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

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Acknowledgments

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- Slides also include contributions from many of my students, postdocs, staff and colleagues at both TAMU and UIUC

- The views presented here are my own
- This presentation is available at overbye.engr.tamu.edu/presentations/

Greetings from the Texas A&M Energy and Power Group (EPG)

This is from the Fall 2022 EPG dinner held at Dr. Kate Davis's house on Oct 1, 2022

A Bright Electric Future

- Our electric energy future could be quite bright!
- Electric grids worldwide are in a time of rapid transition, with many positive developments including the addition of large amounts of renewable generation, transportation electrification, smart grid controls, etc.
  - The grid of the future is likely to be quite different from the one of the recent past
- There are lots of good engineering challenges and it is a great time for students entering the field!!

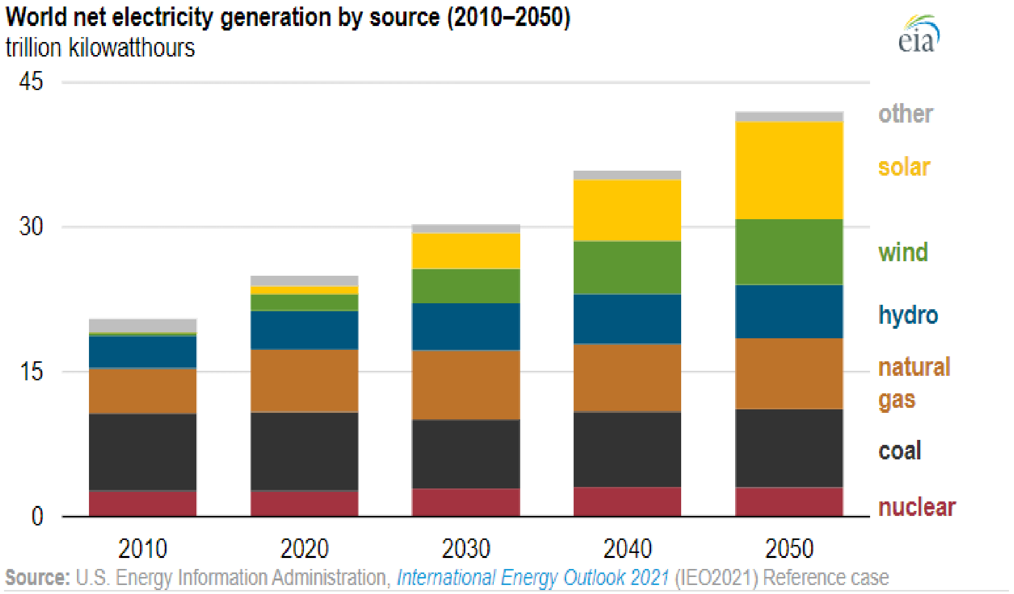


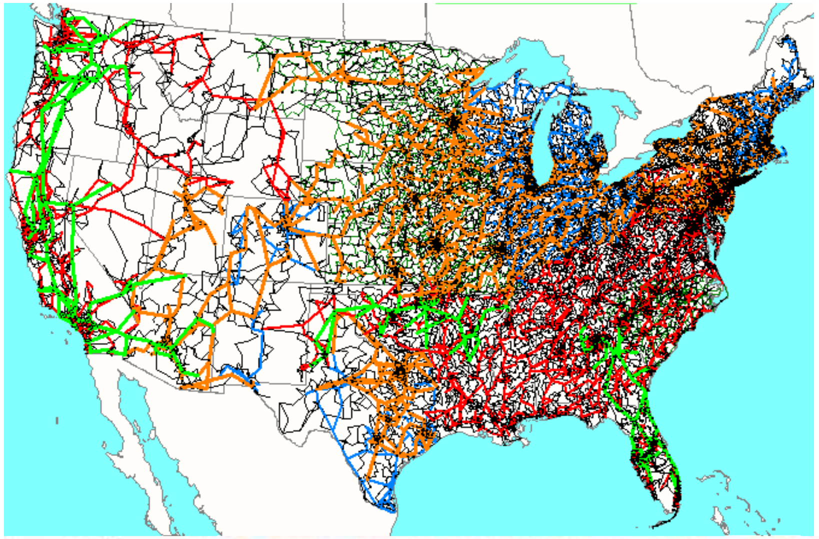
Image source: US EIA International Energy Outlook, 2021

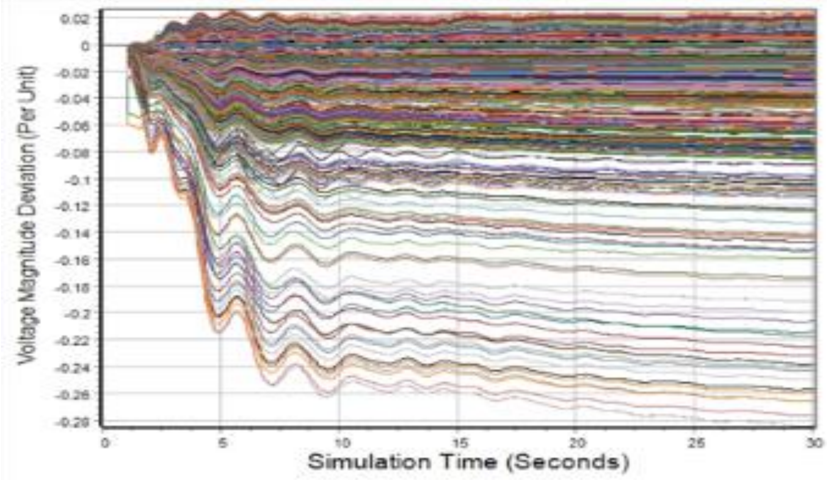
Overview

- However, there are lots of concerns with this transition, particularly in dealing with electric grid resilience and increasingly electric grid complexity
- Meeting these opportunities and challenges requires better techniques for understanding the operation of electric grids (past, present, and especially for the future).
- We also need to effectively convey the story of our rapidly changing smart grid to a wide variety audiences including policymakers
- This presentation focuses on how better electric grid operations visualizations and storytelling can help us achieve this desired future
- This is a great opportunity for smart grid innovation!

Electric Grids Create Lots of Data

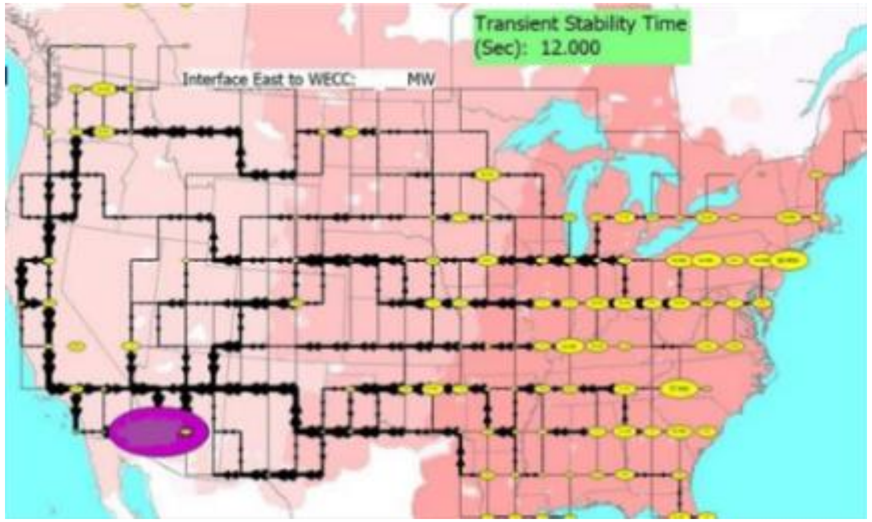
- Power system operations and planning are a rich source of data
  - SCADA has traditionally provided a grid data at scan rates of several seconds
  - Thousands of PMUs are now deployed providing data at 30 times per second
  - In planning many thousand of studies are now routinely run, with a single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





An Example: East-West Dynamics Study

- One project in 2020 looked at the dynamic aspects of an ac interconnection of the Eastern Interconnect and the WECC (with a follow up project now starting)
  - We did lots of dynamic simulations some going out for minutes
  - The Model has 110,000 buses, 244 different types of dynamic models, 48,000 model instances



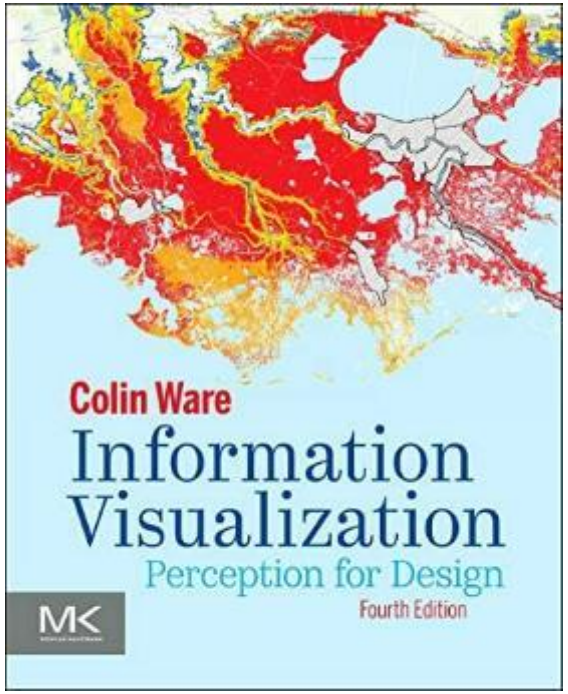
- No major showstoppers with this interconnection
- A human factors challenge was to know what happened in a simulation, and then to explain the results to a variety of different audiences

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)

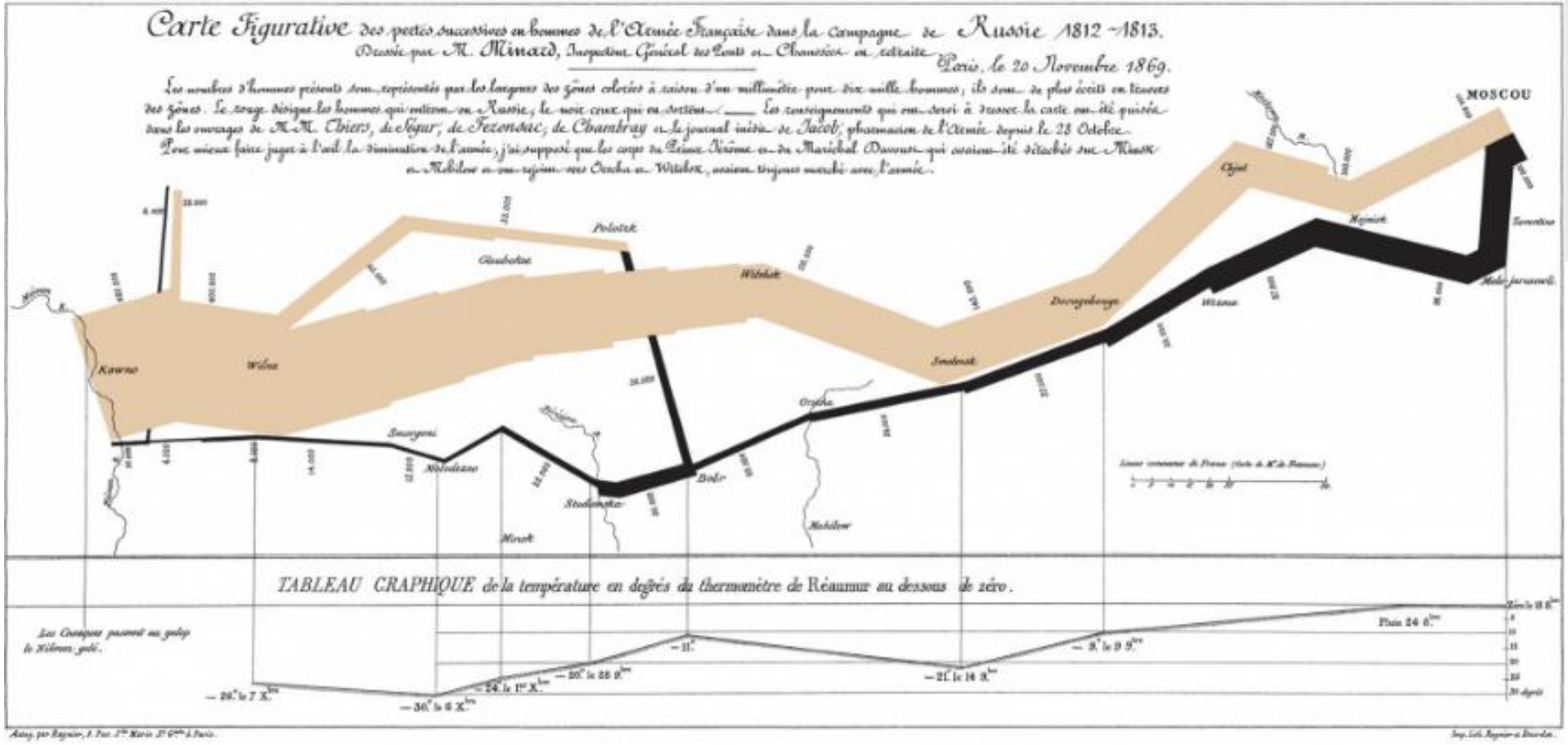
Some Useful General References

- 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



Books by Edward Tufte are a Good Source for Historical Images for Data Visualization

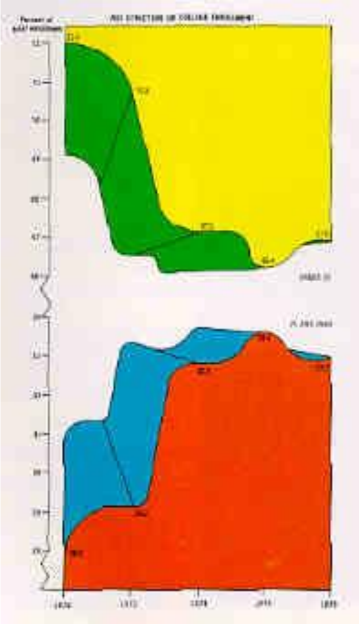
Illustration by Charles Minard from 1869 on Napoleon’s march to, and retreat from Moscow in 1812; Called the “Best Statistical Graphic Ever Drawn”

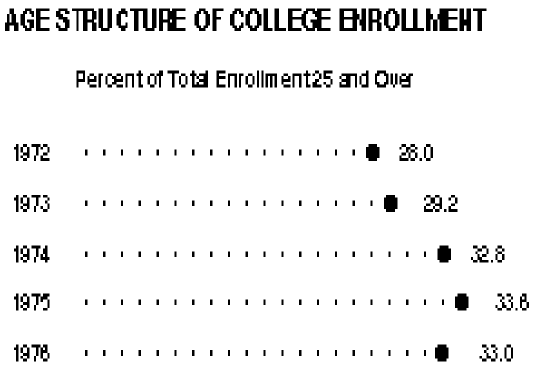


422,000 troops enter Russia in June 1812; 10,000 are left in Dec. 1812

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: A Great Way to Get Your Messaged Noticed and/or to Convey Information Quickly

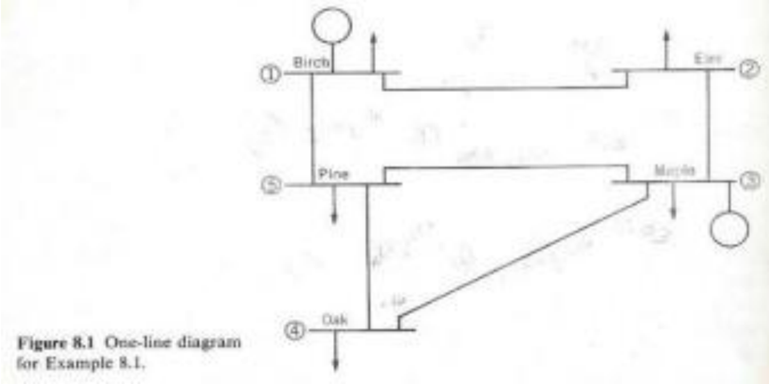
Salt River Project Skills Training Facility, Tempe, AZ

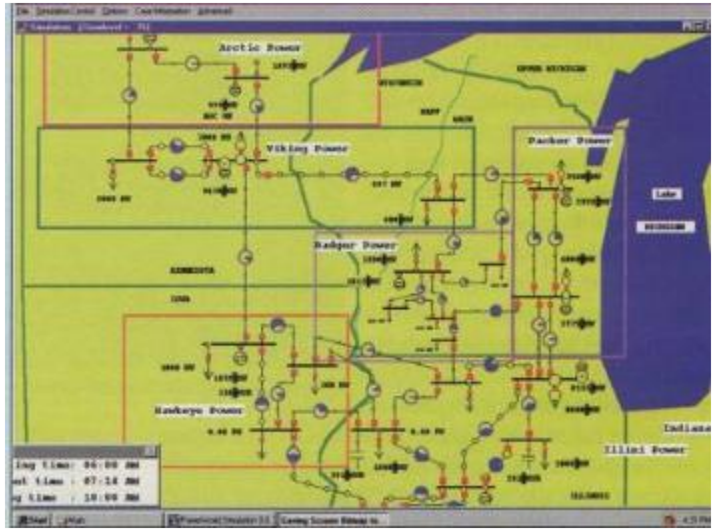
Four-minute US Civil War animation, Abraham Lincoln Museum (Springfield IL)

Source right images: www.lincolnlibraryandmuseum.com/m5.htm

Aside: Real versus Synthetic Grids

- When available I prefer to work with real (actual) grid models and data
- However access to actual power grid models is often restricted (CEII), and this can be a particular concern with storytelling where the focus is on clearly showing aspects of grid strengths and weaknesses
  - Models and data 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 eight years in this area; “realistic but not real”

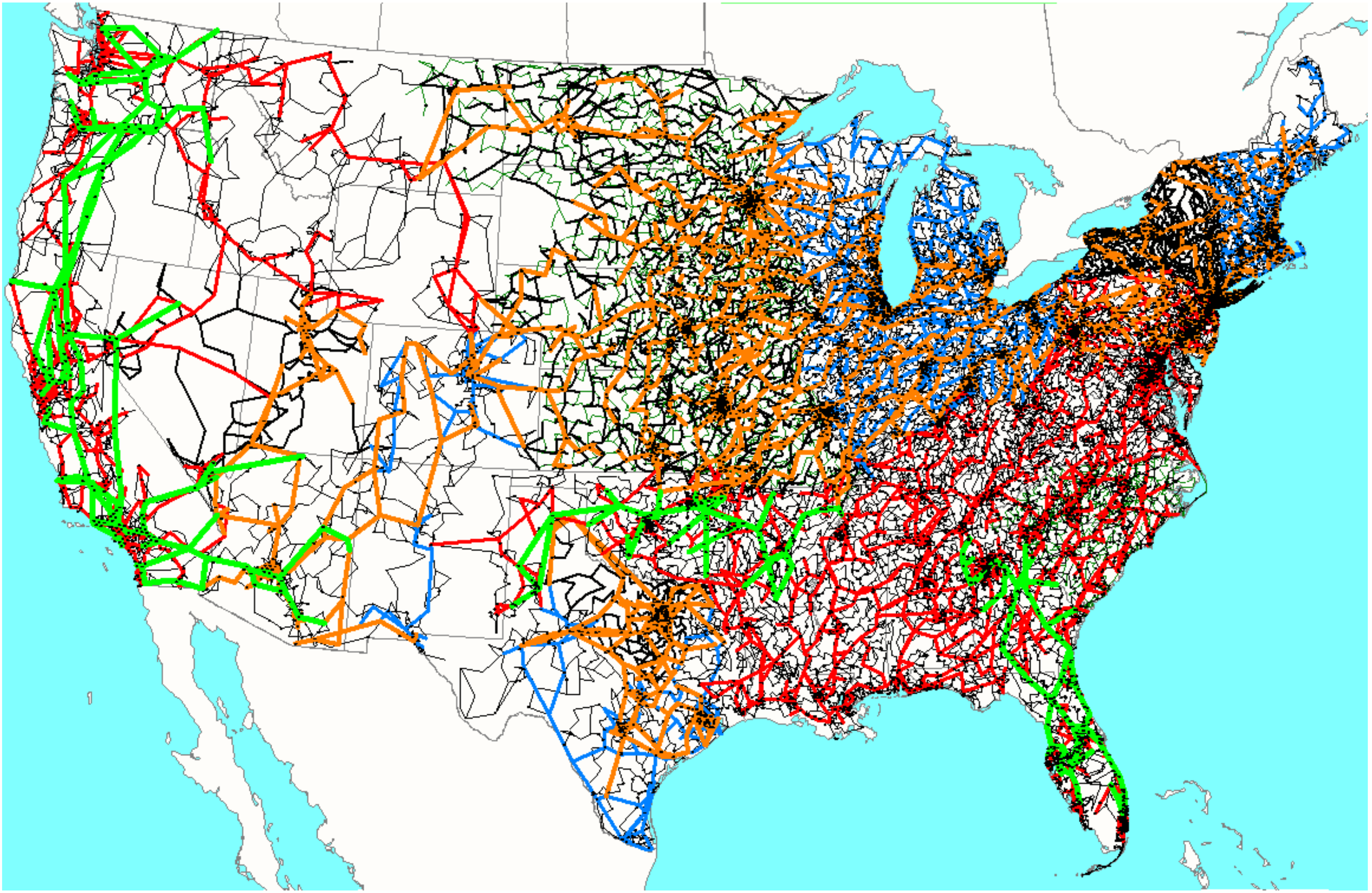




Large-Scale Synthetic Grid Models and Results are Now Available

- There are now synthetic grid models that go up to an 82,000-bus one grid modeling the contiguous US (CONUS)
  - Our synthetic grids have embedded geographic coordinates; the TAMU ones are available at **electricgrids.engr.tamu.edu**
- The widespread availability of these grids is greatly helping research!
- There are lots of challenges with synthetic grids with one being that they have no significant operational history and people really don't have an intuitive feel for their operation

82,000 Bus Synthetic Grid

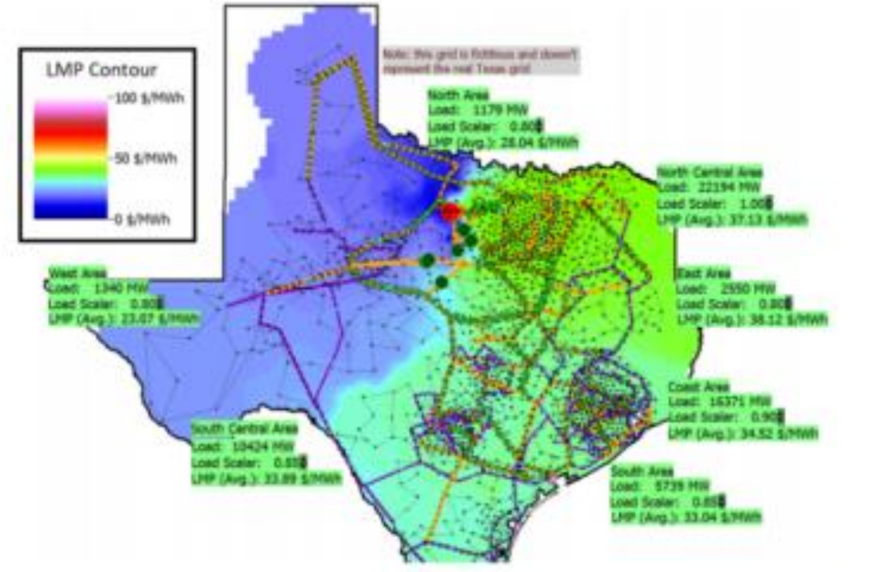


The different colors indicate different nominal kV voltages, with green 765, orange 500, red 345, blue 230, black lower.

