the first edition was in 1955)

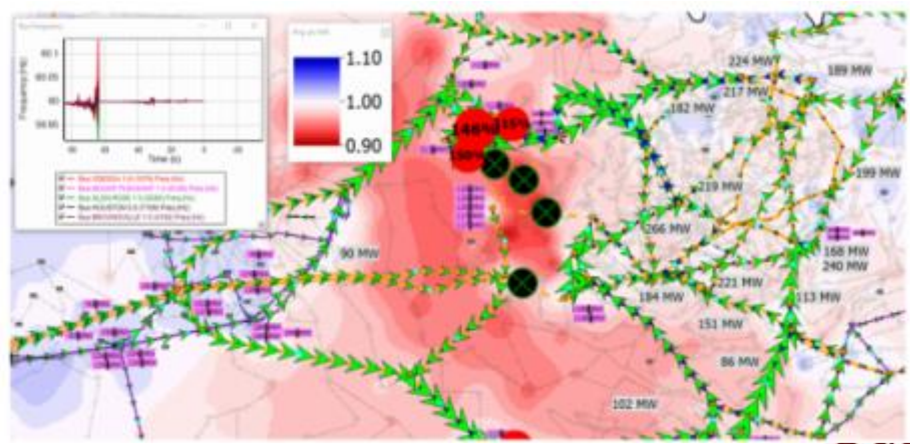
# Synthetic Models Used Here

- Examples presented here will be based synthetic grids ranging in size from several buses up to an 82,000-bus synthetic grid modeling the contiguous US (CONUS)
  - All grids have embedded geographic coordinates and are available at **electricgrids.engr.tamu.edu**
- Geographic coordinates in actual electric grid models has increased rapidly over the last few years, driven in part by their requirement for geomagnetic disturbance (GMD) impact studies

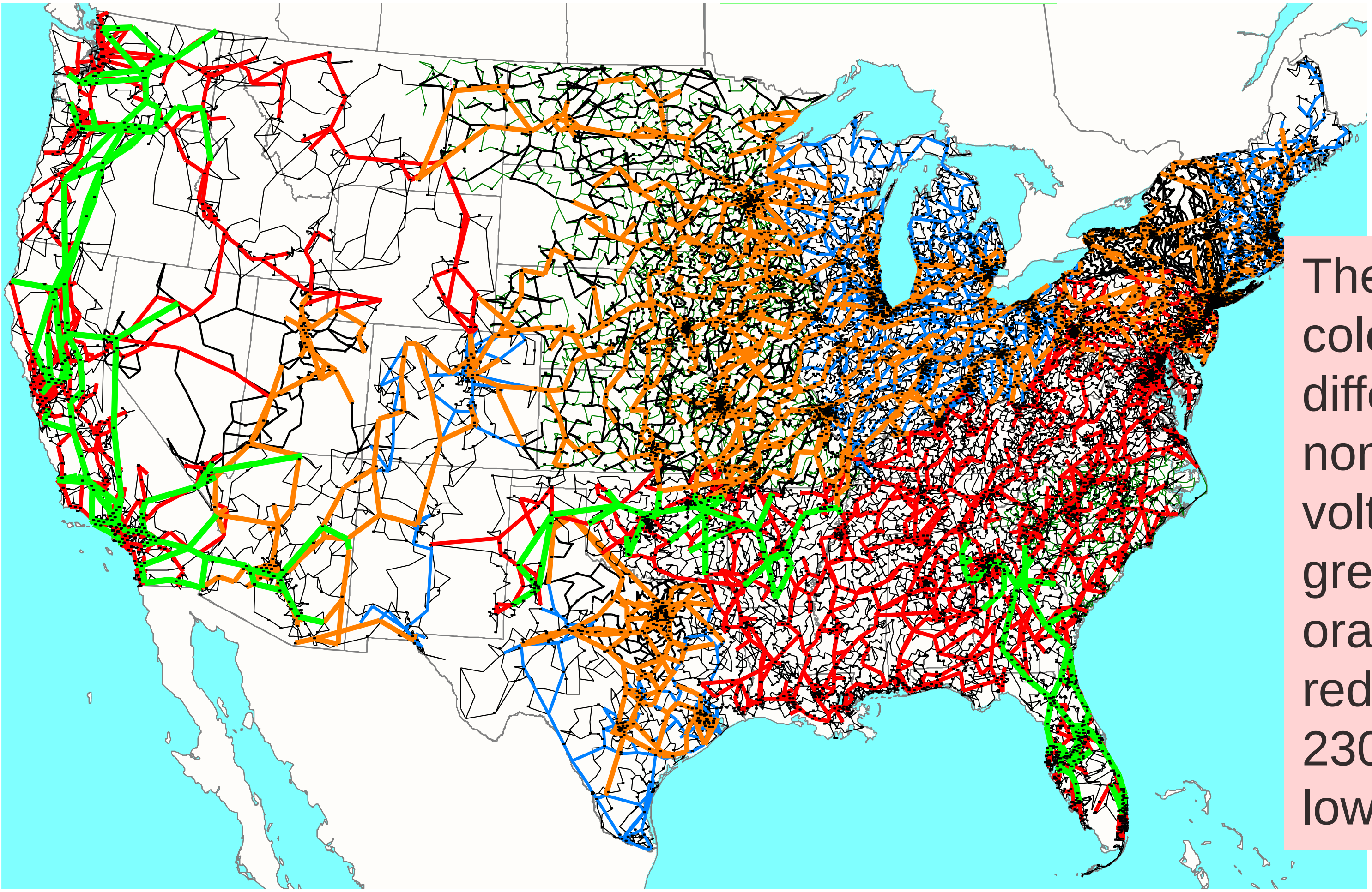
# 2000 Bus Texas Synthetic Grid

- This fictional grid, which has 2000 buses, is designed to serve a load similar to the ERCOT load with a similar geographic distribution
  - The grid was designed using a 500/230/161/115 kV transmission to be different from the actual grid
  - Public generator information is used



# 82,000 Bus Synthetic Grid for East-West Interconnection Studies



The different colors indicate different nominal kV voltages, with green 765, orange 500, red 345, blue 230, black lower.

# Decision Making, Data, Information, Knowledge

- Goal is to help humans make better decisions
- Competing definitions for the process of taking raw “data” and producing something useful
  - Understanding, decisions, wisdom
- Data: symbols, raw, it simply exists
- Information: Data that is given meaning, often in a relational context; some how processed
- Knowledge: Application of information to answer “how.”
- Understanding, and/or wisdom at top

# Understanding the Entire Process is Key

- Understanding the entire processes in which the visualizations are embedded is crucial.
  - What is the “information access” cost?
  - How will the information be used and shared?
  - Is it raw data, or derived values?
  - Should the visualizations sit on top of a model, or is a standalone process sufficient?
  - Ultimately, what are the desired tasks that need to be accomplished?
- We’ll start with a brief coverage of some traditional approaches (tabular, graphs and onelines, then go into some newer ones)

# Example: Tabular Displays

- In many contexts, tabular displays (particularly with interactive features such as sorting, filtering, drill-down, and the ability to enter data) can be a great way to show data

| | Number | Area Name | Name | Nom kV | PU Volt | Volt (kV) | Angle (Deg) | Load MW | Load Mvar | Gen MW | Gen Mvar | Switched Shunts Mvar | Act G Shunt MW | Act B Shunt Mvar | Area Num | Zone Name | Zone Num |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1001 | Far West | ODESSA 2 0 | 115.00 | 0.98089 | 112.802 | -30.18 | 20.78 | 5.89 | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 2 | 1002 | Far West | PRESIDIO 2 0 | 115.00 | 1.01218 | 116.400 | -24.75 | 15.41 | 4.37 | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 3 | 1003 | Far West | O DONNELL 1 | 115.00 | 1.00832 | 115.956 | -25.02 | | | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 4 | 1004 | Far West | O DONNELL 1 | 230.00 | 1.01000 | 232.301 | -26.84 | | | 158.25 | -29.07 | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 5 | 1005 | Far West | BIG SPRING 5 ( | 115.00 | 1.00790 | 115.908 | -22.77 | | | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 6 | 1006 | Far West | BIG SPRING 5 | 13.80 | 1.00147 | 13.820 | -20.60 | | | 25.73 | -4.94 | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 7 | 1007 | Far West | VAN HORN 0 | 115.00 | 1.01973 | 117.268 | -25.10 | 7.01 | 1.99 | | | 0.00 | 0.00 | 0.00 | 1 | Far West T | 9 |
| 8 | 1008 | Far West | IRAAN 2 0 | 115.00 | 1.00133 | 115.153 | -13.78 | | | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 9 | 1009 | Far West | IRAAN 2 1 | 13.80 | 1.00000 | 13.800 | -10.41 | | | 61.87 | -2.55 | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 10 | 1010 | Far West | PRESIDIO 1 0 | 115.00 | 1.01933 | 117.223 | -23.46 | | | | | 0.00 | 0.00 | 0.00 | 1 | Far West T | 9 |
| 11 | 1011 | Far West | PRESIDIO 1 1 | 22.00 | 1.01958 | 22.431 | -22.12 | | | 7.50 | 0.00 | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 12 | 1012 | Far West | SANDERSON ( | 115.00 | 0.98899 | 113.734 | -29.67 | 2.99 | 0.85 | | | 9.29 | 0.00 | 0.00 | 1 | Far West T | 9 |
| 13 | 1013 | Far West | MONAHANS 2 | 115.00 | 1.00167 | 115.192 | -21.95 | 29.23 | 8.28 | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 14 | 1014 | Far West | GRANDFALLS ( | 115.00 | 1.00324 | 115.373 | -18.04 | 2.22 | 0.63 | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 15 | 1015 | Far West | MARFA 0 | 115.00 | 1.02132 | 117.451 | -24.87 | 7.51 | 2.13 | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 16 | 1016 | Far West | GARDEN CITY ( | 115.00 | 1.01758 | 117.022 | -21.94 | 2.89 | 0.82 | | | 31.06 | 0.00 | 0.00 | 1 | Far West T | 9 |
| 17 | 1017 | Far West | ODESSA 4 0 | 115.00 | 0.98205 | 112.936 | -28.53 | 18.34 | 5.20 | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 18 | 1018 | Far West | NOTREES 0 | 115.00 | 0.99128 | 113.997 | -27.25 | 0.07 | 0.02 | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 19 | 1019 | Far West | MIDLAND 4 0 | 115.00 | 1.00078 | 115.090 | -29.70 | 61.78 | 17.50 | | | 143.20 | 0.00 | 0.00 | 1 | Far West T | 9 |
| 20 | 1020 | Far West | BIG SPRING 1 ( | 115.00 | 1.02190 | 117.519 | -21.73 | | | | | 80.13 | 0.00 | 0.00 | 1 | Far West T | 9 |
| 21 | 1021 | Far West | BIG SPRING 1 | 13.80 | 1.00000 | 13.800 | -15.11 | | | 149.63 | -25.59 | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 22 | 1022 | Far West | O DONNELL 2 | 115.00 | 1.01132 | 116.302 | -24.18 | | | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 23 | 1023 | Far West | O DONNELL 2 | 13.80 | 1.01000 | 13.938 | -15.27 | | | 135.00 | 3.21 | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 24 | 1024 | Far West | ODESSA 6 0 | 115.00 | 0.99425 | 114.338 | -26.17 | 63.04 | 17.86 | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 25 | 1025 | Far West | BIG SPRINGS 0 | 115.00 | 1.01805 | 117.076 | -20.73 | | | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 26 | 1026 | Far West | BIG SPRINGS 1 | 13.80 | 1.00000 | 13.800 | -11.21 | | | 93.15 | -4.41 | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 27 | 1027 | Far West | MIDLAND 2 0 | 115.00 | 1.01258 | 116.447 | -32.98 | 101.21 | 28.68 | | | 76.90 | 0.00 | 0.00 | 1 | Far West T | 9 |
| 28 | 1028 | Far West | COAHOMA 0 | 115.00 | 1.01371 | 116.577 | -25.80 | 10.01 | 2.84 | | | | 0.00 | 0.00 | 1 | Far West T | 9 |
| 29 | 1029 | Far West | MIDLAND 3 0 | 115.00 | 1.00868 | 115.998 | -31.93 | 83.18 | 23.57 | | | 40.70 | 0.00 | 0.00 | 1 | Far West T | 9 |

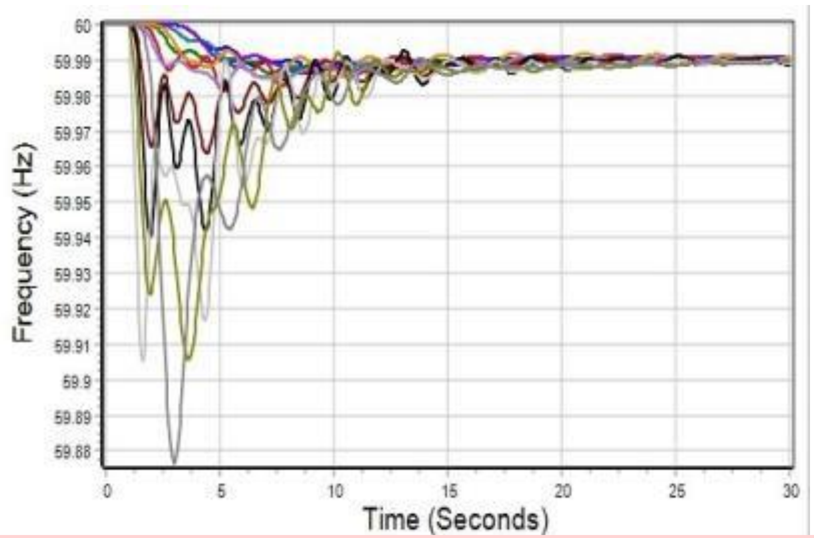
# Use of Color

- Some use of color can be quite helpful
  - 10% of male population has some degree of color blindness (1% for females)
- Do not use more than about ten colors for coding if reliable identification is required
- Color sequences can be used effectively for data maps (like contours)
  - Grayscale is useful for showing shapes but not values
  - Multi-color scales (like a spectrum) have advantages (more steps) but also disadvantages (effectively comparing values) compared to bi-color sequences

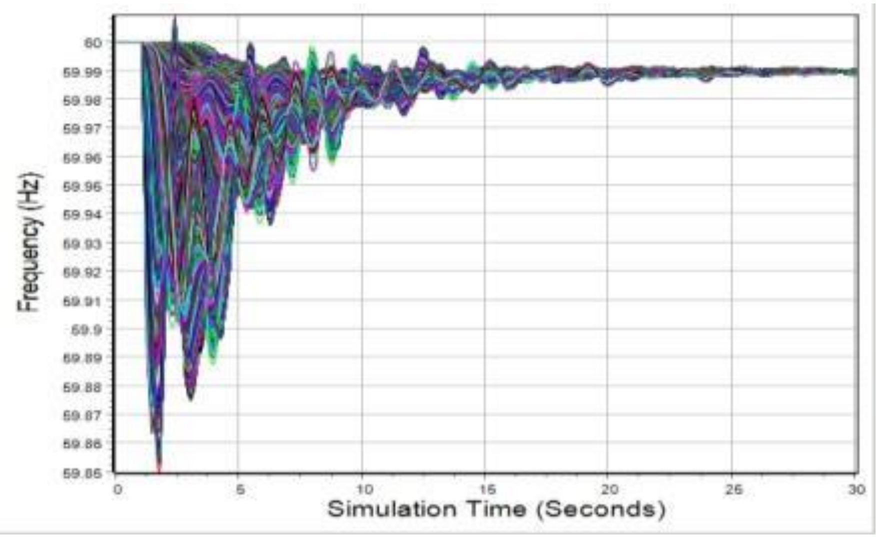
The book by Colin Ware is a great resource

# Graphs

- Graphs are also a great way to show information, particularly for time-variation
- The number of curves needs to match the task

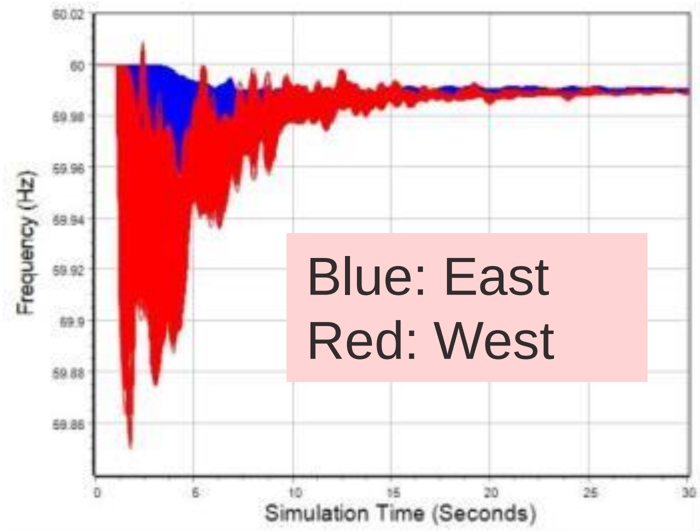



A few curves, detail of each visible, key can identify objects (several thousand values)

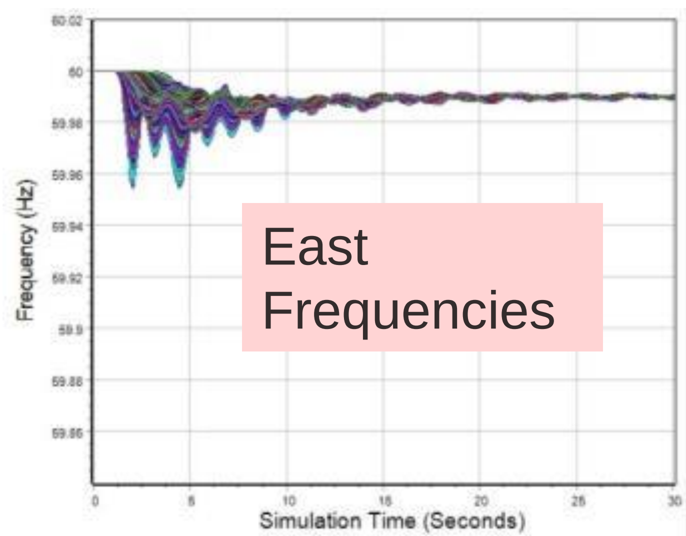


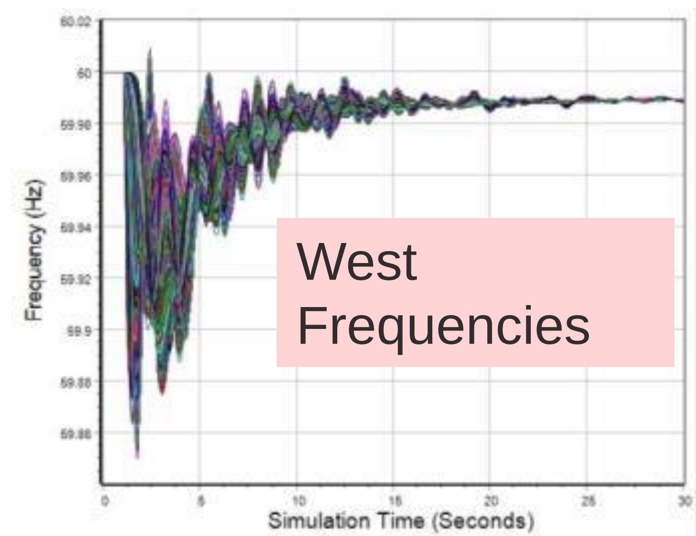

Envelope of response for the 80k bus, 40,000 substation frequencies (24 million values)