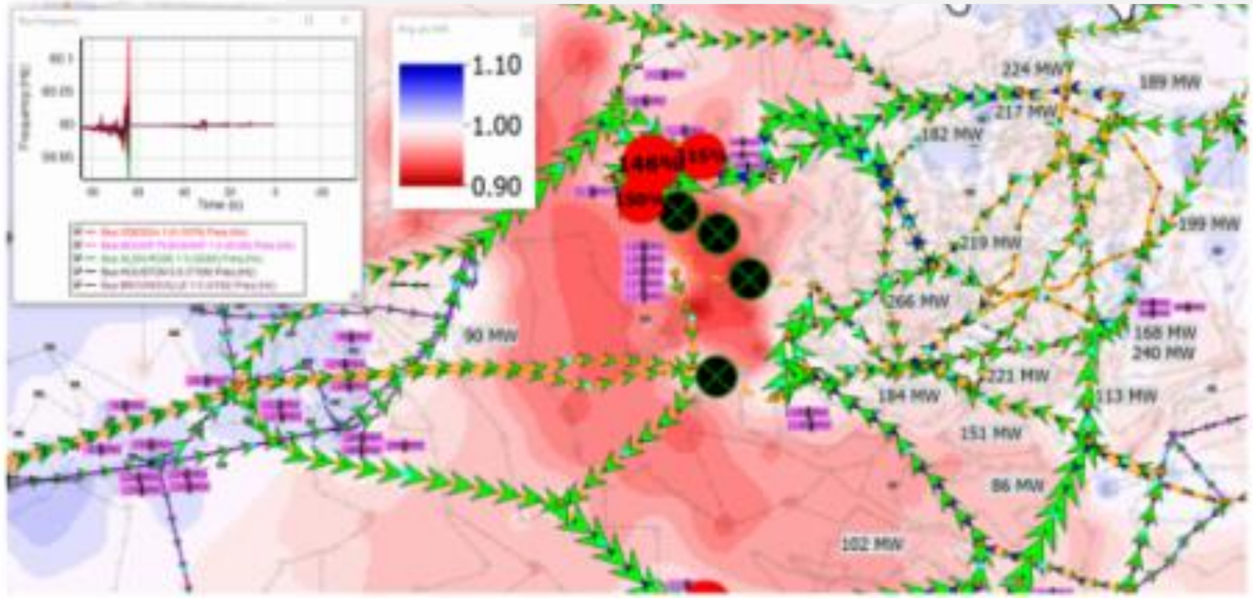
2000 Bus Texas Synthetic Grid

- 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

This grid is widely used, and we use it in the TAMU power classes



6. Diagram display for optimal power flow lab on the fictitious synthetic 2000-bus system. Green fields provide controls for the load scalar in seven of th... areas, and report the average LMP for these areas. The background contour [45] shows that the locational marginal prices.



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

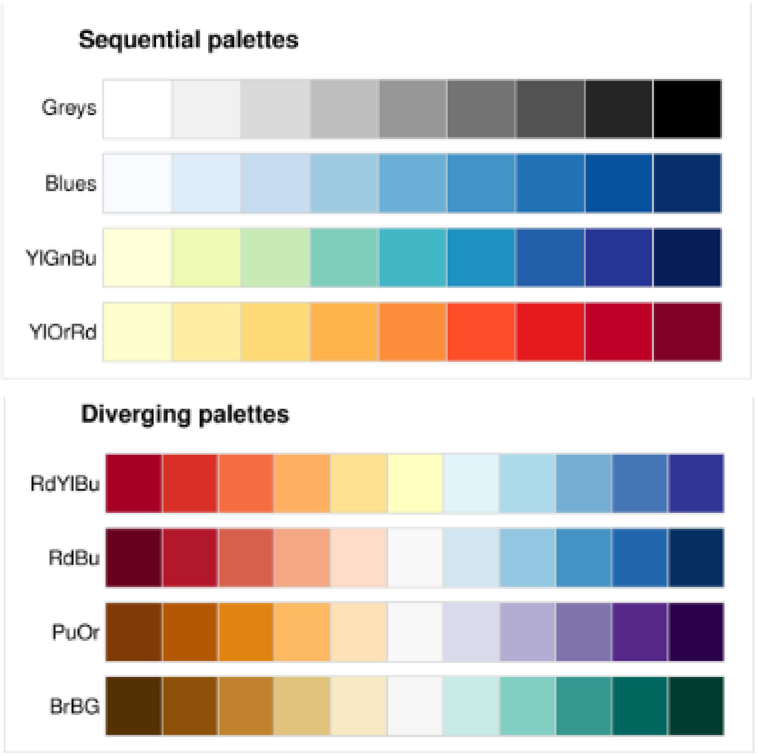
- In many contexts, tabular displays (particularly with interactive features such as sorting, filtering, drill-down, and the ability to enter data) can be a great way to show data

	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
30	1030	Far West	ALPINE 0	115.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			0.00	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
  - 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



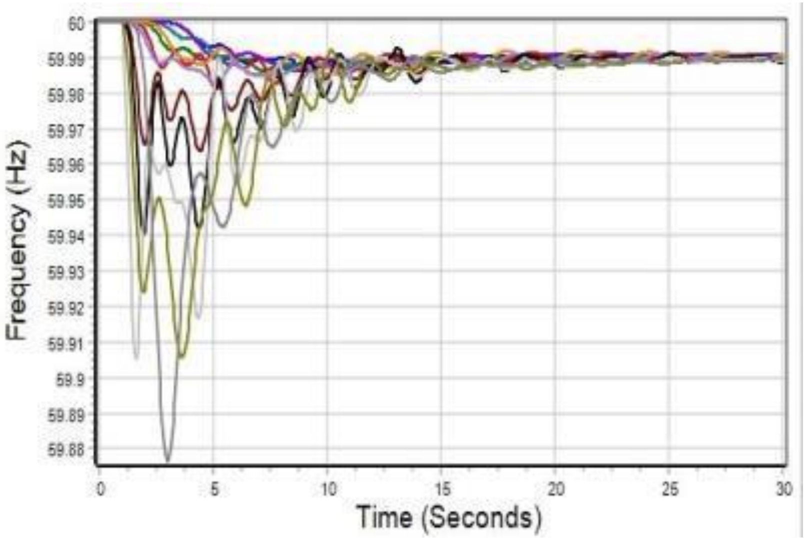
Some diverging palettes from Color Brewer

Images from betterfigures.org/2015/06/23/picking-a-colour-scale-for-scientific-graphics/

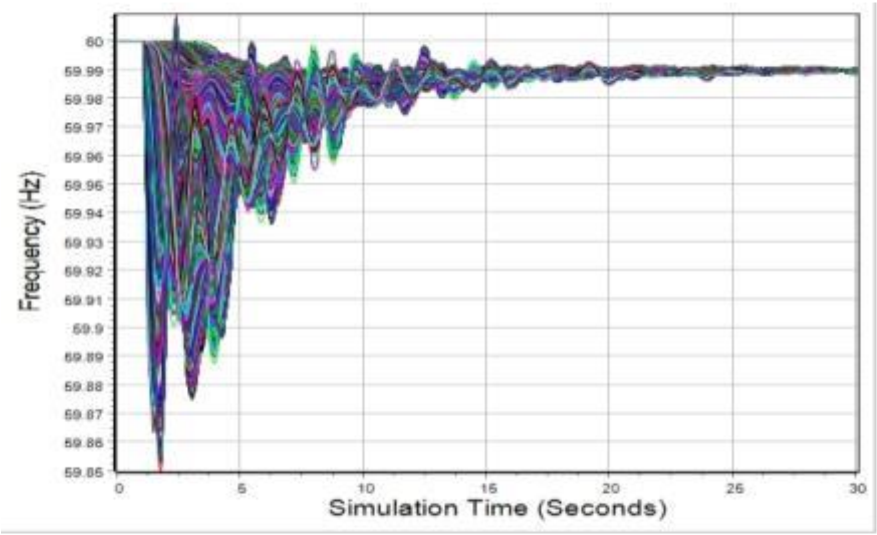
Graphs

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

When showing many curves important features might get covered

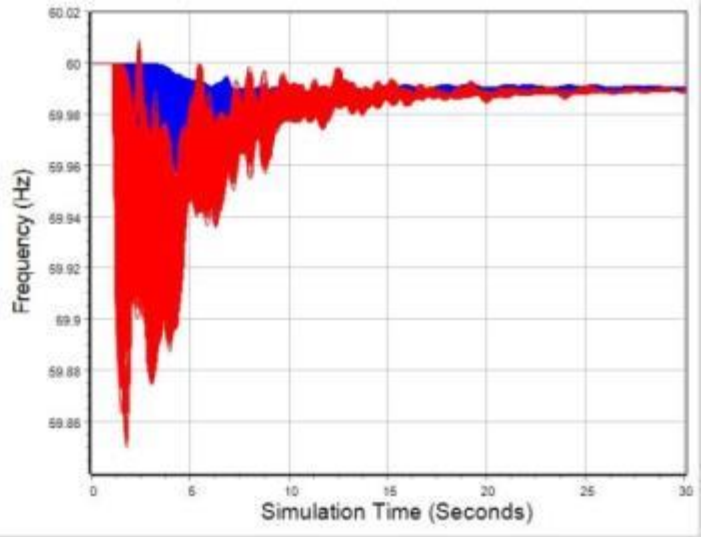


A few curves, detail of each visible, key can identify objects (several thousand values)



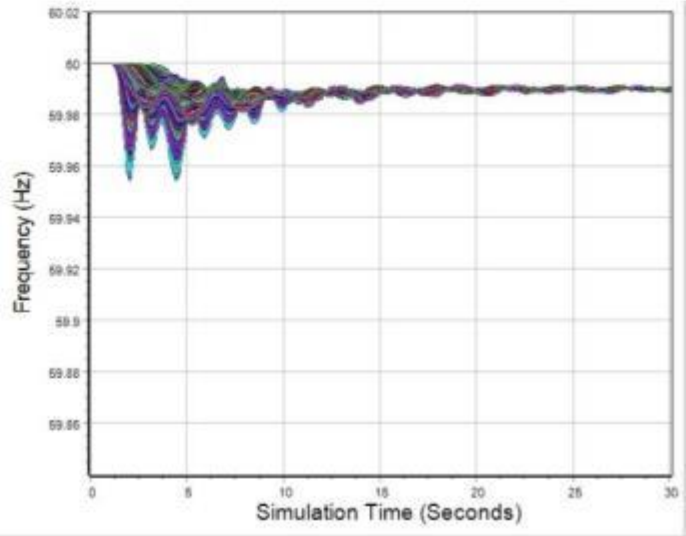
Envelope of response for the 80k bus, 40,000 substation frequencies (24 million values)

Graphs: 40,000 Substation Examples

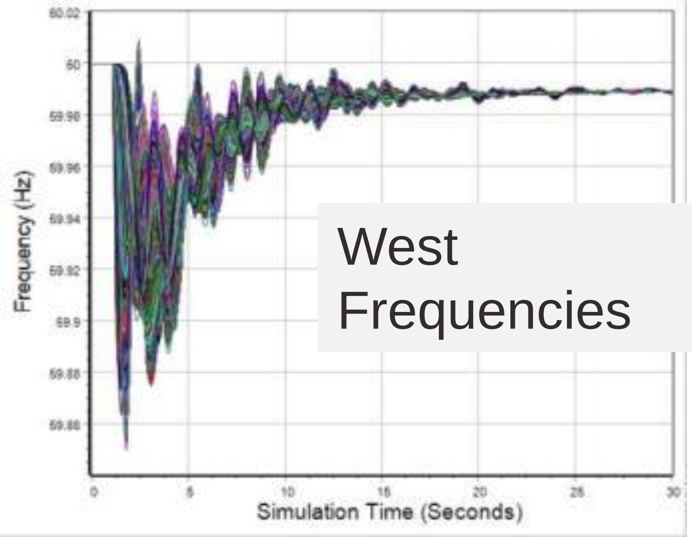


Blue: East
Red: West

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)



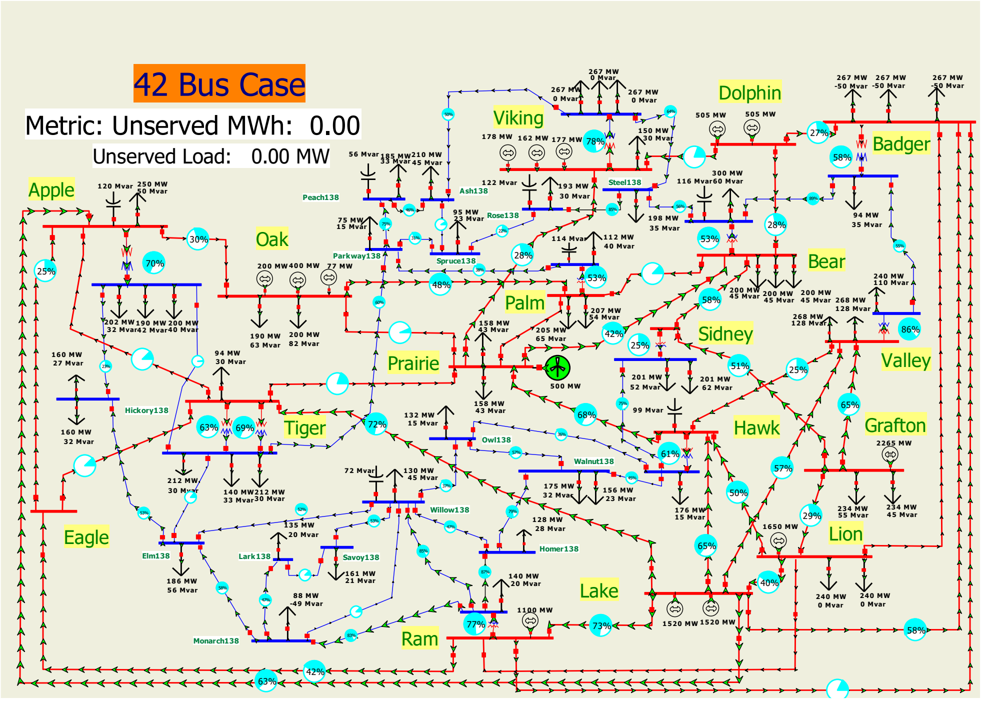
East Frequencies

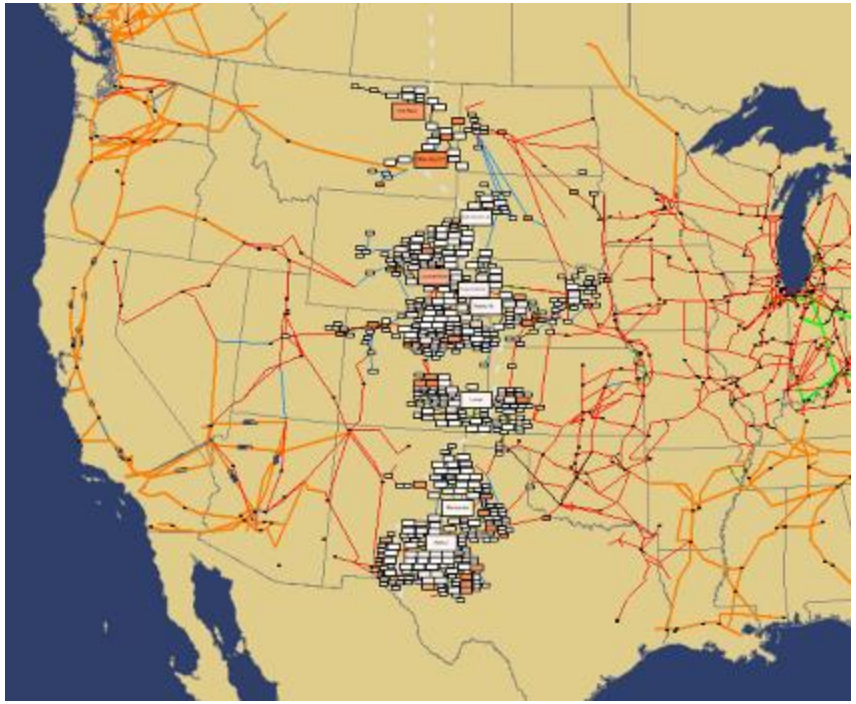


West Frequencies

Onelines

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





New Yorker Image source: en.wikipedia.org/wiki/View_of_the_World_from_9th_Avenue

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

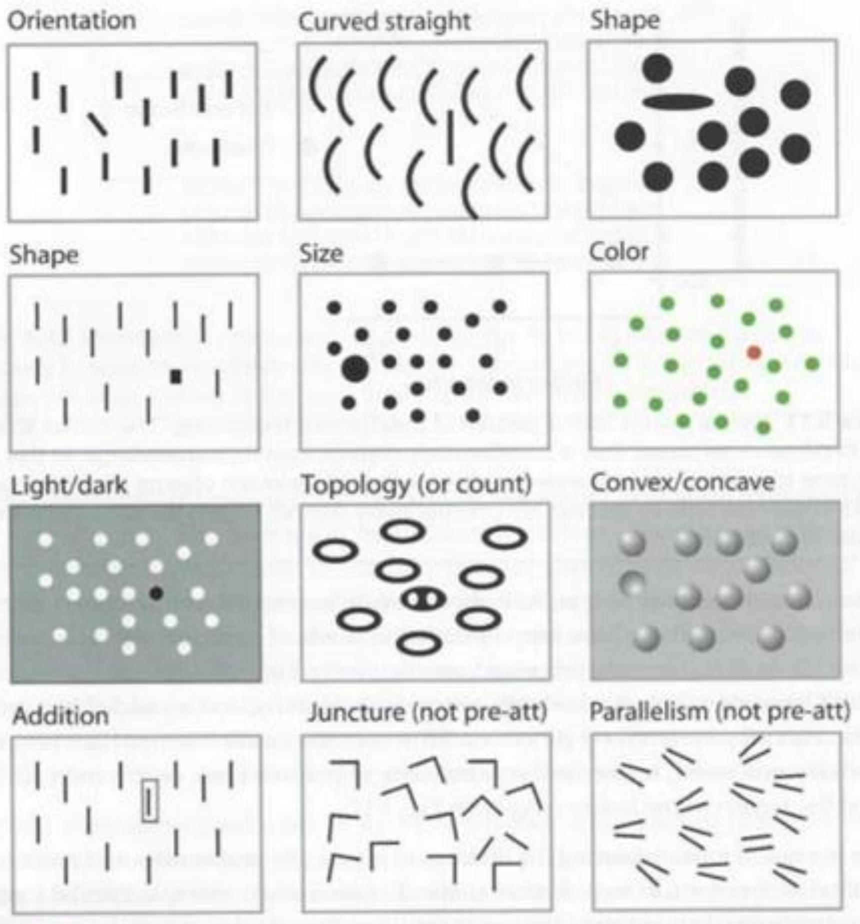
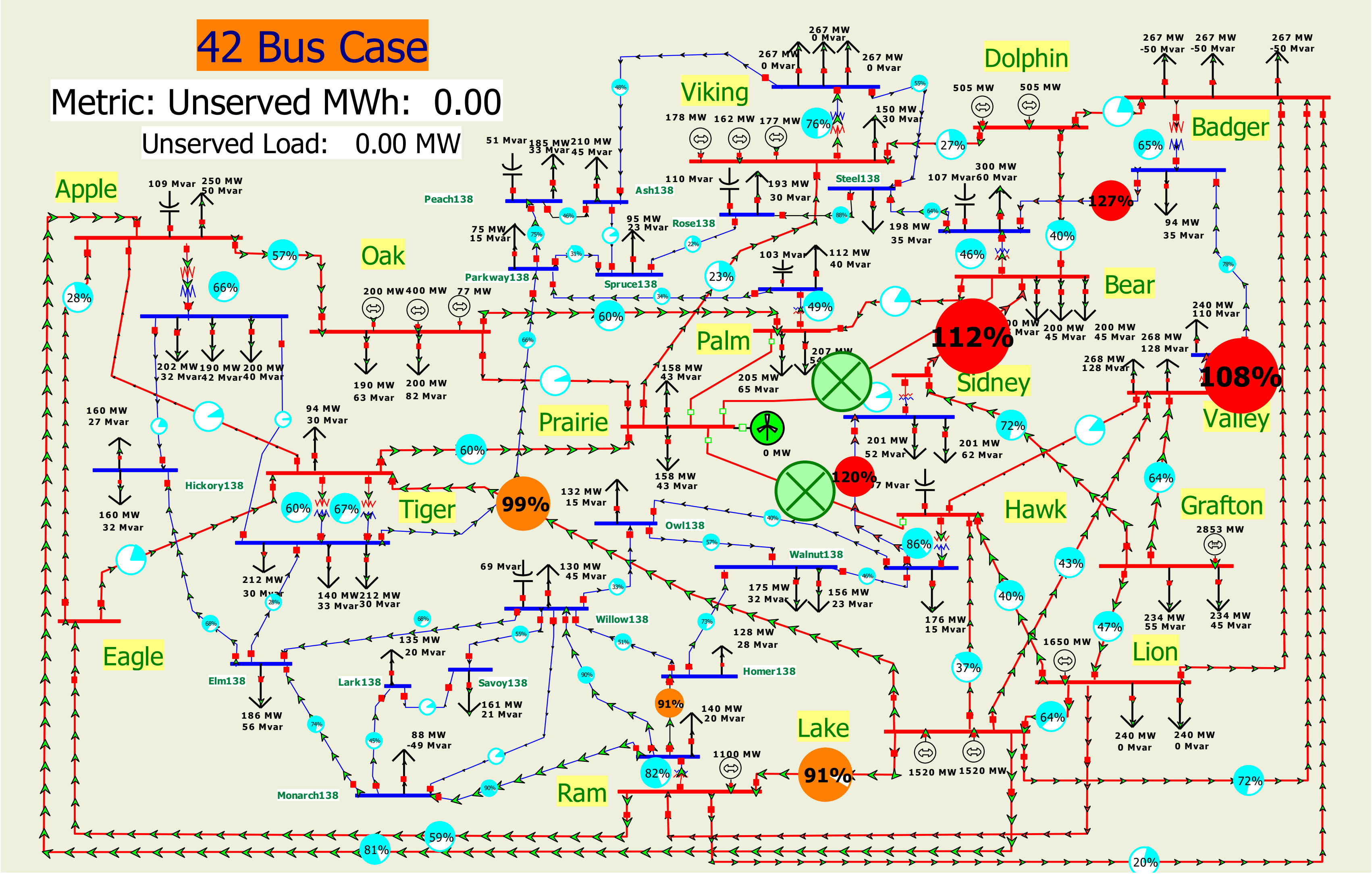


Figure 5.12 Most of the preattentive examples given here can be accounted for by the processing characteristics of neurons in the primary visual cortex.

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

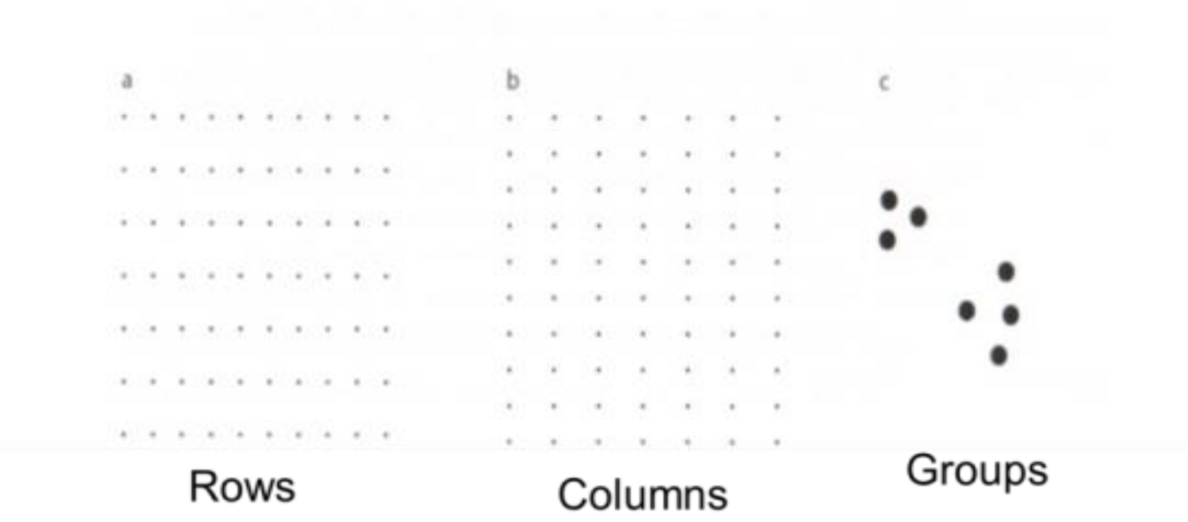
Preattentive Processing with Color & Size

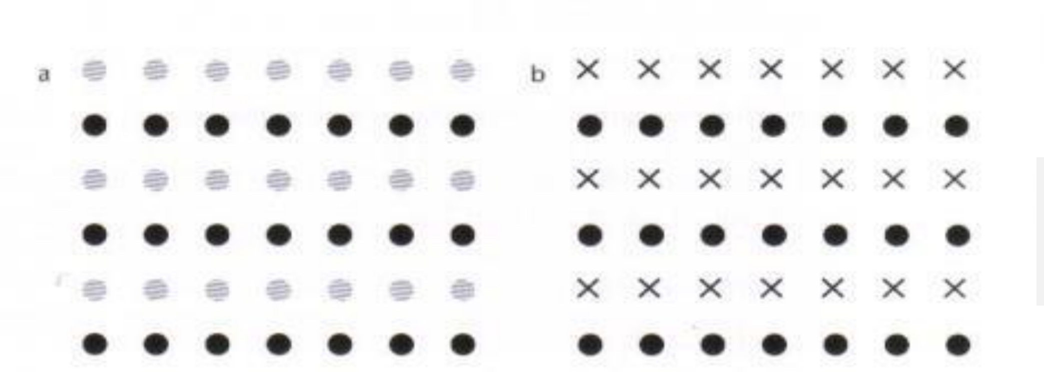


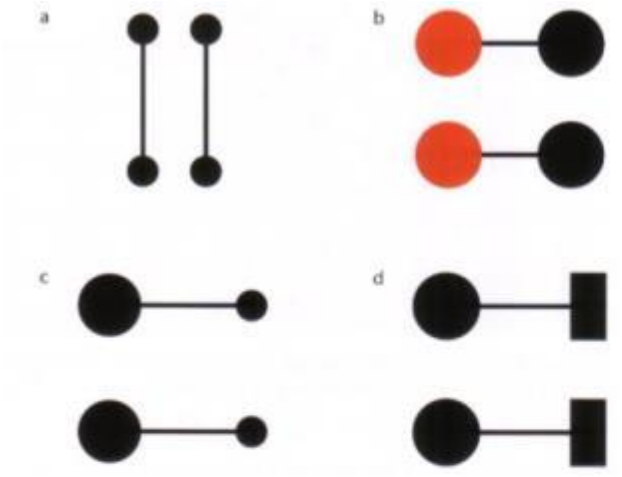
Detecting Patterns

- 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,







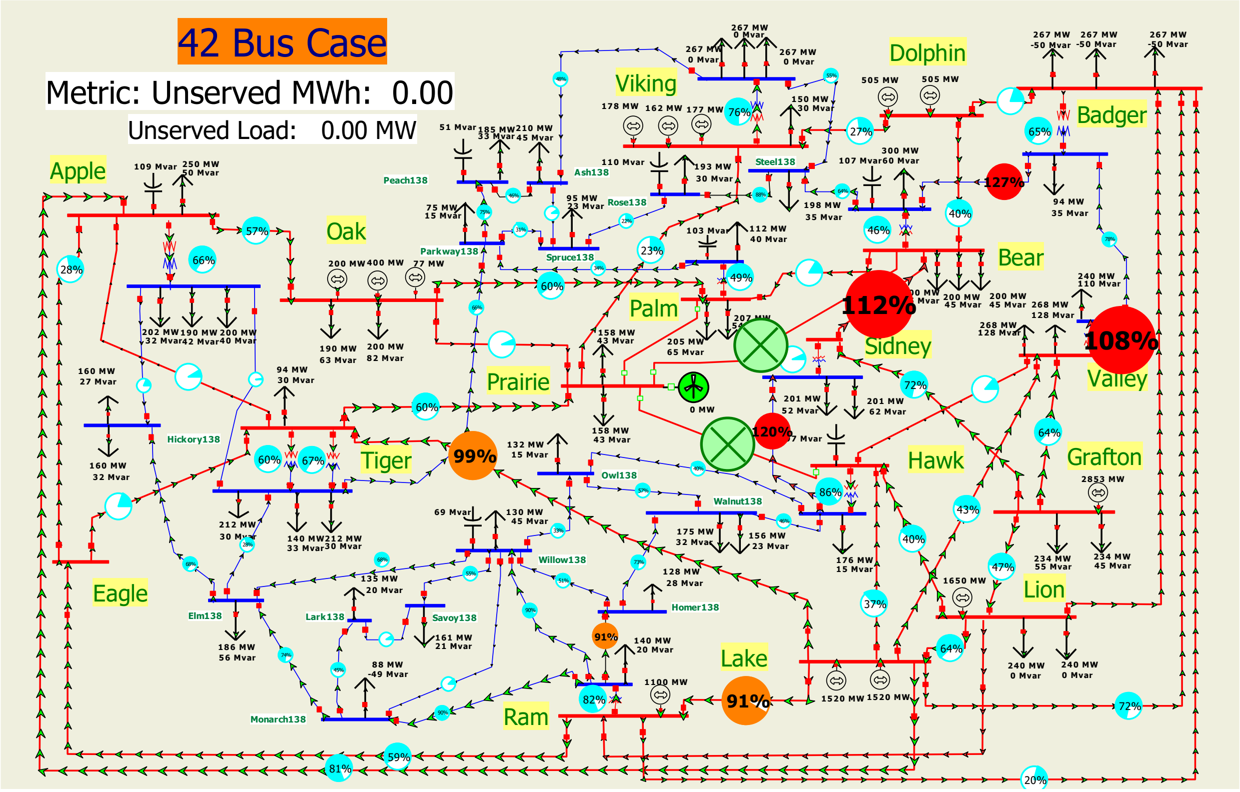
Connectedness is stronger than proximity, color, shape

Similarity makes all perceived as rows

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

Common Fate: Patterns in Motion

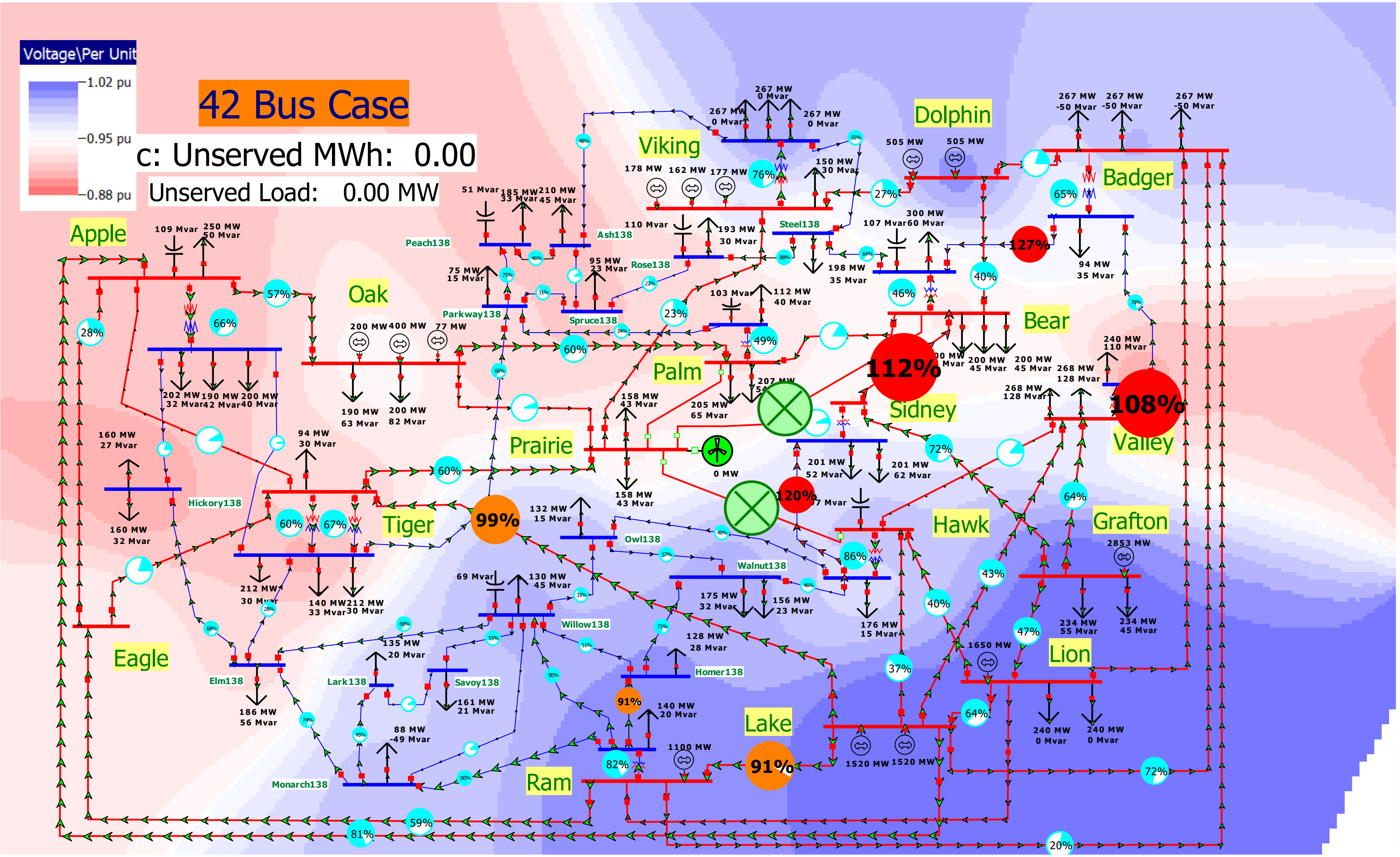
- Motion can be a very effective means for showing relationships between data
- People perceive motion with great sensitivity
- Motion can also be used to convey causality (one event causing another)
- However, too much motion can be a distractor



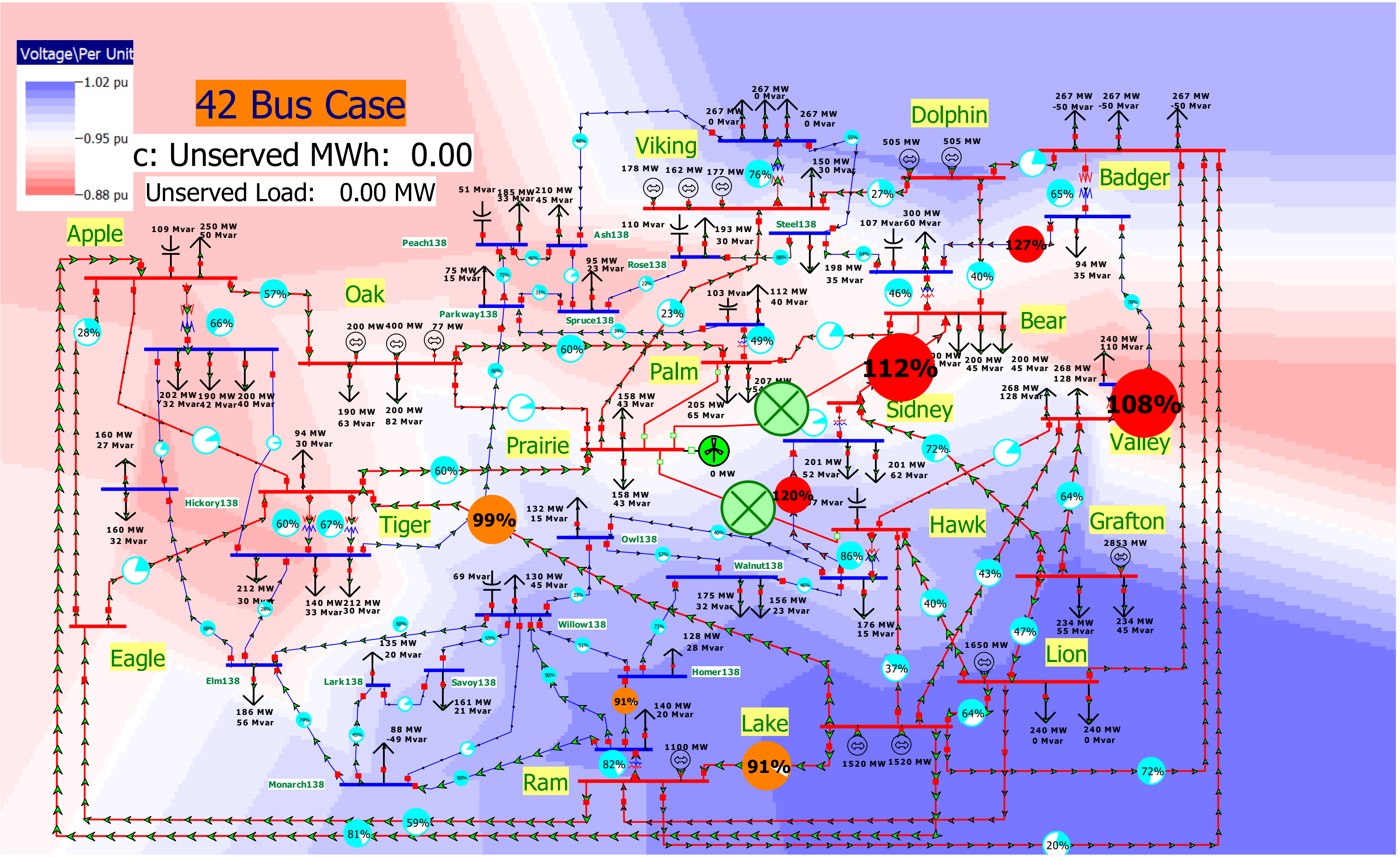
Scattered Data Interpolation (Colored Contouring)

- 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

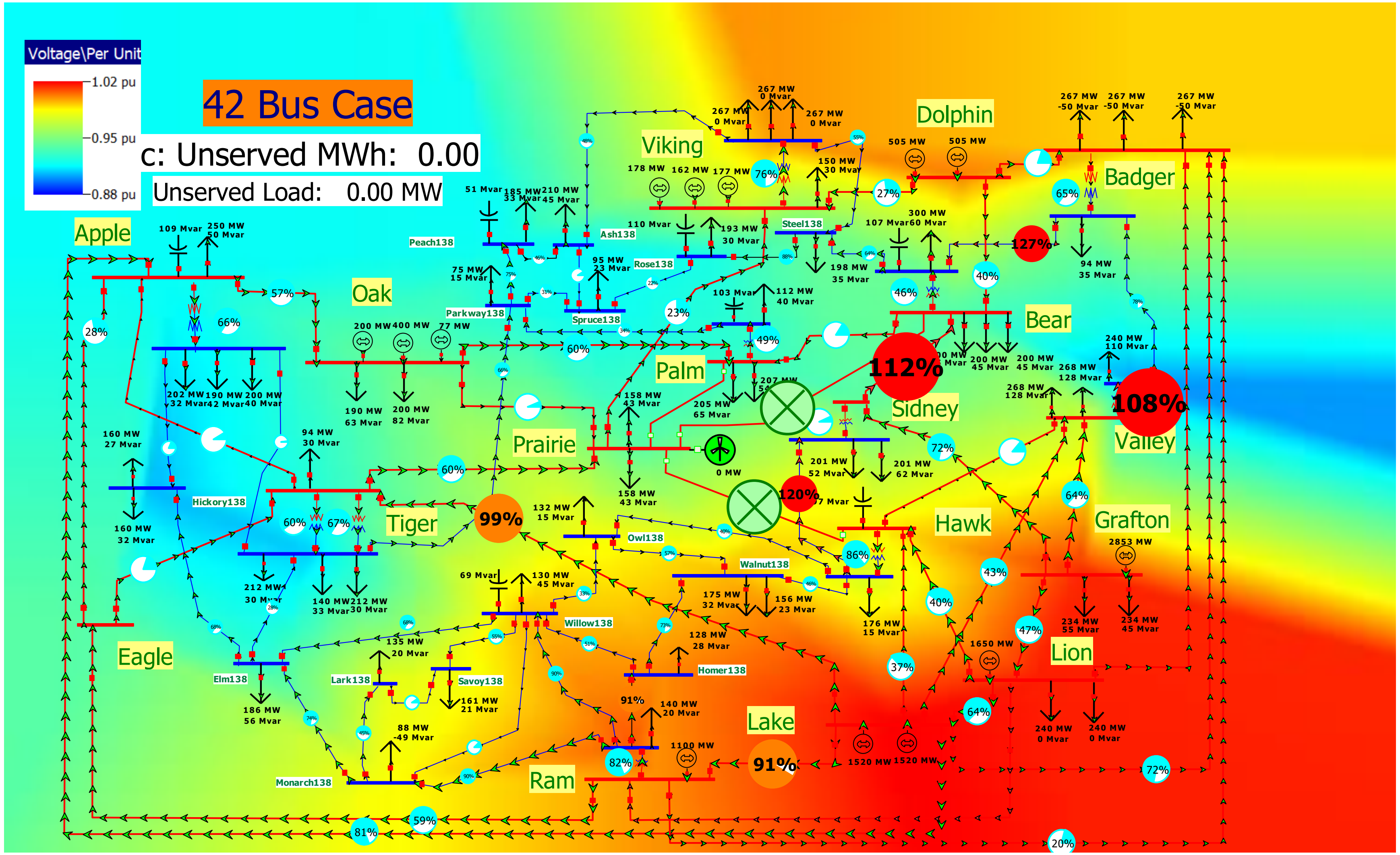
Shepard's Algorithm, Blue/Red Discrete Color mapping