# Graphs: 40,000 Substation Examples



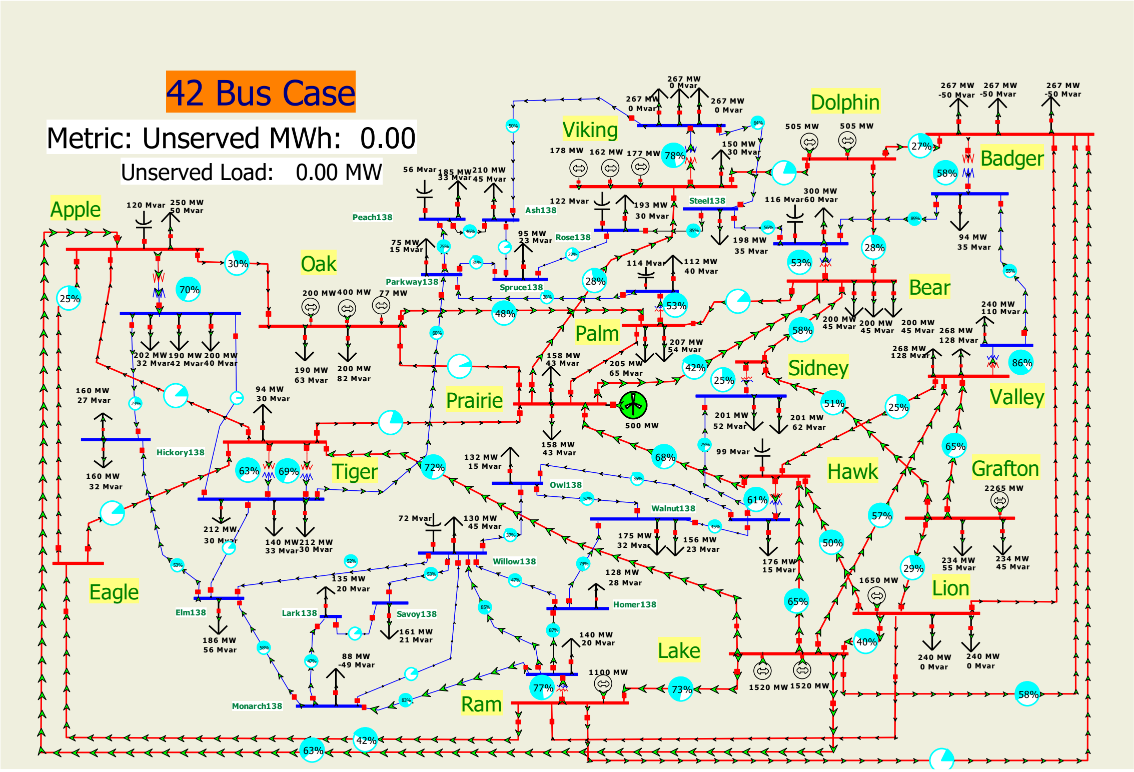

For the 40,000 substation plot, color can be helpful in showing the East response (blue) versus West (red) but the curve order matters.  It is probably better to use two plots, with one for the East and one for the West (obviously using the same scale)



# Onelines

- Widely used and can be quite effective for showing substations (or local regions) or smaller grids; can be slow on larger systems



# Visualization Background: Preattentive Processing

- When displaying large amounts of data, take advantage of preattentive cognitive processing
  - With preattentive processing the time spent to find a “target” is independent of the number of distractors
- Graphical features that are preattentively processed include the general categories of form, color, motion, spatial position

# Preattentive Processing Examples

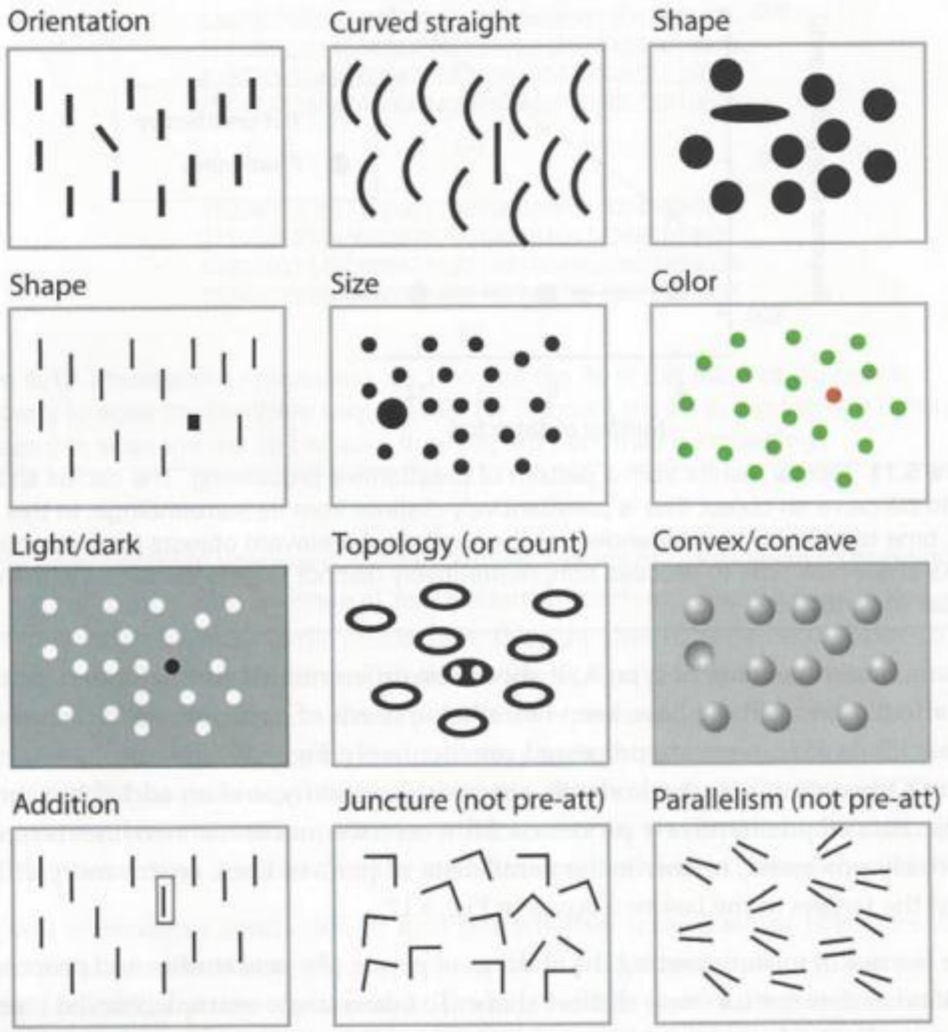
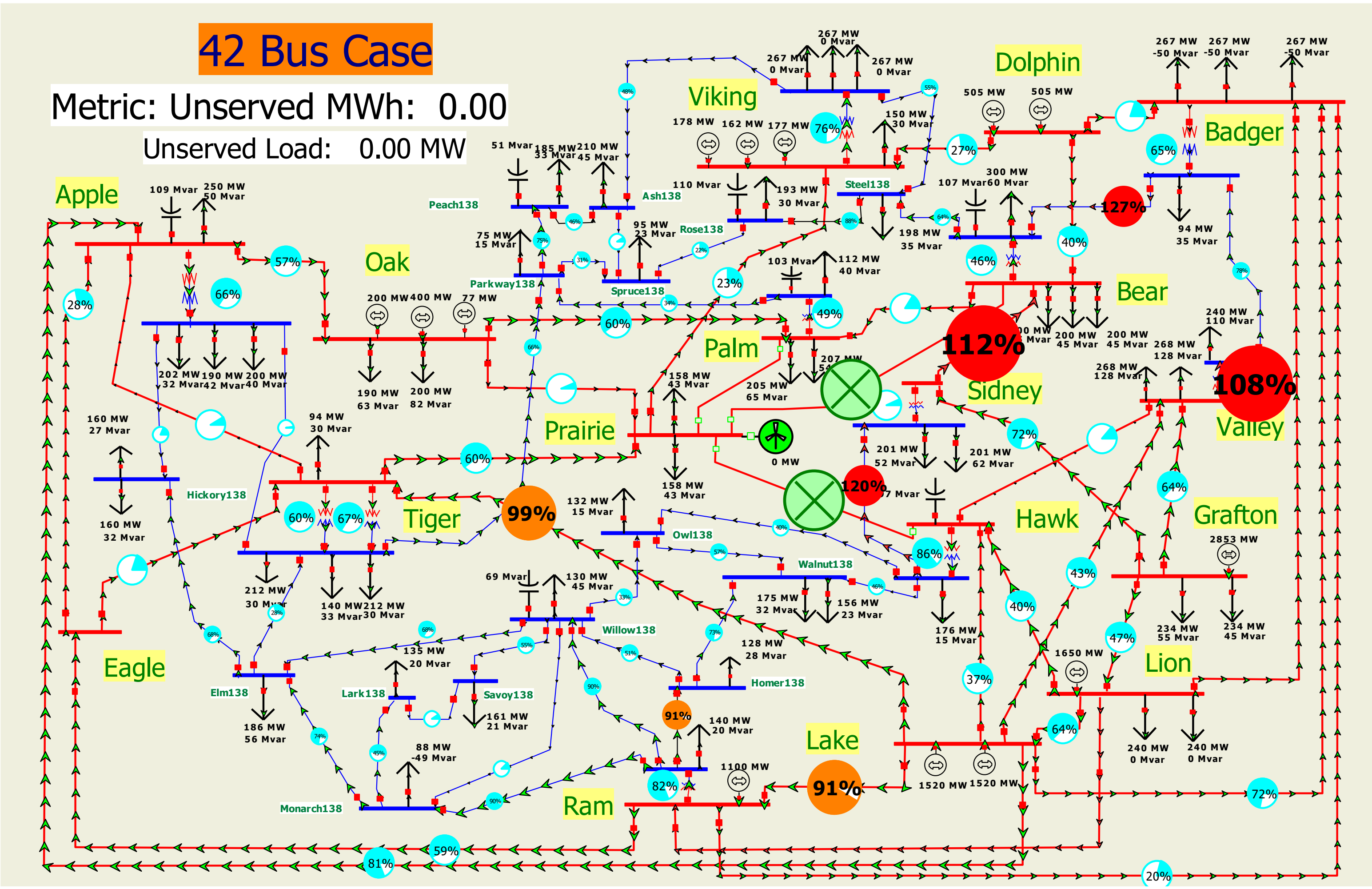



**Figure 5.12** Most of the preattentive examples given here can be accounted for by the processing characteristics of neurons in the primary visual cortex.

All are preattentively processed except for juncture and parallelism; however too many can defeat their purpose

Source: *Information Visualization* (Fourth Edition) by Colin Ware, Fig 5.12

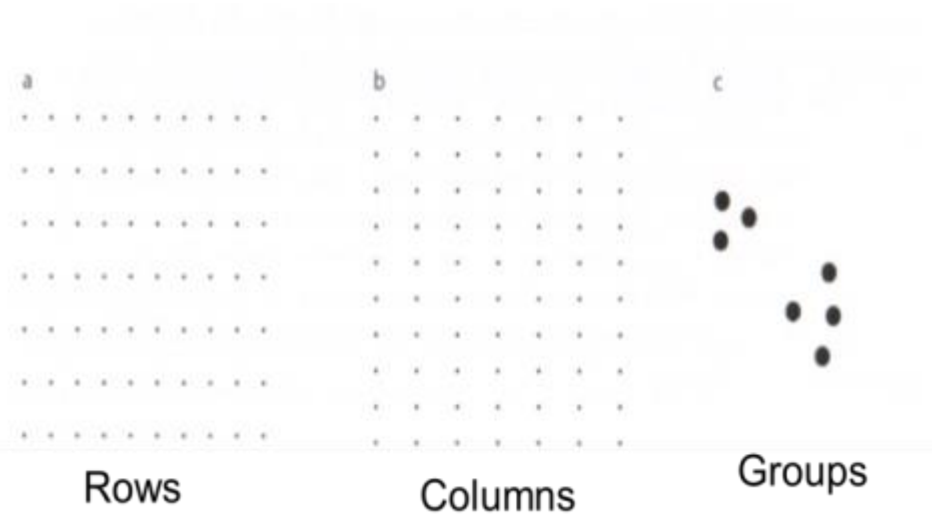
# Preattentive Processing with Color & Size

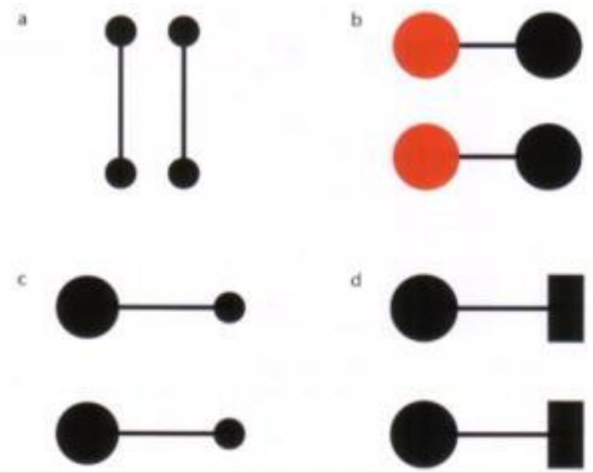


# Detecting Patterns

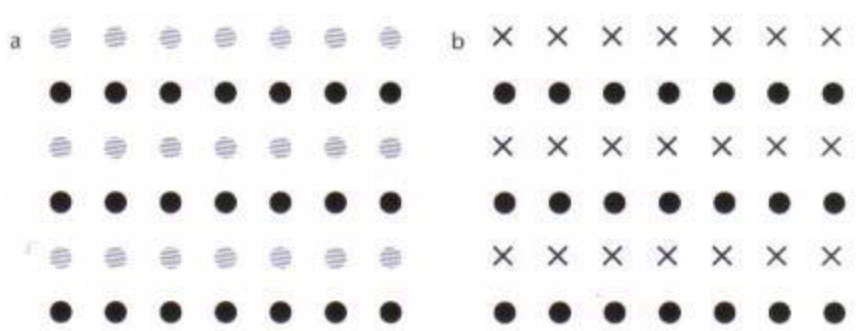
- A large portion of information visualization is associated with detecting patterns
- Gestalt (German for “pattern”) Laws
  - Proximity
  - Similarity (we didn’t discuss color)
  - Connectedness
  - Common Fate (flows)

# Proximity, Similarity, Connectedness,



Connectedness is stronger than proximity, color, shape

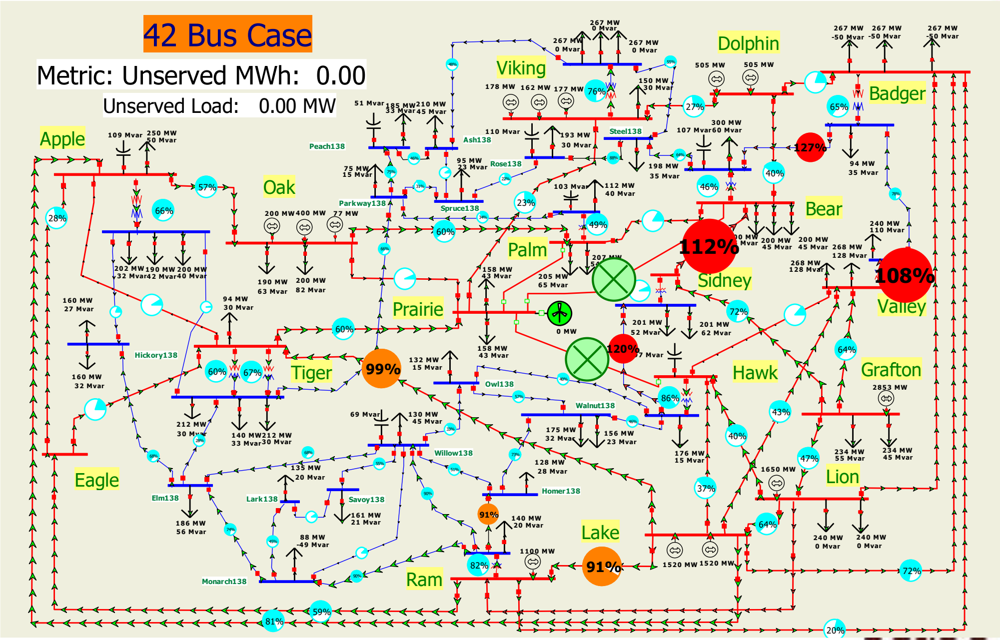


Similarity makes all perceived as rows

Source: *Information Visualization* (Fourth Edition) by Colin Ware, Chapter 6 Images

# Common Fate: Patterns in Motion

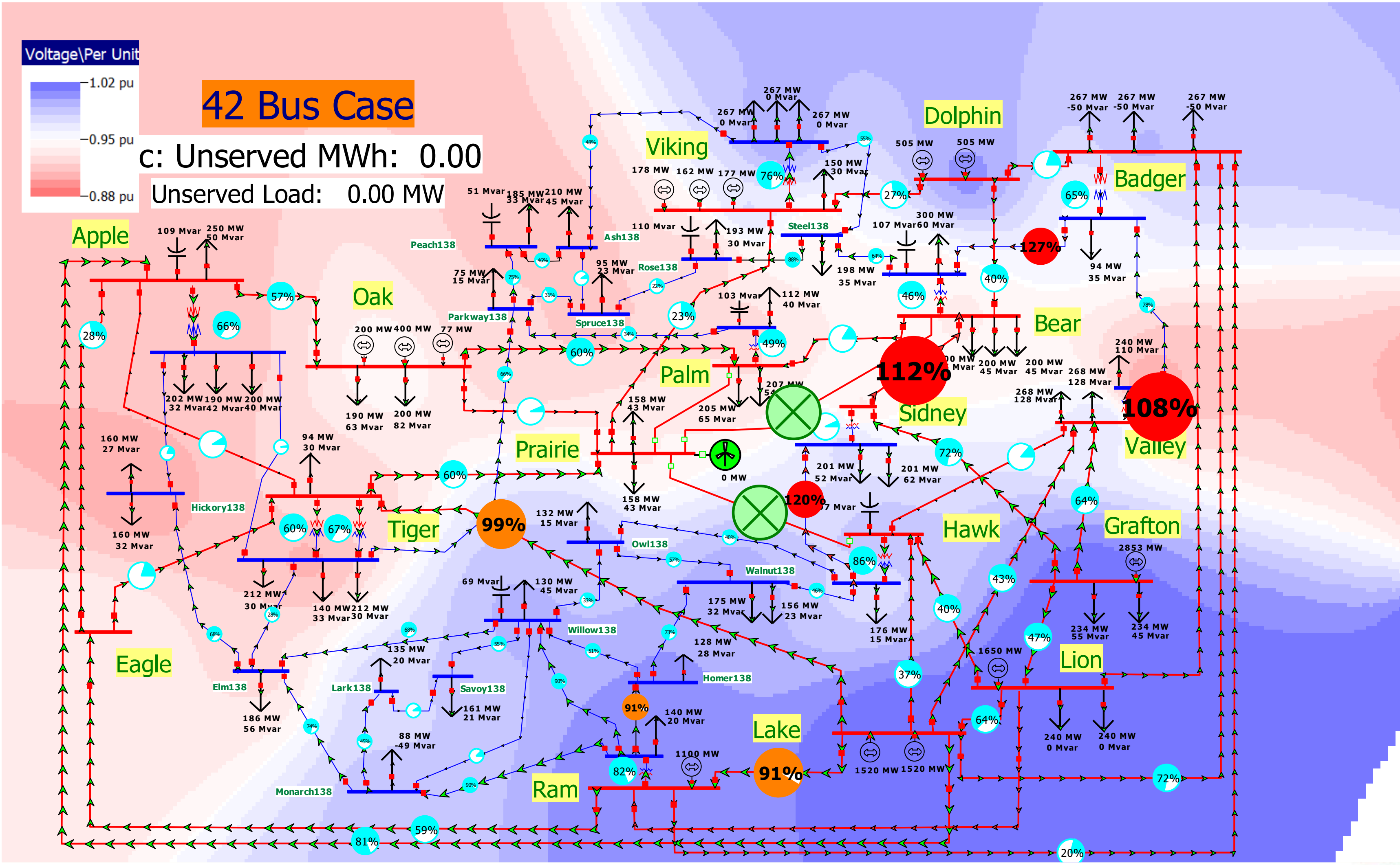
- Motion can be a very effective means for showing relationships between data
- People perceive motion with great sensitivity
- Motion can also be used to convey causality (one event causing another)
- However, too much motion can be a distractor



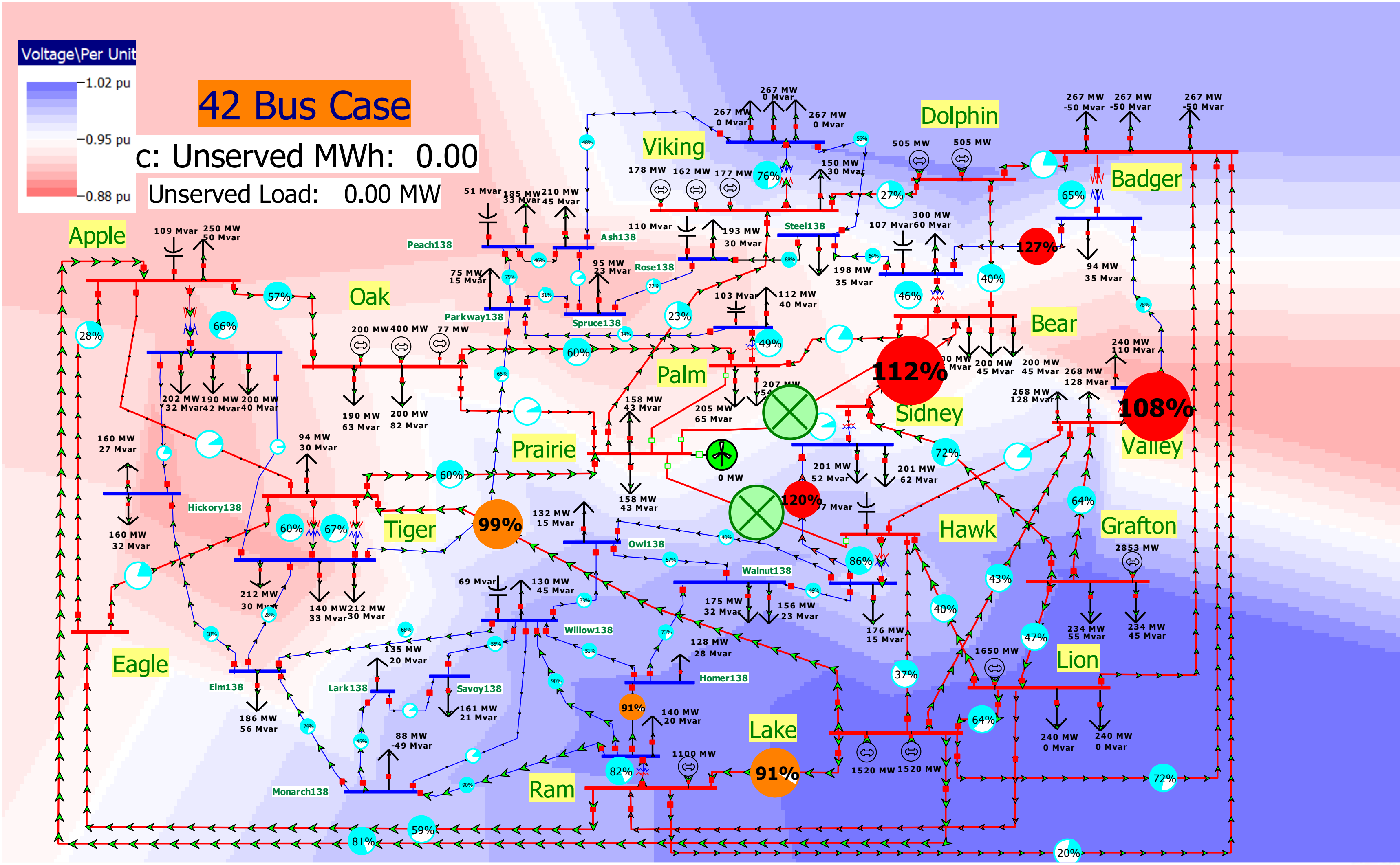
# Scattered Data Interpolation (Colored Contouring)

- For wide-area visualization, contours can be effective for showing large amounts of spatial data
  - Takes advantage that as humans we perceive the world in patterns (sometimes even when none exist!)
  - Now widely used
- Scattered data interpolation algorithms are needed to take the discrete power system data and make it spatially continuous
  - Various algorithms can be used include a modified Shephard's and Delaunay triangulation
- A color mapping is needed

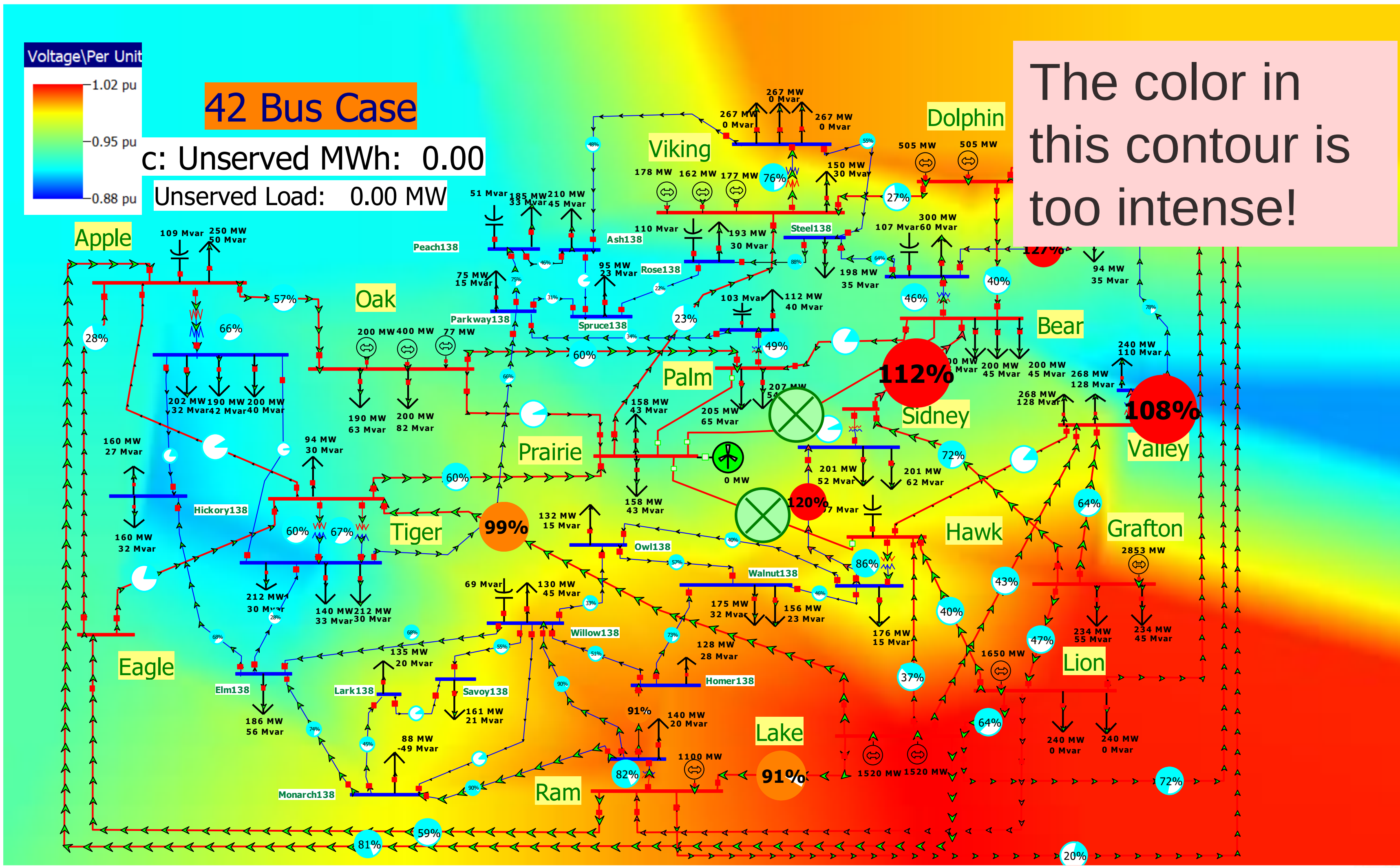
# Shepard's Algorithm, Blue/Red Discrete Color mapping



# Delaunay Algorithm, Blue/Red Discrete Color mapping



# Delaunay Algorithm, Spectrum Continuous Color mapping




The color in this contour is too intense!

# Some General Thoughts on Electric Grid Visualizations

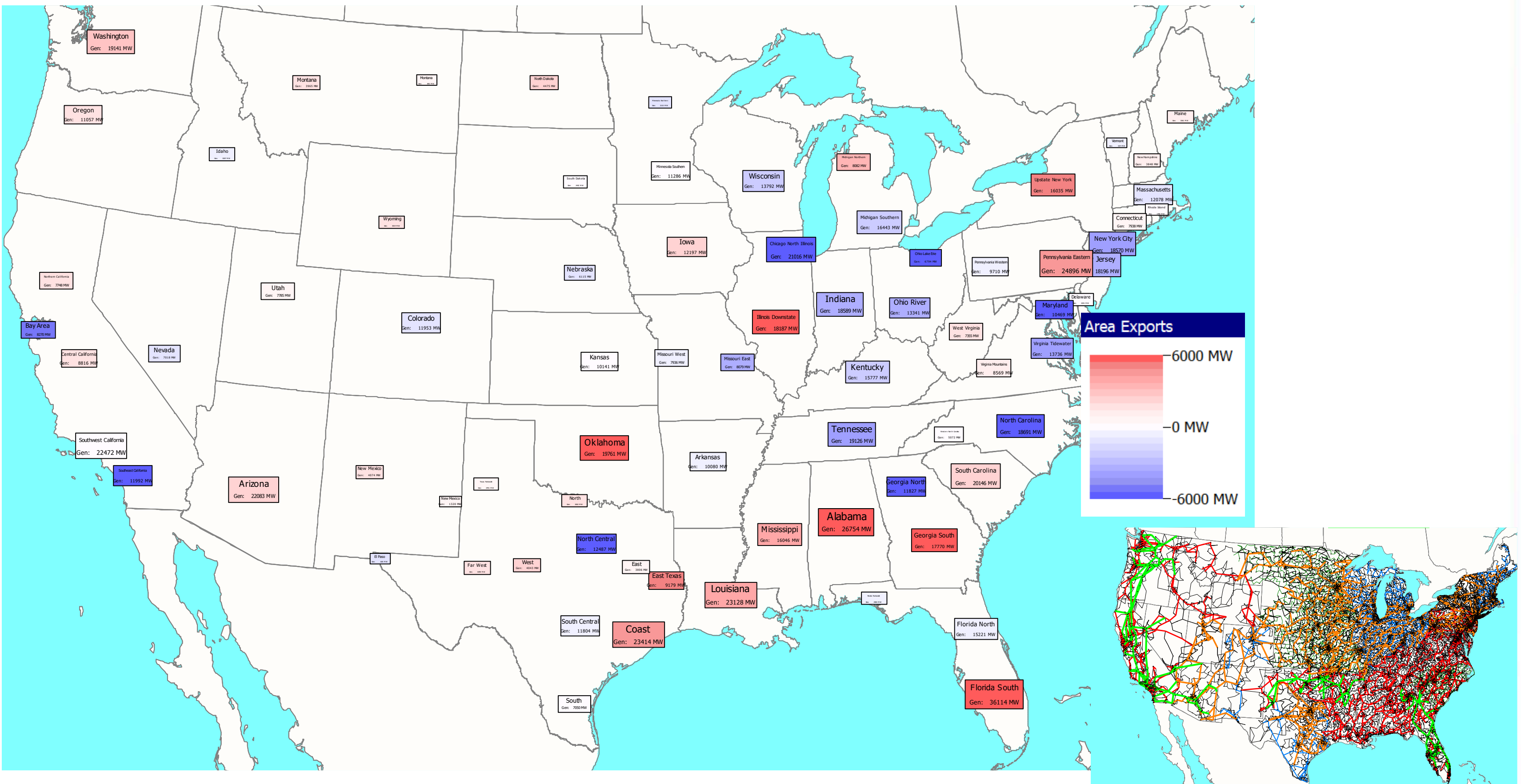
- While the previous techniques can be quite helpful, there is often just too much data to display
- Interactive visualizations, taking advantage of the underlying geographic information, can be quite effective, particularly if the displays can be rapidly customized to show different sets of information
- Also, much of the data should first be pre-processed using potentially quite sophisticated algorithms

# Geographic Data Views

- One way to make visualizations more interactive is to use underlying geographic information to quickly auto-create displays
  - Known as geographic data views (GDVs)
- GDVs can be used either on individual objects (like generators, buses, or substations), or on aggregate objects (like areas and zones)
- The GDV display attributes (e.g., size, color) can be used to show object data
- The GDV displays can be saved for later use and links to the underlying objects allow for drilldown

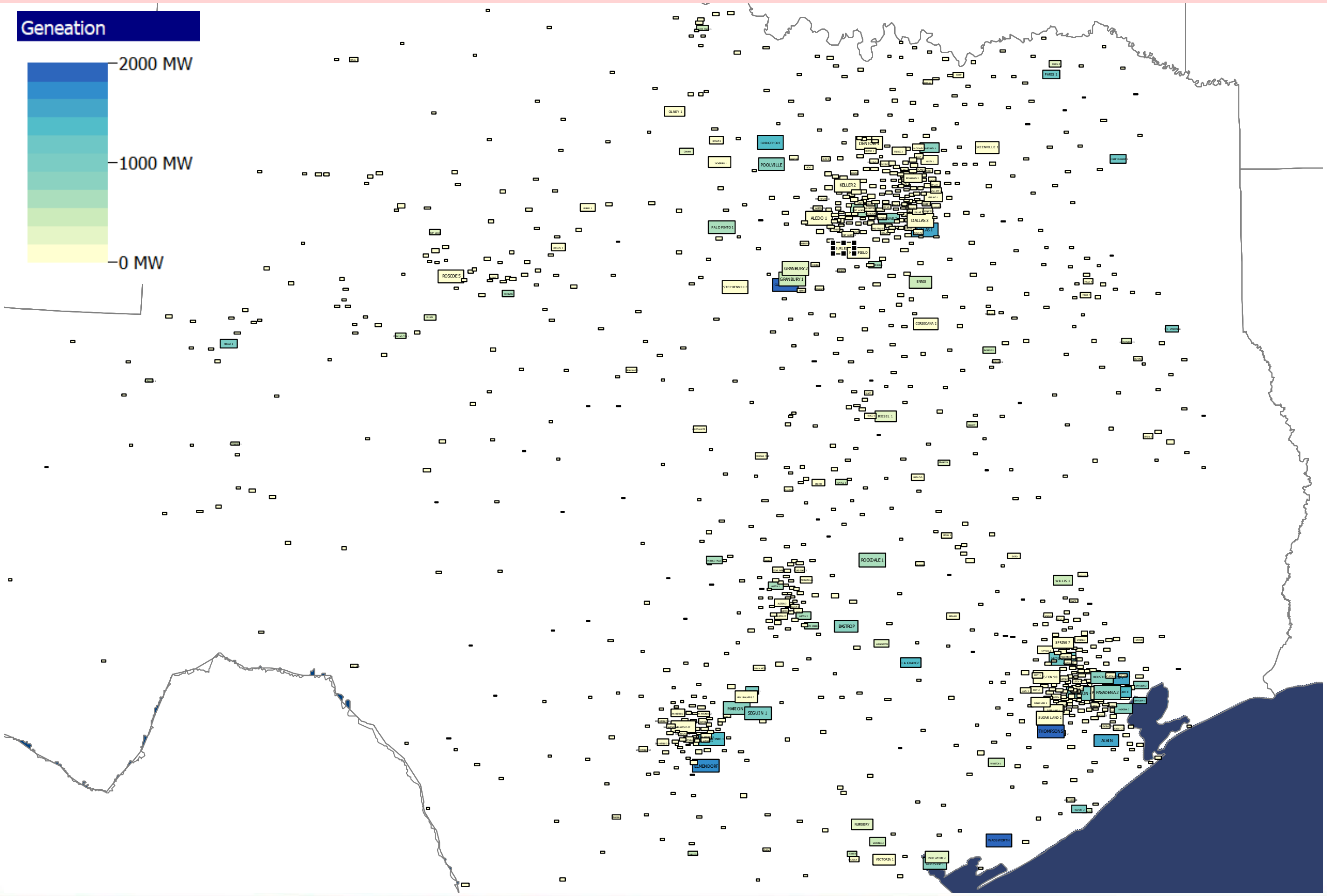
# 82,000 Bus System Area GDV Example

Size is proportional to the area’s generation, while the color is based on the amount of exports



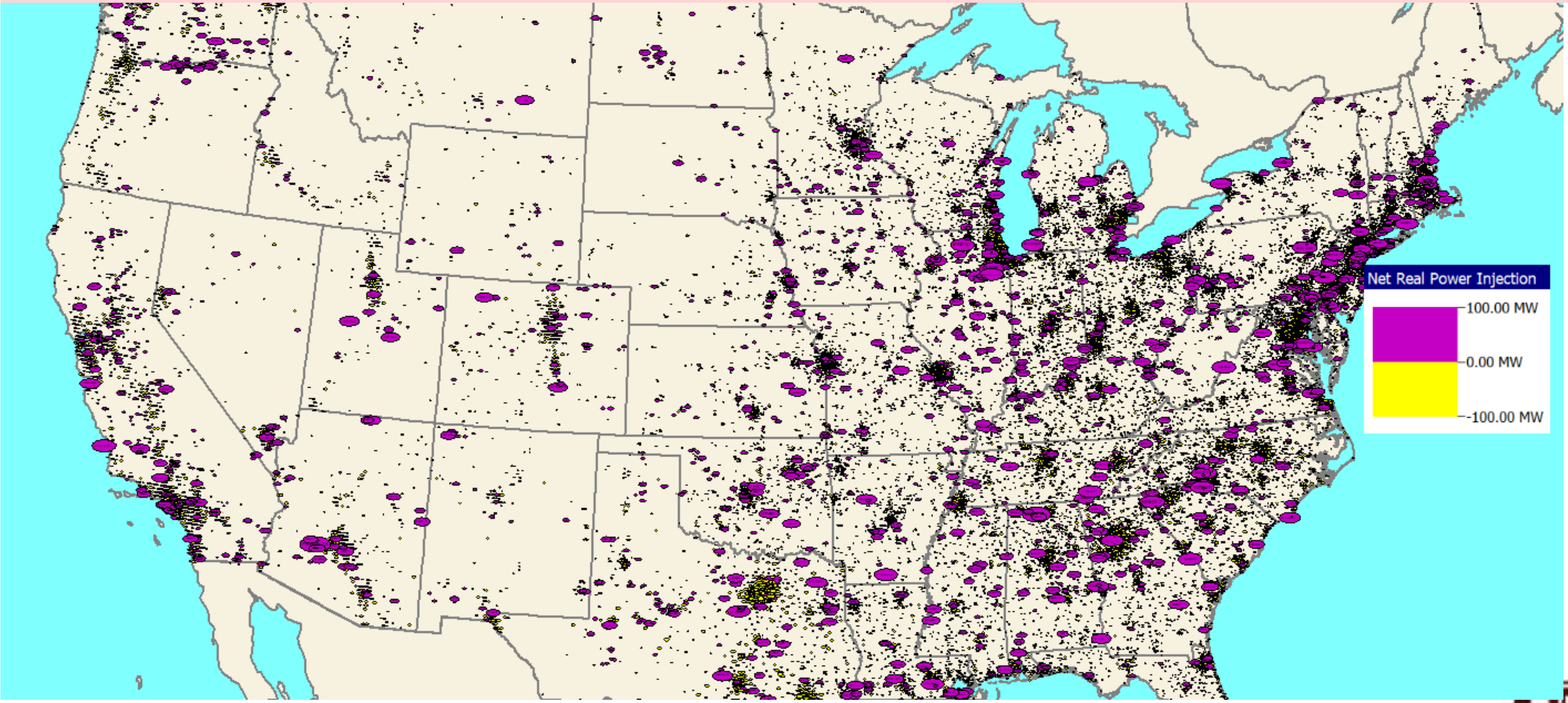
# Texas 2000 Substation GDV

Size is proportional to the substation MW throughput, while the color is based on the amount of substation generation



# 82,000 Bus Example GDV

Each GDV is linked, the GDVs can easily be customized, and the display can be saved (generation substations are magenta, load substations are yellow)