Delaunay Algorithm, Blue/Red Discrete Color mapping

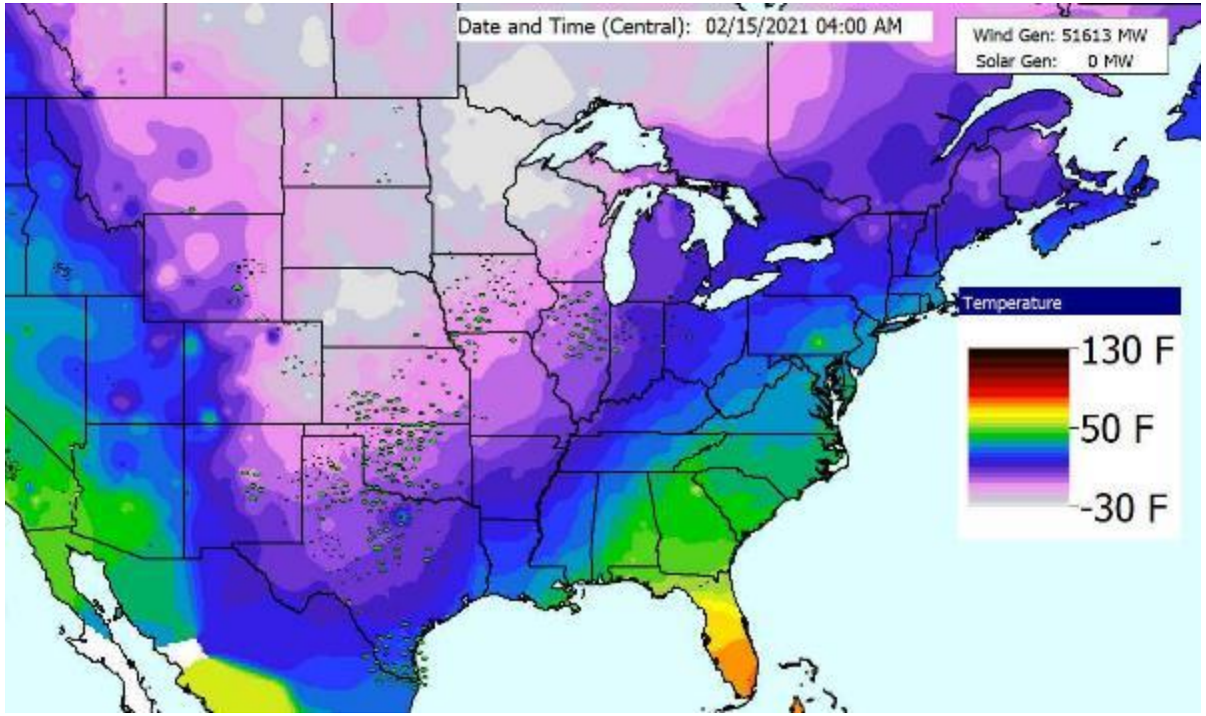


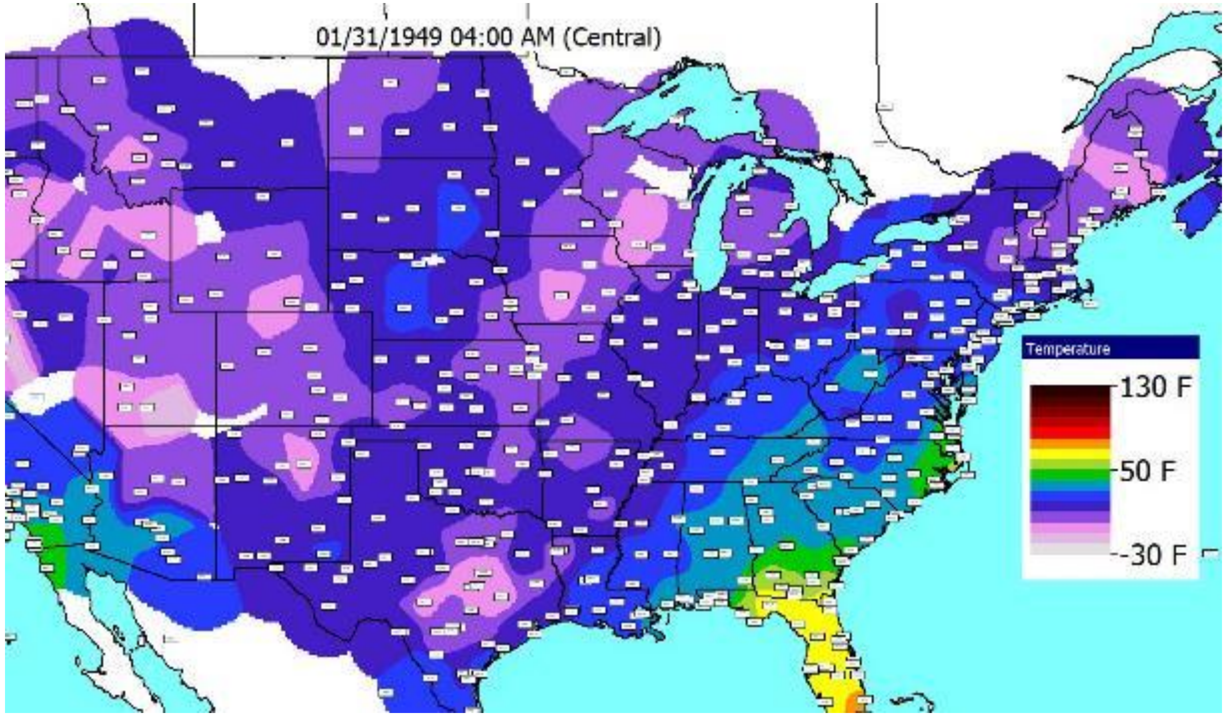
Delaunay Algorithm, Spectrum Continuous Color mapping



The color in this contour is too intense!

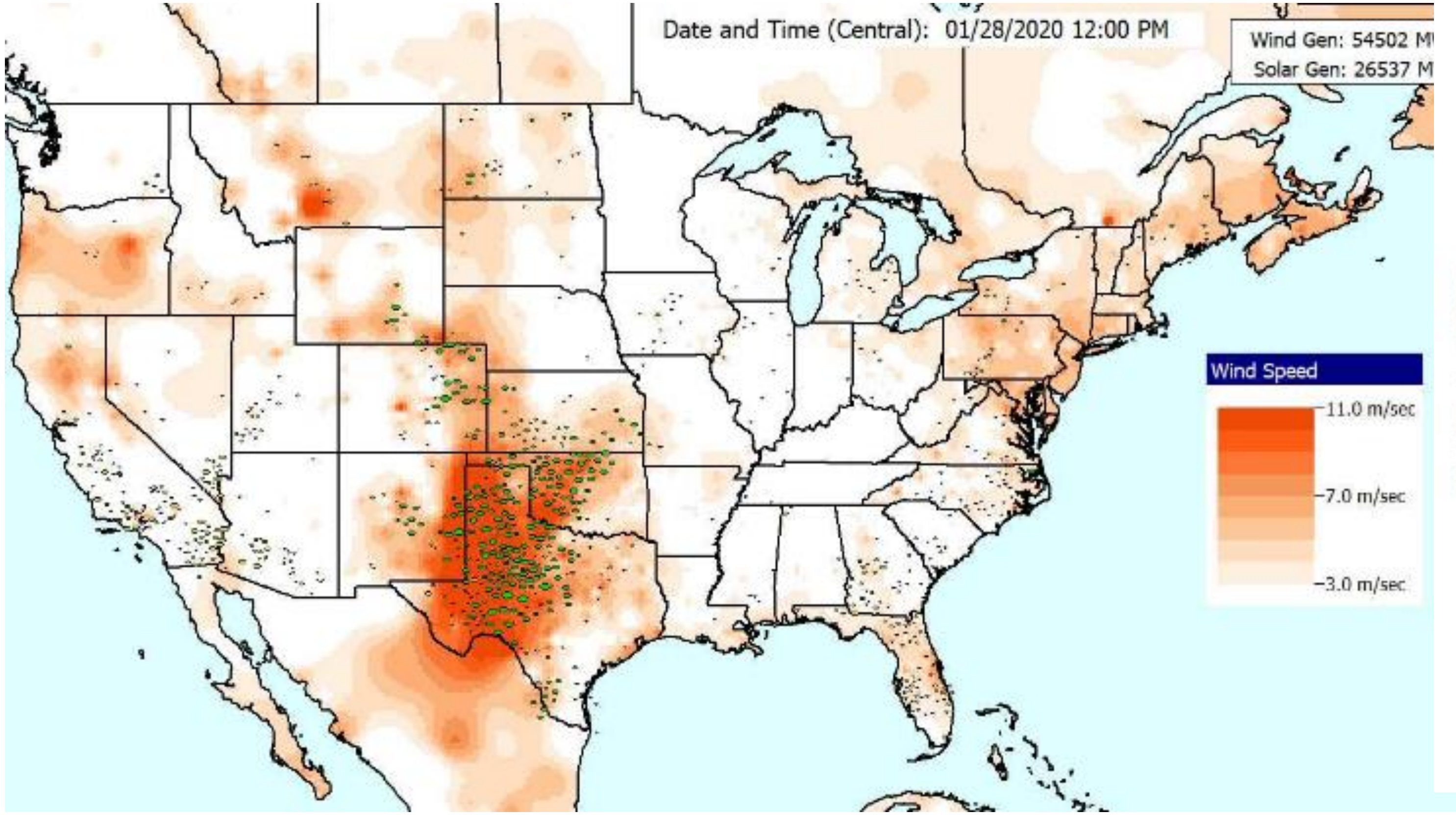
Contour Visualizations of Winter Storm Uri and 1949

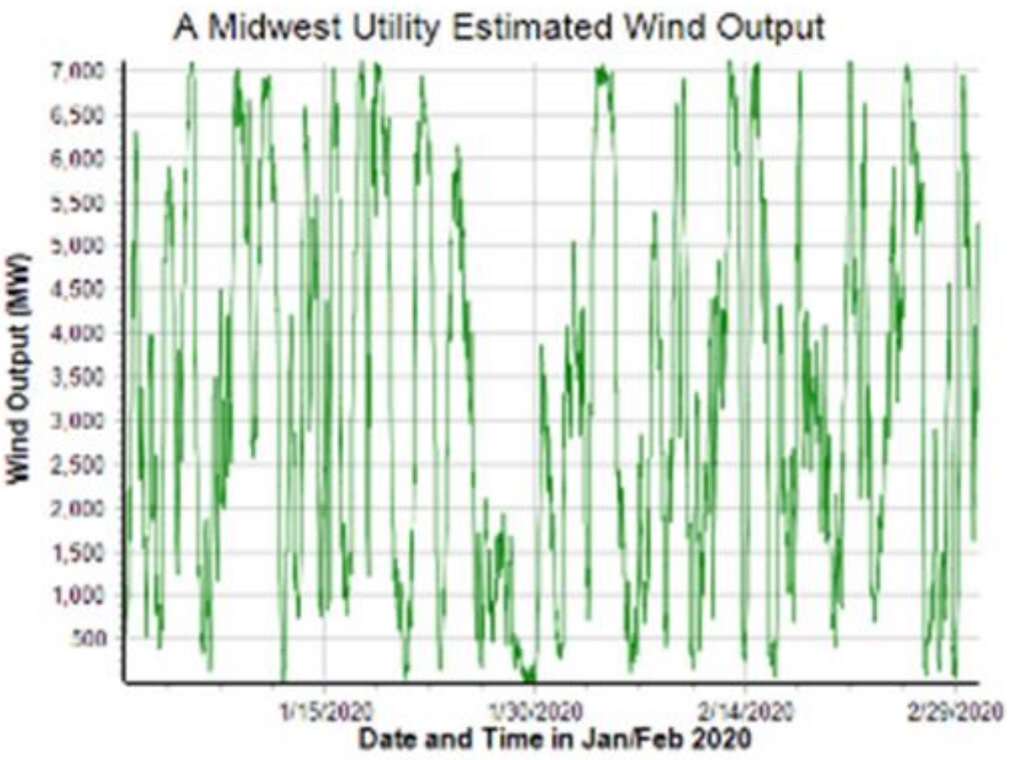




A paper describing the use of weather in the power flow is T. J. Overbye, F. Safdarian, W. Trinh, Z. Mao, J. Snodgrass, J. Yeo, "*An Approach for the Direct Inclusion of Weather Information in the Power Flow*,," Proc. 56th Hawaii International Conference on System Sciences (HICSS), January 2023; it is available at overbye.engr.tamu.edu/publications as the first one in 2023.

Midwest January 2020 Wind Drought Visualization





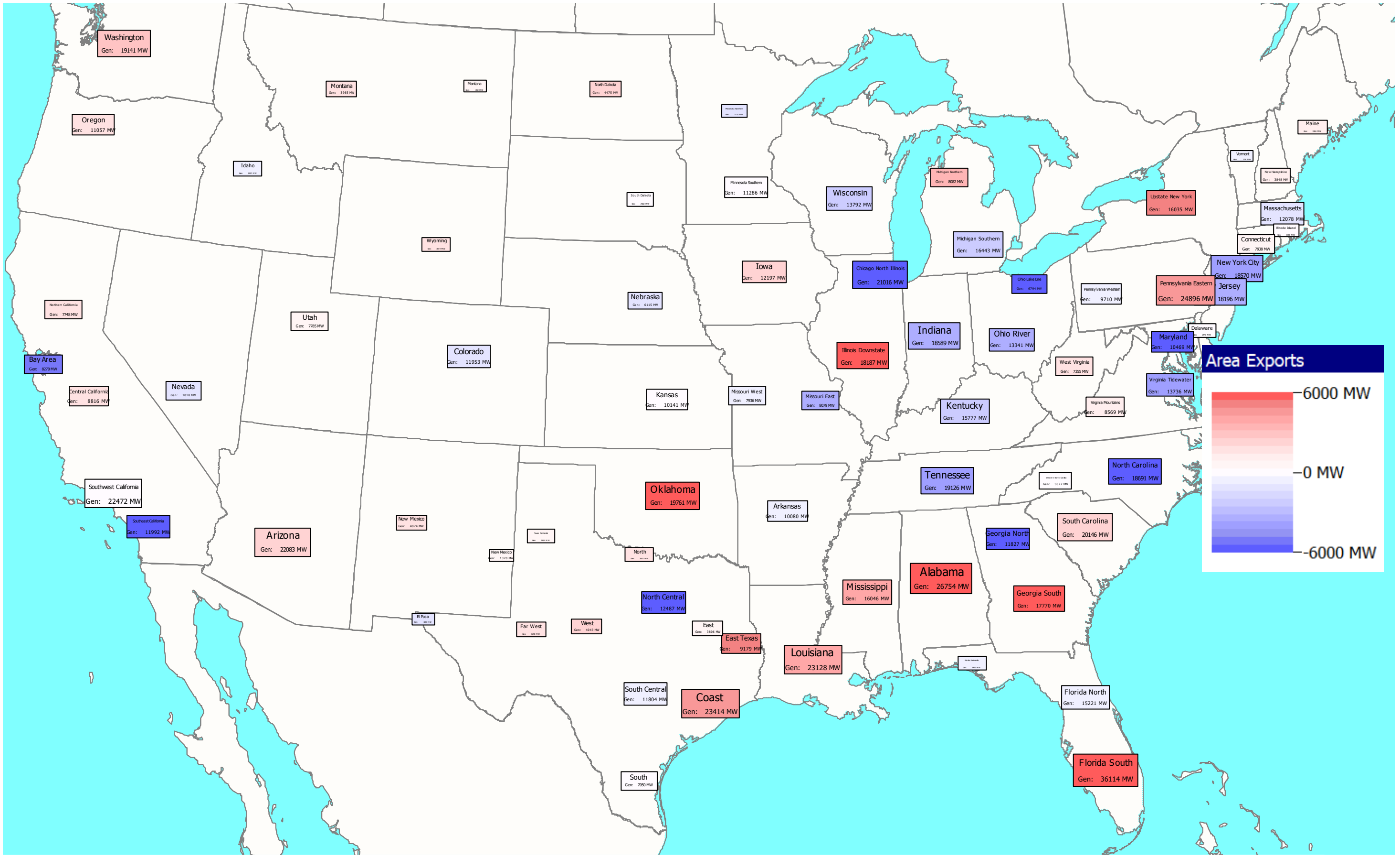
Some General Thoughts on Electric Grid Visualizations