# Layout Algorithms Can Help

- Force-based layout algorithms can be used with GDVs to improve readability

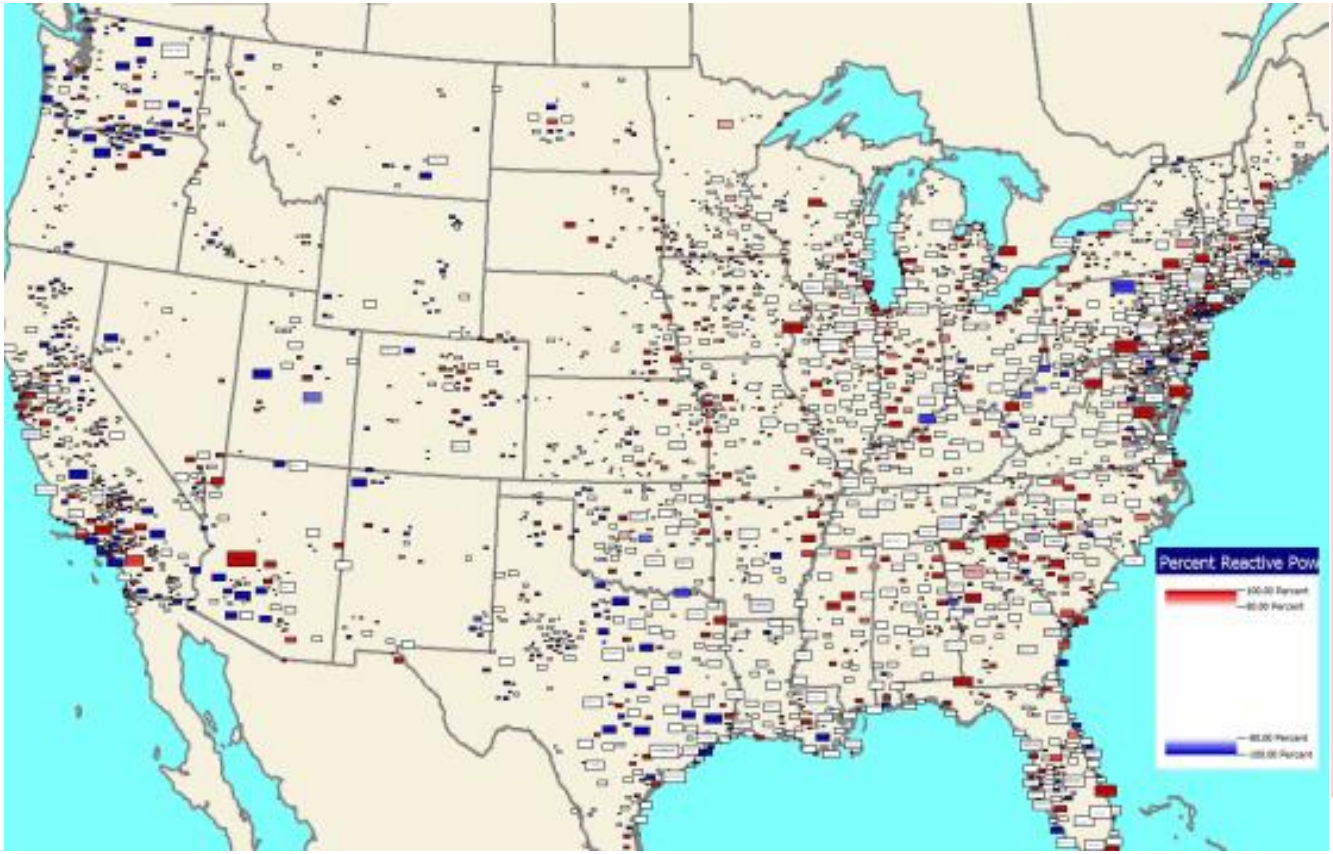
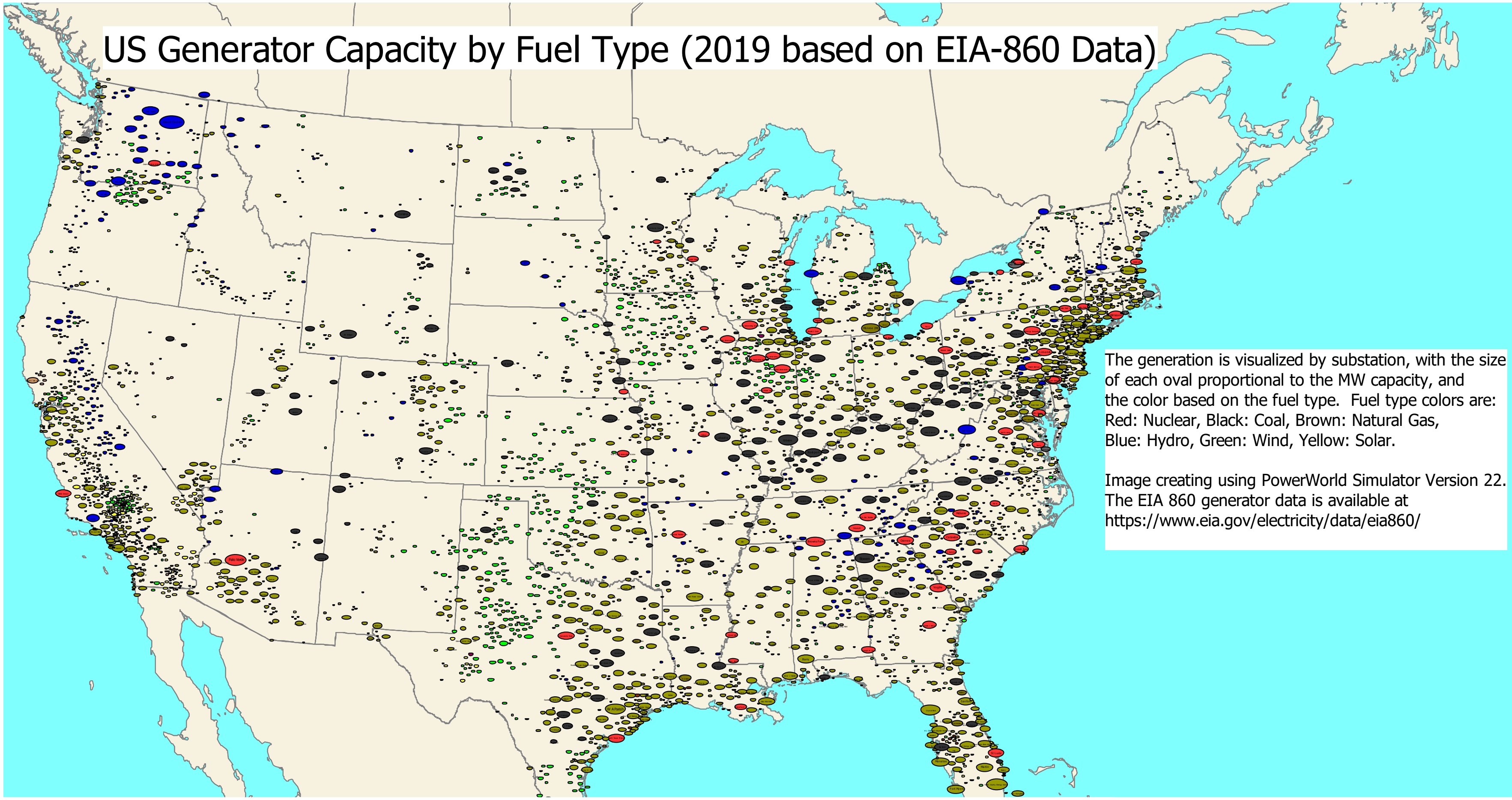


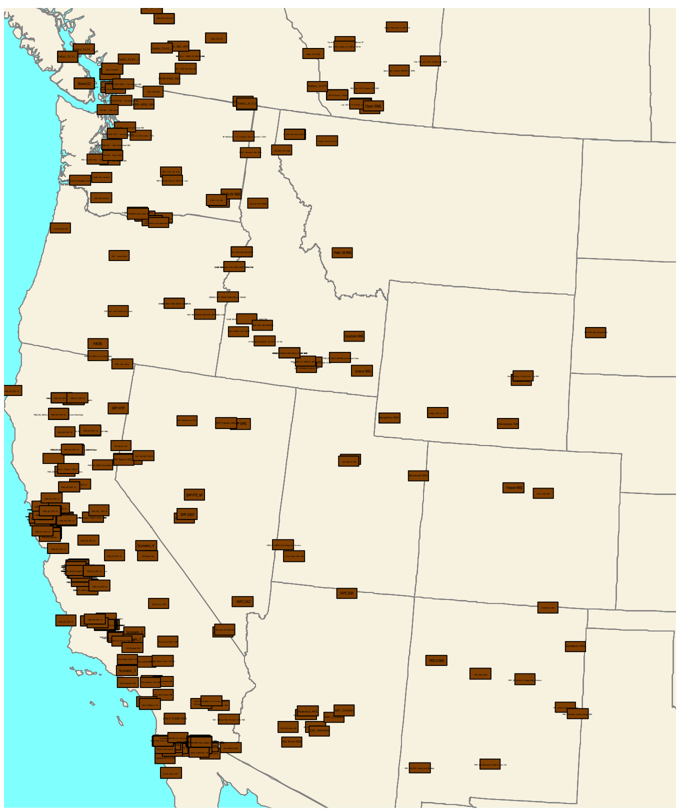

Image shows the 82K case generation with size proportional to MW output; color indicating percent reactive power. At a glance it is clear many units are at their reactive power limits.

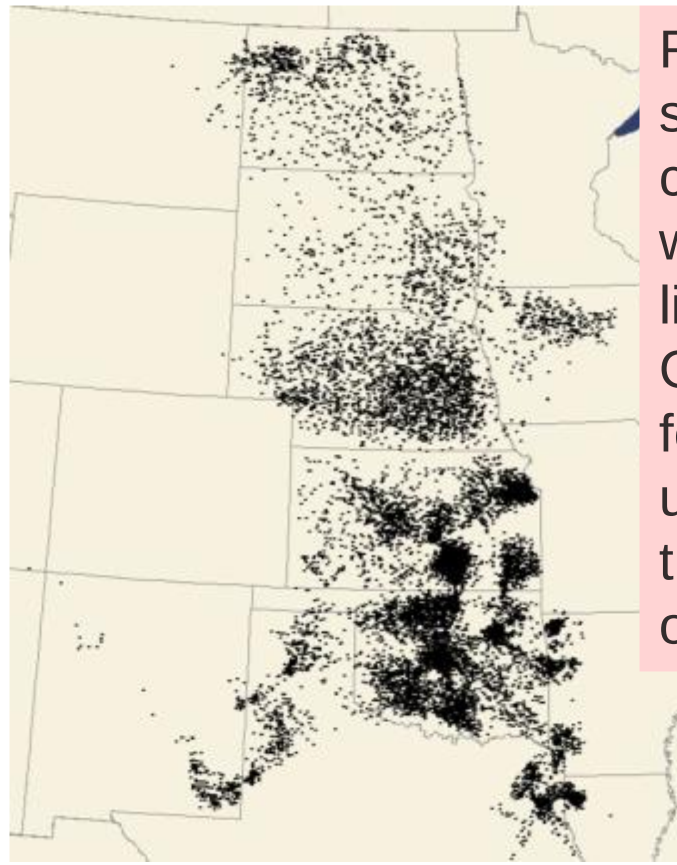
# Actual US Generation GDV Example



# GDVs for Contingencies and Remedial Action Schemes

- Many other power system objects can be shown using this approach





Right image shows 250,000 contingencies, with each one linked. The GDV dynamic formatting is used to highlight the small subset of interest.

# Pseudo-Geographic Mosaic Displays

- GDVs can be quite useful, but there is a tradeoff between geographic accuracy and maximum display space usage
  - Much of the electric grid is concentrated in small (primarily urban) areas
- Pseudo-Geographic Mosaic Displays (PGMDs) utilize a tradeoff of geographic accuracy to maximize display space

# 80,000 Bus System Area PGMD

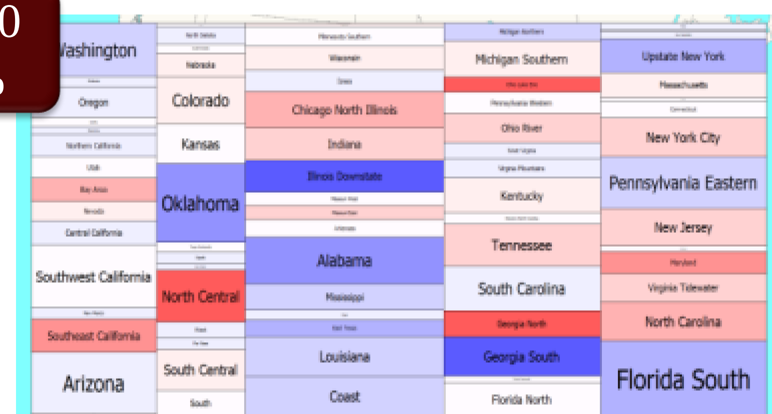
GDVs are as before (size = area gen MW, color = interchange); the percentages show the amount of transition

0%

25 %

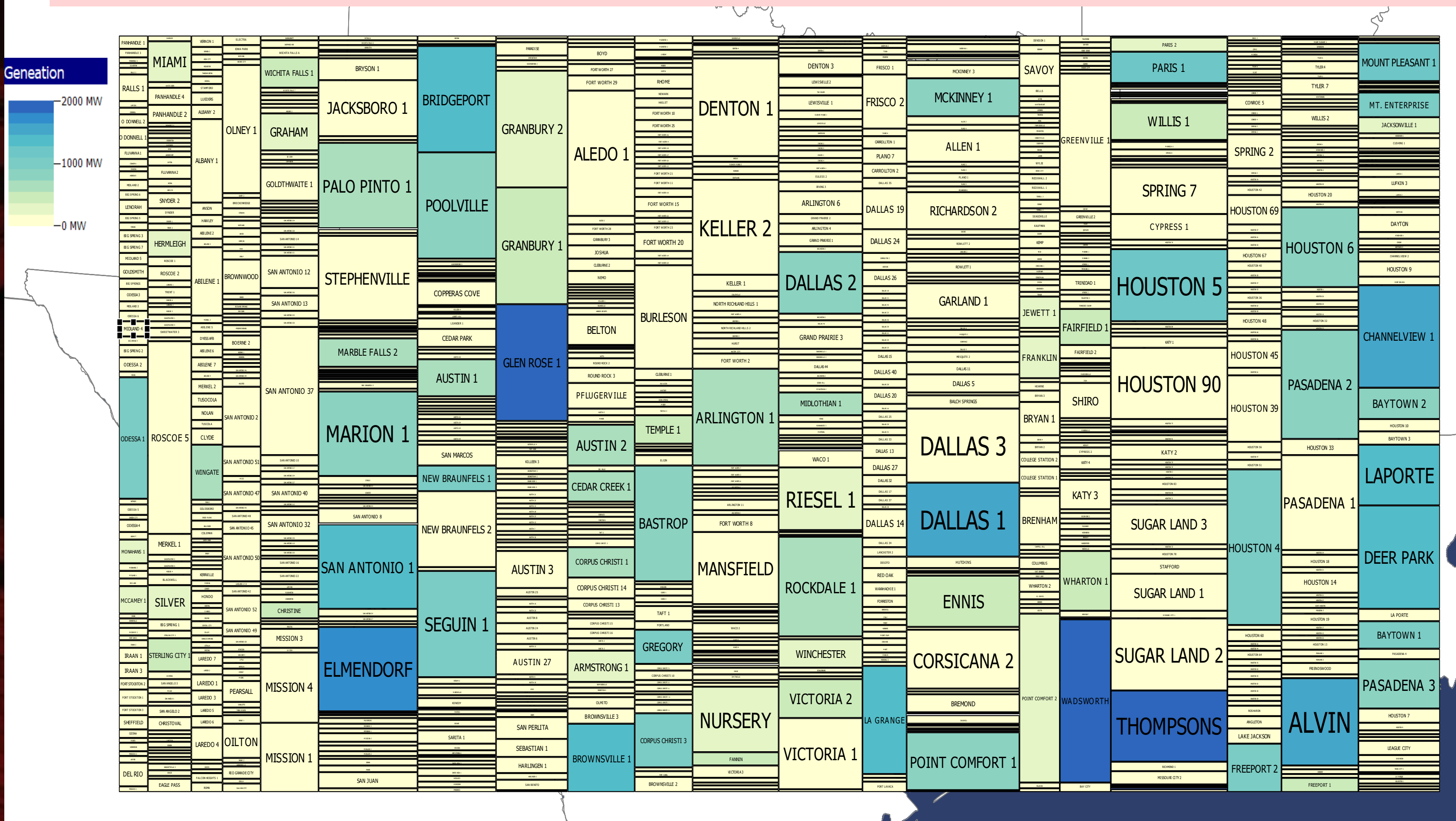
60%


100 %



# Texas 2000 Substation PGMD

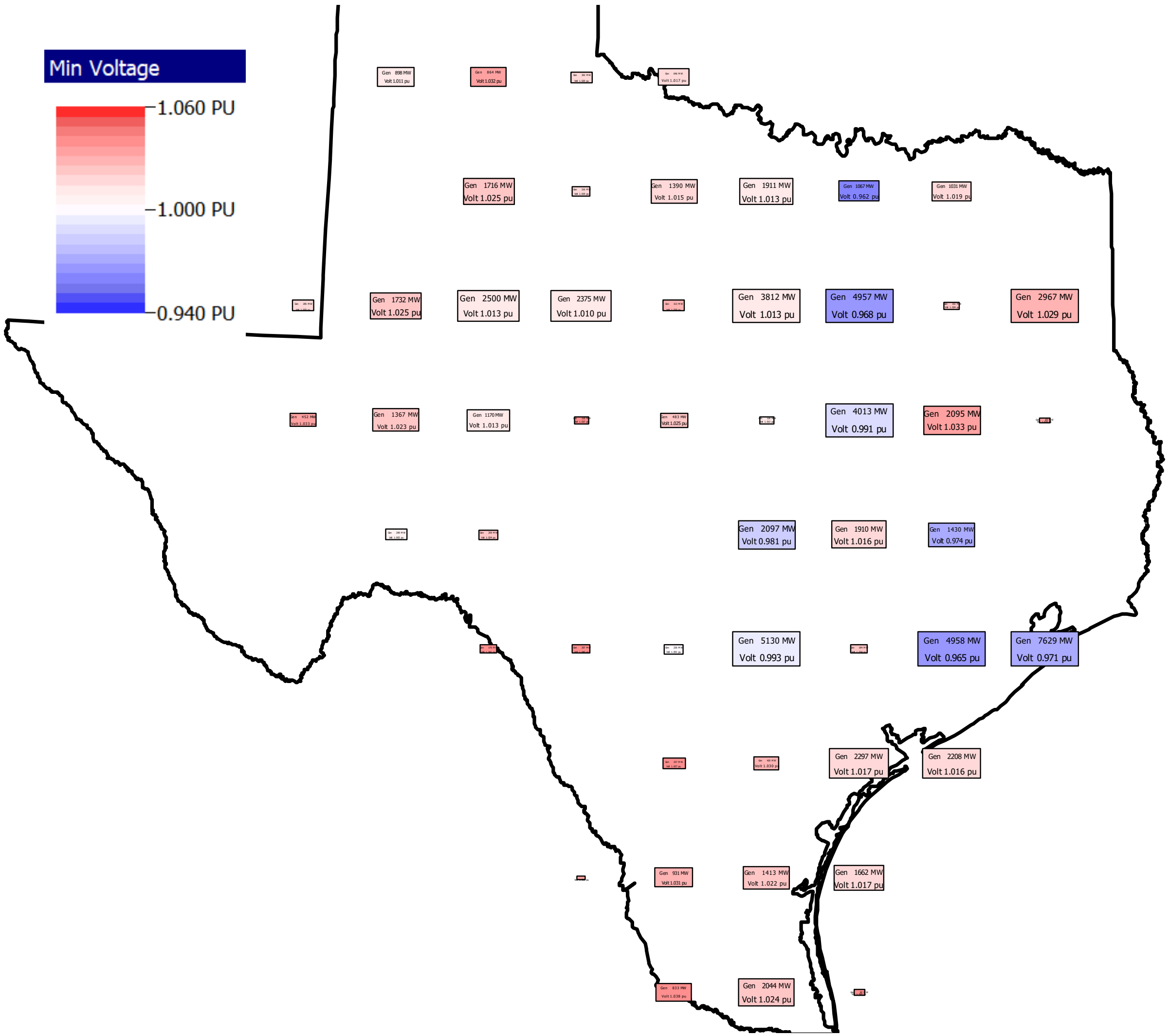
Size is proportional to the substation MW throughput, while the color is based on the amount of substation generation



# GDV Grouping

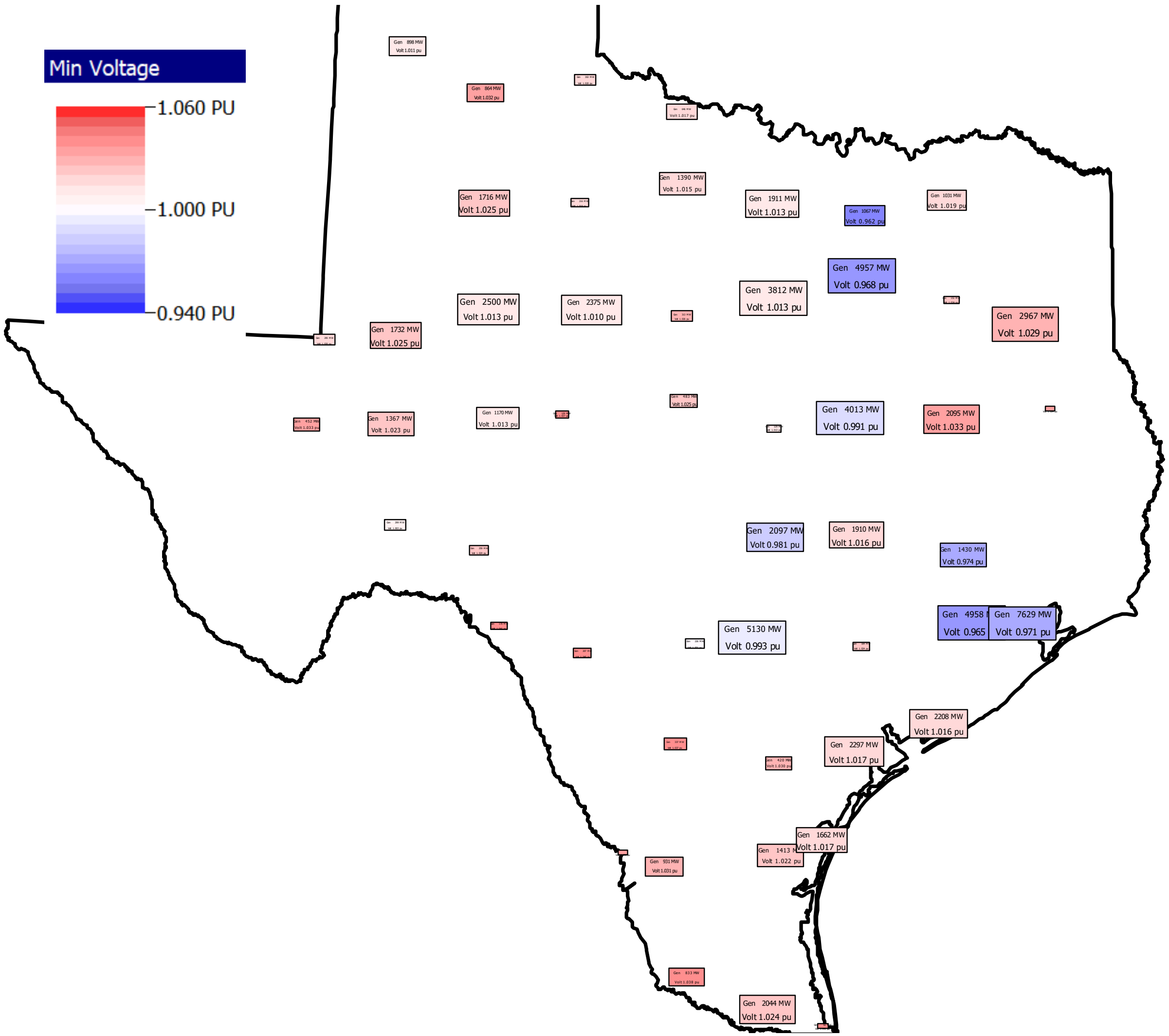
- Oftentimes there are just too many objects, so they need to be grouped
- There are many different ways to group them, with common ones by area, zone, substation, owner.
- GDV objects can also be grouped geographically with interactive grouping possible
  - Grouped object attributes can then be summarized different ways, such as sum, abs sum, average, minimum, maximum, etc.
  - Called GDV Summary Objects (GSOs)

# Texas 7K, 10 by 10 Grid



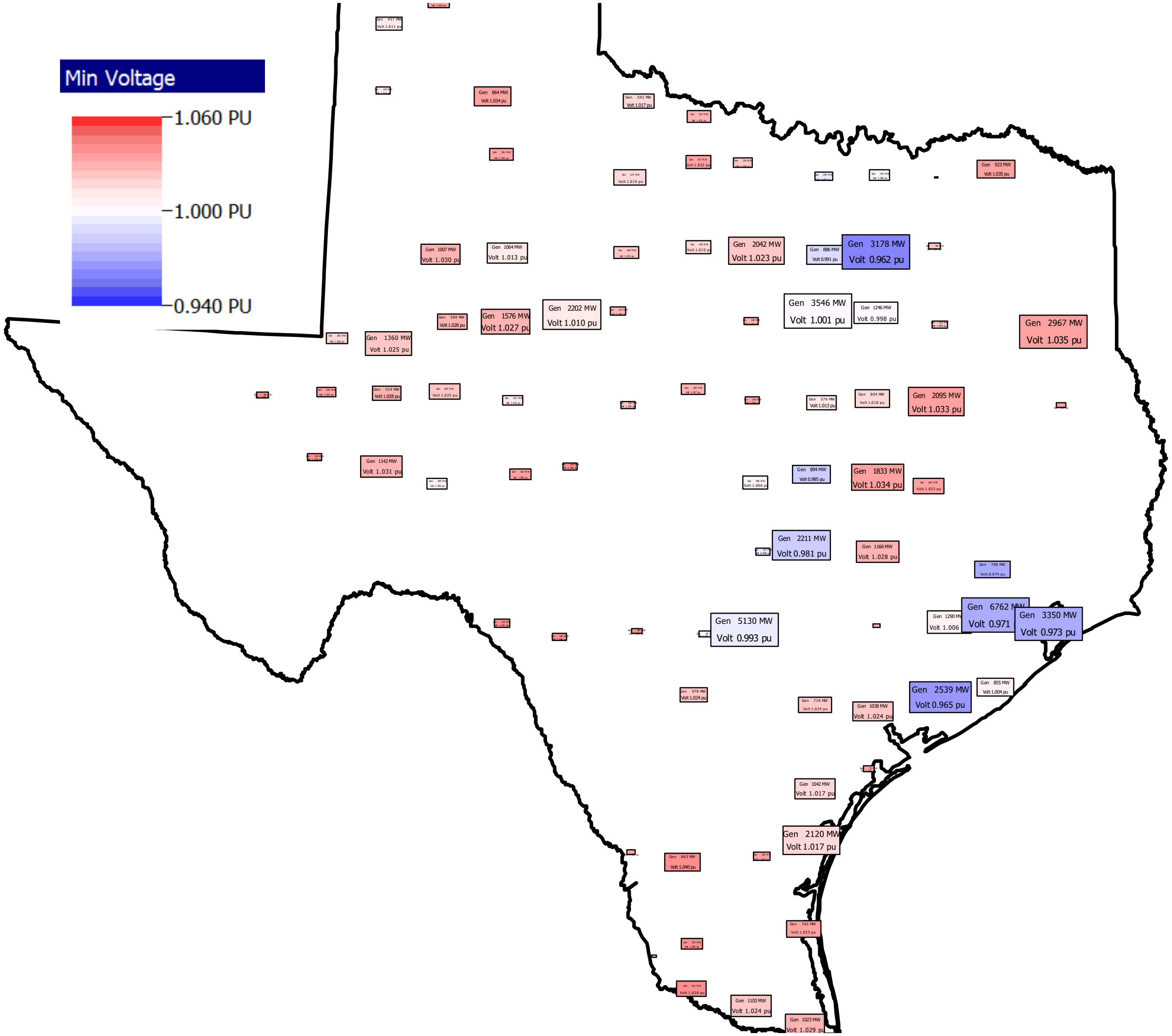

This is a 10 by 10 latitude/longitude grid with the GSO center based on the grid point. The disadvantage of this is some objects are outside the border. The size is generation, the color is the minimum voltage.

# Texas 7K, 10 by 10 Grid, Weighted Center



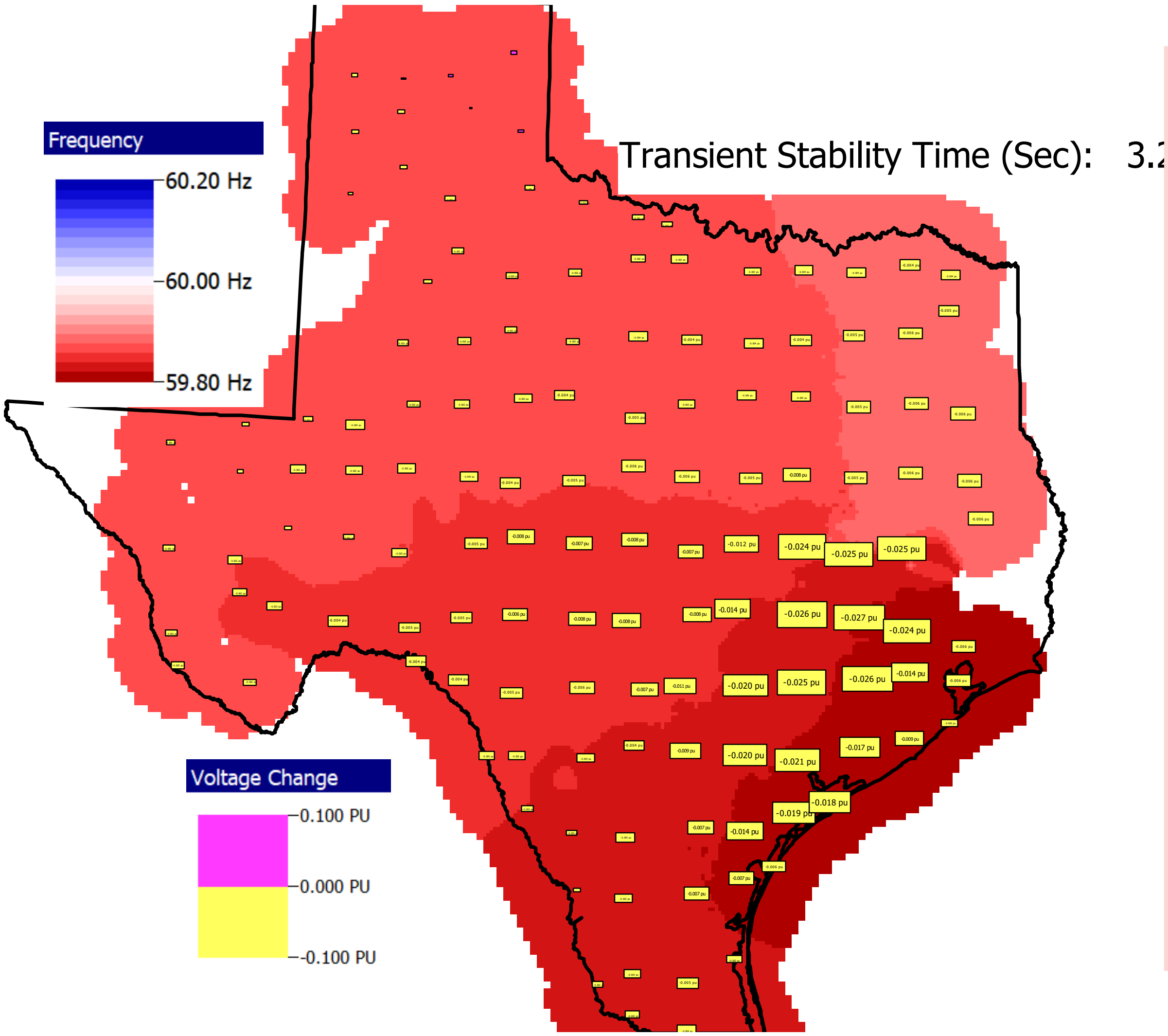

This is the same grid, except the GSO center is based on the average of all its elements. This approach is often preferred.

# The Grid Size Can be Easily Modified




This shows results for a 15 by 15 grid, with the same scale as before.

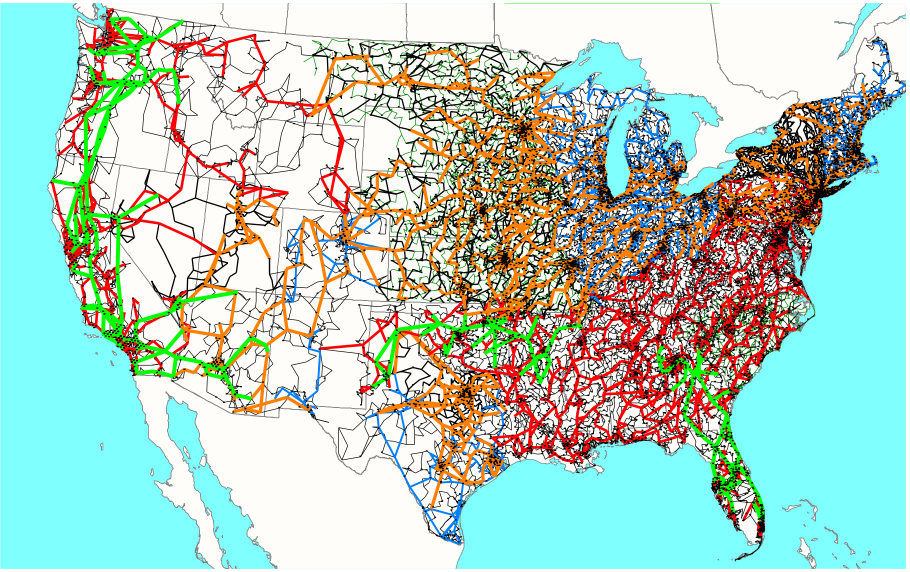
# Visualizing Multiple Values



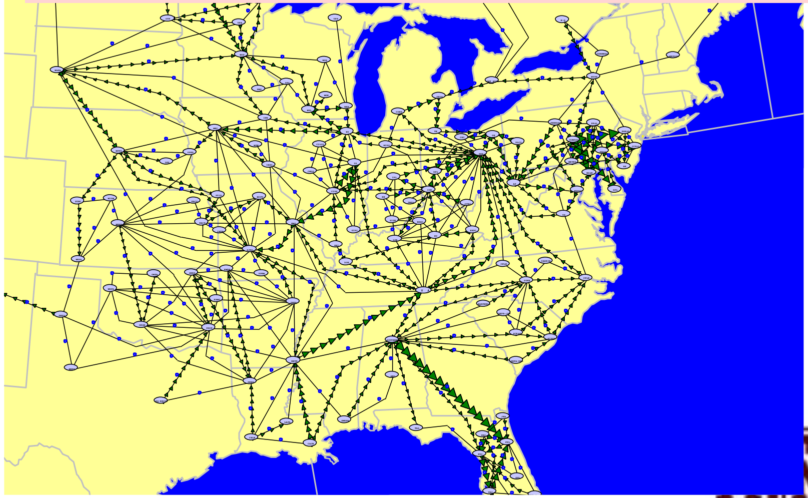

We commonly combine the GSO displays with contours to visualize multiple values. This image (from a stability run) shows a frequency contour (made by substation GDVs) with GSOs showing the voltage change.

# Visualizing Transmission System Flows

- The previous techniques can be quite helpful for showing many power system values, but don't scale well for showing transmission system flows
- Flows aggregations (interfaces) can be used

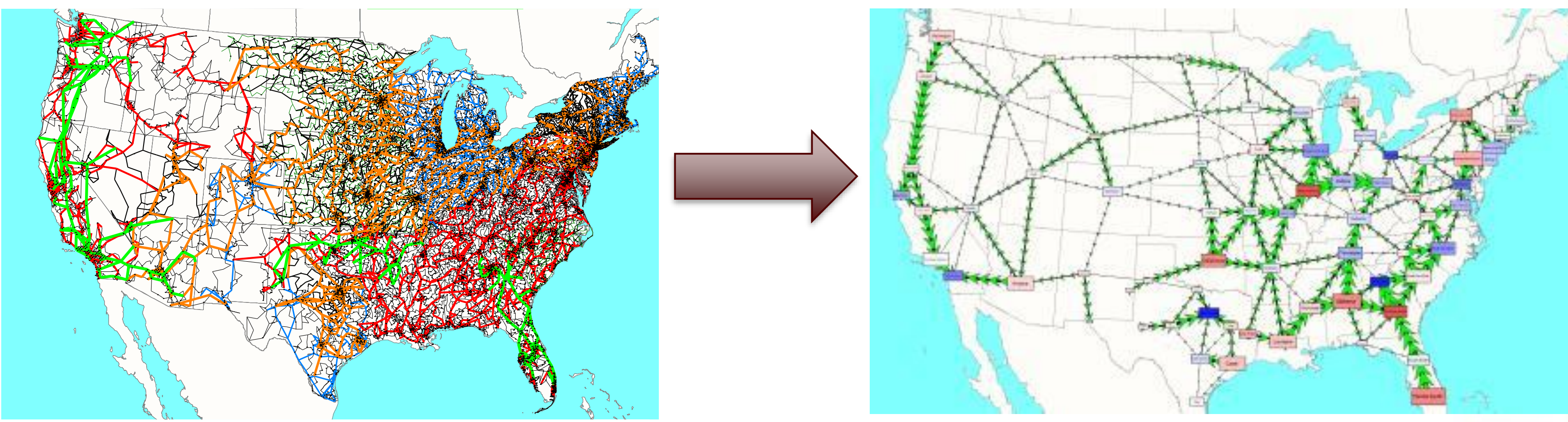


Area to area flow visualization, EPSON, 1998, Zurich, CH



# Delaunay Triangulation Based Wide-Area Flow Aggregation

- The next several slides present
  - An algorithm for visualizing power system flows using a Delaunay triangulation approach (giving a planar graph)
  - A demonstration of the algorithm on grids of all sizes, different levels of aggregation and different flows



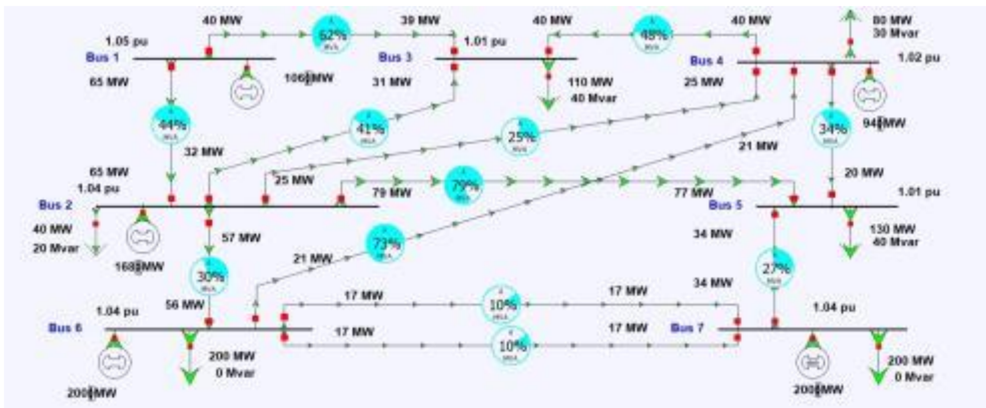
T.J. Overbye, J. Wert, K. Shetye, F. Safdarian, and A. Birchfield, "Delaunay Triangulation Based Wide-Area Visualization of Electric Transmission Grids," Kansas Power and Energy Conference (KPEC), Apr. 2021.

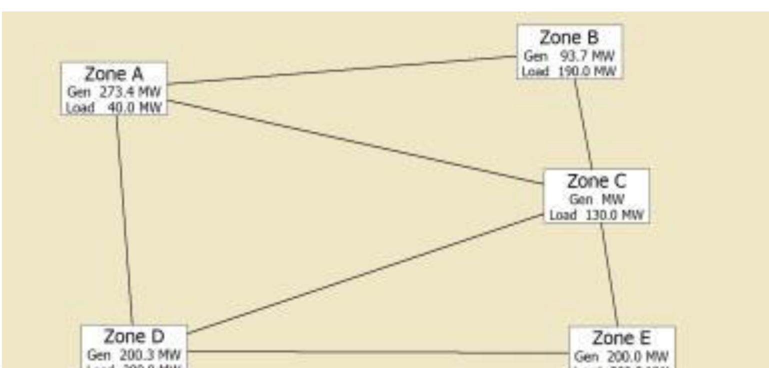
# Delaunay Triangulation Based Wide-Area Flow Aggregation

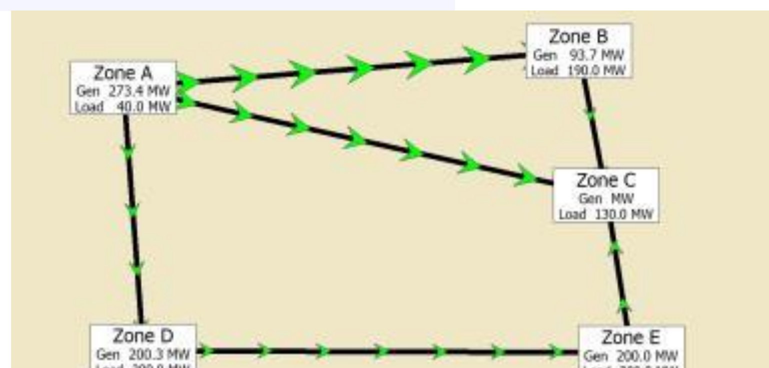
- The algorithm is simple and fast
  - Assume *n* buses, *m* bus groups and *b* branches joining the buses, with geographic information available for the buses
  - Map each branch to its terminal bus group(s)
  - Do a Delaunay triangulation of the *m* bus groups to create a set *S* of segments
  - For each branch quickly determine a segment path between its terminal bus groups adding it to the list for each segment

# Seven Bus Example

- This can be illustrated with a seven bus example with five bus groups, A={1,2}, B={3,4}, C={5}, D={6}, E={7}



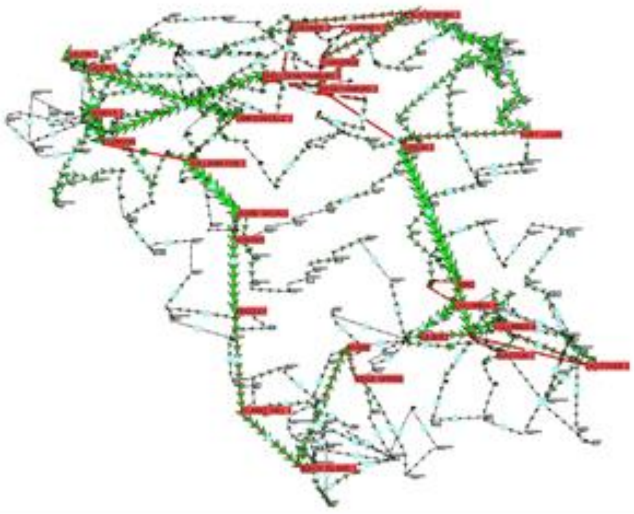



# Computing Path Between Two Groups

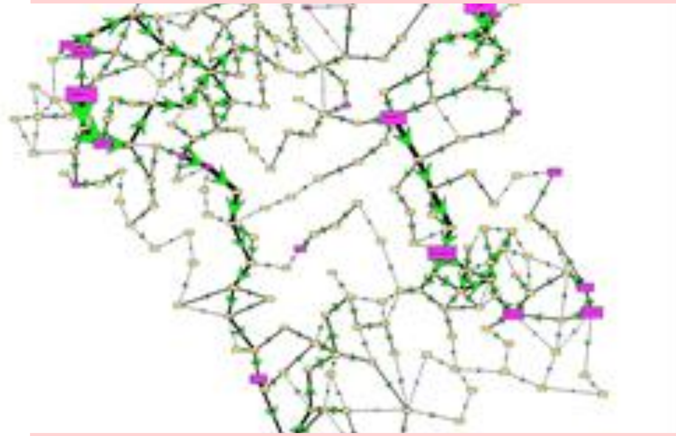
- In general calculating the path between two bus groups is not exceptionally fast (given that is has to be applied to each branch)
- However, when the graph is based on a Delaunay triangulation paths can be calculated very quickly
- Different algorithms exist to do this, with the paper using a Greedy Routing algorithm
- Determining the path for a branch between its terminal bus groups has three options
  1. Both ends in same group so branch is ignored
  2. Ends are in first neighbor groups so simple
  3. Use the Greedy Routing algorithm