- 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

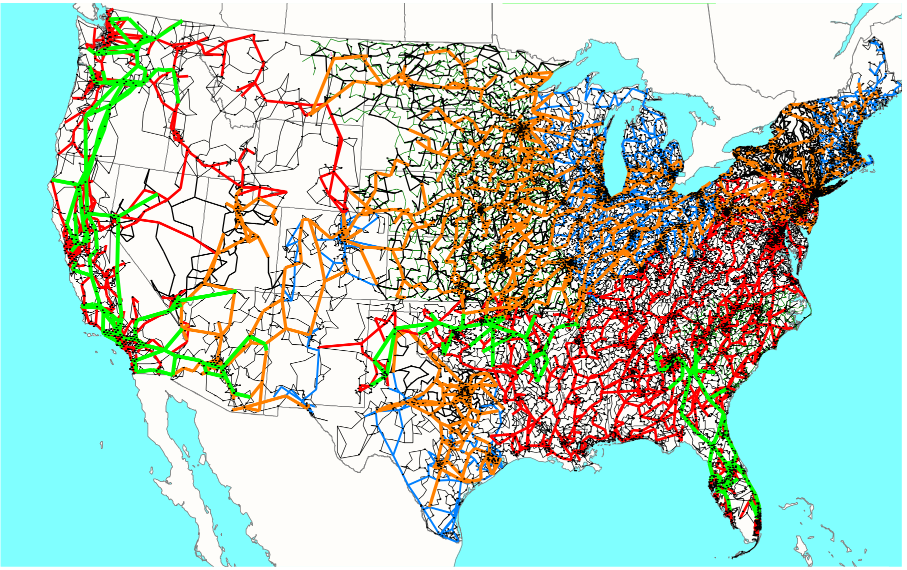
Geographic Data Views

- 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

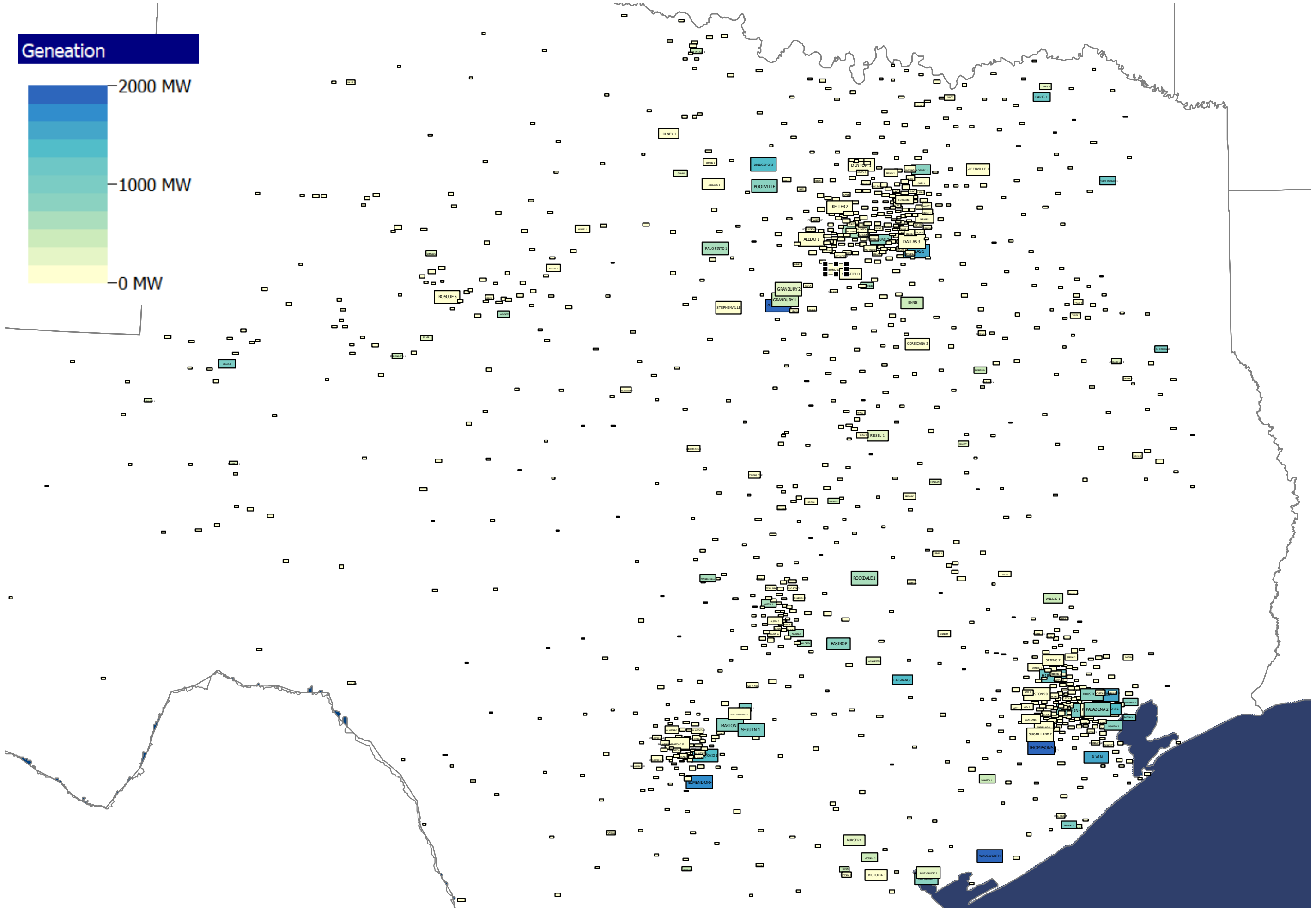
82,000 Bus System Area GDV Example



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

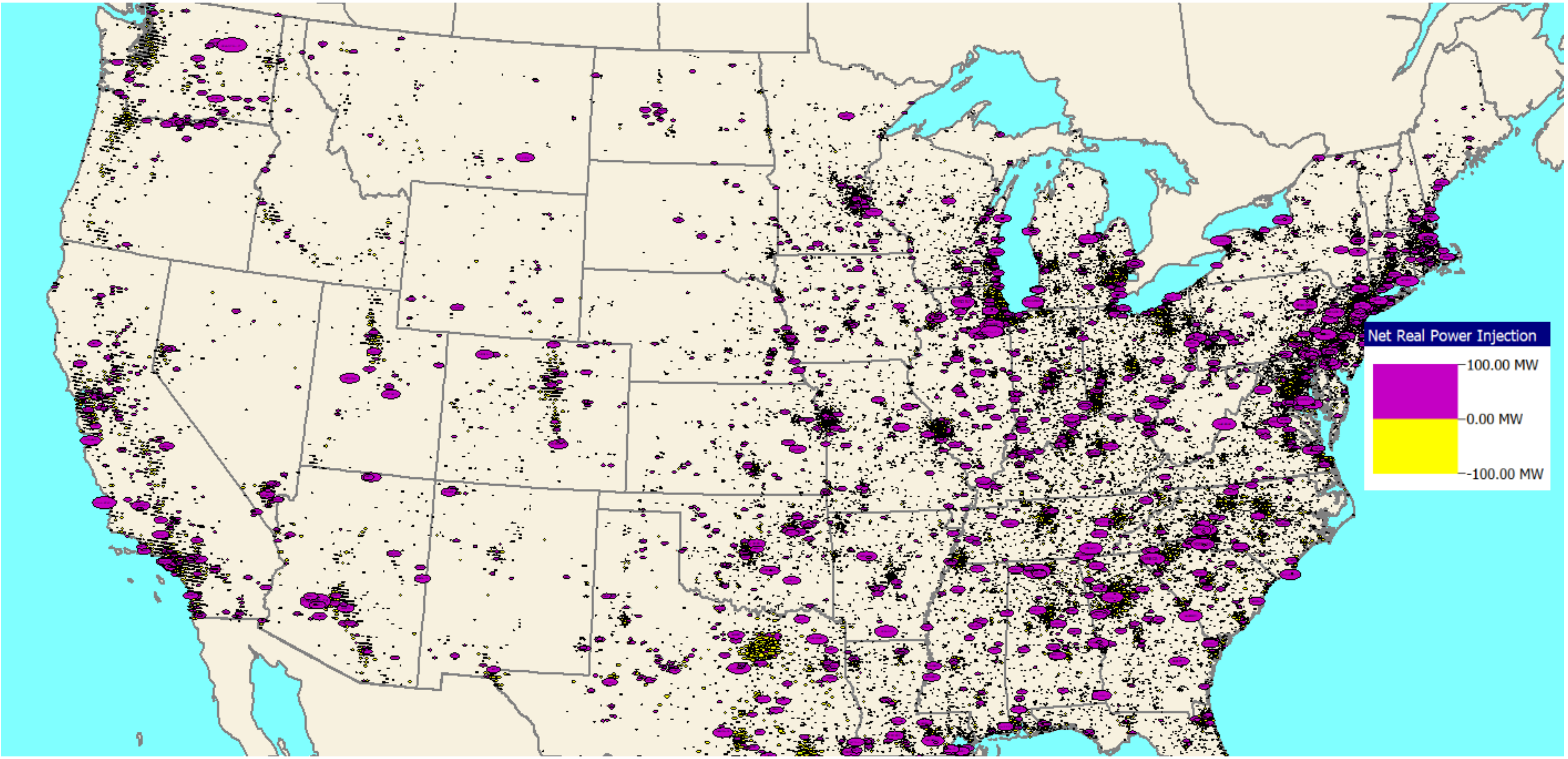


Texas 2000 Substation GDV



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

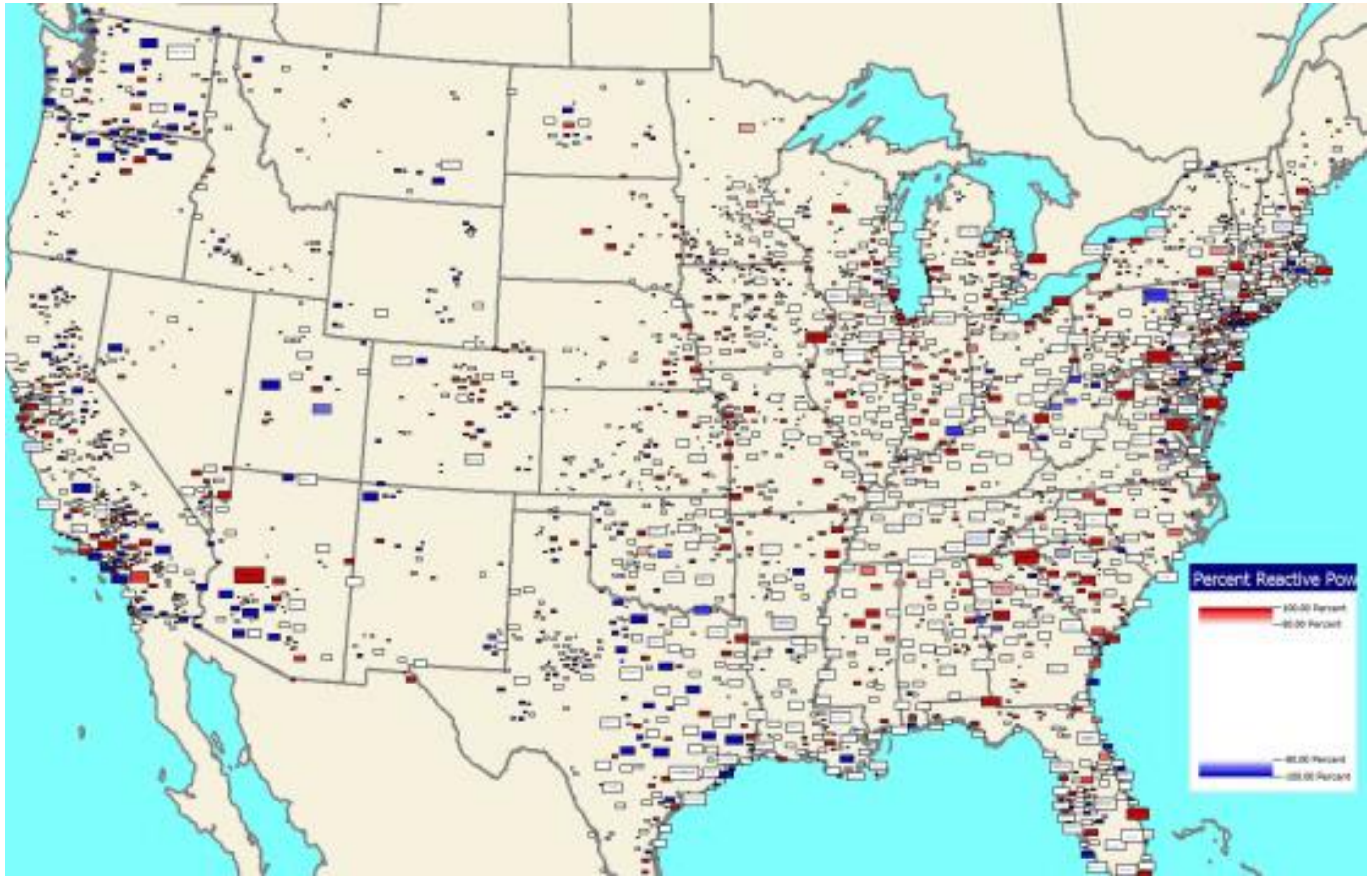
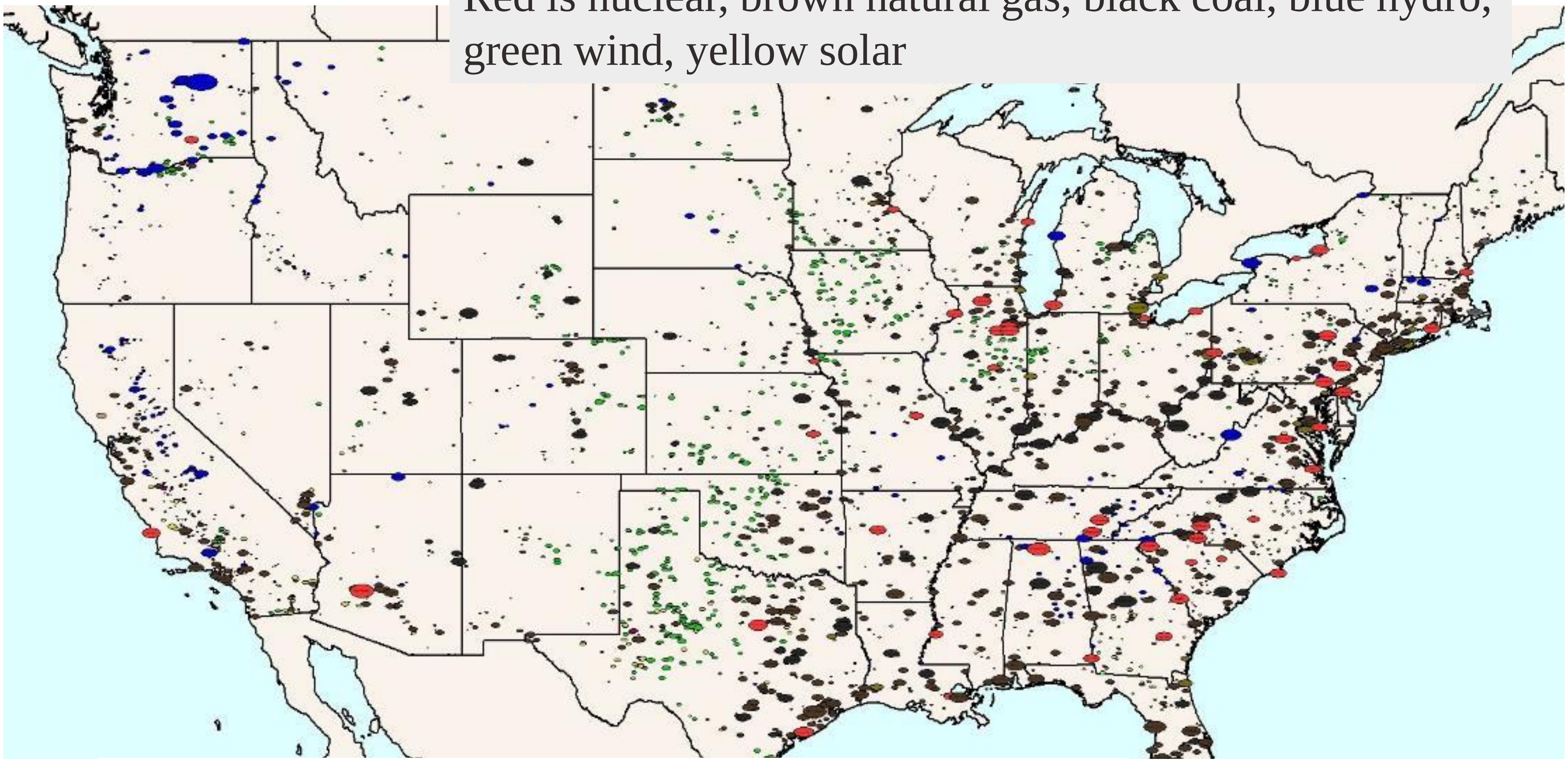


Image shows the 82K case generation with size proportional to MW output; color indicating percent reactive power. At a glance it is clear many units are at their reactive power limits.

Actual US Generation Capacity (2021) GDV Example

Red is nuclear, brown natural gas, black coal, blue hydro, green wind, yellow solar



Oval size is proportional to the substation generation; image shows public data from EIA Form 860, 2021

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

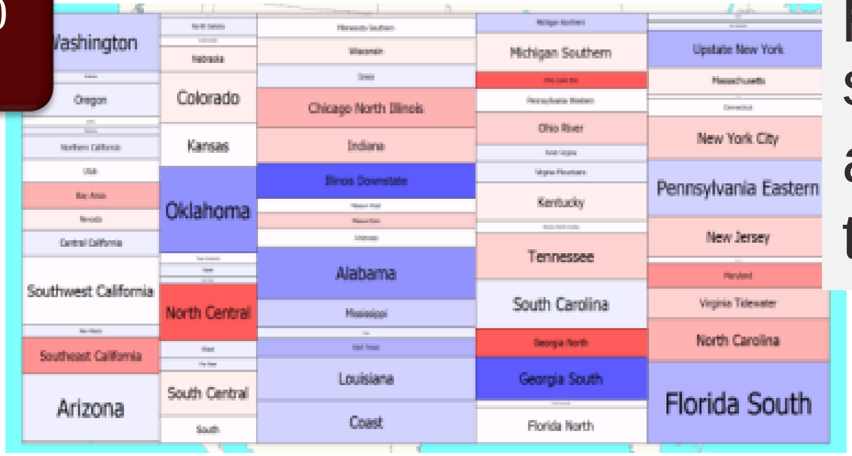
80,000 Bus System Area PGMD

0%

25%

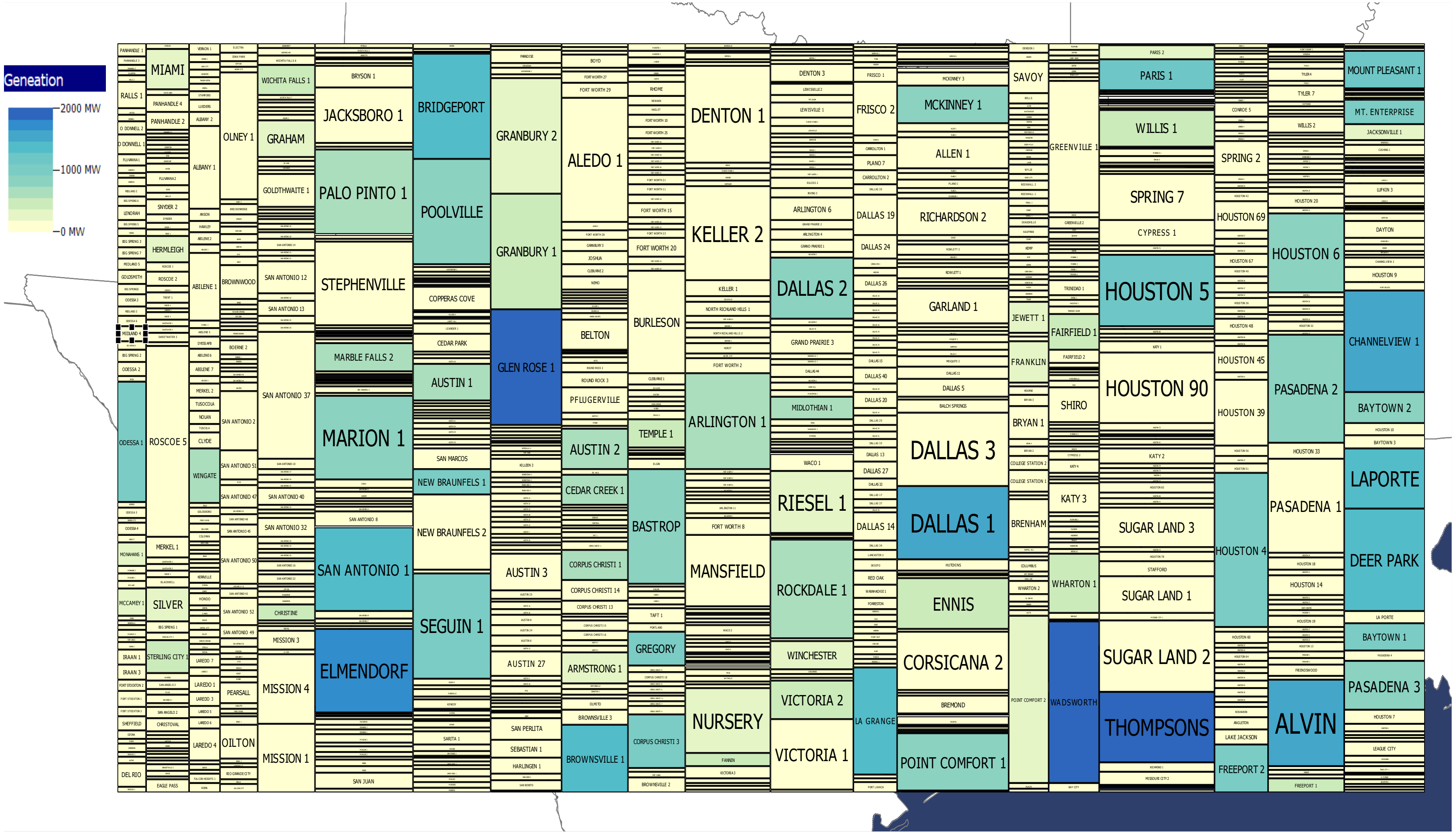
60%

100 %



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

Texas 2000 Substation PGMD

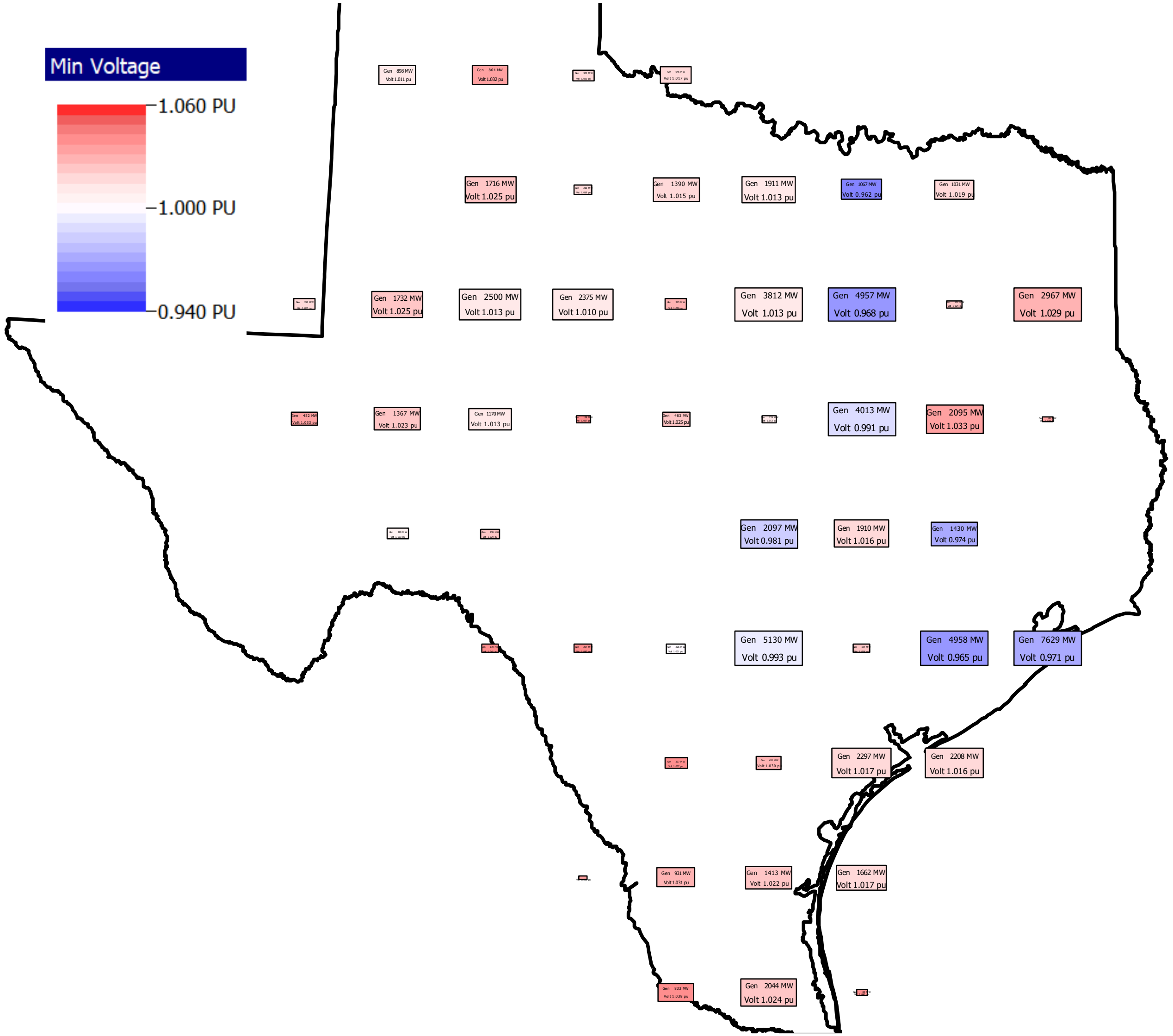


Size is proportional to the substation MW throughput, while the color is based on the amount of substation generation