# 500 Bus Example

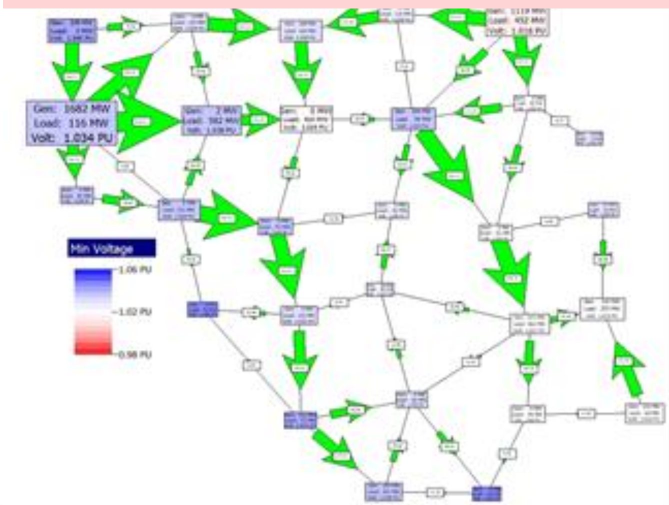
- Slide shows the original network with several intersecting branches an then two applications of the algorithm



Original System, b=599



Algorithm m =208, s=311

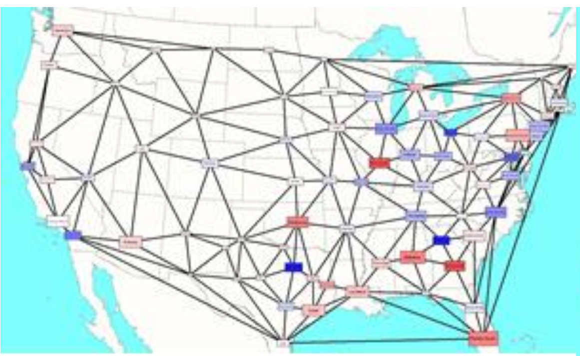


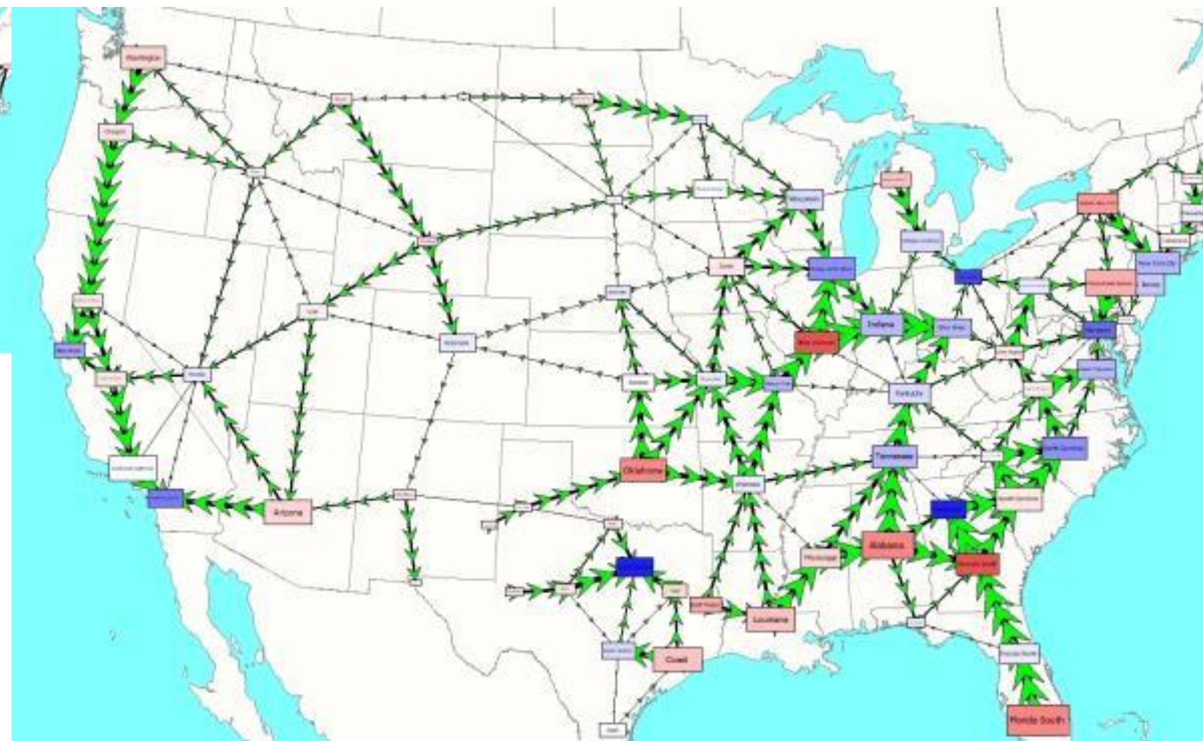

Algorithm m =28, s=49

# Algorithm on 82,000 Bus Grid

- In all cases for the following slides the algorithm took less than one second

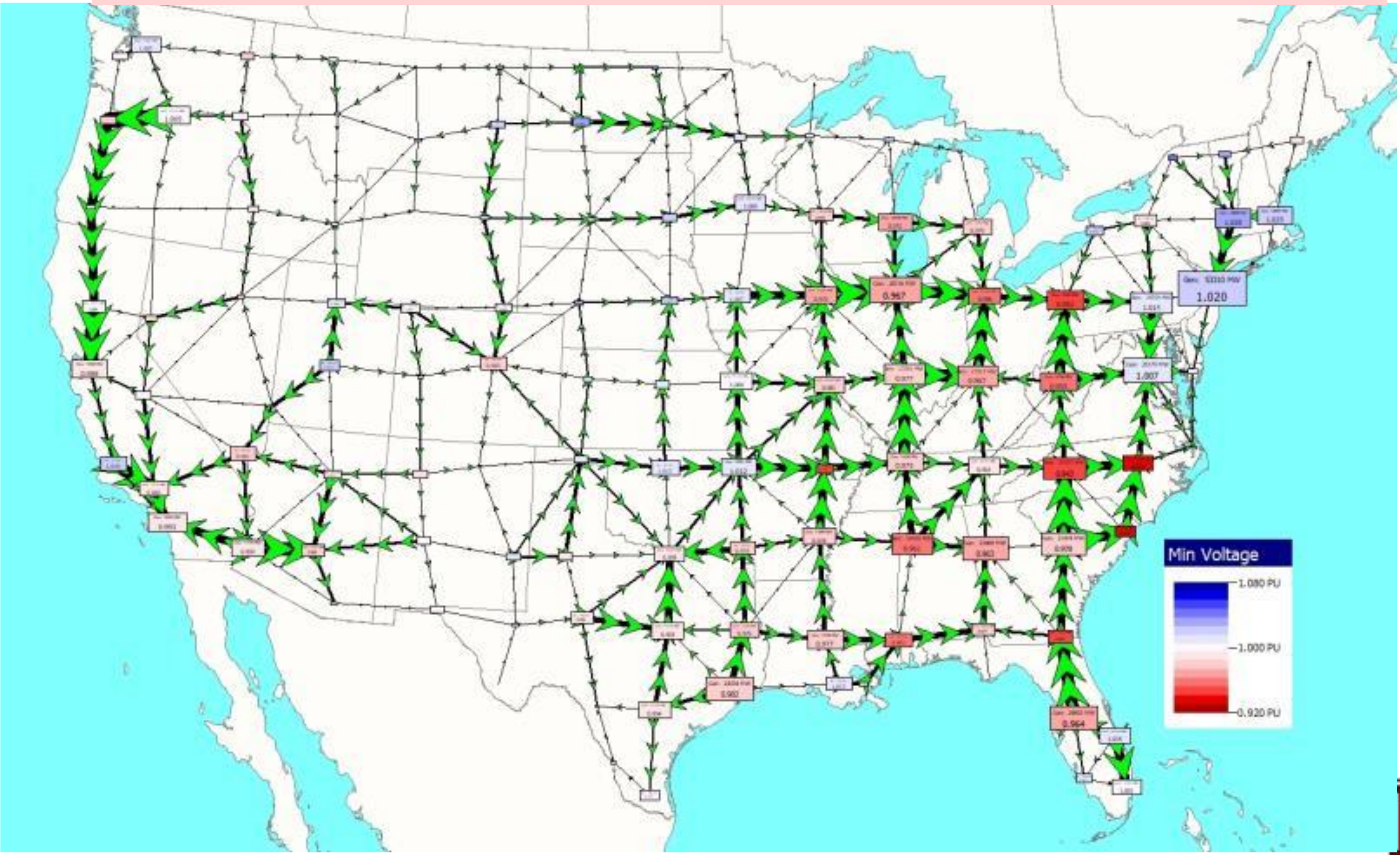
Algorithm m =76, s=114 (after removing zero branch segments)





# Algorithm on 82,000 Bus Grid

Algorithm using a 10 by 16 latitude/longitude GSO grid

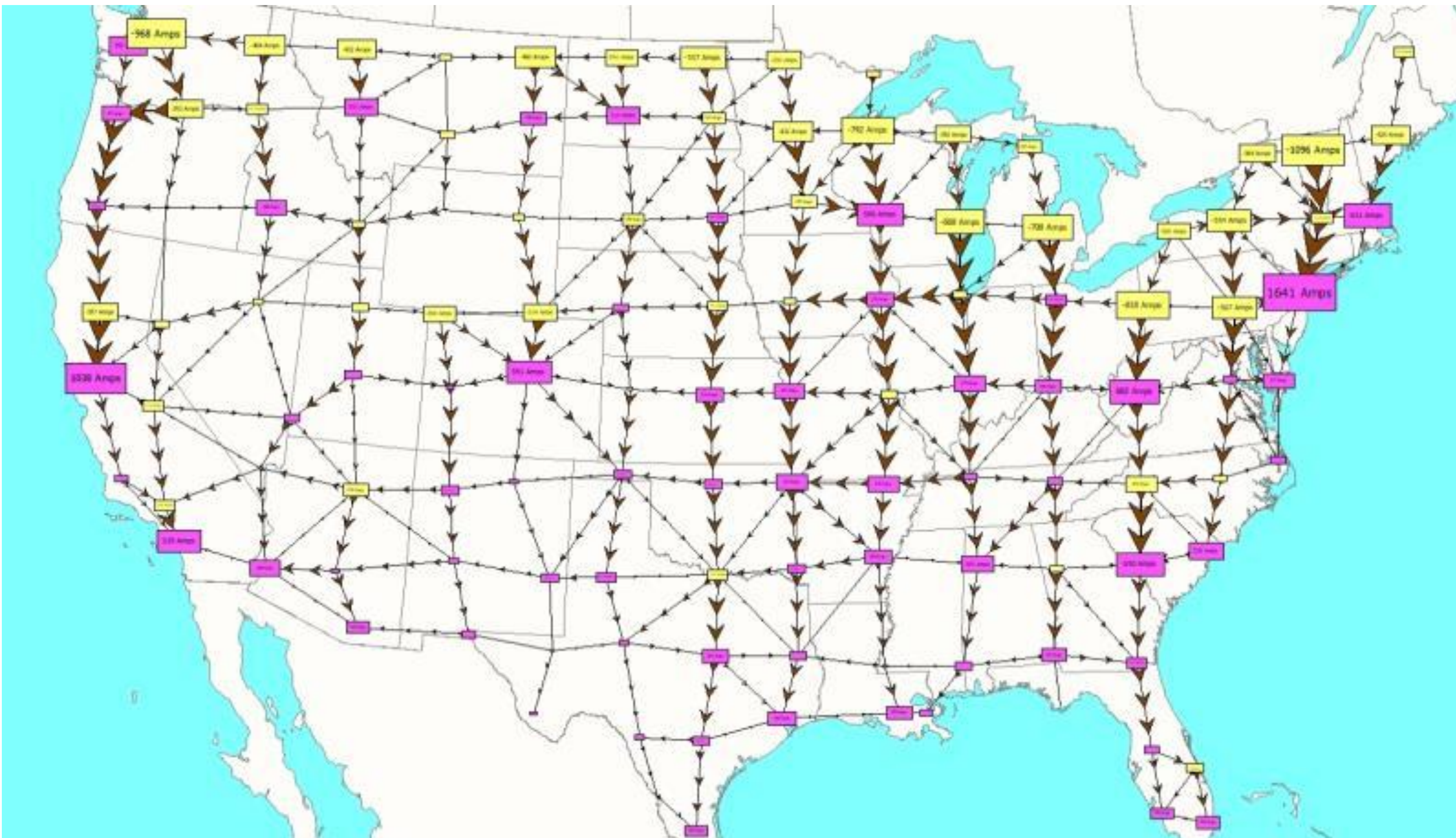


# Algorithm on 82,000 Bus Grid, PTDFs

Algorithm using areas for the bus groups with labels added to show the exact PTDF values (Maine to Washington State)

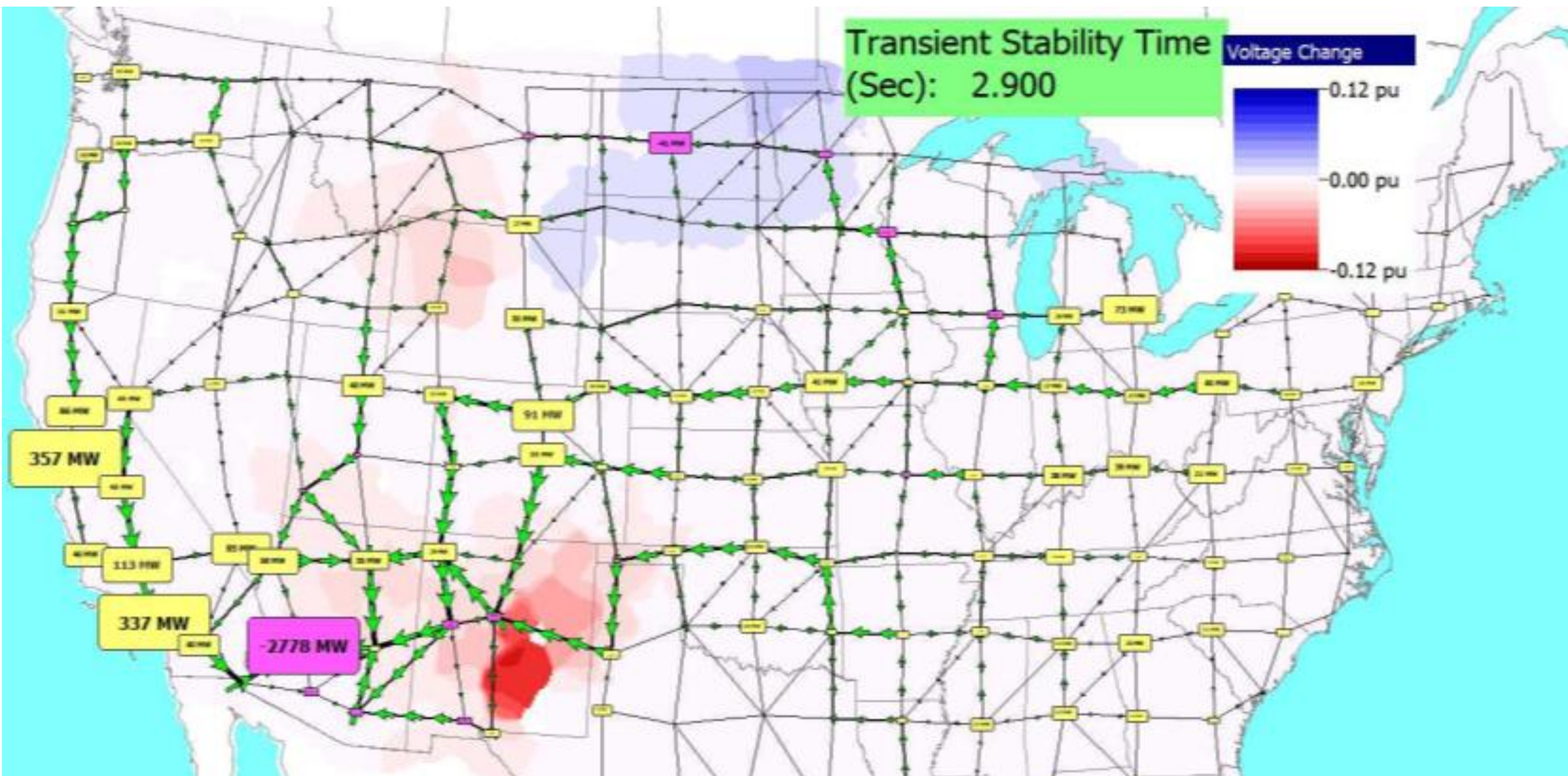
# Algorithm on 82,000 Bus Grid, GICs

The impact of the assumed North-South electric field is readily apparent; yellow indicates GIC sources, magenta sinks



# Visualization of Stability Results, 82K

Image is snapshot from a stability results movie for a generator loss contingency, with GDVs showing the voltage change contour, GSOs the generation change, and GSLOs the line flow changes.



# Some Techniques for Dealing with Time-Varying Data

- Need to keep in mind the desired task!
- Tabular displays
- Time-based graphs (strip-charts for real-time)
- Animation loops
  - Can be quite effective with contours, but can be used with other types of data as well
- Data analysis algorithms, such as clustering, to detect unknown properties in the data
  - There is often too much data to make sense without some pre-processing analysis!

# Animation loops

- Animation loops trade-off the advantages of snapshot visualizations with the time needed to play the animation loop
  - A common use is in weather forecasting
- In power systems applications the length/speed of the animation loops would depend on application
  - In real-time displays could update at either SCADA or PMU rates
  - Could be played substantially faster than real-time to show historical or perhaps anticipated future conditions

# Wide-Area Contours Can be Quickly Created Using GDVs

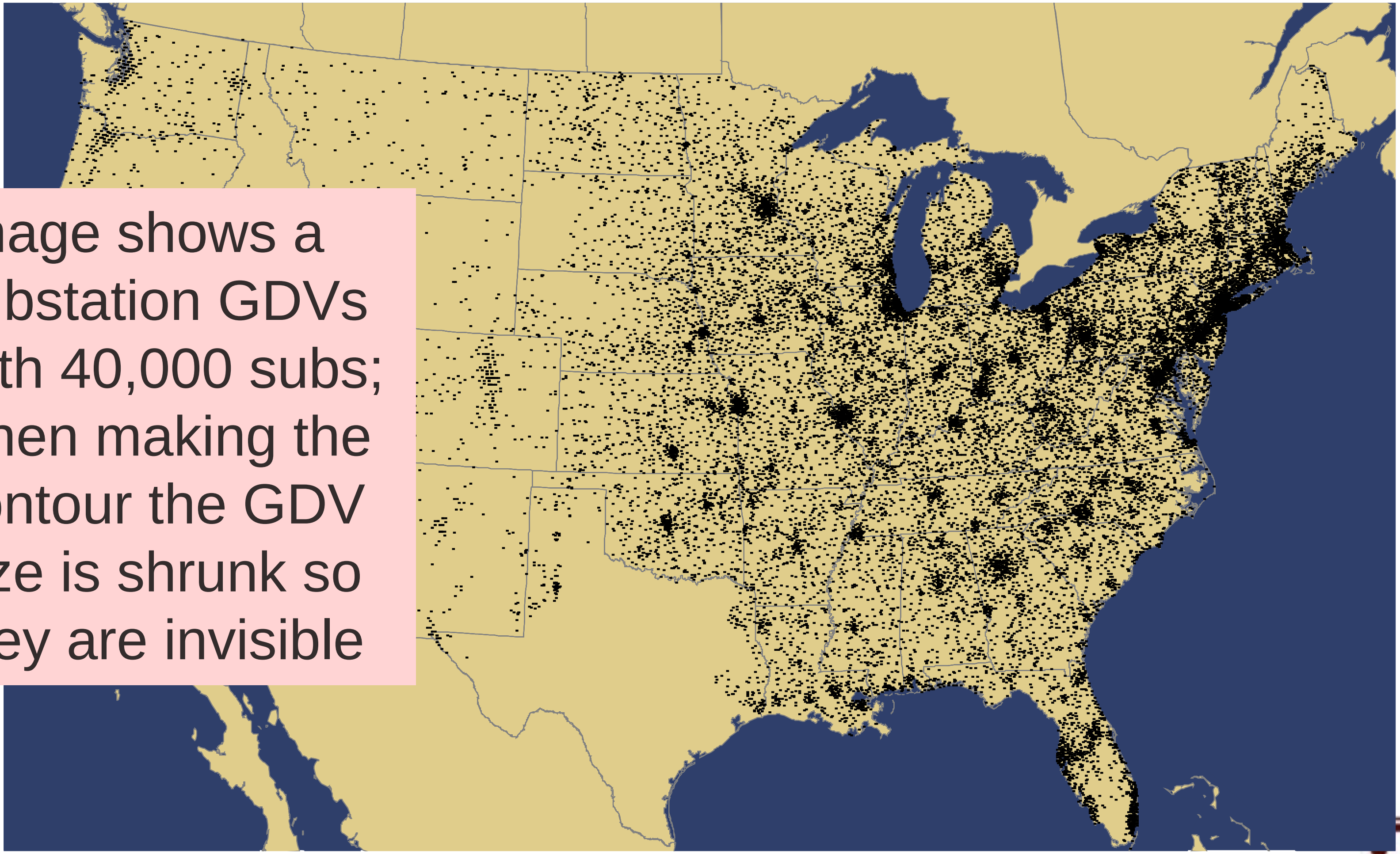
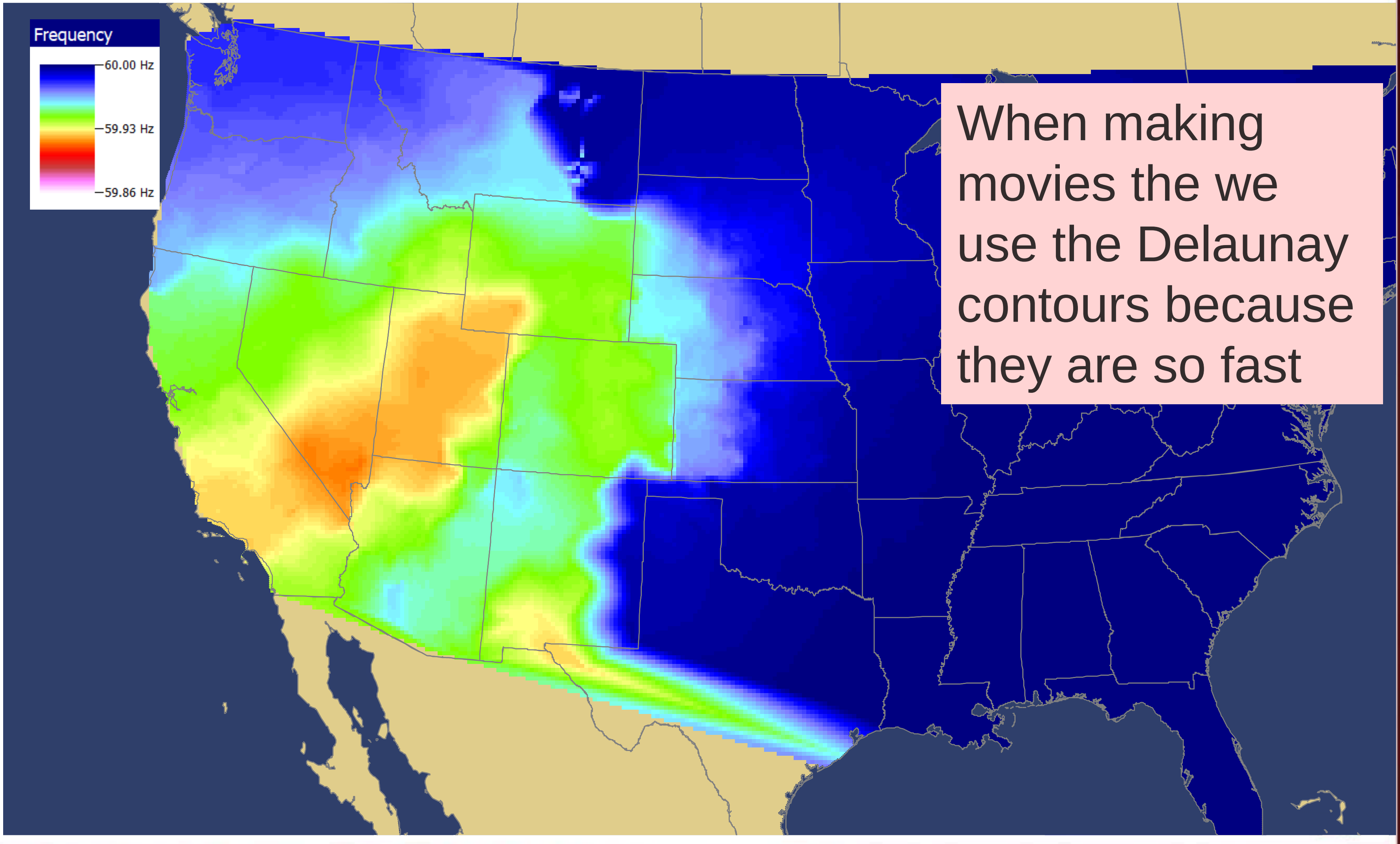


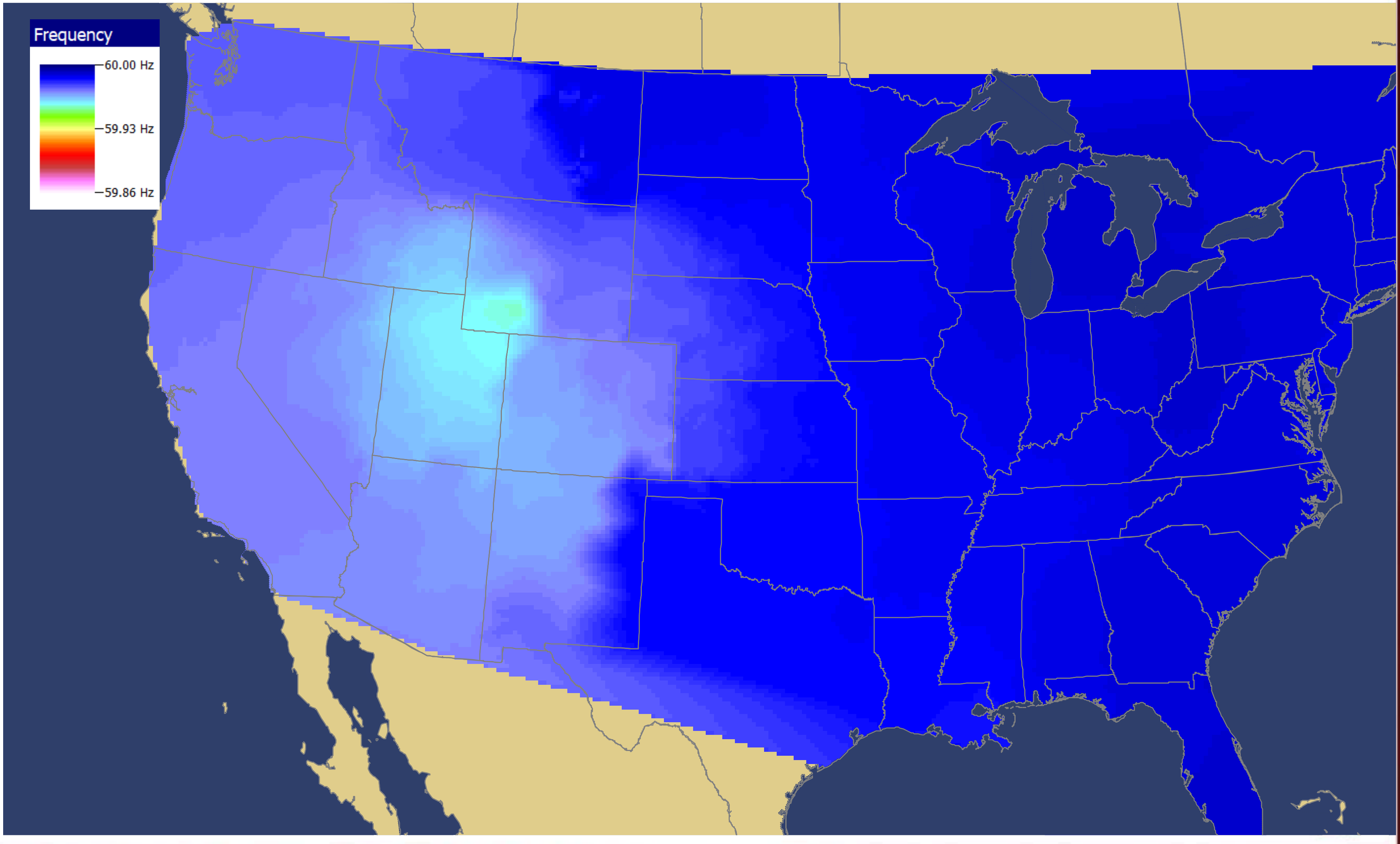
Image shows a substation GDVs with 40,000 subs; when making the contour the GDV size is shrunk so they are invisible

# 80K-Bus Frequency Variation (Substation Contour; Time = 2.0 Seconds)

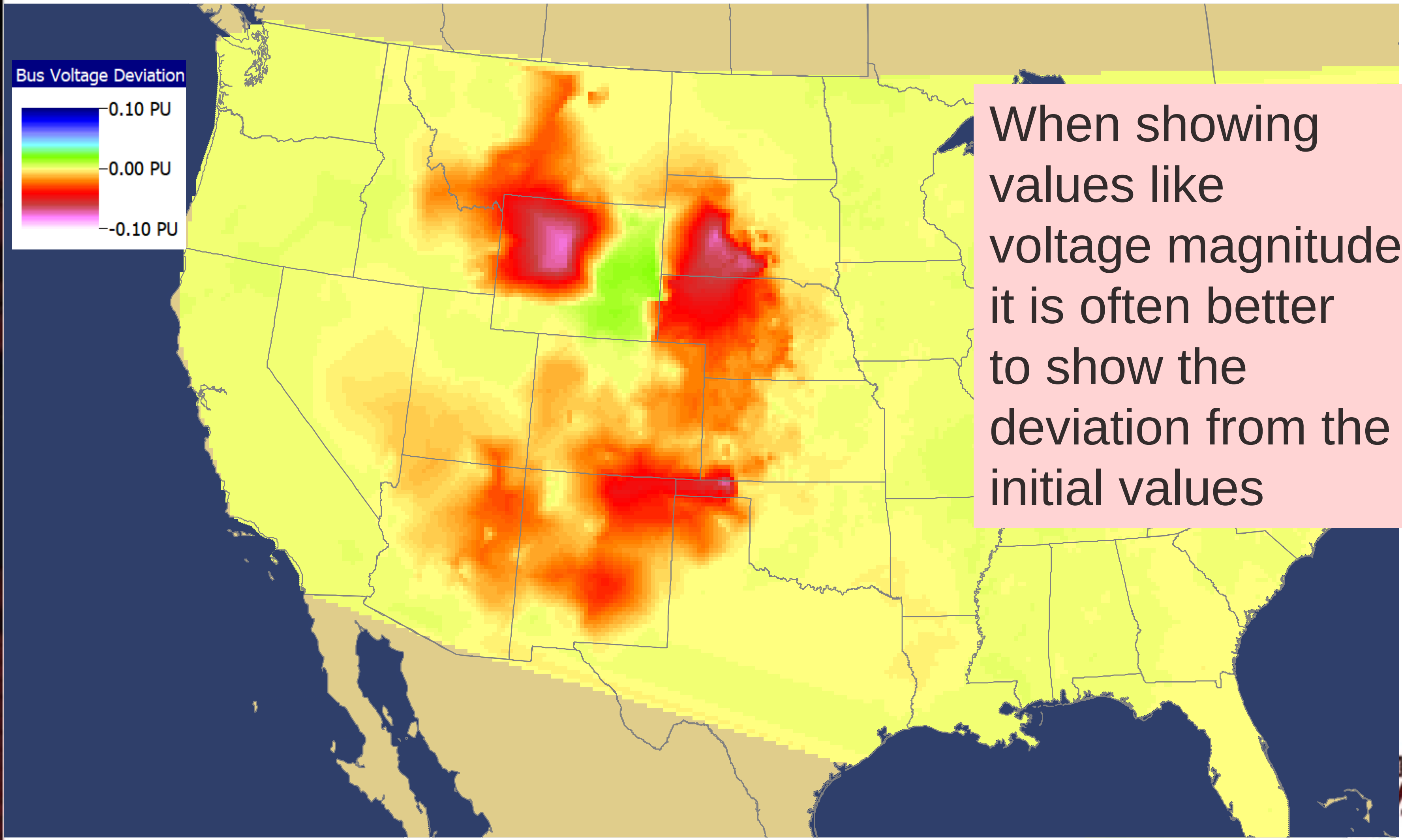



When making movies the we use the Delaunay contours because they are so fast

# 80K-Bus Frequency Variation (Substation Contour; Time = 8.0 Seconds)

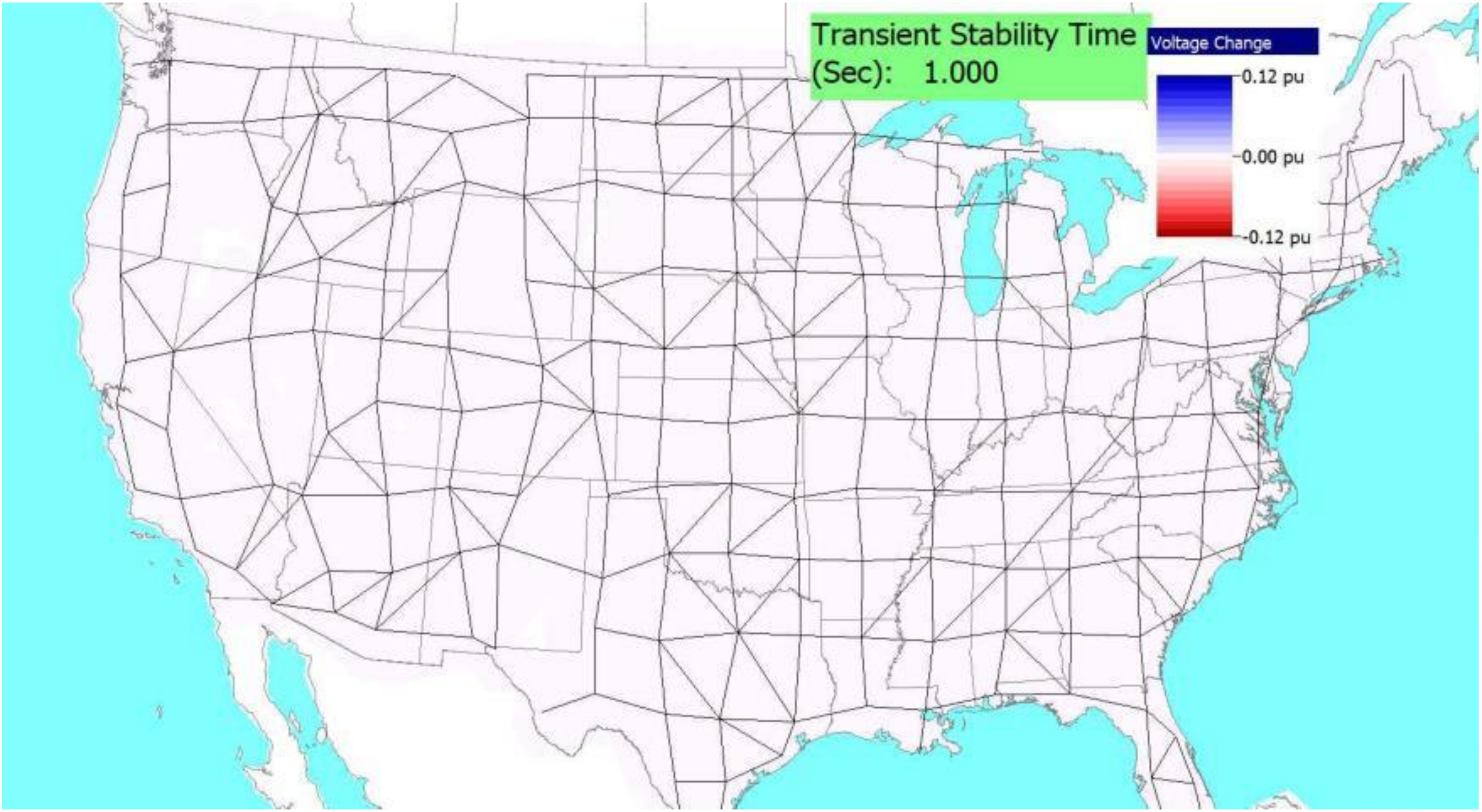


# 80K-Bus Voltage Magnitude Variation (Substation Contour; Time = 5.0 Seconds)

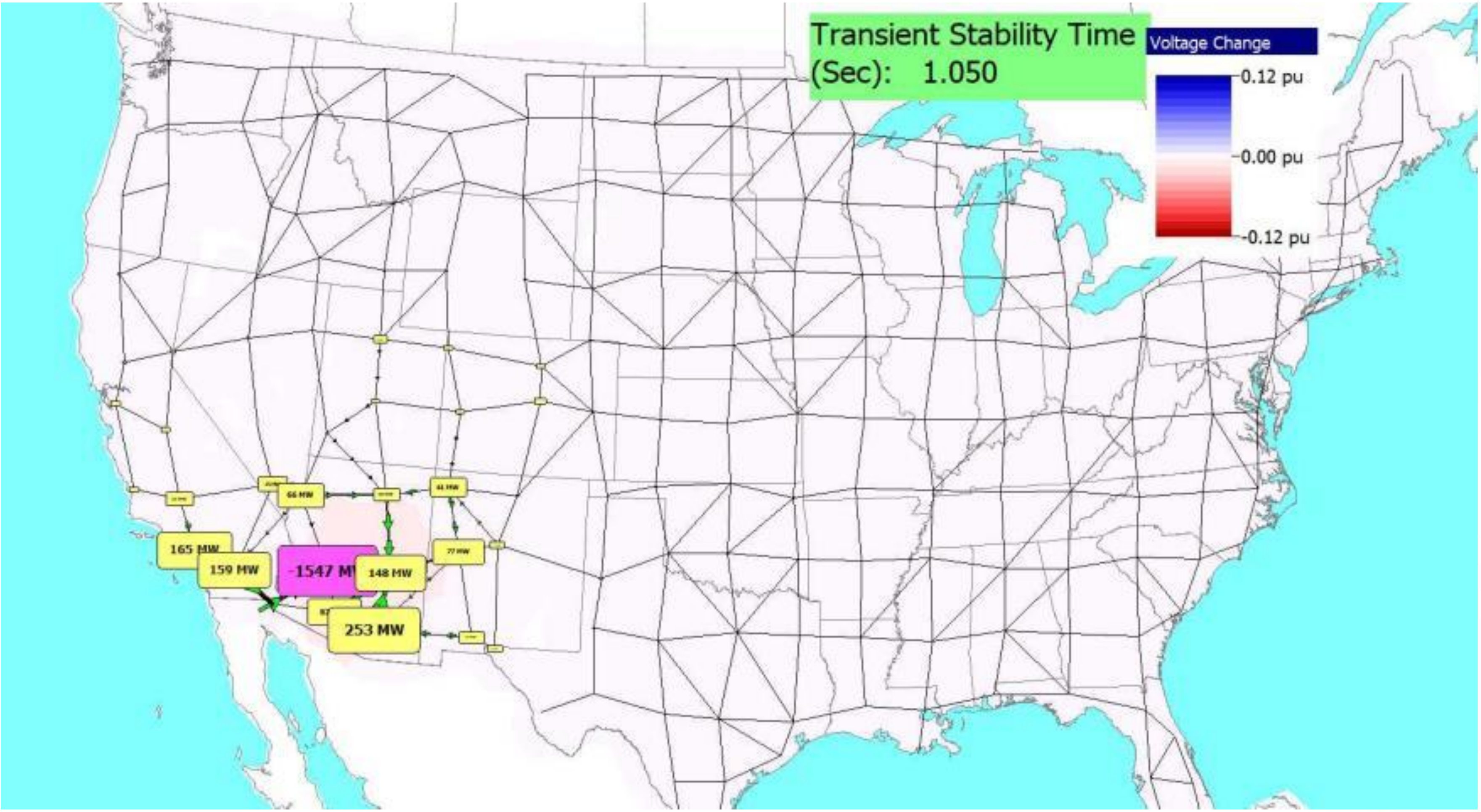



When showing values like voltage magnitudes it is often better to show the deviation from the initial values