GDV Grouping

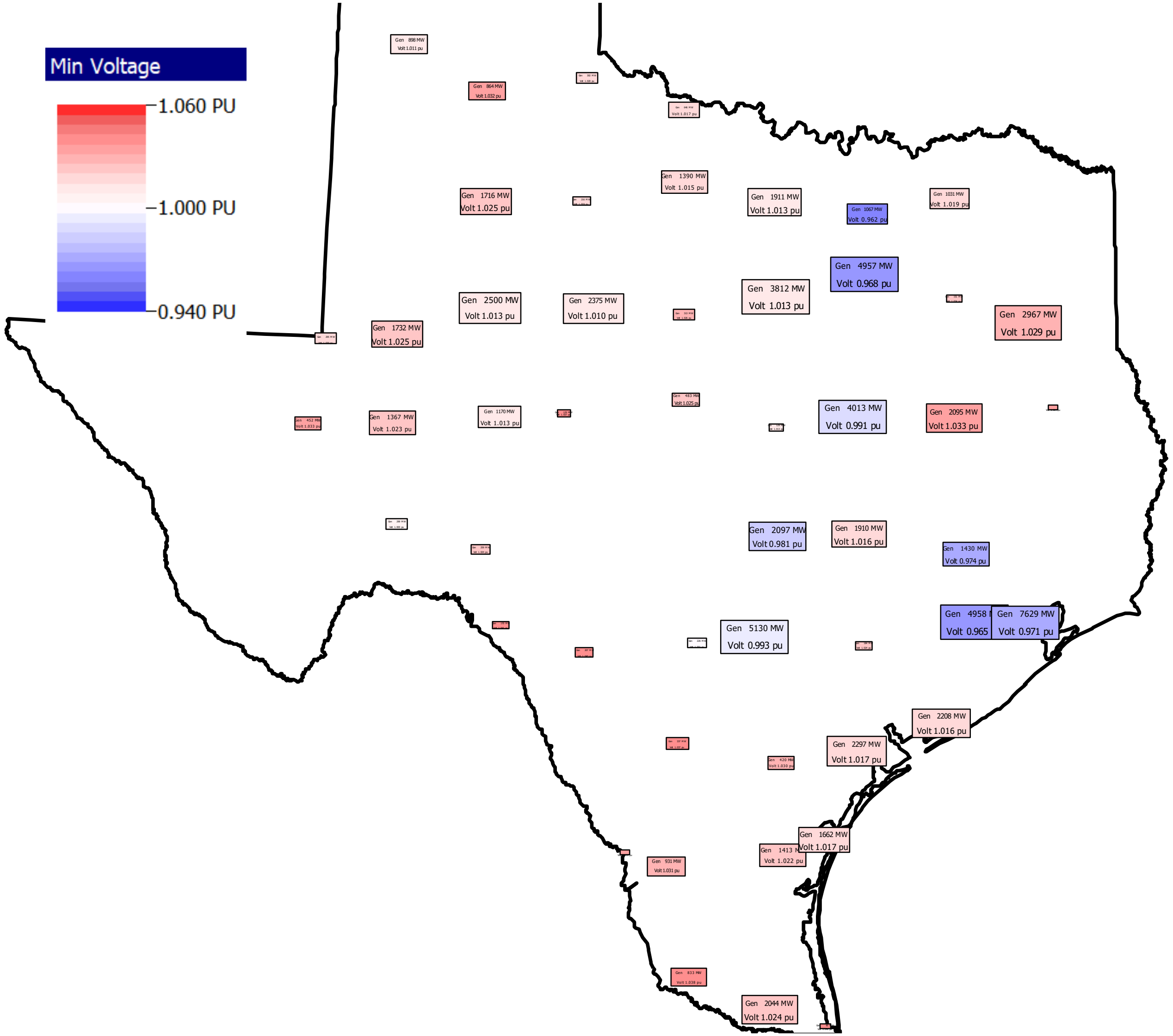
- Oftentimes there are just too many objects, so they need to be grouped
- There are many different ways to group them, with common ones by area, zone, substation, owner.
- GDV objects can also be grouped geographically with interactive grouping possible
  - Grouped object attributes can then be summarized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

Texas 7K, 10 by 10 Grid



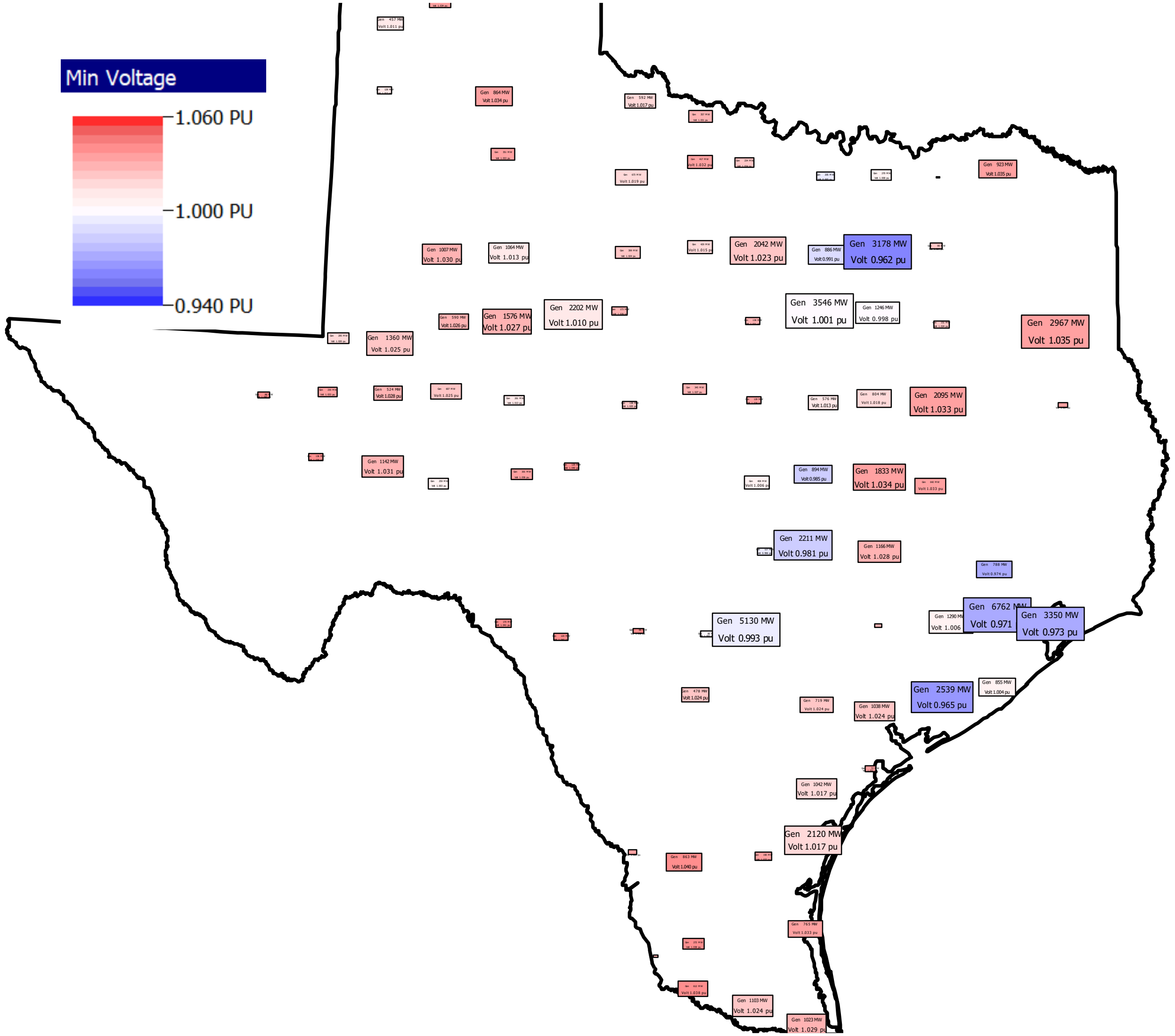
This is a 10 by 10 latitude/longitude grid with the GSO center based on the grid point. The disadvantage of this is some objects are outside the border. The size is generation, the color is the minimum voltage.

Texas 7K, 10 by 10 Grid, Weighted Center



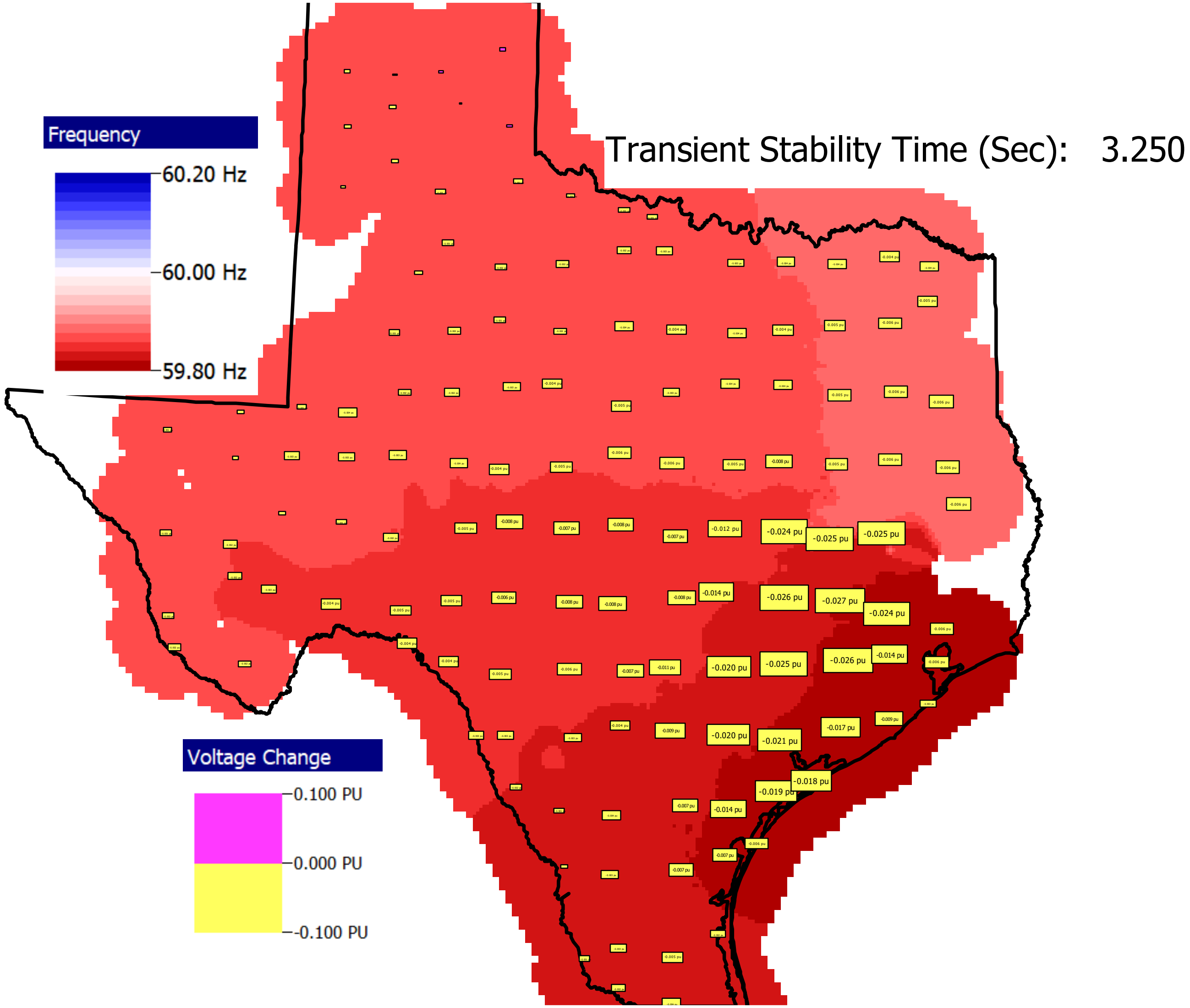
This is the same grid, except the GSO center is based on the average of all its elements. This approach is often preferred.

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

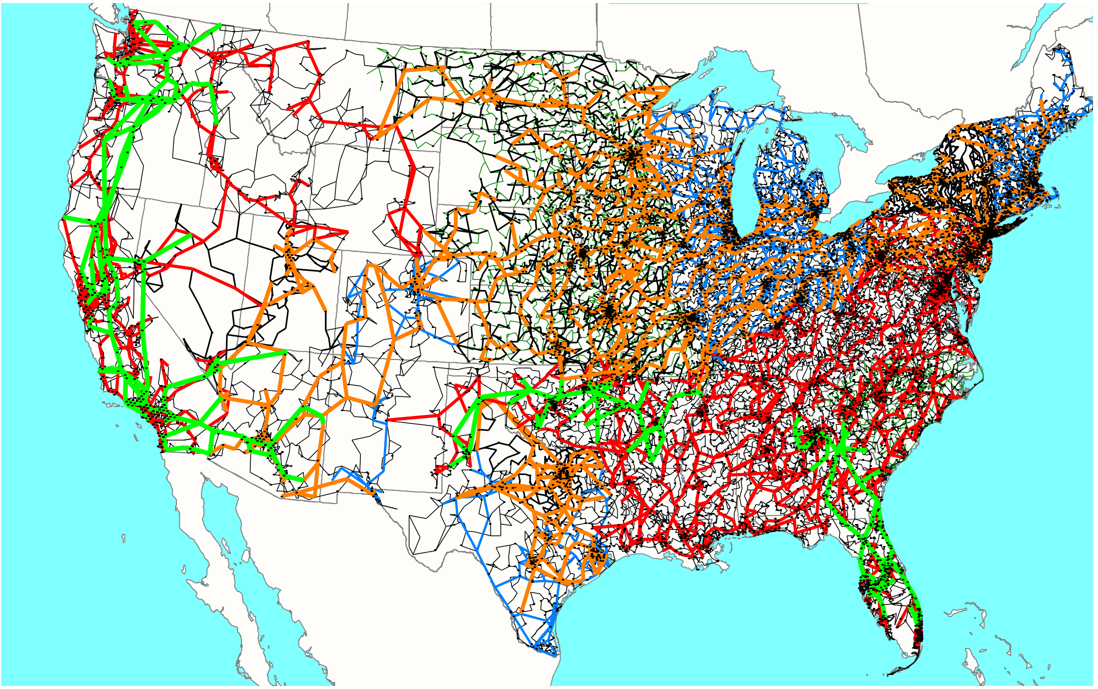


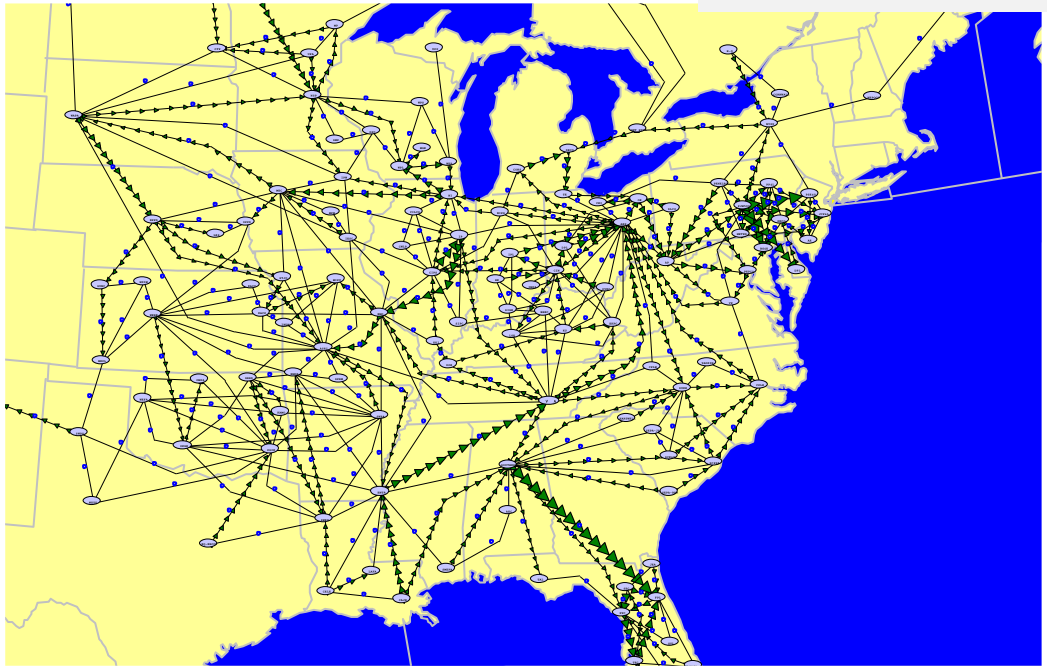
We commonly combine the GSO displays with contours to visualize multiple values. This image (from a stability run) shows a frequency contour (made by substation GDVs) with GSOs showing the voltage change.

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

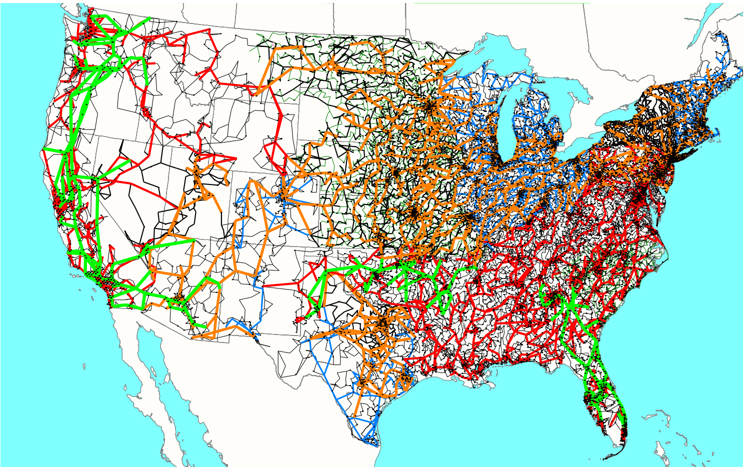
Area to area flow visualization, EPSON, 1998, Zurich, CH

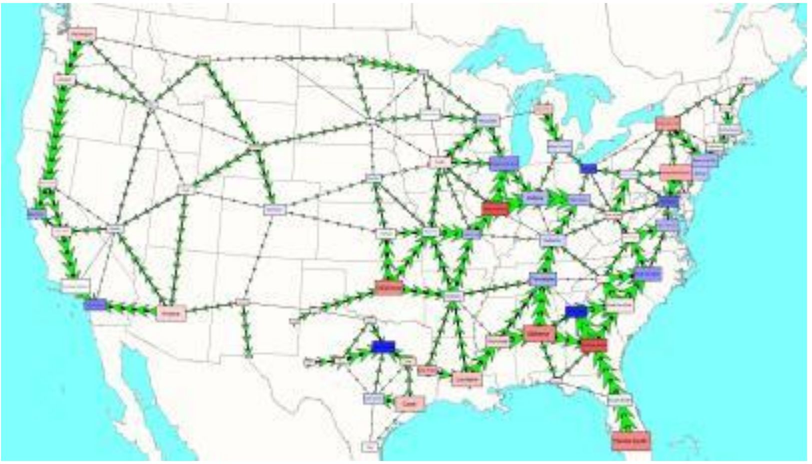




Delaunay Triangulation Based Wide-Area Flow Aggregation

- 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





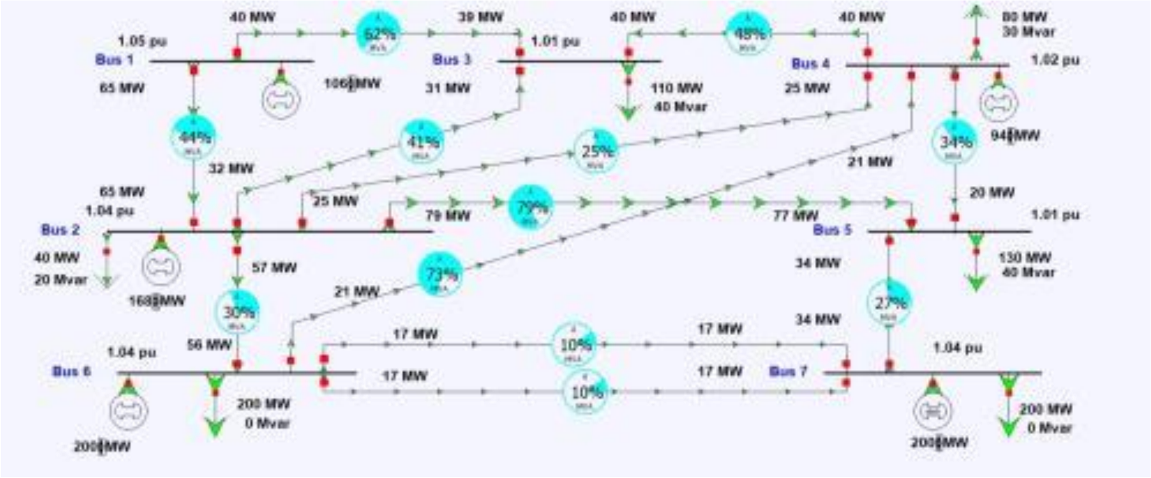
T.J. Overbye, J. Wert, K. Shetye, F. Safdarian, and A. Birchfield, "Delaunay Triangulation Based Wide-Area Visualization of Electric Transmission Grids," Kansas Power and Energy Conference (KPEC), Apr. 2021.

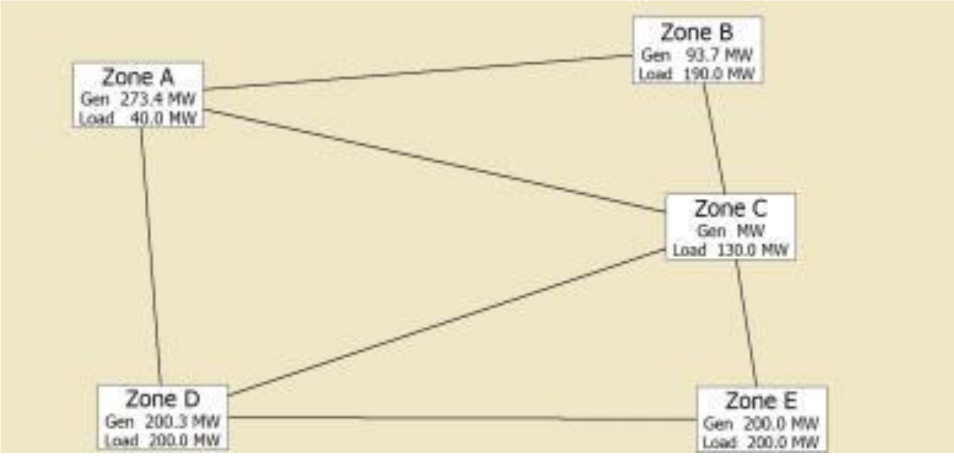
Delaunay Triangulation Based Wide-Area Flow Aggregation

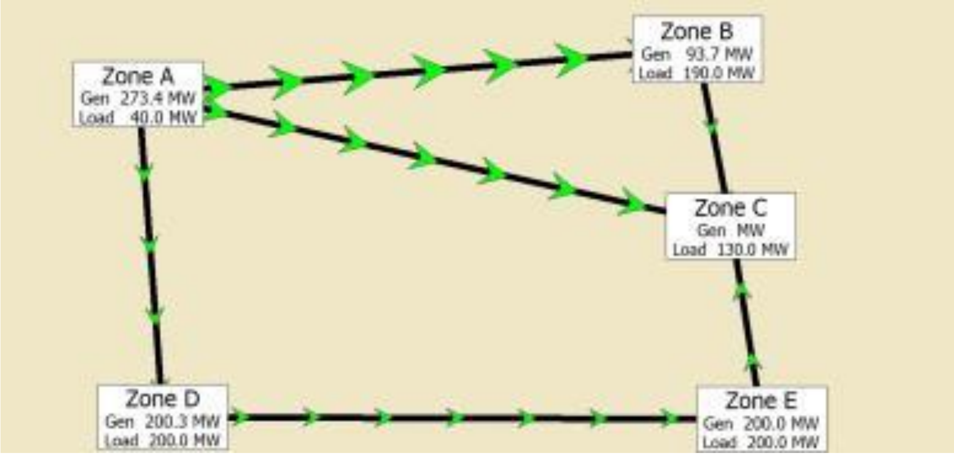
- The algorithm is simple and fast
  - Assume *n* buses, *m* bus groups and *b* branches joining the buses, with geographic information available for the buses
  - Map each branch to its terminal bus group(s)
  - Do a Delaunay triangulation of the *m* bus groups to create a set *S* of segments
  - For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

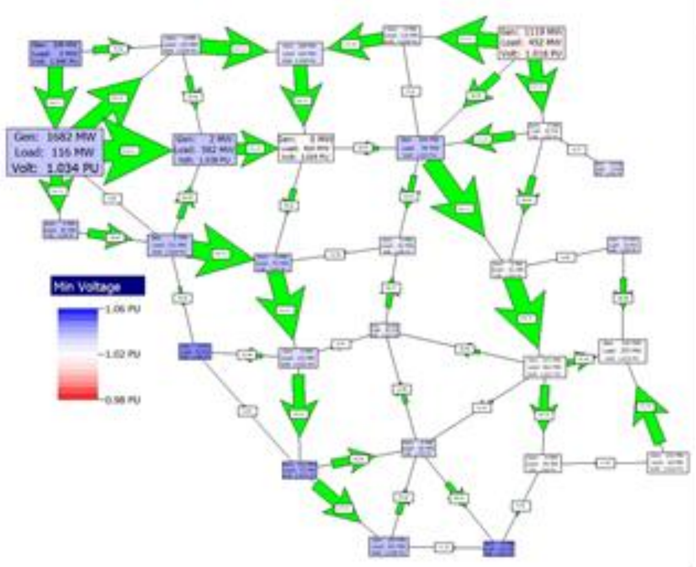
- In general calculating the path between two bus groups is not exceptionally fast (given that is has to be applied to each branch)
- However, when the graph is based on a Delaunay triangulation paths can be calculated very quickly
- Different algorithms exist to do this, with the paper using a Greedy 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 and then two applications of the algorithm

Original System, b=599

Algorithm
m =208, s=311

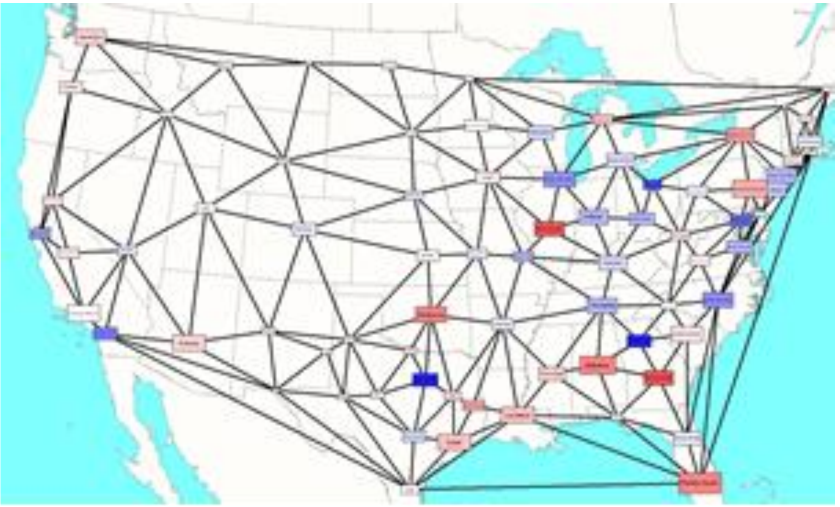


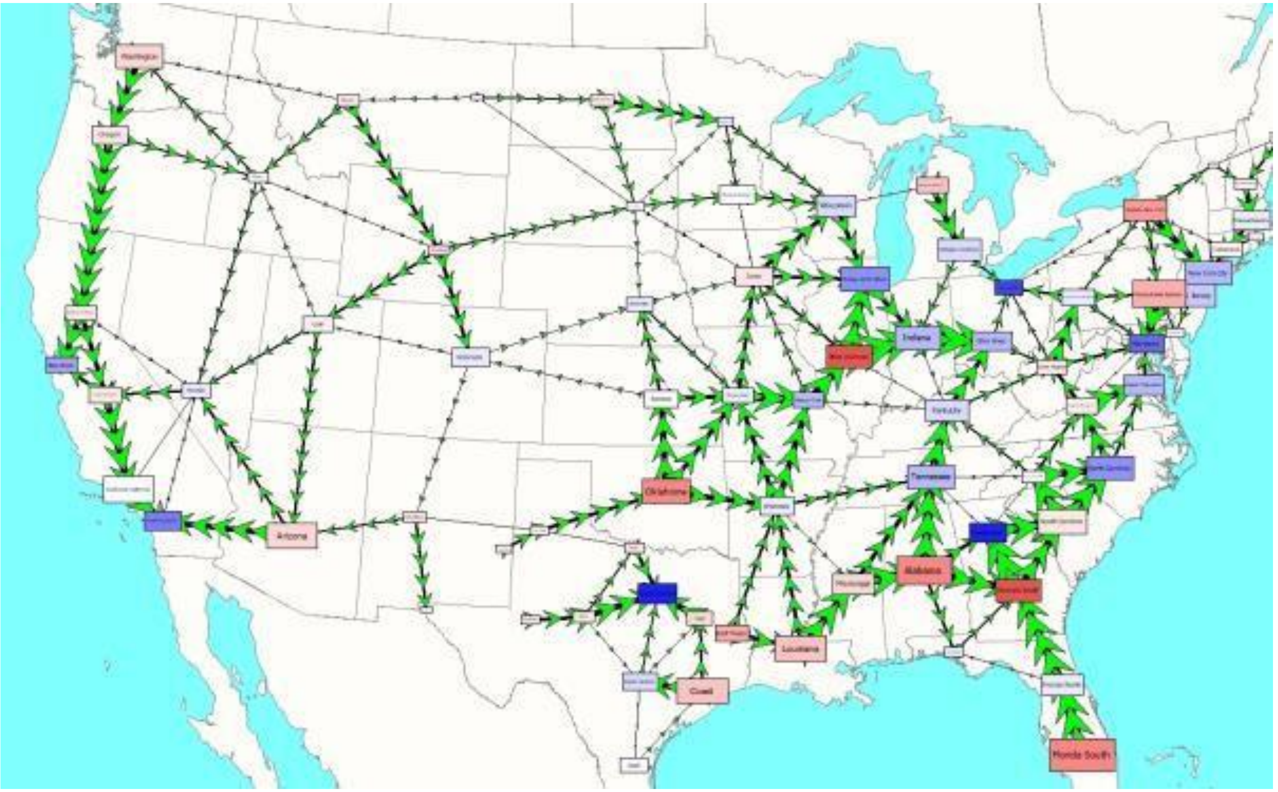
Algorithm
m =28, s=49

Algorithm on 82,000 Bus Grid

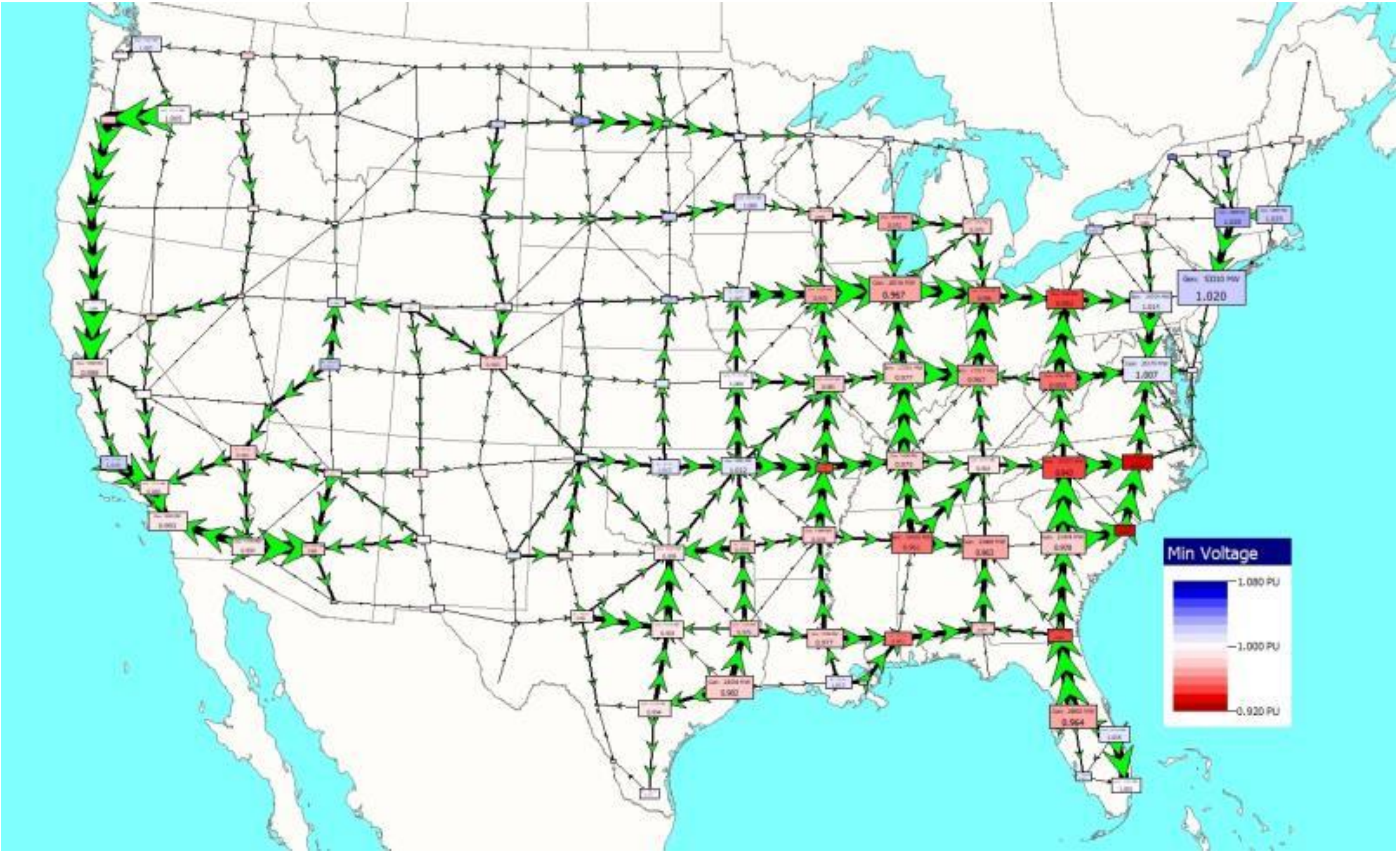
- In all cases for the following slides the algorithm took less than one second

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



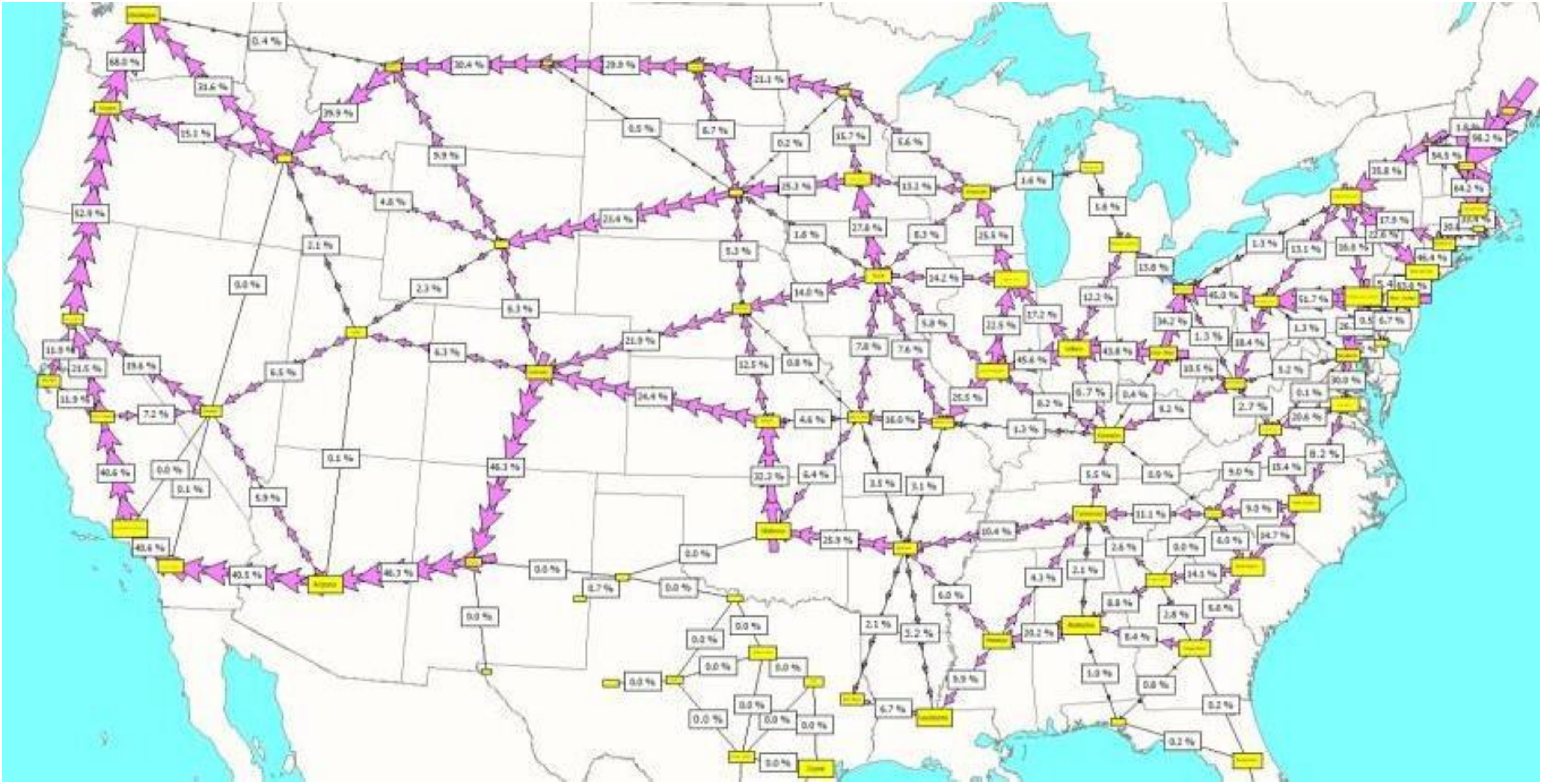


Algorithm on 82,000 Bus Grid



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)

Visualization of Stability Results, 82K

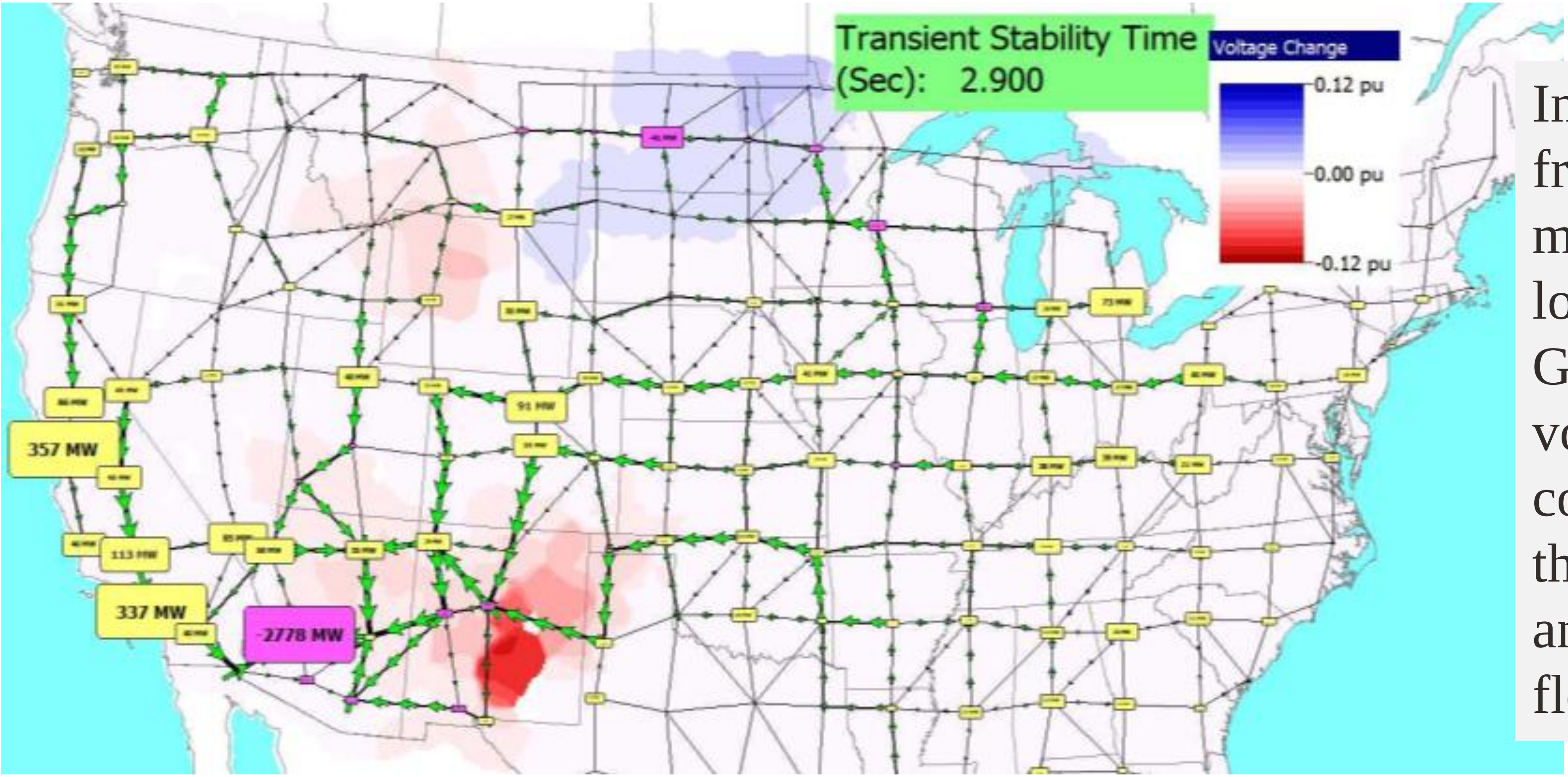


Image is snapshot from a stability results movie for a generator loss contingency, with GDVs showing the voltage change contour, GSOs the generation change, and GSLOs the line flow changes.