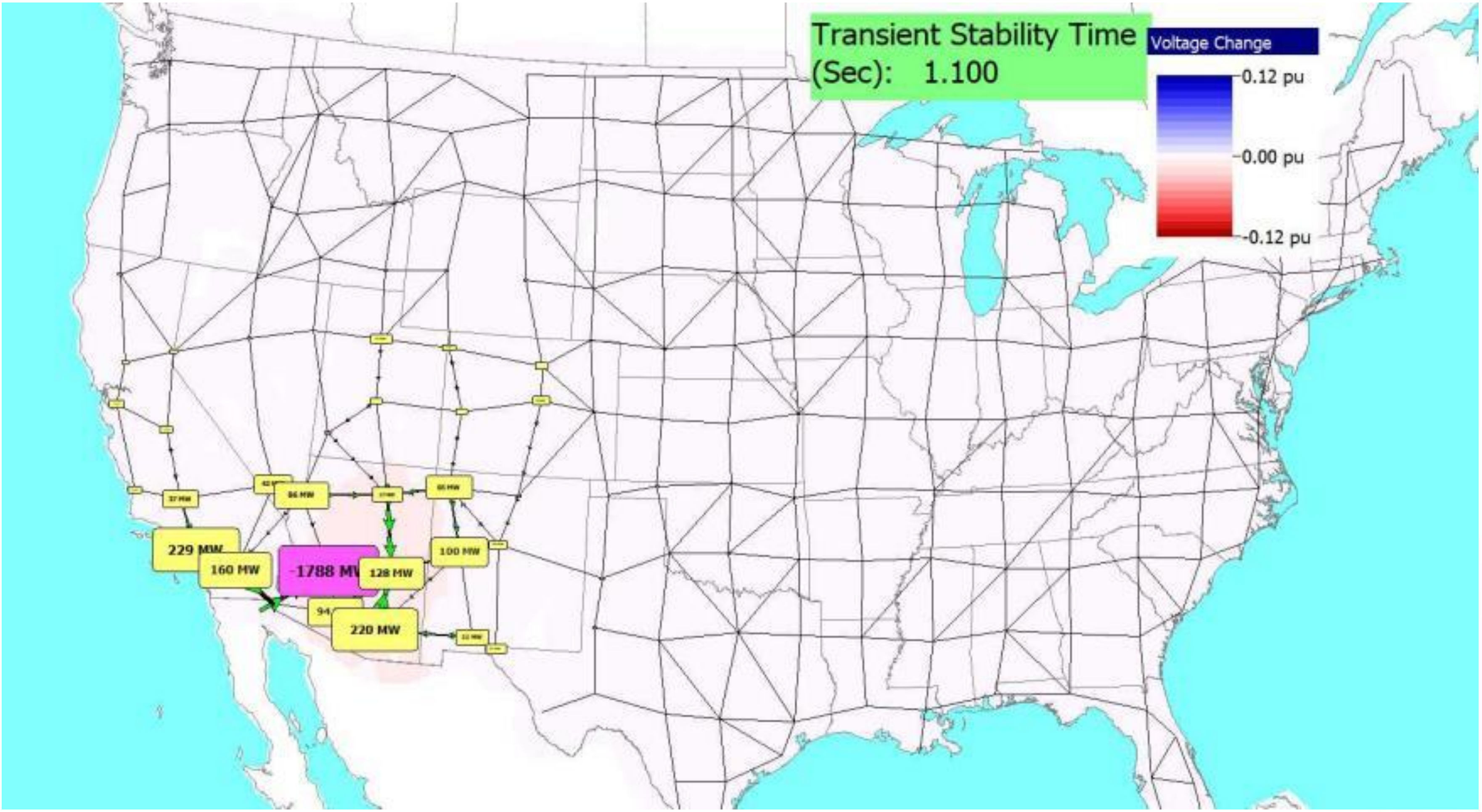
# Animation Example: 1.00 Seconds



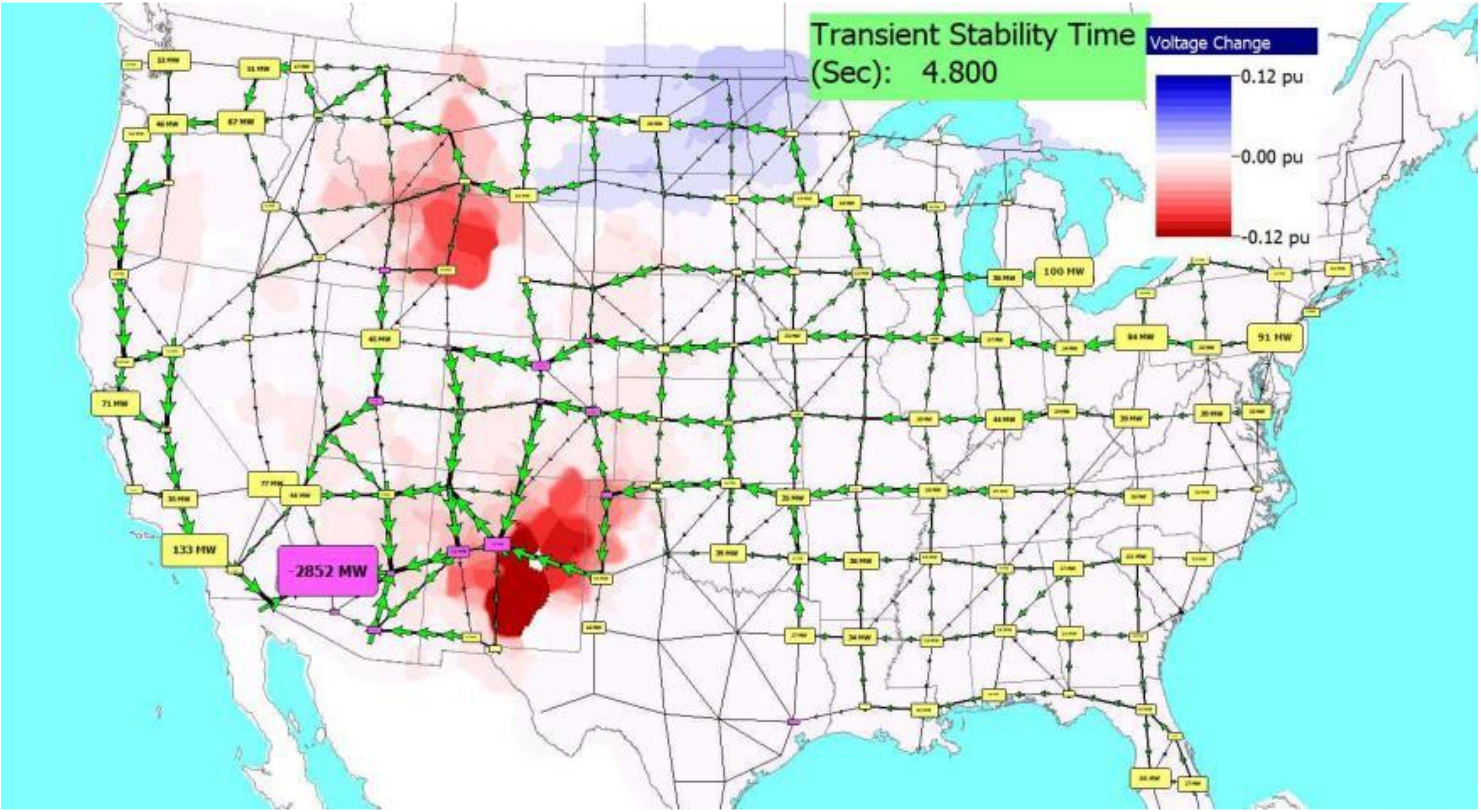
# Animation Example: 1.05 Seconds



# Animation Example: 1.10 Seconds

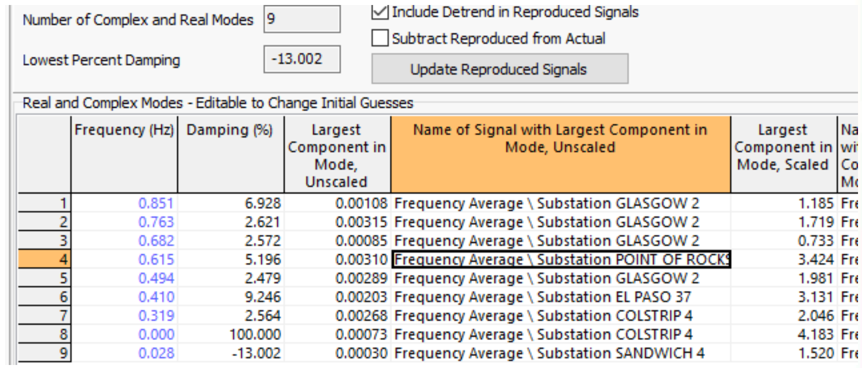


# Animation Example: 4.80 Seconds



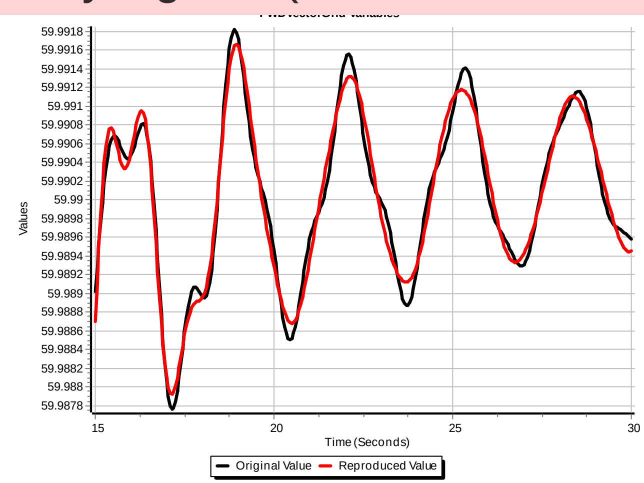
# Data Analysis Results Visualization: Example Modal Analysis

- Idea is to determine the frequency and damping of power system signals after an event
  - Reproduce a signal, such as bus frequency, using exponential functions
- The Iterative Matrix Pencil (IMP) provides a great way to quickly process and verify lots of signals

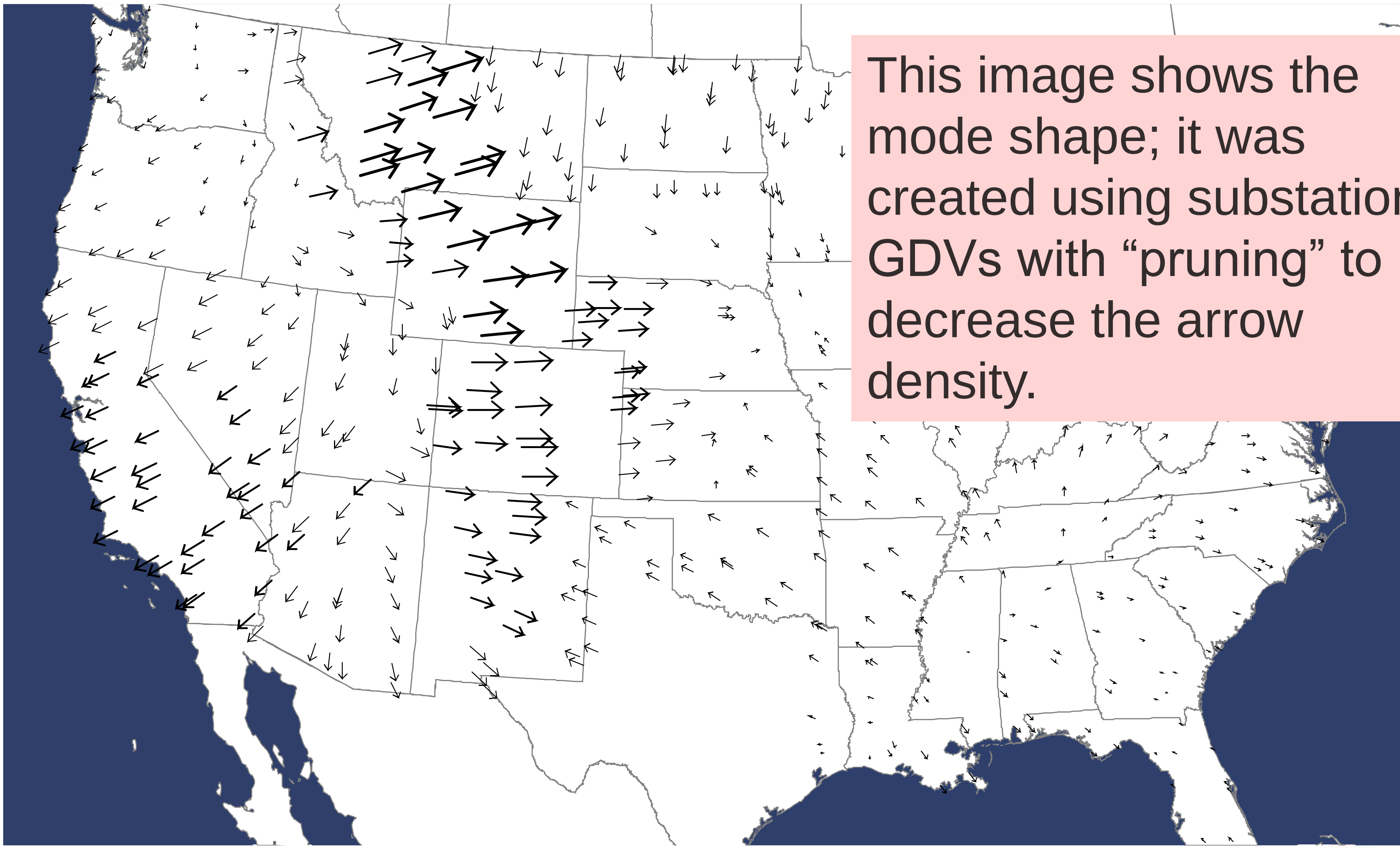



| | Frequency (Hz) | Damping (%) | Largest Component in Mode, Unscaled | Name of Signal with Largest Component in Mode, Unscaled | Largest Component in Mode, Scaled | Na wi Co Mo |
|---|---|---|---|---|---|---|
| 1 | 0.851 | 6.928 | 0.00108 | Frequency Average \ Substation GLASGOW 2 | 1.185 | Fre |
| 2 | 0.763 | 2.621 | 0.00315 | Frequency Average \ Substation GLASGOW 2 | 1.719 | Fre |
| 3 | 0.682 | 2.572 | 0.00085 | Frequency Average \ Substation GLASGOW 2 | 0.733 | Fre |
| 4 | 0.615 | 5.196 | 0.00310 | Frequency Average \ Substation POINT OF ROCKS | 3.424 | Fre |
| 5 | 0.494 | 2.479 | 0.00289 | Frequency Average \ Substation GLASGOW 2 | 1.981 | Fre |
| 6 | 0.410 | 9.246 | 0.00203 | Frequency Average \ Substation EL PASO 37 | 3.131 | Fre |
| 7 | 0.319 | 2.564 | 0.00268 | Frequency Average \ Substation COLSTRIP 4 | 2.046 | Fre |
| 8 | 0.000 | 100.000 | 0.00073 | Frequency Average \ Substation COLSTRIP 4 | 4.183 | Fre |
| 9 | 0.028 | -13.002 | 0.00030 | Frequency Average \ Substation SANDWICH 4 | 1.520 | Fre |

The worst match out of 40,000 substation frequency signals (15 to 30 seconds)



# Visualization of Lightly Damped 0.5 Hz Mode



This image shows the mode shape; it was created using substation GDVs with "pruning" to decrease the arrow density.

# Conclusions

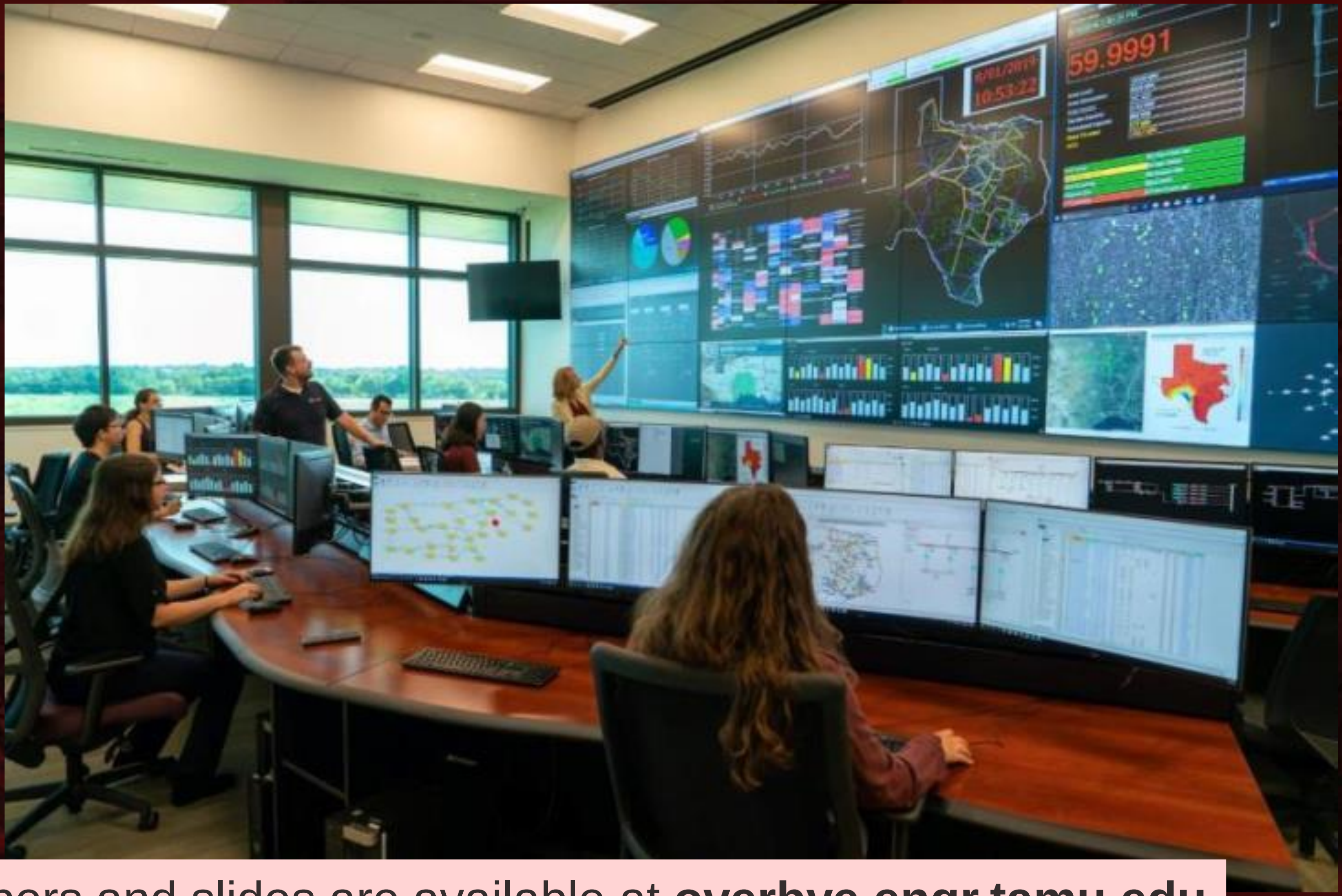
- We've reached the point in which there is too much data to handle most of it directly
  - Certainly the case with much time-varying data
- How data is transformed into actionable information is a crucial, yet often unemphasized, part of the software design process
- There is a need for continued research and development in this area
  - Synthetic power grid cases, including dynamics, are now emerging to provide input for this research

# Some Recent Papers…

- T.J. Overbye, J. Wert, K. Shetye, F. Safdarian, and A. Birchfield, “Delaunay Triangulation Based Wide-Area Visualization of Electric Transmission Grids,” Kansas Power and Energy Conference (KPEC), Apr. 2021.
- K.S. Shetye, T.J. Overbye, H. Li, J. Thekkemathiote, and H. Scribner, “Considerations for Interconnection of Large Power Grid Networks,” IEEE Power and Energy Conference at Illinois (PECI), Champaign, IL, April 2021.
- T.J. Overbye, K.S. Shetye, J.L. Wert, W. Trinh, and A. Birchfield, “Techniques for Maintaining Situational Awareness During Large-Scale Electric Grid Simulations,” IEEE Power and Energy Conference at Illinois (PECI), Champaign, IL, April 2021.
- 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, College Station, TX, Feb. 2021.
- T.J. Overbye, J. Wert, A.B. Birchfield, and J.D. Weber, “Wide-Area Electric Grid Visualization Using Pseudo-Geographic Mosaic Displays,” 2019 North American Power Symposium (NAPS), Wichita, KS
- A.B. Birchfield and T.J. Overbye, “Mosaic Packing to Visualize Large-Scale Electric Grid Data,” accepted in *IEEE Open Access Journal of Power and Energy*, Jun. 2020
- A.B. Birchfield, Z. Mao, J. Weber, M. Davis, and T.J. Overbye, “An Interactive, Stand-Alone and Multi-User Power System Simulator for the PMU Time Frame,” in IEEE Texas Power and Energy Conference (TPEC) 2019
- A.B. Birchfield, T.J. Overbye, and K. R. Davis, “Educational Applications of Large Synthetic Power Grids”,” *IEEE Transaction on Power Systems*, vol. 34(1), pp. 765-772, Jan. 2019

All are available at **overbye.engr.tamu.edu/publications**

# Thank You!
# Questions?




Papers and slides are available at **overbye.engr.tamu.edu**