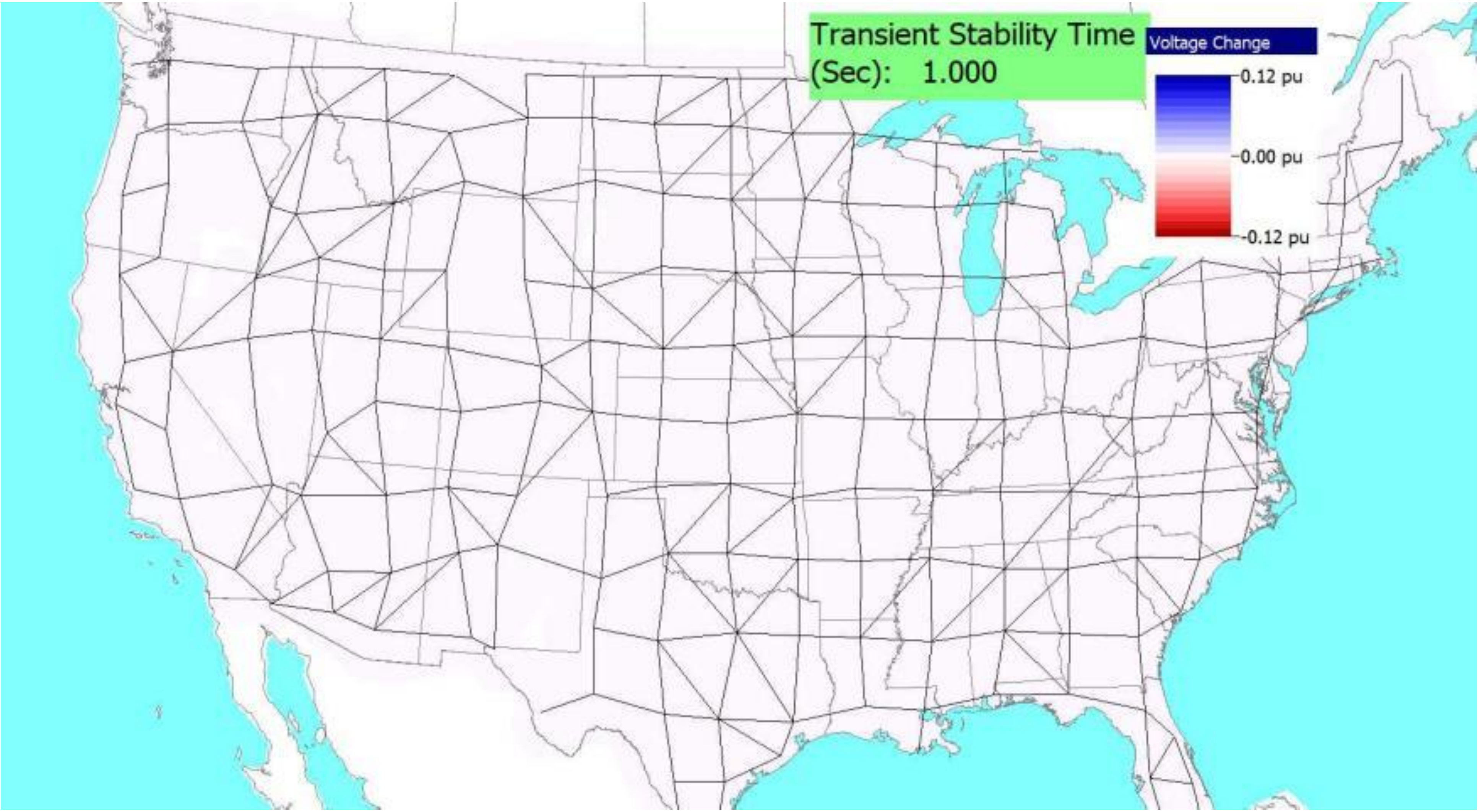
Some Techniques for Dealing with Time-Varying Data

- 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!

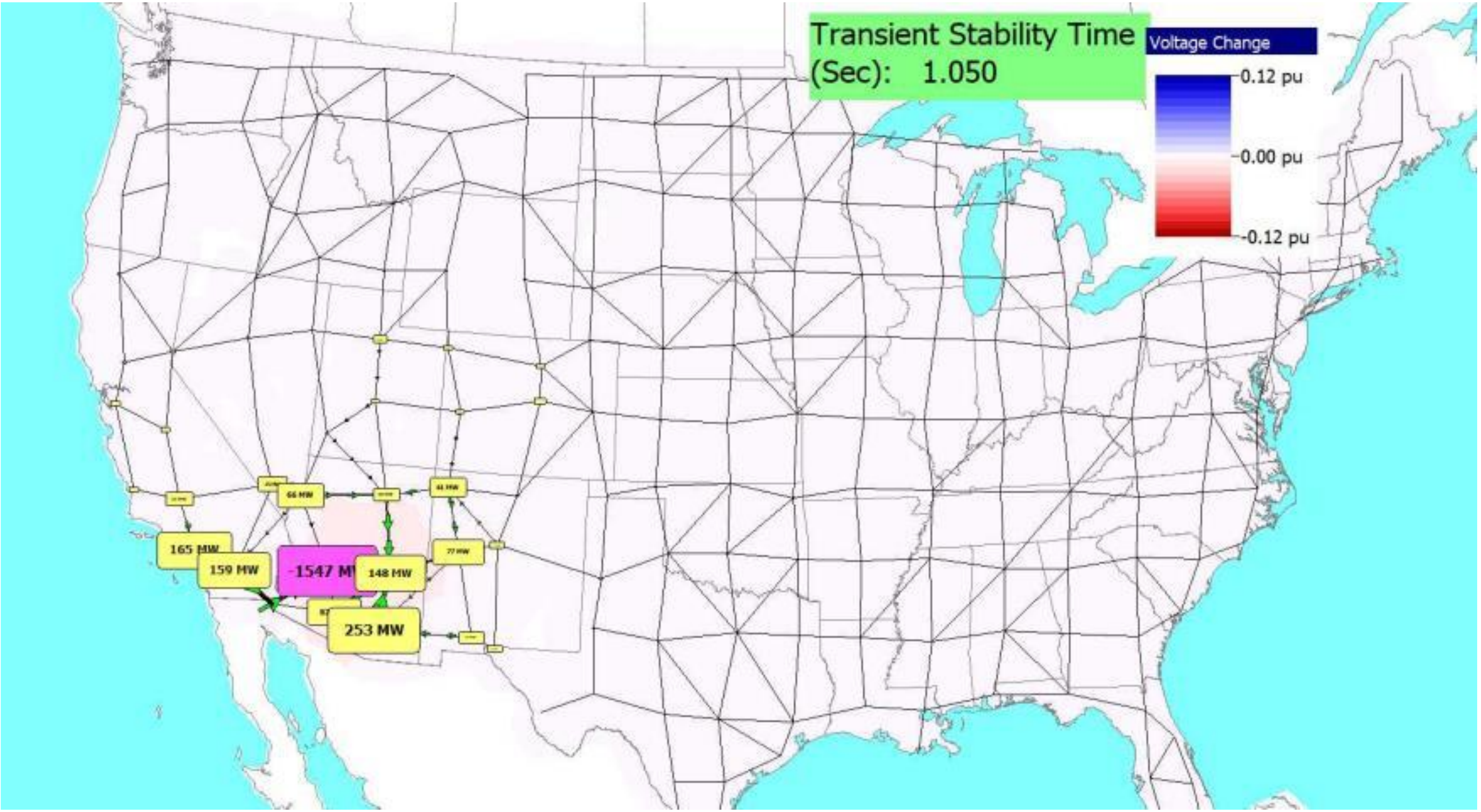
Animation loops

- 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

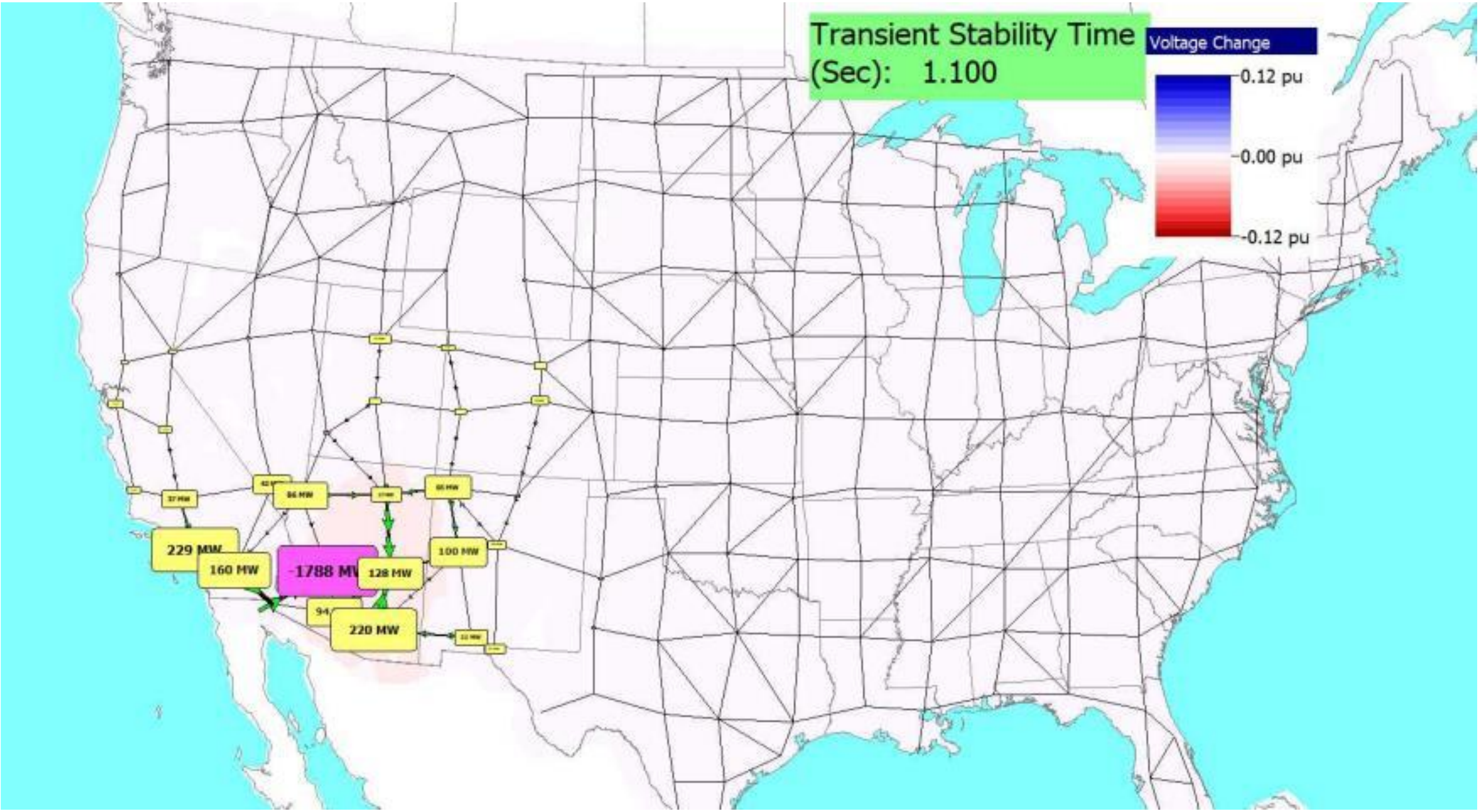
Animation Example: 1.00 Seconds



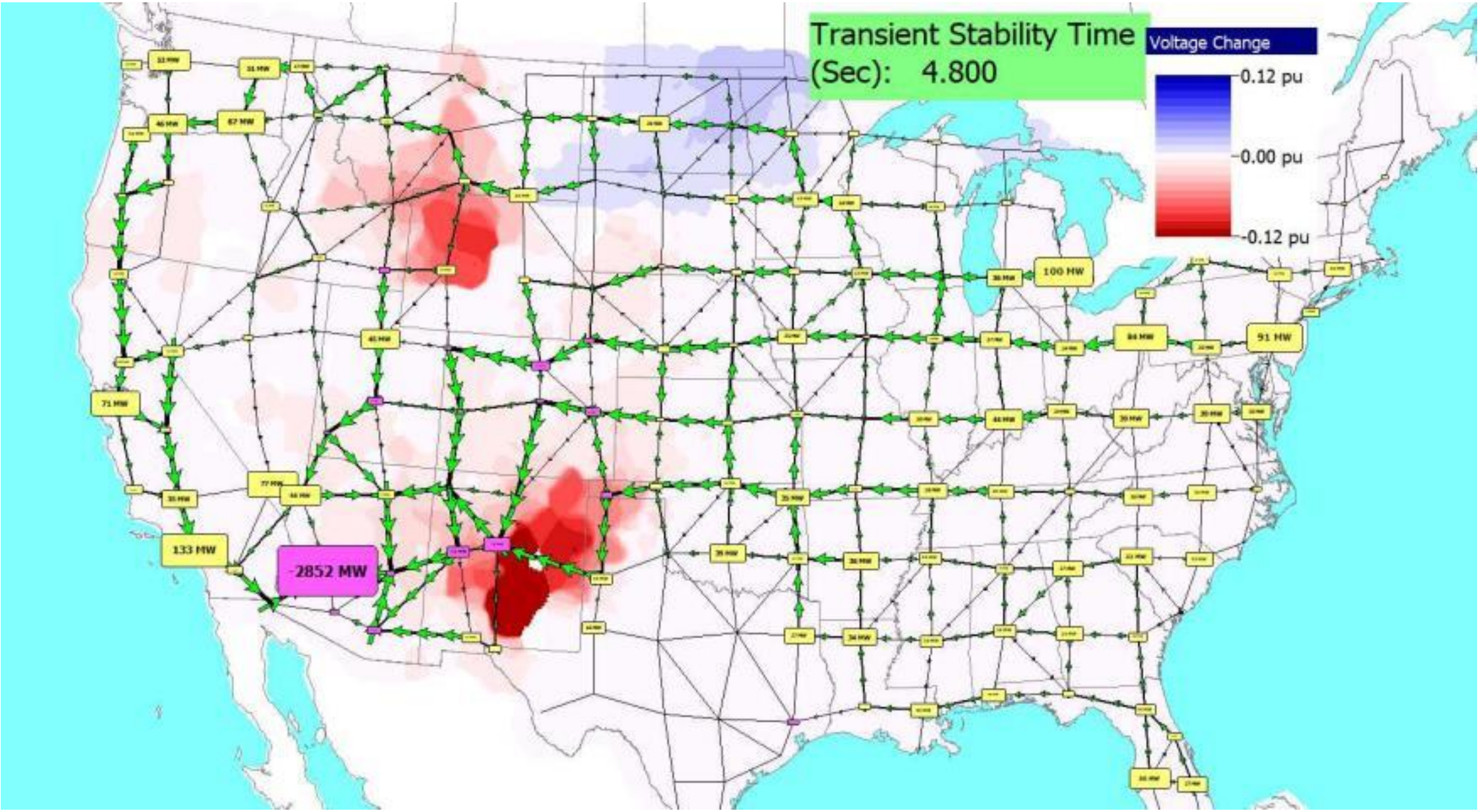
Animation Example: 1.05 Seconds



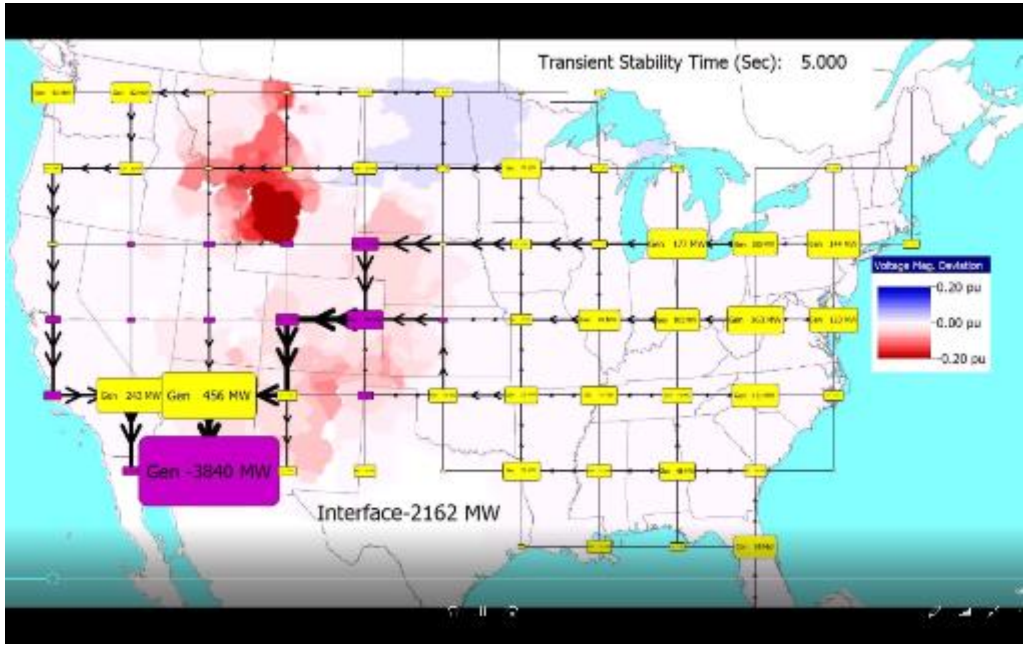
Animation Example: 1.10 Seconds

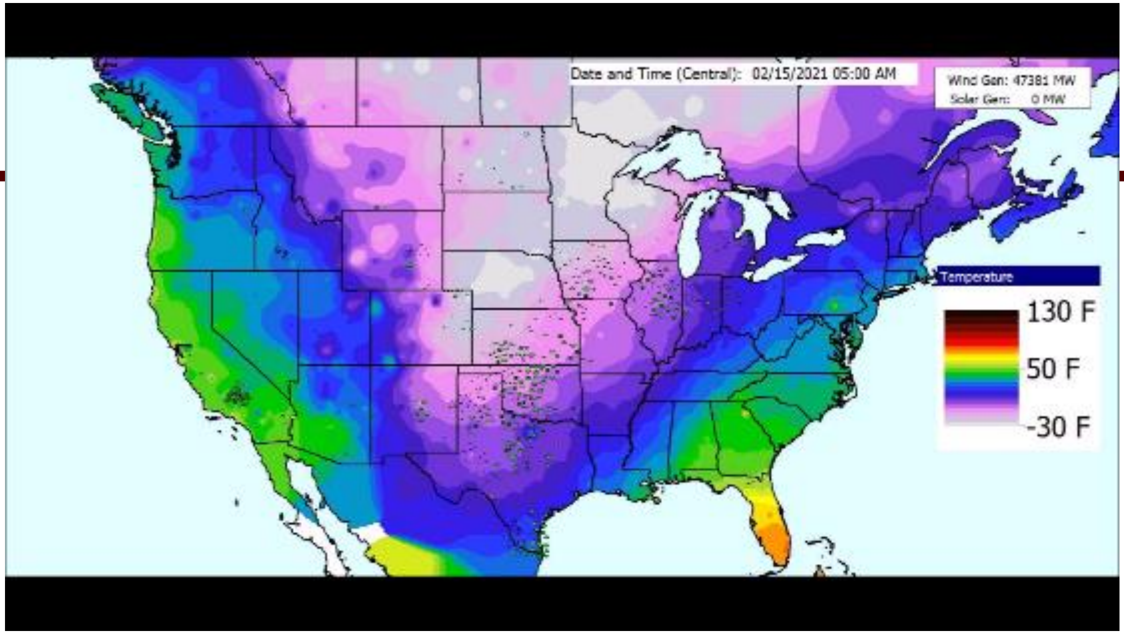


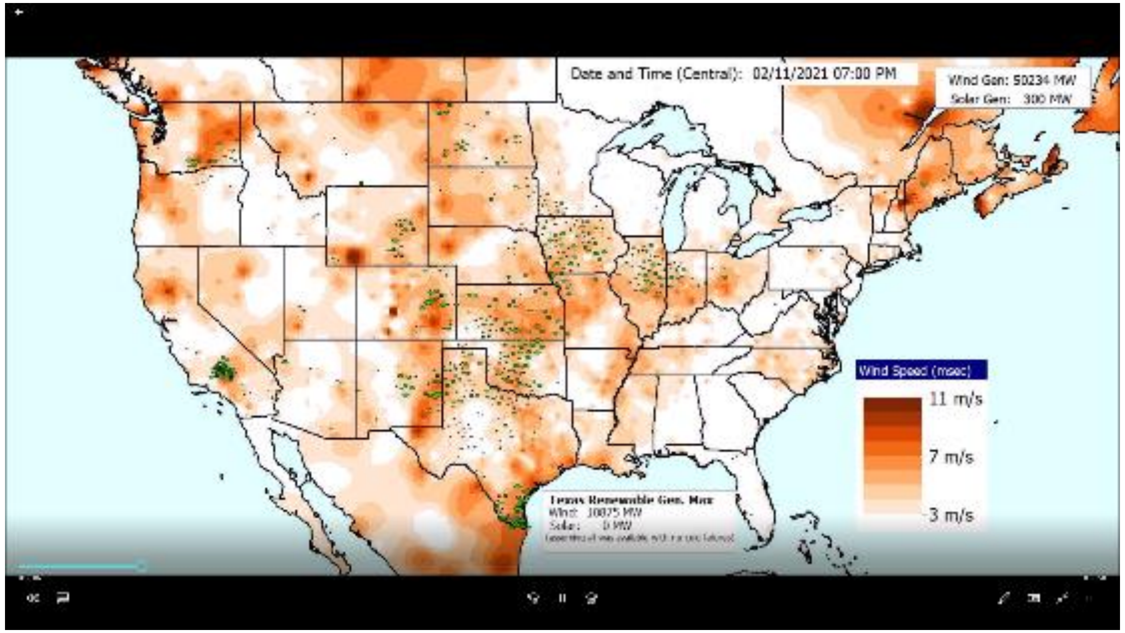
Animation Example: 4.80 Seconds



A Few Animations







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, F. Safdarian, W. Trinh, Z. Mao, J. Snodgrass, J. Yeo, "*An Approach for the Direct Inclusion of Weather Information in the Power Flow,*," Proc. 56th Hawaii International Conference on System Sciences (HICSS), January 2023.
- J.L. Wert, F. Safdarian, T.J. Overbye, D.J. Morrow, "*Case Study on Design Considerations for Wide-Area Transmission Grid Operation Visual Storytelling*," in the IEEE Kansas Power and Energy Conference (KPEC), Manhattan, KS, April 2022.
- 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?

This presentation is available at overbye.engr.tamu.edu/presentations/